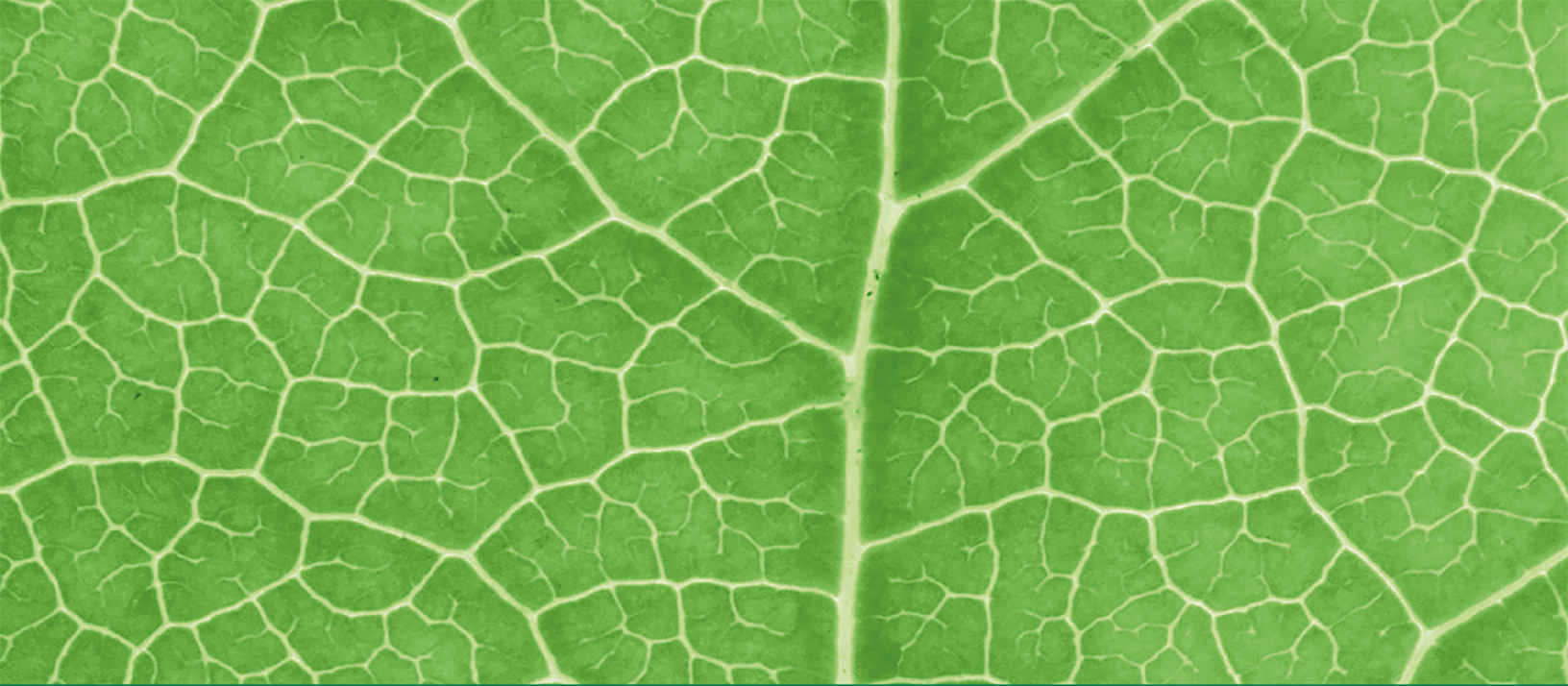




CARBON-NEGATIVE FARMING

PATHWAYS, PRACTICES, AND POLICIES FOR SUSTAINABLE AGRICULTURAL FUTURES

Farooq Ahmad Khan, Zaffar Mahdi Dar, Saddam Hussain
and Sumati Narayan





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Preface

The accelerating climate crisis has placed agriculture at the center of both the problem and the solution. While traditional farming practices contribute significantly to global greenhouse gas emissions, innovative systems rooted in ecological restoration and carbon stewardship are redefining agriculture's role in climate action. This book, *Carbon-Negative Farming*, emerges from that imperative, an effort to synthesize science, technology, and practice into a coherent framework for transforming agriculture from a net emitter to a net sink of carbon.

Drawing from the latest global and Indian research, this book explores the science, methods, and policy mechanisms that enable farms to achieve net-negative greenhouse gas outcomes. It translates complex concepts, such as carbon sequestration, regenerative land use, biochar application, enhanced rock weathering, and carbon accounting, into actionable insights for researchers, practitioners, and policymakers. The chapters provide both conceptual clarity and practical guidance, linking field-based evidence with emerging innovations in digital monitoring, carbon markets, and sustainable finance.

The purpose of this book is two-fold: first, to deepen scientific understanding of how farming systems can actively remove carbon dioxide from the atmosphere; and second, to present replicable pathways for scaling these practices in diverse agro-ecological regions. By integrating soil science, plant physiology, ecology, and economics, *Carbon-Negative Farming* aspires to serve as a comprehensive reference for advancing climate-positive agriculture. The inclusion of plant physiological principles highlights the central role of photosynthesis, carbon allocation, and plant–soil interactions in determining the efficiency of carbon capture and storage within agricultural ecosystems.

At its core, this book recognizes that the journey to net-negative agriculture is not only a technical transition but a philosophical one, a return to harmony between human activity and natural systems. The integration of indigenous wisdom, regenerative principles, and circular resource use offers a vision of farming that restores the earth while feeding its people.

It is hoped that this book will serve researchers, students, development professionals, and policymakers seeking a science-based, systems-oriented understanding of carbon-negative agriculture. The ideas presented here reflect both the urgency of the climate challenge and the optimism that resilient, restorative, and carbon-absorbing food systems are within our reach.

Authors

About the Authors

Dr. Farooq Ahmad Khan is a Professor-cum-Chief Scientist specializing in Plant Physiology with extensive experience and contributions in the field of agricultural and horticultural sciences. With a distinguished career marked by over three decades of research, teaching, and leadership, Dr. Khan has significantly advanced understanding in areas such as physiological stress management in crops, post-harvest physiology, seed priming, and sustainable production techniques including hydroponics and microgreens. He has authored numerous peer-reviewed research papers, books, and book chapters, contributing to climate-smart agriculture, sustainable horticulture, and plant stress physiology. Dr. Khan has led major research projects and regularly serves as a keynote speaker at international and national conferences. His work integrates innovative practices in plant science to support climate resilience and enhance agricultural productivity, making him a leading authority in sustainable farming solutions.

Dr. Zaffar Mahdi Dar is an Associate Professor and Senior Scientist in Plant Physiology at the Faculty of Horticulture, Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K), Shalimar, Jammu and Kashmir, India. He obtained his B.Sc. (Agriculture) in 2002, M.Sc. (Plant Physiology) in 2004, and Ph.D. (Plant Physiology) in 2008, specializing in *salicylic acid-mediated stress alleviation in crops*.

With over 15 years of academic and research experience, Dr. Dar has established expertise in plant stress physiology, biofertilizers, sustainable agriculture, and crop management under temperate Himalayan conditions. His research encompasses drought and salinity tolerance, antioxidant defense mechanisms, soil microbial diversity, hydroponics,

vermicomposting, and organic production systems, with particular focus on high-altitude agroecosystems.

A prolific researcher and educator, Dr. Dar has published more than 80 research papers, 30 review articles, and five books in reputed national and international outlets. He has guided several postgraduate and doctoral scholars and actively organizes training programs and workshops on experimental crop physiology and eco-innovative farming. His current work emphasizes drought stress memory, precision nutrient management, hydroponic crop production, and climate-resilient agriculture.

Saddam Hussain is a researcher in plant physiology and sustainable horticulture, pursuing his Ph.D. at Sher-e-Kashmir University of Agricultural Sciences and Technology, Kashmir. He holds a master's degree with distinction from Sam Higginbottom University, Prayagraj, and a B.Sc. (Hons.) Agriculture from Sri Karan Narendra Agriculture University, Jobner. His research on microgreens, hydroponics, and PGPR applications advances sustainable solutions for food and nutritional security. A recipient of the *Best Presentation Award* (2024) and holder of a patent for a seed-coating device, he has co-edited *Innovative Practices in Sustainable Horticulture*, reviewed for reputed journals, and published internationally. Passionate about innovation and collaboration, he promotes leadership and community engagement through research and outreach.

Dr. Sumati Narayan is a distinguished Scientist and Professor at the Sher-e-Kashmir University of Agricultural Sciences and Technology of Kashmir (SKUAST-K). A native of the rural Etawah district of Uttar Pradesh, he inherited a strong passion for agriculture from his father, the eminent agronomist **Dr. S. S. Prajapati**. He earned his **B.Sc. (Hons.) Agriculture** from Kanpur University, **M.Sc. (Agronomy)** from Meerut University, and **Ph.D. (Agronomy)** from SKUAST-K. With over three decades of academic

and research experience at institutions including **GBPUA&T, Pantnagar,** and **SKUAST-K,** Dr. Narayan is recognized for his leadership in **organic and sustainable farming.** His research focuses on **natural resource conservation, ecosystem restoration, and climate-resilient agriculture.** He has authored and edited several **books, monographs, and research papers,** developed **innovative technologies and crop varieties,** and guided **more than 25 postgraduate and doctoral scholars.** Dr. Narayan has also led multiple **externally funded projects** and received numerous **awards** for his contributions to Indian agriculture.

Chapter - 1

Introduction

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The global climate crisis stands as one of the most pressing challenges of the 21st century, with greenhouse gas (GHG) emissions reaching unprecedented levels. Atmospheric concentrations of carbon dioxide (CO₂) have risen from pre-industrial levels of approximately 280 ppm to over 420 ppm in 2024, primarily driven by fossil fuel combustion, deforestation, and intensive agricultural practices ([IPCC, 2023](#); NASA, 2023). This increase amplifies the greenhouse effect, trapping heat in the atmosphere and driving global warming, with wide-ranging consequences including extreme weather events, sea-level rise, biodiversity loss, and ocean acidification (IPCC, 2021; NOAA, 2022).

Agriculture plays a significant role in this crisis. Direct agricultural activities such as methane (CH₄) emissions from rice cultivation and livestock, nitrous oxide (N₂O) emissions from fertilized soils, and CO₂ emissions from land-use change account for approximately 11% of global GHG emissions. Expanding the scope to the Agriculture, Forestry, and Other Land Use (AFOLU) sector brings this figure to about 21% of global emissions ([Nabuurs *et al.*, 2022](#)), while the entire food system, including production, processing, and distribution, contributes 25–30% of total emissions ([Ritchie, 2021](#)).

Paradoxically, agriculture also holds immense potential as a part of the solution. Through the adoption of regenerative and climate-smart practices, such as enhancing soil organic carbon (SOC), restoring degraded lands, integrating agroforestry, and improving nutrient and water efficiency, the

sector can transition from a net emitter to a net carbon sink ([Smith *et al.*, 2020](#); [Lal, 2020](#)). Central to this transition is the distinction between carbon neutrality and carbon negativity. While carbon neutrality seeks to balance emissions with removals to achieve net-zero impact, carbon negativity actively removes more CO₂ than is emitted, creating a net atmospheric drawdown ([UNEP, 2022](#); [Rockström *et al.*, 2017](#)). Carbon-negative farming integrates scientific innovation, ecological restoration, and traditional knowledge to produce food while enhancing CO₂ removal. This approach aligns with the Paris Agreement's dual goals of emission reduction and carbon sink enhancement and supports several Sustainable Development Goals ([United Nations, 2015](#)). Transforming agriculture into a net absorber of carbon is critical to stabilizing the climate and fostering a sustainable future.

Carbon-negative farming refers to agricultural systems and practices that achieve a net removal of greenhouse gases (GHGs) from the atmosphere, with removals exceeding emissions generated by the farming operation. This concept extends beyond carbon neutrality by not only offsetting on-farm emissions but actively contributing to atmospheric carbon drawdown ([Lal, 2020](#); [Smith *et al.*, 2020](#)). The scope of carbon-negative farming encompasses diverse land management strategies including soil carbon sequestration, biochar application, agroforestry, integrated crop-livestock systems, and renewable energy integration. Collectively, these enhance the carbon storage capacity of soils, vegetation, and biomass while minimizing non-CO₂ GHG emissions such as methane (CH₄) and nitrous oxide (N₂O).

It is important to distinguish carbon-negative farming from sustainable and regenerative agriculture. Sustainable agriculture aims to meet present food needs without compromising future generations' ability to do the same ([FAO, 2018](#)), while regenerative agriculture emphasizes restoring

ecosystem functions and soil health ([Rhodes, 2017](#)). However, carbon-negative farming prioritizes quantifiable net-negative GHG outcomes. Sustainable systems may still be net emitters if emissions reductions are not coupled with active removal mechanisms. Regenerative agriculture often overlaps with carbon-negative approaches through techniques such as cover cropping and reduced tillage but does not necessarily guarantee removals exceeding emissions. Thus, carbon-negative farming is an outcome-driven, climate-specific framework embedded within broader sustainability and regeneration paradigms.

The core principle underlying carbon-negative farming is carbon drawdown the removal of CO₂ from the atmosphere and its storage in stable pools such as soil organic carbon (SOC) and longlived biomass. This can be achieved through multiple pathways including soil carbon sequestration via cover crops, perennial planting, minimal soil disturbance, and organic amendments ([Paustian *et al.*, 2016](#)); agroforestry and perennial systems that enhance biomass carbon storage both above and below ground ([Nair *et al.*, 2010](#)); biochar application which locks carbon in stable forms for centuries while improving soil fertility ([Lehmann *et al.*, 2011](#)); and integration of renewable energy on farms to displace fossil fuel-based energy use ([Pretty & Bharucha, 2014](#)).

The quantification of carbon drawdown is critical and requires robust measurement, reporting, and verification (MRV) systems to ensure that net-negative outcomes are scientifically verifiable and not offset by leakage or rebound effects ([Yin *et al.*, 2023](#)). Hence, carbon-negative farming is more than a set of practices; it represents a measurable climate mitigation pathway within agriculture.

The urgency of exceeding net-zero targets to reverse climate impacts cannot be overstated. The latest Intergovernmental Panel on Climate

Change (IPCC) reports emphasize that limiting global warming to 1.5 °C requires not only deep emissions reductions but also large-scale deployment of carbon dioxide removal (CDR) strategies ([IPCC, 2023](#)). Net-zero commitments, while crucial, only represent a balancing point where emissions equal removals, insufficient to reverse the accumulation of greenhouse gases already causing irreversible damage such as accelerated glacial melt, biodiversity loss, and more frequent extreme weather events ([Steffen *et al.*, 2018](#); [Maruf *et al.*, 2024](#)). Carbonnegative farming, by actively removing more CO₂ from the atmosphere than is emitted, creates the negative emissions necessary to gradually restore climatic stability.

This approach aligns directly with global goals including the Paris Agreement's Article 4, which calls for balancing anthropogenic emissions and removals in the latter half of this century ([UNFCCC, 2015](#)). Furthermore, carbon-negative farming contributes significantly to multiple United Nations Sustainable Development Goals (SDGs), such as SDG 13 (Climate Action) by delivering measurable GHG reductions and removals; SDG 15 (Life on Land) through regenerative land use, biodiversity conservation, and soil restoration; SDG 2 (Zero Hunger) by enhancing soil fertility, crop resilience, and farm productivity; and SDG 7 (Affordable and Clean Energy) when integrated with renewable energy systems on farms ([FAO, 2018](#)).

Beyond climate mitigation, carbon-negative farming serves as a catalyst for ecosystem restoration and rural livelihood enhancement. Practices like agroforestry, cover cropping, and organic soil amendments rebuild soil organic matter, improve water infiltration, reduce erosion, and foster biodiversity ([Griscom *et al.*, 2017](#)). Restored degraded lands boost productivity and resilience, laying a foundation for sustainable rural economies. Additionally, carbon-negative systems can create new income

streams through carbon credit markets, sustainable product premiums, and reduced input costs, enabling rural communities to transition from climate vulnerability to climate resilience and green economy leadership ([Lokuge & Anders, 2022](#)).

Carbon-negative farming is underpinned by interconnected principles and processes that collectively drive net atmospheric carbon removal. Soil carbon sequestration is central, involving minimal tillage, cover cropping, agroforestry, and organic amendments to increase soil organic carbon (SOC) stocks while enhancing soil health and resilience ([Paustian *et al.*, 2016](#)). Enhancement of photosynthetic efficiency is achieved through diversified cropping systems, perennial plants, and optimal canopy management to maximize CO₂ uptake and biomass accumulation ([Long *et al.*, 2015](#)). Circular resource use and renewable energy integration reduce fossil fuel dependence and non-CO₂ emissions by recycling organic waste into compost or biochar, capturing livestock methane for biogas, and powering farm operations with solar, wind, or bioenergy systems ([Pretty & Bharucha, 2014](#)). Nature-based solutions including wetland restoration, silvopasture, and rewilding leverage ecological processes to enhance carbon storage, restore biodiversity, and strengthen ecosystem resilience, delivering co-benefits for climate, nature, and livelihoods ([Griscom *et al.*, 2017](#)). Together, these principles provide a holistic and measurable pathway for agriculture to evolve from a major GHG emitter to a proactive climate stabilizer.

Carbon-negative farming practices are being adopted worldwide, though the scale and nature of adoption differ between developed and developing countries. In developed regions such as the United States, Australia, and parts of Europe, large-scale mechanized farms are incorporating precision agriculture, biochar application, agroforestry, and renewable energy systems

to achieve measurable carbon drawdown while complying with stringent sustainability standards ([Lal, 2020](#); [Smith *et al.*, 2020](#)). Government incentives, carbon credit markets, and advanced monitoring technologies facilitate this adoption.

Conversely, in developing countries like Kenya, Brazil, and Nepal, carbon-negative approaches often involve lower-cost, labor-intensive strategies such as agroecology, integrated crop, livestock systems, and community-led afforestation, which align closely with rural livelihoods and climate resilience goals ([Reppin *et al.*, 2020](#)). However, these regions face scaling challenges due to limited access to finance, technical expertise, and secure land tenure.

In India, the potential for carbon-negative farming is substantial, given its diverse agro-climatic zones, extensive agricultural workforce, and rising interest in climate-smart agriculture. Practices such as crop residue management, biochar production from surplus biomass, agroforestry on degraded lands, and organic amendments could yield both mitigation and adaptation benefits ([Tebkew *et al.*, 2024](#)). Yet barriers like fragmented landholdings, high initial costs for renewable energy integration, limited awareness of carbon markets, and MRV capacity gaps persist. Overcoming these hurdles through targeted policy support, capacity building, and rural green infrastructure investment could establish India as a leader in carbon-negative agriculture, contributing significantly to national and global climate goals.

Despite increasing recognition of carbon-negative farming's potential, several challenges impede its widespread adoption. Key among these are knowledge and awareness gaps; many farmers and stakeholders lack sufficient understanding of carbon sequestration processes, the long-term benefits of regenerative practices, and the technical expertise necessary for

effective implementation ([Lal, 2020](#); [Smith *et al.*, 2020](#)). This is often exacerbated by limited extension services, inadequate training opportunities, and a shortage of locally relevant research tailored to diverse agro-ecological contexts ([Powlson *et al.*, 2014](#)).

Technological and financial constraints also pose significant barriers. Innovations such as precision agriculture, biochar application, and enhanced rock weathering require upfront investments and access to specialized inputs or equipment that smallholder farmers, especially in developing regions, may find prohibitive ([Paustian *et al.*, 2016](#); David *et al.*, 2019). Furthermore, the long time horizon required to realize carbon sequestration benefits challenges farmers' immediate economic incentives and cash flow needs ([Montagnini & Nair, 2004](#)).

Policy and market limitations further restrict adoption; many agricultural policies lack incentives for carbon-negative practices or fail to incorporate carbon accounting frameworks essential for participation in carbon credit markets ([Lipper *et al.*, 2014](#)). Market structures often do not adequately reward sustainable production, and uncertainty around carbon pricing and regulatory support discourages farmer engagement ([Raina *et al.*, 2024](#)). Addressing these challenges demands coordinated action across research, extension, finance, and policy domains to foster enabling environments that promote knowledge dissemination, technology access, and market-based incentives for carbon-negative farming globally ([Smith *et al.*, 2020](#)).

The primary purpose of this book is to provide a comprehensive, research-based, and practice-oriented exploration of carbon-negative farming, responding to the urgent demand for sustainable agricultural systems that advance climate change mitigation and food security. By synthesizing cutting-edge scientific knowledge with actionable field practices, the book seeks to bridge the gap between academic research and

practical implementation, serving a broad audience that includes researchers, policymakers, farmers, and non-governmental organizations involved in sustainable agriculture and climate resilience ([Lal, 2020](#); [Smith et al., 2020](#)).

Researchers will find in-depth analyses of carbon sequestration processes, emerging technologies, and ecological principles, while policymakers will gain evidence-based recommendations for designing effective incentives and supportive regulatory frameworks ([Paustian et al., 2016](#)). For farmers and NGOs, the book offers practical guidelines and case studies demonstrating successful carbon-negative practices adapted to various agro-ecological settings ([Montagnini & Nair, 2004](#)).

The scope covers critical thematic areas such as soil carbon dynamics, regenerative land management, digital agriculture innovations, policy mechanisms, and socio-economic factors influencing adoption. Subsequent chapters provide a structured journey through the fundamentals of the carbon cycle, detailed descriptions of carbon-negative farming practices, challenges and opportunities for scaling, technological advancements, and robust frameworks for monitoring, reporting, and verification of carbon sequestration. Collectively, this equips readers with the holistic knowledge and tools needed to foster sustainable farming systems worldwide ([Lipper et al., 2014](#); Raina et al., 2024).

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Chapter - 2

The Science Behind Carbon-Negative Farming

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1. Introduction

Carbon-negative farming refers to agricultural practices and systems that remove more carbon dioxide (CO₂) and other greenhouse gases (GHGs) from the atmosphere than they emit over their lifecycle. This is achieved through strategies that actively sequester carbon in soils, vegetation, or long-lived biomass products, while simultaneously reducing emissions from cultivation, processing, and distribution ([Paustian et al., 2019](#)). Unlike conventional farming, which is often a net source of GHGs, carbon-negative systems create a net carbon sink by enhancing natural biological processes, optimizing input use, and integrating innovative technologies such as biochar production, agroforestry, and regenerative soil management ([Lal, 2020](#)). A carbon-negative approach often combines multiple mechanisms: soil organic carbon (SOC) accumulation, afforestation/reforestation, enhanced photosynthetic capture, and utilization of carbon-storing amendments to ensure that the total carbon removed exceeds the emissions generated from energy use, fertilizers, livestock, and other sources ([Bossio et al., 2020](#)).

While the terms *carbon-neutral*, *low-carbon*, and *carbon-negative* are sometimes used interchangeably in popular discourse, they have distinct meanings in climate science and policy. *Carbon-neutral agriculture* aims to balance greenhouse gas (GHG) emissions with equivalent offsets or

sequestration, resulting in a net-zero carbon footprint, typically through a combination of emission reductions and external offsets ([FAO, 2022](#)). *Low-carbon agriculture* focuses on reducing emissions intensity, measured as GHGs per unit of agricultural output, without necessarily achieving net-zero status, often through practices such as precision agriculture, reduced tillage, renewable energy integration, and optimized fertilizer application ([Smith et al., 2020](#)). In contrast, *carbon-negative agriculture* goes beyond neutrality by achieving a net removal of atmospheric carbon, meaning that the system sequesters more carbon than it emits, thereby contributing to a measurable decline in atmospheric CO₂ concentrations over time ([Lal et al., 2018](#)). In practical terms, carbon-neutrality maintains the status quo of atmospheric GHG concentrations, whereas carbon-negativity actively reverses them.

Agriculture contributes approximately 10–12% of global anthropogenic GHG emissions, with additional impacts from land-use change and deforestation ([IPCC, 2019](#)). Transitioning from conventional to carbon-negative farming systems represents a dual opportunity: mitigating climate change while enhancing the resilience and productivity of food systems. From a climate perspective, carbon-negative farming aligns with the *drawdown pathway* proposed by climate scientists, where global warming can be stabilized and potentially reversed through large-scale deployment of negative emissions strategies ([Rogelj et al., 2018](#)). Soils alone are estimated to have the potential to sequester 1.5–3.0 gigatonnes of CO₂ annually under improved management (Paustian et al., 2019). From a food security standpoint, carbon-negative farming improves soil health, water retention, and nutrient cycling factors that increase crop yields and resilience to climate stresses such as drought and heatwaves ([FAO, 2022](#); Lal, 2020). Practices like agroforestry and cover cropping also diversify production systems, creating additional income streams for farmers and reducing

dependence on monocultures vulnerable to pests, diseases, and market fluctuations ([Pretty *et al.*, 2018](#)). Thus, carbon-negative farming represents a scientifically grounded, economically viable, and ecologically sustainable pathway to address both the urgent climate crisis and the long-term challenge of feeding a growing population. The next sections detail the mechanisms, technologies, and practices that operationalize the concept of carbon-negative farming in real-world agricultural systems.

- Greenhouse Gas Emissions in Agriculture
- The Carbon Cycle and Sequestration
- Soil Organic Carbon (SOC)
- Photosynthesis and Plant Biomass
- Regenerative Agricultural Practices
- Biostimulants and Natural Inputs
- Carbon Accounting and Measurement
- Ecosystem Services and Co-Benefits Conclusion

2. Greenhouse Gas Emissions in Agriculture

Agriculture is a significant contributor to global greenhouse gas (GHG) emissions, accounting for approximately 19–24% of total anthropogenic emissions worldwide, depending on accounting methodologies and land-use categories ([IPCC, 2022](#)). The three primary greenhouse gases emitted from agricultural activities are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), each differing in their sources, atmospheric lifetimes, and global warming potentials (GWPs). Global Warming Potential is a standardized metric that compares the heat-trapping ability of different greenhouse gases relative to CO₂ over a specified time horizon, typically 20, 100, or 500 years. CO₂ is assigned a GWP of 1 by definition, serving as the reference gas. GWP represents the cumulative radiative forcing i.e., heat

energy trapped in the atmosphere caused by a unit mass of a gas over the selected time period compared to the same mass of CO₂. The commonly used time frame is 100 years (GWP₁₀₀). This metric enables scientists, policymakers, and carbon accounting systems to express diverse GHG emissions as CO₂-equivalent units (CO₂e), facilitating consistent comparisons and informed climate strategies. Notably, methane and nitrous oxide have GWPs approximately 28–34 and 265–298 times that of CO₂ over 100 years, respectively ([Myhre *et al.*, 2013](#)).

2.1 Sources and Significance of Carbon Dioxide (CO₂) Emissions

Agricultural CO₂ emissions largely arise from indirect processes rather than direct biological emissions. One of the most significant sources is land-use change particularly deforestation and peatland drainage for agricultural expansion. These activities release vast stores of carbon previously sequestered in biomass and soils. According to the Food and Agriculture Organization (FAO), land-use change accounts for nearly 45% of agriculture-related GHG emissions in tropical regions, underscoring CO₂'s critical role in the agricultural carbon footprint ([FAO, 2023](#)). Soil tillage accelerates the oxidation of soil organic matter, releasing stored carbon and leading to a gradual decline in soil organic carbon (SOC) stocks, thereby diminishing soils' capacity as carbon sinks ([Lal, 2004](#)). Additionally, on-farm fuel combustion primarily from tractors, irrigation pumps, and harvesters adds to CO₂ emissions. Although often overshadowed by CH₄ and N₂O in agricultural GHG discussions, these CO₂ emissions are significant, particularly in mechanized farming systems. Furthermore, the production, packaging, and transportation of synthetic fertilizers and agrochemicals contribute substantially to upstream CO₂ emissions. For example, nitrogen fertilizer manufacture is energy-intensive and heavily

reliant on fossil fuels, indirectly increasing CO₂ emissions associated with crop production ([Snyder *et al.*, 2009](#)).

2.2 Sources and Dynamics of Methane (CH₄) Emissions

Methane (CH₄) is one of the most potent agricultural greenhouse gases, with a GWP₁₀₀ approximately 28–34 times greater than CO₂ ([IPCC, 2021](#)). The majority of agricultural methane emissions originate from enteric fermentation in ruminant livestock such as cattle, sheep, and goats. This natural microbial process occurs in the digestive systems of these animals, where anaerobic microbes decompose complex carbohydrates, producing methane as a metabolic by-product that is subsequently released via belching. Livestock manure also represents a significant methane source, especially when stored or treated under anaerobic conditions, such as in lagoons or pits. In oxygen-limited environments, methanogenic archaea dominate decomposition, resulting in methane production ([USEPA, 2022](#)). Flooded rice paddies are another major contributor. The anaerobic conditions created by standing water during rice cultivation promote methanogenic bacteria in soils, which decompose organic matter and release methane. This methane escapes through diffusion or via plant aerenchyma during the growing season. Emission levels vary depending on water management practices, organic inputs, and soil characteristics (Sapkota *et al.*, 2020; [Xuan *et al.*, 2025](#)). Given methane's relatively short atmospheric lifetime but high radiative forcing, mitigating CH₄ emissions offers near-term climate benefits. Strategies include improving livestock diets, employing anaerobic digesters for manure management, adopting intermittent rice field drainage (alternate wetting and drying), and breeding low-emission rice cultivars.

2.3 Sources and Dynamics of Nitrous Oxide (N₂O) Emissions:

Nitrous oxide (N_2O) is a highly potent GHG with a GWP_{100} approximately 265–298 times that of CO_2 and an atmospheric lifetime exceeding 100 years ([IPCC, 2021](#)). In agriculture, N_2O emissions primarily arise from microbial nitrogen transformations in soils, especially following the application of synthetic fertilizers or organic manures exceeding crop requirements. The two dominant microbial processes are nitrification and denitrification. Nitrification involves oxidation of ammonium (NH_4^+) to nitrate (NO_3^-) by soil bacteria, while denitrification reduces nitrate to gaseous nitrogen forms, including N_2O and dinitrogen (N_2), particularly under anaerobic or waterlogged conditions. These processes are strongly influenced by soil moisture, temperature, pH, and oxygen availability ([Butterbach-Bahl *et al.*, 2013](#)). Excess nitrogen can move beyond the application site via leaching into water bodies, contributing to eutrophication, or volatilize and deposit off-site, causing additional N_2O emissions in wetlands and riparian zones. This “nitrogen cascade” complicates emissions accountability and broadens agriculture’s ecological footprint ([Reay *et al.*, 2012](#)). Mitigation measures include precision nutrient management, use of nitrification inhibitors, improved manure handling, and legume-based rotations to reduce synthetic fertilizer dependence. Due to its high potency and persistence, reducing N_2O emissions is essential in climate-smart agriculture strategies.

Collectively, agricultural greenhouse gas emissions primarily involve carbon dioxide from land-use change, fuel use, and fertilizer production; methane from enteric fermentation, manure management, and flooded rice cultivation; and nitrous oxide from soil microbial processes following nitrogen fertilizer application. Methane and nitrous oxide exhibit much higher global warming potentials than carbon dioxide, making their management critical. Effective mitigation strategies include reduced tillage,

optimized livestock and fertilizer management, and improved water management in rice systems.

3. Carbon Cycle and Sequestration

The carbon cycle is a fundamental biogeochemical process that governs the exchange of carbon among Earth's major reservoirs: the biosphere, pedosphere, geosphere, hydrosphere, and atmosphere. This dynamic cycle plays a crucial role in regulating climate, sustaining plant life, and maintaining ecosystem balance ([Schlesinger & Bernhardt, 2020](#)). Carbon exists in various forms within these reservoirs, including gaseous carbon dioxide (CO₂) and methane (CH₄) in the atmosphere, organic compounds in living organisms, and carbonate minerals within the lithosphere. The carbon cycle is composed of two interconnected sub-cycles: the *fast carbon cycle* and the *slow carbon cycle* ([Berner, 2004](#)).

The fast carbon cycle, or surface carbon cycle, involves rapid carbon exchanges between the atmosphere, biosphere, and hydrosphere. Key processes include photosynthesis, respiration, decomposition, and fossil fuel combustion. During photosynthesis, plants capture atmospheric CO₂ and convert it into organic matter, which flows through food webs and eventually returns to the atmosphere via respiration, decomposition, or combustion ([Falkowski et al., 2000](#)). In contrast, the slow carbon cycle operates over geological timescales, involving the movement of carbon between rocks, sediments, oceans, and the biosphere. Processes such as rock weathering, sedimentation, and the formation of sedimentary rocks sequester carbon for millions of years. For example, the weathering of silicate rocks removes CO₂ from the atmosphere, while volcanic activity recycles carbon back via subduction zones. Though slow, this cycle is critical for Earth's long-term carbon balance ([Kump et al., 2000](#)).

3.1 Natural Carbon Pathways

Carbon distribution on Earth is highly uneven among reservoirs, ranging from dynamic active pools like the atmosphere and terrestrial biomass to vast, long-term geological stores such as sedimentary rocks and fossil fuels. Sedimentary rocks and ocean sediments contain the overwhelming majority of Earth's carbon, approximately 100 million gigatonnes (GtC), representing over 99% of total carbon and acting as a relatively inert long-term store. More active reservoirs include soils (about 1,500 GtC), oceans (39,000 GtC), fossil fuels (4,000 GtC), the atmosphere (720 GtC), and terrestrial vegetation (560 GtC). Soils alone hold more carbon than the atmosphere and vegetation combined, underscoring their critical role in climate regulation. The oceans serve as the largest active carbon sink, substantially buffering atmospheric CO₂ concentrations.

3.2 Carbon Sequestration Strategies for Climate Change Mitigation

Since the Industrial Revolution, human activities, particularly fossil fuel combustion, deforestation, and intensive agriculture, have disrupted the carbon cycle, increasing atmospheric CO₂ from approximately 280 parts per million (ppm) in the pre-industrial era to over 420 ppm today (IPCC, 2021). This disruption is the primary driver of global warming and climate change. Carbon sequestration, the capture and long-term storage of atmospheric CO₂, is increasingly recognized as a vital climate mitigation strategy. Since the Industrial Revolution, human activities particularly fossil fuel combustion, deforestation, and intensive agriculture, have disrupted the carbon cycle, increasing atmospheric CO₂ from approximately 280 parts per million (ppm) in the pre-industrial era to over 420 ppm today (IPCC, 2021). This disruption is the primary driver of global warming and climate change. Carbon sequestration, the capture and long-term storage of atmospheric

CO₂, is increasingly recognized as a vital climate mitigation strategy. Mitigation efforts encompass a combination of biological, geological, and oceanic approaches to reduce atmospheric carbon and limit the impacts of climate change.

Biological sequestration leverages natural processes such as photosynthesis to capture carbon and store it in vegetation, soils, and oceans. Ecosystems like forests, wetlands, and grasslands serve as major carbon sinks. Agricultural practices including afforestation, agroforestry, biochar application, and conservation agriculture enhance carbon storage in biomass and soils ([Lal, 2004](#)). Notably, soil organic carbon (SOC) accumulation achieved through no-till farming, cover cropping, and organic amendments both sequesters carbon and improves soil health and productivity ([Paustian *et al.*, 2016](#)). Geological sequestration involves capturing CO₂ emissions at their source and injecting them into deep geological formations such as depleted oil and gas reservoirs, deep saline aquifers, or unmineable coal seams. This approach provides a long-term solution to stabilize atmospheric CO₂ levels, contingent upon careful site selection and monitoring to prevent leakage ([Benson & Cole, 2008](#)). Carbon Capture and Storage (CCS) technology is central to this method, although challenges related to cost and infrastructure remain significant. Oceanic sequestration plays a vital role in absorbing roughly a quarter of anthropogenic CO₂ emissions annually. Marine phytoplankton uptake CO₂ during photosynthesis, forming the foundation of oceanic food webs. Some of this carbon is transported to the deep ocean through the biological pump, where it can be sequestered for centuries ([Sabine *et al.*, 2004](#)). However, increasing ocean acidification from excessive CO₂ absorption threatens marine ecosystems and may diminish the ocean's future carbon sequestration capacity.

4. Soil Organic Carbon (SOC)

Soil Organic Carbon (SOC) constitutes a fundamental component of soil health and functions as a vital carbon sink within the global carbon cycle. It encompasses the carbon stored in organic compounds found in soils, primarily derived from the decomposition of plant residues, root biomass, microbial organisms, and soil fauna. The accumulation and stabilization of SOC act as a natural reservoir for atmospheric carbon dioxide (CO₂), playing a crucial role in carbon-negative farming systems that aim to mitigate climate change by enhancing long-term carbon storage in soils.

Carbon-negative farming, also referred to as regenerative or climate-smart agriculture, focuses on sequestering more CO₂ than is emitted by increasing SOC stocks through sustainable land management. These practices include cover cropping, reduced or no-tillage, organic amendments such as compost and biochar, agroforestry integration, and diversified crop rotations. Such practices not only elevate SOC levels but also improve soil physical structure, nutrient cycling, water retention capacity, and soil biodiversity, all of which synergistically boost crop productivity and enhance ecosystem resilience ([ADB, 2024](#)).

SOC dynamics are governed by the balance between carbon inputs such as plant litter, root exudates, and organic amendments and outputs, including microbial respiration, erosion, and leaching losses. The long-term stabilization of SOC depends on physical protection within soil aggregates and chemical recalcitrance, which limits microbial degradation. A key process in this stabilization is humification, whereby decomposed organic matter transforms into stable humic substances, effectively locking carbon within soil matrices for decades to centuries ([Schmidt *et al.*, 2011](#)).

Recent research highlights the substantial global potential for soils to sequester carbon. Improved agricultural practices could enhance SOC

stocks by approximately 0.4 to 1.2 gigatons of carbon annually, offering a significant offset against global anthropogenic CO₂ emissions ([Paustian et al., 2016](#); [Tikuye et al., 2025](#)). Notably, the integration of perennial crops and agroforestry systems has been shown to substantially enhance soil organic carbon stocks, with accumulation rates exceeding 2 tons of carbon per hectare per year in long-term systems, highlighting the critical role of diversified farming practices in climate change mitigation ([Siddique et al., 2023](#); [Barman et al., 2025](#); [Pan et al., 2025](#)).

However, the capacity for SOC sequestration is highly influenced by climatic conditions, soil texture, and historical land use. Tropical soils typically experience rapid SOC turnover due to warmer temperatures and higher microbial activity, which can limit long-term carbon storage. Conversely, temperate soils tend to favor greater accumulation of stable organic carbon, owing to slower decomposition rates ([Xiang et al., 2023](#)). These variations necessitate the development of region-specific carbon-negative farming strategies tailored to local soil and climatic contexts.

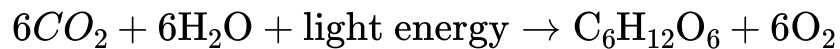
Beyond climate mitigation, enhanced SOC contributes to improved soil fertility, nutrient availability, water-holding capacity, and biological activity, thereby supporting sustainable and productive agricultural landscapes. Consequently, managing soil organic carbon effectively is central to carbon-negative farming, as it simultaneously bridges ecological functions and food security goals.

5. Photosynthesis and Plant Biomass

At the core of carbon-negative agriculture lies the natural and highly efficient process of photosynthesis, which enables the conversion of atmospheric carbon dioxide (CO₂) into plant biomass. Through photosynthesis, plants capture solar energy and transform it into chemical energy, sequestering carbon within their leaves, stems, roots, and ultimately

in the soil organic matter. This fundamental process not only sustains plant growth and agricultural productivity but also serves as a critical pathway for atmospheric carbon removal, forming a foundational pillar in climate change mitigation strategies associated with regenerative and carbon-negative farming systems.

The photosynthetic reaction can be summarized by the equation:



Photosynthesis occurs primarily within chloroplasts, where light-dependent reactions generate ATP and NADPH, which fuel the Calvin cycle to assimilate CO₂ into carbohydrates. One of the key measures of photosynthetic success and ecosystem carbon sequestration potential is Net Primary Productivity (NPP), defined as the net carbon fixed in plant biomass after subtracting carbon lost to plant respiration. Terrestrial ecosystems worldwide fix approximately 60 gigatons of carbon annually through NPP, underscoring the immense capacity of plants to draw down atmospheric CO₂ ([Friedlingstein *et al.*, 2022](#)).

Carbon-negative farming systems aim to maximize biomass production while simultaneously minimizing carbon losses through soil disturbance, erosion, and microbial decomposition. This balance is achieved through practices that increase photosynthetic efficiency, optimize canopy development, and extend the duration of active growth periods. Techniques such as multi-cropping, agroforestry, and cover cropping have demonstrated significant increases in total annual photosynthetic activity and biomass accumulation, thus enhancing carbon sequestration potential ([Balasundram *et al.*, 2023](#)).

A particularly crucial yet often underappreciated component of carbon sequestration is root biomass. Root-derived carbon exhibits greater stability

in soils compared to aboveground residues, largely due to its enhanced protection within soil aggregates and stronger chemical associations with minerals ([Kell, 2012](#)). Consequently, farming systems that incorporate deep-rooted perennial species, including perennial grains, legumes, and grasses, tend to achieve more durable carbon storage and improved soil structure over time.

Advancements in agronomy and plant genetics are pushing the frontier of improving photosynthetic efficiency. For instance, efforts to engineer plants with enhanced Rubisco enzyme kinetics, improved light interception and distribution within dense canopies, and optimized leaf anatomical traits have shown promising results in increasing photosynthetic rates and biomass yield ([Ort *et al.*, 2015](#)). Complementary agronomic practices such as balanced nutrient management, use of biofertilizers, and adoption of water-efficient irrigation techniques help alleviate environmental stresses and resource limitations, thereby sustaining high photosynthetic performance under field conditions.

The ultimate carbon balance of an agricultural system hinges on the fate of plant biomass carbon. Systems where a substantial fraction of biomass is returned to the soil and stabilized through practices like reduced or no-tillage, composting, and biochar amendment, effectively transform the land into a net carbon sink. Integrating fast-growing biomass crops with soil conservation strategies can sequester upwards of 2–3 tons of CO₂ per hectare annually in many agroecological regions (Smith *et al.*, 2020).

In summary, enhancing photosynthetic capacity and biomass productivity is vital not only for meeting global food and fiber demands but also as a strategic lever for drawing down atmospheric carbon. Carbon-negative farming practices rely on optimizing this natural, solar-driven process to ensure that ecosystems sequester more carbon than they release, thereby

contributing meaningfully to climate change mitigation and sustainable agricultural intensification.

6. Regenerative Agricultural Practices

Regenerative agriculture has gained prominence as a transformative approach within carbonnegative farming, emphasizing practices that restore and enhance soil health, boost biodiversity, and sequester atmospheric carbon dioxide (CO₂) into both biomass and soil organic matter. In contrast to conventional agricultural systems that often degrade natural resources and diminish ecosystem functionality, regenerative systems actively rebuild biological processes and ecological balance while simultaneously drawing down atmospheric carbon.

One of the foundational regenerative practices is **cover cropping**, which entails planting specific species such as legumes, grasses, and brassicas during periods when the main cash crops are not grown. Cover crops serve multiple functions: they prevent soil erosion, enhance soil organic matter through biomass input, and stimulate microbial activity vital for nutrient cycling ([Zhu et al., 2024](#)). Their root systems improve soil structure by increasing porosity and aggregate stability, while their residues provide substrates for soil microbial biomass, collectively fostering enhanced carbon sequestration.

Conservation tillage or **no-till farming** represents another cornerstone of regenerative agriculture. These methods reduce or eliminate mechanical soil disturbance, thereby preserving existing soil carbon stocks, minimizing organic matter oxidation, and maintaining stable soil aggregates crucial for long-term carbon stabilization ([Lal, 2015](#)). Empirical evidence demonstrates that no-till systems, especially when integrated with cover crops and diversified crop rotations, can substantially increase soil organic carbon over extended periods, thereby reversing soil degradation trends.

Crop diversification and rotation are vital components in strengthening the carbon-negative potential of regenerative systems. Rotating crops disrupts pest and disease cycles, enhances nutrient cycling efficiency, and promotes deeper and more extensive root growth, all of which contribute to improved soil carbon stabilization ([Pimentel *et al.*, 2005](#)). The inclusion of perennial crops and agroforestry elements further amplifies carbon sequestration by increasing both aboveground biomass and belowground carbon inputs via extensive root systems.

The use of **organic amendments**, including compost, manure, and biochar, significantly contributes to building and maintaining long-term soil carbon pools. Particularly, biochar a highly stable form of carbon produced through the pyrolysis of organic materials can persist in soils for centuries to millennia, improving soil fertility, enhancing water retention, and providing a habitat for beneficial microorganisms ([Lehmann & Joseph, 2015](#)). These amendments not only replenish carbon but also improve the overall nutrient and water-holding capacity of soils.

Another regenerative practice is **managed grazing**, where livestock are rotated systematically across pastures to simulate natural herd movements. This practice encourages uniform manure distribution, promotes vigorous pasture regrowth, and stimulates root biomass production all of which enhance soil carbon inputs and improve pasture ecosystem health ([Teague *et al.*, 2016](#)). Managed grazing systems can also reduce methane emissions per unit of animal product by improving forage quality and animal health.

Collectively, these regenerative practices operate in concert to increase soil organic carbon (SOC), reduce reliance on synthetic fertilizers and pesticides, and lower greenhouse gas emissions from agricultural landscapes. By revitalizing ecosystem functions and enhancing resilience to climatic stresses, regenerative agriculture emerges as a scientifically

validated and scalable pathway toward sustainable food systems and meaningful climate change mitigation.

7. Biostimulants and Natural Inputs

Biostimulants and natural inputs have rapidly become indispensable components in the transition towards sustainable and carbon-negative farming systems. By enhancing plant growth, improving soil structure, and stimulating beneficial microbial activity, these substances contribute not only to increased agricultural productivity and resilience but also to enhanced carbon sequestration within soils, thereby playing a critical role in climate change mitigation efforts.

Microbial biostimulants, encompassing beneficial fungi, bacteria, and other microorganisms, serve as key agents in improving soil health and carbon dynamics. These microbes establish symbiotic relationships with plant roots, promoting nutrient uptake, increasing root biomass, and stimulating the release of root exudates that serve as vital substrates for soil microbial communities. Through these interactions, microbial biostimulants enhance soil aggregation and stabilize organic matter, fostering long-term carbon retention. For example, a fungal biostimulant developed by Loam Bio has demonstrated remarkable efficacy, reportedly more than doubling soil carbon sequestration capacity compared to conventional regenerative practices ([Financial Times, 2024](#)). This innovation not only increases soil carbon storage but also improves water retention and crop yields by optimizing soil microbial networks and enhancing soil physical properties.

In addition to microbial inputs, **seaweed-derived biostimulants** have emerged as vital natural inputs in regenerative agriculture. Rich in macro and micronutrients, humic acids, polysaccharides, and natural phytohormones such as cytokinins and auxins, these formulations enhance plant tolerance to abiotic stresses including drought, heat, and salinity.

Research indicates that seaweed extracts improve nutrient uptake efficiency, elevate chlorophyll concentrations, and optimize water use efficiency, leading to healthier, more vigorous plant growth even under suboptimal environmental conditions ([Wikipedia, 2024](#)). Such physiological enhancements indirectly support carbon sequestration by increasing photosynthetic biomass production and root exudation, thereby enriching soil organic matter pools.

Biochar, a highly stable carbonaceous material produced by the pyrolysis of organic biomass under oxygen-limited conditions, is widely recognized for its dual role in carbon sequestration and soil health improvement. With its porous structure and large surface area, biochar enhances soil aeration, nutrient retention, and water-holding capacity. Critically, biochar stabilizes carbon in the soil for centuries to millennia, effectively serving as a long-term carbon sink. Furthermore, biochar application has been shown to reduce emissions of potent greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) from soils, contributing to a reduction in the agricultural carbon footprint ([SpringerOpen, 2024](#); [Wikipedia, 2024](#)).

Recent technological advancements have further propelled the efficacy of biostimulants through the integration of **nanotechnology**, giving rise to nano-biostimulants. These nanoformulations improve the bioavailability and controlled release of active ingredients, enabling precision delivery of nutrients and bioactive compounds to plants. By enhancing uptake efficiency, nano-biostimulants reduce required application rates and minimize environmental losses, thus lowering the ecological footprint of crop production systems. Their potential for sustainable and carbon-conscious agriculture is increasingly recognized, as they offer improved

plant growth promotion, stress tolerance, and soil microbial stimulation ([SpringerLink, 2024](#)).

In the Indian context, the regulatory framework governing biostimulants is evolving rapidly to support safe and effective use within agriculture. Under the Fertilizer Control Order (FCO), biostimulant products including humic acids, seaweed extracts, and plant-derived formulations, have been incorporated into Schedule VI, which mandates quality standards, licensing requirements, and manufacturing protocols. This regulatory oversight ensures product consistency, efficacy, and farmer safety, fostering greater confidence and wider adoption of biostimulants in Indian agriculture ([BioAgWorldDigest, 2024](#); Cultivation Ag, 2024).

Overall, the integration of biostimulants and natural inputs into farming systems enhances plant productivity, soil carbon sequestration, and resilience against climatic stresses. These inputs complement regenerative practices, enabling carbon-negative farming to advance as a viable, scalable, and environmentally sound approach for sustainable agriculture and climate change mitigation.

8. Conclusion and Way Forward

Carbon-negative farming represents a powerful convergence of cutting-edge science and time-tested agricultural wisdom, offering a transformative pathway toward sustainable food systems and climate resilience. By integrating fundamental scientific principles such as photosynthesis, soil organic carbon dynamics, microbial interactions, and biogeochemical cycles with practical, regenerative farming solutions, this approach not only mitigates greenhouse gas emissions but actively reverses carbon accumulation in the atmosphere. The synergy of biological, geological, and oceanic sequestration strategies, combined with innovative technologies and natural inputs, underscores the multidisciplinary nature of carbon-

negative agriculture and its potential to restore ecosystem health while securing global food production.

Looking ahead, future research must focus on scaling these practices through region-specific adaptation, advancing precision agriculture tools, and unraveling complex soil-plant-microbe interactions that drive carbon stabilization. Emphasis on developing robust monitoring frameworks and policy incentives will be essential to support farmers in adopting carbon-negative techniques at scale. Moreover, enhancing public-private partnerships and investing in education and capacity building can accelerate the transition toward widespread implementation.

Ultimately, carbon-negative farming embodies a hopeful vision one where science empowers farmers to heal the soil, increase biodiversity, and foster resilient landscapes that nourish both people and the planet. Through continued innovation and collaboration, this paradigm offers a viable, scalable solution to the pressing challenges of climate change and food security in the 21st century.

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Chapter - 3

Principles of Carbon-Negative Farming

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1. Introduction

As global agriculture grapples with the dual challenges of feeding a growing population and mitigating climate change, carbon-negative farming has emerged as a promising solution to achieve both food security and environmental sustainability. This approach is distinguished by its potential to remove more atmospheric carbon dioxide (CO₂) than it emits, thereby acting as a net carbon sink rather than a source. While conventional agriculture is a significant contributor to greenhouse gas (GHG) emissions accounting for roughly 10–12% of global anthropogenic emissions ([Smith et al., 2014](#)) carbon-negative farming offers a pathway to reverse this trend through regenerative practices, enhanced soil management, and system-level innovation.

Recent scientific discourse and policy interest have converged on the idea that agricultural soils can play a critical role in climate mitigation. According to the Intergovernmental Panel on Climate Change (IPCC), improving soil organic carbon stocks and adopting land use strategies that enhance carbon sequestration are key components in limiting global temperature rise ([IPCC, 2022](#)). Furthermore, the potential of sustainable farming systems to sequester carbon in soil and biomass while concurrently improving productivity and resilience has been well-documented ([Paustian et al., 2016](#)). These systems offer co-benefits, including enhanced biodiversity, improved water retention, and reduced dependency on fossil fuel-based inputs.

The urgency of adopting carbon-negative practices is amplified by the increasing frequency of extreme weather events and land degradation globally. A growing body of evidence supports the claim that climate-resilient agricultural practices rooted in both traditional knowledge and modern agroecology can deliver long-term sustainability ([Altieri *et al.*, 2015](#)). Notably, integrating climatesmart cropping systems, reducing tillage, recycling organic waste, and applying bio-based inputs have been shown to reduce emissions and improve farm-level carbon balances (Lal, 2020).

To operationalize the vision of carbon-negative agriculture, a clear set of guiding principles is essential. These principles encapsulate the strategic pathways through which farming systems can achieve net carbon drawdown while enhancing ecological integrity and productivity. Drawing from scientific evidence, traditional knowledge, and practical innovation, the following nine principles offer a comprehensive framework for designing and implementing effective carbon-negative interventions across diverse agroecosystems:

- **Net Carbon Drawdown:** The core goal of carbon-negative farming is to remove more CO₂ from the atmosphere than is emitted. This principle defines the very essence of the approach and underscores its potential to transform agriculture from a carbon source to a carbon sink.
- **Soil Carbon Sequestration:** As a central mechanism of long-term carbon storage, increasing soil organic carbon through practices like composting, cover cropping, and reduced tillage is fundamental to carbon-negative strategies. It forms the backbone of most regenerative and climate-smart agricultural frameworks.
- **Enhancement of Photosynthetic Efficiency:** Increasing the capacity of crops to capture atmospheric CO₂ through enhanced

photosynthesis whether via plant breeding, optimized nutrient management, or species diversification contributes significantly to carbon capture and overall system productivity.

- **Regenerative Land Management:** Practices such as no-till farming, agroforestry, silvopasture, and organic amendments not only increase soil carbon stocks but also restore ecosystem function, biodiversity, and soil health, making regeneration a vital pillar of carbon-negative farming.
- **Optimization of Inputs:** Using water, fertilizers, and energy more efficiently through precision agriculture, sensor-based irrigation, and renewable-powered systems reduces GHG emissions while maximizing resource-use efficiency and sustainability.
- **Circular Resource Use:** By recycling organic waste (e.g., crop residues, manure, food waste) into compost, biochar, or bioenergy, and reintegrating nutrients into the farming system, circularity reduces emissions, enhances soil health, and minimizes environmental impacts.
- **Climate-Resilient Cropping Systems:** Diversified and adaptive cropping systems that can withstand droughts, floods, heat stress, and other climatic shocks are integral to sustaining productivity while ensuring long-term carbon sequestration potential.
- **Low-Impact Soilless Cultivation:** Innovative systems such as hydroponics, aeroponics, and aquaponics when integrated with renewable energy sources offer a path to food production with minimal land use, reduced input requirements, and lower overall emissions.
- **Integration of Traditional Knowledge and Modern Science:** Synthesizing indigenous agricultural practices with contemporary

scientific advances fosters context-specific, culturally relevant, and ecologically sound solutions, enhancing the adoption and efficacy of carbon-negative interventions.

2. Net Carbon Drawdown and Minimization of Greenhouse Gas Emissions

Net carbon drawdown and the minimization of greenhouse gas (GHG) emissions together constitute the foundational principle of carbon-negative farming. This integrated approach seeks not only to remove more atmospheric CO₂ than is emitted, but also to reduce emissions of potent GHGs such as methane (CH₄), nitrous oxide (N₂O), and carbon dioxide (CO₂) from agricultural systems. By combining carbon sequestration with emission reduction strategies, carbon-negative farming transforms agriculture from a net emitter into a climate-positive system, one that removes more greenhouse gases than it emits.

At the heart of net carbon drawdown is the carbon cycle, where photosynthetic plants absorb atmospheric CO₂ and convert it into organic matter. A significant portion of this carbon is deposited into the soil through roots, residues, and microbial activity, increasing soil organic carbon (SOC) pools ([Lal, 2004](#)). As soils store more carbon than the atmosphere and vegetation combined, enhancing SOC is pivotal in climate mitigation ([Paustian *et al.*, 2016](#)).

Carbon-negative farming employs a suite of **regenerative practices** to maximize drawdown and minimize emissions:

- **No-till and reduced tillage** systems reduce soil disturbance, preventing the oxidation of stored carbon into CO₂ ([Smith *et al.*, 2020](#)) and lowering fuel use in field operations by up to 60% ([West & Marland, 2002](#)).

- **Cover cropping** maintains live root systems that continually feed soil organic matter and reduce erosion ([Blanco-Canqui et al., 2013](#)), while **perennial crops** with deep roots deposit carbon deeper into the soil profile ([Jackson et al., 2017](#)).
- **Agroforestry** integrates trees into cropping systems, providing long-term carbon sinks both above and below ground, alongside ecosystem co-benefits ([Zomer et al., 2022](#)).
- **Organic amendments**, such as compost and **biochar**, stabilize carbon in soils for decades to centuries. Biochar, in particular, is highly resistant to microbial degradation and enhances water retention and nutrient availability ([Lehmann & Joseph, 2015](#); [Woolf et al., 2010](#)).

These practices collectively contribute to reducing greenhouse gas emissions while drawing down atmospheric CO₂ and enhancing soil carbon sequestration. Alongside carbon sequestration, **GHG emission minimization** targets key sources of emissions in agriculture. Efficient **nutrient management** including precision fertilization, split applications, and use of Biofertilizers, reduces N₂O emissions by improving nitrogen use efficiency ([Snyder et al., 2009](#); Lal, 2020). Replacing synthetic fertilizers with organic sources also enhances microbial health and contributes to SOC buildup.

Methane emissions, especially from rice paddies and ruminants, can be curtailed through practices like **alternate wetting and drying (AWD)** in rice fields, **manure management**, and **dietary additives** that suppress enteric fermentation. Improved livestock feeding and breeding can cut CH₄ emissions per unit of product by 30–50% ([Herrero et al., 2016](#)).

Precision agriculture technologies, including GPS-based input application, sensors, and automation, reduce both emissions and resource

use. These tools support efficient water and nutrient use, minimizing excess N and its conversion into N₂O ([Ferland et al., 2024](#)). The inclusion of **biostimulants and beneficial microbes** further enhances nutrient uptake and suppresses GHG production from soils ([AP News, 2023](#)).

Crucially, the **synergistic combination of emission reduction and carbon sequestration practices**, such as pairing cover crops with compost or integrating biochar into conservation tillage, enhances system resilience, biodiversity, and nutrient cycling.

Thus, carbon-negative farming hinges on **creating agricultural ecosystems that both capture and store carbon and minimize GHG emissions**. This principle provides a science-based foundation for transforming agriculture into a key solution for climate change mitigation while maintaining productivity, ecological balance, and long-term sustainability.

3. Soil Carbon Sequestration

Soil carbon sequestration is a foundational pillar of carbon-negative farming, aiming to draw down atmospheric CO₂ and store it in the soil in the form of stable organic carbon. This process not only mitigates climate change but also improves soil health, fertility, and resilience to climatic stresses. Several synergistic practices enable effective soil carbon storage in agricultural systems.

One such practice is cover cropping, which involves the cultivation of non-cash crops during fallow periods to enhance soil cover, reduce erosion, and increase organic matter input. As [Lal \(2004\)](#) explains, “cover crops contribute biomass both above and below ground, which upon decomposition, increases soil organic carbon (SOC) stocks.” Leguminous cover crops, in particular, fix atmospheric nitrogen, further enhancing microbial activity and organic matter buildup.

Reduced tillage or no-till farming is another critical practice that minimizes soil disturbance, thus preserving existing SOC and reducing its oxidation. [Frelih-Larsen *et al.* \(2022\)](#) emphasize that “no-till systems protect soil aggregates and microbial habitats, leading to reduced CO₂ emissions and improved carbon retention.” Tillage, by contrast, exposes soil organic matter to air and accelerates decomposition, resulting in carbon loss.

Composting plays a vital role by recycling organic waste into stable humus-like substances. When applied to soil, compost not only contributes to SOC but also stimulates microbial diversity and enzymatic activity that favor humification. According to [Ryals and Silver \(2013\)](#), “compost application increased grassland soil carbon storage by 1 Mg C ha⁻¹ year⁻¹ over a three-year period, with effects persisting beyond the application year.”

Another promising technique is the application of biochar a form of stable carbon-rich charcoal produced through pyrolysis of biomass. [Lehmann and Joseph \(2015\)](#) note that “biochar amendments can remain in the soil for hundreds to thousands of years, acting as a recalcitrant carbon pool while enhancing nutrient retention and microbial function.” These practices work synergistically. For instance, combining cover cropping with compost and biochar creates a multilayered strategy for both immediate and long-term carbon storage, while precision agriculture technologies can optimize inputs and monitor SOC dynamics. The integration of these approaches within a regenerative or agroecological framework transforms conventional farming into a carbon sink, contributing meaningfully to climate mitigation targets while fostering resilient and productive agroecosystems. Soil Carbon Sequestration” and “Net Carbon Drawdown”

are closely related concepts within carbon-negative farming, they differ in scope, mechanisms, and emphasis.

4. Enhancement of Photosynthetic Efficiency

One of the fundamental principles of carbon-negative farming involves the enhancement of photosynthetic efficiency to maximize plant biomass production and deepen root systems, thereby increasing the capture of atmospheric CO₂. Photosynthesis is the primary biological process by which atmospheric CO₂ is converted into organic compounds that form the basis of plant biomass. Improving photosynthetic efficiency enables plants to fix more carbon dioxide, thus increasing the overall carbon input into agroecosystems ([Falkowski *et al.*, 2000](#)). This increased fixation is critical, as it directly influences the amount of carbon stored in plant tissues and, upon root turnover and residue decomposition, in soil organic matter ([Lal, 2004](#)).

One strategy to enhance photosynthesis involves the use of plant varieties or species with inherently efficient photosynthetic pathways, such as C₄ or CAM plants, which exhibit higher water- and nitrogen-use efficiency and greater carbon assimilation under certain conditions ([ACIAR, 2014](#); [Omokpariola *et al.*, 2025](#)). For example, C₄ crops like maize and sugarcane outperform C₃ crops in photosynthetic carbon fixation especially under high light intensity and temperature, which makes them valuable in carbon-negative cropping systems.

Furthermore, agronomic practices such as optimized nutrient management, particularly nitrogen fertilization, improve photosynthetic capacity by supporting the synthesis of chlorophyll and key enzymes like Rubisco (ribulose-1,5-bisphosphate carboxylase/oxygenase) responsible for carbon fixation ([Mu and Chen, 2021](#)). The integration of bio-stimulants and mycorrhizal associations can also enhance photosynthetic rates by

improving nutrient uptake and stress resilience ([Calvo *et al.*, 2014](#); [Carillo, 2025](#)).

Beyond above-ground biomass, root system development plays a vital role in carbon sequestration. Deep-rooted plants transfer photosynthetically fixed carbon into the soil via root biomass and exudates, promoting soil organic carbon accumulation in deeper soil layers, which are less prone to rapid decomposition and loss ([Paustian *et al.*, 2016](#)). Practices such as agroforestry, intercropping with deep-rooted species, and cover cropping increase root biomass diversity and soil carbon stocks, creating a more stable and long-term carbon sink ([Jose, 2009](#)).

Moreover, management practices that reduce soil disturbance, such as no-till farming, help preserve the integrity of root systems and soil microbial communities, thereby enhancing soil carbon stabilization ([Lal, 2015](#)). When combined, these strategies create synergistic effects that optimize photosynthetic carbon capture and promote sustainable carbon storage, which is the hallmark of carbon-negative farming systems ([Smith, 2016](#)).

In sum, enhancing photosynthetic efficiency in crops and associated vegetation through genetic, agronomic, and ecological approaches is crucial for maximizing carbon uptake and retention, thus playing a pivotal role in mitigating climate change via carbon-negative farming.

5. Regenerative Land Management

Regenerative land management is a cornerstone of carbon-negative farming, emphasizing the restoration of degraded soils, enhancement of biodiversity, and improvement of ecosystem services to create resilient and productive agroecosystems. Degraded soils, characterized by loss of organic matter, nutrient depletion, and reduced microbial activity, pose significant challenges to sustainable agriculture and carbon sequestration ([Montgomery, 2007](#)). Regenerative practices aim to reverse these trends by

rebuilding soil health, thereby increasing the soil's capacity to sequester carbon and support plant growth ([Lal, 2016](#)).

One of the most effective regenerative strategies is agroforestry, which integrates trees with crops or livestock to enhance carbon storage both above and below ground ([Jose, 2009](#)). Trees contribute substantial biomass and root carbon inputs, while their canopy and litterfall improve microclimatic conditions and nutrient cycling ([Nair et al., 2010](#)). Similarly, silvopasture systems combine forestry with managed grazing, promoting biodiversity and soil structure improvement through diversified root systems and organic inputs ([Poudel et al., 2024](#)). These systems enhance soil aggregation and microbial diversity, key factors in stabilizing soil organic carbon ([Six et al., 2002](#)).

Rotational grazing further contributes to soil regeneration by mimicking natural herbivore movements, preventing overgrazing, and promoting uniform manure distribution, which replenishes soil nutrients and organic matter ([Teague et al., 2011](#)). This practice stimulates root growth and microbial activity, which in turn enhances soil carbon stabilization. In contrast to continuous grazing, rotational grazing allows for plant recovery periods, thus improving forage quality and soil cover, which reduces erosion and water runoff ([Kim et al., 2023](#)).

Beyond biomass inputs, regenerative land management practices foster biodiversity at multiple levels, from soil microorganisms to aboveground fauna, which is critical for ecosystem resilience and function ([Brussaard et al., 2007](#)). Diverse microbial communities drive nutrient cycling, organic matter decomposition, and disease suppression, all of which contribute to improved soil health and carbon storage ([Fierer et al., 2007](#)). Furthermore, increased plant species diversity in these systems supports pollinators and

natural pest predators, reducing dependence on chemical inputs ([Altieri, 1999](#)).

Ultimately, regenerative land management aligns ecological restoration with agricultural productivity, creating carbon-negative systems that mitigate climate change while enhancing food security and ecosystem services ([Schreefel *et al.*, 2020](#)). By prioritizing soil health, biodiversity, and ecological complexity, these practices transform degraded lands into vibrant, carbon-rich landscapes capable of long-term sustainability.

6. Optimization of Inputs

The optimization of agricultural inputs is a fundamental principle in carbon-negative farming aimed at reducing greenhouse gas (GHG) emissions, minimizing resource overuse, and improving input-use efficiency while maintaining or enhancing productivity. Modern agriculture is often associated with high input intensity particularly in the use of synthetic fertilizers, pesticides, and irrigation which contributes significantly to CO₂, CH₄, and N₂O emissions ([Tilman *et al.*, 2002](#)). Transitioning toward carbon-negative systems requires strategies that maximize outputs per unit of input while minimizing environmental impacts through precision management and ecological intensification.

Precision agriculture technologies play a pivotal role in input optimization by enabling site-specific management of resources such as water, nutrients, and energy. Tools such as GPS-guided machinery, soil sensors, variable rate applicators, and remote sensing technologies allow farmers to apply inputs at the right time, place, and quantity, thereby reducing excess application and associated emissions ([Gebbers & Adamchuk, 2010](#)). For example, variable rate nitrogen application based on real-time crop sensing has been shown to significantly reduce nitrogen

losses and improve nitrogen use efficiency ([Raun et al., 2002](#)), contributing to lower nitrous oxide emissions, a potent GHG.

In addition to precision tools, biostimulants such as humic substances, seaweed extracts, microbial inoculants (e.g., *Azospirillum*, *Trichoderma*, *Rhizobium*), and protein hydrolysates are being increasingly used to stimulate plant metabolism, enhance nutrient uptake, and improve stress tolerance ([Calvo et al., 2014](#)). Biostimulants contribute indirectly to carbon-negative outcomes by promoting root growth and photosynthetic efficiency, which increase biomass production and soil carbon inputs while reducing dependence on synthetic fertilizers.

Organic amendments such as compost, vermicompost, and biochar also enhance soil fertility and carbon sequestration. Compost application improves soil structure, water retention, and microbial activity while returning organic carbon to the soil ([Diacono & Montemurro, 2010](#)). Biochar, a stable carbon-rich product of biomass pyrolysis, has shown exceptional potential to sequester carbon in soils over long timescales while also improving soil pH, cation exchange capacity, and microbial diversity ([Lehmann et al., 2006](#)). These organic inputs also improve nutrient cycling and reduce the leaching of nitrate and phosphate, further decreasing environmental pollution.

Integrated Nutrient Management (INM), which combines organic, inorganic, and biological sources of nutrients, ensures sustained soil fertility and productivity while reducing the environmental footprint of nutrient use ([Roy et al., 2006](#)). INM practices promote nutrient synchronization with crop demand, reduce nutrient imbalances, and mitigate N₂O emissions associated with excessive nitrogen use ([Palm et al., 2001](#)). Moreover, INM improves soil health, which is central to enhancing carbon storage capacity in the root zone.

Overall, optimization of inputs through technological, biological, and ecological innovations is essential to the success of carbon-negative farming systems. These practices not only improve resource-use efficiency and reduce environmental degradation but also synergistically enhance carbon sequestration and system resilience ([Pretty & Bharucha, 2014](#)).

7. Circular Resource Use

Circular resource use is a fundamental pillar of carbon-negative farming that emphasizes the internal recycling of nutrients, organic matter, and water within the agroecosystem to minimize waste, lower greenhouse gas emissions, and reduce reliance on external inputs. Unlike the linear “take-make-dispose” model common in conventional agriculture, circular farming seeks to emulate natural cycles where waste becomes a resource, thereby promoting ecological balance and sustainability ([Pearce & Turner, 1991](#)).

One of the core practices supporting circularity is **composting**, which transforms crop residues, food scraps, and animal manures into nutrient-rich organic amendments. Composting stabilizes organic matter, reduces methane emissions compared to landfilling, and returns essential macro- and micronutrients to the soil ([Bernal *et al.*, 2009](#)). The application of compost enhances soil organic carbon (SOC) stocks, improves water retention, and fosters beneficial microbial activity, all crucial for soil carbon sequestration and climate resilience ([Lal, 2004](#)).

Vermiculture, or vermicomposting, goes a step further by utilizing earthworms to convert organic wastes into highly bioavailable and microbially active vermicast. Vermicompost not only improves soil structure and fertility but also enhances plant growth-promoting hormone levels and microbial diversity, reducing the need for synthetic fertilizers ([Edwards *et al.*, 2010](#)). As a closed-loop bioconversion system, vermiculture is ideal for smallholder farms and urban agriculture, offering a

low-cost method of waste management and soil rejuvenation ([Arancon *et al.*, 2006](#)).

Water reuse is another essential aspect of circular resource use, particularly in regions facing water scarcity. Greywater recycling and wastewater treatment using natural systems like constructed wetlands or biofiltration units can supply irrigation needs while reducing the pressure on freshwater resources ([Wiley-Blackwell, 2011](#)). Integrating water-efficient irrigation methods such as drip systems with recycled water ensures that every drop is used productively, reducing energy and water footprints ([Foley *et al.*, 2011](#)).

Moreover, **integrated closed-loop farming systems** which combine crop, livestock, and aquaculture operations exemplify circularity in action. For instance, integrated rice-fish farming allows fish waste to fertilize crops, while crop residues feed fish or livestock, forming a nutrient feedback loop ([Prein, 2002](#)). Similarly, in agroecological livestock systems, manure is composted or digested anaerobically to produce biogas and slurry, which serves as a soil amendment and energy source, reducing fossil fuel dependency and methane release (Moller & Muller, 2012).

Adopting circular systems reduces nutrient leakages, improves input efficiency, and contributes to long-term soil fertility and carbon storage. Importantly, circularity in resource use also enhances farm economics by reducing input costs and creating value-added products such as compost, biogas, or fish, thereby aligning environmental and economic sustainability ([De Boer & van Ittersum, 2018](#)).

In sum, circular resource use not only closes nutrient and energy loops within farms but also drives the transformation toward regenerative, climate-positive agriculture. By minimizing waste, maximizing recycling, and enhancing internal resilience, circular farming systems offer a scalable

path to achieving carbon-negative outcomes in both rural and peri-urban settings.

8. Climate-Resilient Cropping Systems

Climate-resilient cropping systems form a critical pillar of carbon-negative farming, ensuring agricultural productivity under changing climate conditions while enhancing the capacity of farms to sequester carbon. These systems are designed to cope with the increasing frequency of droughts, floods, extreme temperatures, and shifting growing seasons. They not only adapt to climate stressors but also contribute actively to climate change mitigation through improved soil health, reduced emissions, and higher biomass carbon capture ([Vermeulen *et al.*, 2012](#)).

A key strategy is the adoption of **stress-tolerant crop varieties**, including drought-, heat-, and salt-tolerant cultivars, that maintain yields under adverse conditions while supporting year-round carbon assimilation. For instance, drought-resilient varieties of millet, sorghum, and legumes have shown promise in enhancing food security and stabilizing carbon inputs in semi-arid regions ([Lobell *et al.*, 2008](#)). The use of **deep-rooted crops** further contributes to subsoil carbon sequestration and enhances ecosystem resilience through better water and nutrient access ([Kell, 2012](#)).

Intercropping systems, where two or more crops are grown together, improve climate resilience by enhancing biodiversity, resource-use efficiency, and ecosystem functions. Legume-based intercropping (e.g., maize-cowpea or millet-pigeon pea) fixes atmospheric nitrogen, increases soil organic matter, and buffers against crop failure under erratic weather conditions ([Brooker *et al.*, 2015](#)). Intercropping has also been associated with higher carbon sequestration potential in soils due to continuous root activity and residue inputs ([Cong *et al.*, 2015](#)).

The promotion of **perennial crops** and agroforestry systems is another powerful strategy. Unlike annual crops, perennials such as pigeon pea, fruit trees, and vetiver grass maintain root biomass yearround, reducing erosion and continuously drawing CO₂ from the atmosphere. Perennial systems like **silvopasture** and **alley cropping** integrate trees with crops or livestock, resulting in higher total productivity, improved microclimate regulation, and long-term soil carbon storage ([Jose, 2009](#); [Nair et al., 2010](#)).

Vertical farming and other controlled-environment agriculture (CEA) systems provide climate resilience through protection from external weather shocks. These systems, though energy-intensive, can become carbon-negative when powered by renewables and optimized for resource efficiency. Vertical farms offer high biomass output per unit area and allow for year-round production in urban settings, reducing land-use change and transport emissions ([Beacham et al., 2019](#)). With innovations in LED lighting and nutrient recycling, such systems represent scalable climate-resilient models for high-value crops.

Additionally, **climate-resilient crop rotations**, which involve the planned sequencing of different crops over time, are essential for maintaining soil fertility, breaking pest and disease cycles, and improving organic matter accumulation. Rotations that incorporate cover crops, legumes, and green manures enhance soil microbial diversity and contribute to carbon capture during off-seasons ([Snapp et al., 2005](#)).

Together, these systems contribute to both **adaptation and mitigation**, ensuring yield stability and ecosystem services while improving the carbon balance of agricultural landscapes. The resilience and multifunctionality of such systems are crucial in the transition toward climate-smart and carbonnegative food production ([Campbell et al., 2017](#)).

9. Low-Impact Soilless Cultivation

Low-impact soilless cultivation is an emerging principle in carbon-negative farming that leverages advanced technologies such as **hydroponics**, **aquaponics**, and **aeroponics** to produce high-value crops with minimal environmental impact. These systems replace conventional soil-based agriculture with nutrient solutions and controlled environments, dramatically reducing land requirements, eliminating soil degradation, and curbing nutrient runoff, while enabling efficient, year-round food production ([Resh, 2022](#)).

Hydroponics, the practice of growing plants in a nutrient-rich water solution without soil, allows precise control over plant nutrition and environmental parameters. Because water and nutrients are recirculated, hydroponic systems can use up to 90% less water than traditional field farming ([Jones, 2016](#)). Moreover, by avoiding soil, hydroponics eliminates many conventional agricultural emissions related to tillage, erosion, and nitrous oxide release from nitrogen fertilizers ([Barbosa et al., 2015](#)). When powered by renewable energy and optimized with closed-loop systems, hydroponic farming can contribute to carbon-negative outcomes by reducing fossil fuel dependence and external input use.

Aquaponics combines hydroponic crop production with aquaculture, wherein nutrient-rich fish waste provides a natural fertilizer for plants, while the plants, in turn, help filter and purify the water for fish reuse. This symbiotic system mimics natural ecosystems, converting waste into a resource and closing nutrient cycles. Research shows that aquaponics can reduce water usage by over 90% compared to soil farming and simultaneously reduce nutrient leaching and ammonia emissions from aquaculture ([Goddek et al., 2015](#)). In terms of carbon savings, aquaponics can be strategically integrated into urban settings, thereby reducing food miles and associated transportation emissions ([Love et al., 2014](#)).

Aeroponics, a system where plant roots are suspended in air and intermittently misted with a nutrient solution, represents the most water- and input-efficient of all soilless methods. This technique is particularly effective for leafy greens and high-value crops, offering faster growth rates and up to 98% water savings compared to traditional agriculture ([Kumar and Verma, 2024](#)). Aeroponics also facilitates vertical stacking and indoor farming, drastically reducing land footprint and enabling food production in non-arable zones such as cities, deserts, or degraded lands ([Al-Kodmany, 2018](#)).

By integrating these technologies with **renewable energy systems**, carbon-negative performance becomes feasible. Solar-powered greenhouses, LED lighting for photosynthetically efficient wavelengths, and real-time digital monitoring through IoT-based automation ensure minimal energy waste and precise resource application ([Benke & Tomkins, 2017](#)). Furthermore, soilless systems can be designed for **zero-discharge**, preventing the environmental damage commonly associated with agricultural runoff, such as eutrophication of water bodies ([Blanchard et al., 2020](#)).

Another key benefit is **year-round production**, which increases yield per square meter and enables consistent food supply even in regions affected by seasonal or climate variability. This stability supports food security while maximizing photosynthetic potential and carbon capture through continuous vegetative cycles ([Touliatos et al., 2016](#)).

Despite their initial energy and infrastructure demands, **low-impact soilless cultivation systems** can become part of carbon-negative farming when integrated with sustainable practices such as organic nutrient sourcing, localized inputs, composted fish feed or algae-based fertilizers, and solar-based energy management. These systems particularly shine in

urban and peri-urban areas where land is scarce but demand for fresh produce and climate resilience is high.

10. Integration of Traditional Knowledge and Modern Science

Integrating traditional knowledge systems with modern scientific innovations is an essential principle in the transition to carbon-negative farming. This synergy supports the co-creation of resilient, sustainable, and socially inclusive agricultural systems that not only sequester carbon but also sustain livelihoods, biodiversity, and cultural heritage. Indigenous and traditional agricultural practices, honed over centuries through close observation of local ecosystems, offer time-tested strategies for soil fertility enhancement, biodiversity conservation, and climate adaptation ([Altieri, 1995](#)).

Traditional ecological knowledge (TEK) embodies deep understandings of natural cycles, seasonal variations, soil behavior, and plant-animal interactions. For instance, rotational shifting cultivation in the Eastern Himalayas, the **Zai pit system** in the Sahel, and **agroforestry traditions** among indigenous communities in Central America have demonstrated long-term sustainability and carbon sequestration capabilities ([Pretty, 2008](#); [Altieri & Toledo, 2011](#)). These methods typically emphasize diversity, organic inputs, minimal tillage, and a harmonious relationship with natural processes, key principles aligned with carbon-negative outcomes.

In India, practices such as **zero-budget natural farming (ZBNF)** and **Panchagavya-based cultivation**, which rely on locally available bio-inputs like cow dung, cow urine, buttermilk, and crop residues, are rooted in indigenous knowledge and have shown potential to reduce synthetic input use, improve soil microbial activity, and lower greenhouse gas emissions ([Khadse et al., 2018](#)). These traditional formulations are increasingly being

validated and optimized through scientific experimentation for broader agroecological applications.

Modern agroecology, with its emphasis on system-level thinking, biodiversity enhancement, and ecological feedbacks, provides the scientific lens to assess, refine, and scale up traditional methods. The integration of **GIS mapping, remote sensing, precision agriculture, and microbiome analysis** allows the documentation and improvement of traditional practices, ensuring they are efficient and scalable without losing their ecological essence ([Tuttonell, 2014](#)). For example, pairing indigenous weather forecasting knowledge with modern climate modeling enhances farmers' ability to respond to extreme weather events and manage planting schedules more effectively.

Moreover, the use of **underutilized and indigenous crops** such as millets, legumes, tubers, and leafy greens forms a critical part of this integrative strategy. These crops are naturally resilient to drought, pests, and poor soils and often have deeper root systems and higher carbon capture potential compared to modern monocultures ([Padulosi et al., 2013](#)). Integrating them into diversified cropping systems not only boosts dietary diversity and income security but also contributes to agroecosystem resilience and soil carbon enrichment.

Importantly, social acceptance and farmer participation are more readily achieved when scientific interventions build upon culturally familiar practices. Participatory research approaches such as **farmer field schools, community seed banks, and on-farm experimentation** help bridge the gap between tradition and science. They empower farmers to evaluate innovations, adapt them locally, and take ownership of knowledge transitions ([Chambers et al., 1989](#)).

In the context of carbon-negative farming, this integration ensures that solutions are not only technically sound but also **ecologically rooted, culturally relevant, and economically viable**. Such an approach contributes to long-term sustainability and equity by preserving **agrobiodiversity**, enhancing **climate adaptability**, and acknowledging the intellectual contributions of indigenous and local communities.

11. Conclusion and Way Forward

Carbon-negative farming represents a paradigm shift in agriculture, transforming it from a net emitter to a proactive solution in the fight against climate change. The guiding principles outlined throughout this chapter provide a holistic framework for achieving negative emissions while restoring ecological integrity, improving soil health, and enhancing livelihoods.

At the core of carbon-negative agriculture are practices that promote **net carbon drawdown**, such as soil carbon sequestration, enhancement of photosynthetic efficiency, and regenerative land management. **Optimization of inputs, circular resource use**, and the integration of **climateresilient cropping systems** further strengthen the capacity of farms to become long-term carbon sinks. Additionally, the incorporation of **low-impact soilless cultivation, digital technologies**, and the **fusion of traditional knowledge with modern science** ensures both innovation and inclusivity in the transition process.

These principles are not isolated actions but **interconnected strategies** that, when implemented together, can restore natural cycles, reduce emissions, and build resilient food systems. Farmers are no longer just food producers, they are **climate stewards**, custodians of carbon, and pivotal agents in ecological regeneration.

Looking forward, the vision for carbon-negative agriculture is one of **systemic transformation**, where sustainability is embedded in every aspect of farming. Future food systems must operate within planetary boundaries, guided by science, empowered by technology, and rooted in equity.

Key enablers of this future include:

- Supportive policies and carbon markets that reward sequestration efforts.
- Research and innovation to refine techniques like biochar, agroforestry, and enhanced rock weathering.
- Community-driven models that combine **local wisdom** with **climate-smart innovations**.
- Education and awareness to shift mindsets toward ecological thinking.

Ultimately, carbon-negative farming offers a **hopeful path forward** not just to mitigate climate change, but to **regenerate ecosystems, empower rural communities, and secure food sovereignty** for generations to come. The journey ahead calls for collaboration, courage, and a shared commitment to cultivating a climate-positive future.

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Chapter - 4

Key Practices of Carbon-Negative Farming

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1. Introduction

Carbon-negative farming refers to a suite of agricultural practices that actively remove more carbon dioxide (CO₂) from the atmosphere than they emit, thereby reversing the net carbon balance of farming systems. Unlike carbon-neutral approaches that merely aim to balance emissions and sequestration, carbon-negative farming seeks to go a step further by enhancing carbon sinks through biological, ecological, and technological interventions ([Paustian *et al.*, 2016](#)). This strategy addresses the dual challenges of climate change mitigation and sustainable food production.

The agricultural sector currently contributes around 19–29% of global greenhouse gas (GHG) emissions ([Vermeulen *et al.*, 2012](#)). However, with appropriate land management, it has the potential to become a significant carbon sink, particularly through practices that enhance soil organic carbon (SOC), reduce fossil fuel dependency, and increase biomass accumulation both above and below ground. Techniques such as agroforestry, regenerative grazing, biochar application, and conservation tillage can permanently lock atmospheric carbon into soils and vegetation, while reducing emissions from fertilizers, energy use, and livestock operations (Smith *et al.*, 2008).

Adopting carbon-negative farming is not only a climate imperative but also offers ecological and economic co-benefits. Ecologically, it enhances

soil health, biodiversity, and water regulation, while economically, it can reduce input costs, increase farm resilience, and open access to carbon markets and green finance mechanisms ([Fuss et al., 2018](#)). Moreover, it contributes to restoring degraded lands, reducing dependency on external inputs, and building local circular economies that are more sustainable in the long term.

This transition aligns closely with the goals of the Paris Agreement and United Nations Sustainable Development Goals (SDGs), particularly SDG 13 (Climate Action), SDG 2 (Zero Hunger), and SDG 15 (Life on Land). By promoting low-emission, high-resilience agricultural systems, carbon-negative farming is emerging as a critical lever in the global response to climate change ([IPCC, 2019](#)).

Furthermore, as agriculture continues to expand to feed a growing population, there is an urgent need to decouple agricultural productivity from environmental degradation. Carbon-negative farming provides a holistic solution that integrates productivity with planetary boundaries, offering a pathway to sustainable intensification that benefits both people and the planet ([Lal, 2020](#)).

To operationalize carbon-negative farming, a wide range of practices have emerged that not only draw down atmospheric carbon but also regenerate ecological systems and optimize resource use. This chapter systematically explores these **key practices**, grouped into four major thematic areas: *Ecological Land Use Systems for Carbon Sequestration*, *Soil Health and Organic Carbon Enrichment*, *Smart Inputs and Resource Optimization*, and *Controlled and Renewable Systems*. Each section highlights proven techniques, such as agroforestry, perennial cropping, biochar application, and precision farming that synergize productivity with climate action. By integrating these innovations across diverse

agroecosystems, carbon-negative farming offers a transformative pathway toward resilient, regenerative, and climate-smart agriculture.

2. Ecological Land Use Systems for Carbon Sequestration

Land use is one of the most critical determinants of the **carbon dynamics within agricultural landscapes**, directly influencing both carbon emissions and sequestration potential. **Ecological land use systems** are designed to work in harmony with natural processes by integrating **trees, perennial vegetation, livestock, wetlands, and aquatic systems** into farm management. These systems enhance the capacity of agricultural land to act as a **net carbon sink** while improving productivity, biodiversity, and ecosystem services ([Lal, 2004](#); [Smith et al., 2008](#)).

Through practices like **agroforestry, perennial cropping, and wetland restoration**, carbon is captured from the atmosphere and stored **long-term in biomass and soil organic carbon (SOC)** pools. For instance, **trees and perennial root systems contribute significantly to below-ground carbon storage**, while **wetlands and peatlands** are known to store vast amounts of carbon in anaerobic conditions, preventing its release as CO₂ ([FAO, 2012](#)). At the same time, such systems also **reduce greenhouse gas (GHG) emissions** from conventional practices like intensive tillage, synthetic inputs, and monocropping ([Paustian et al., 2016](#)).

Moreover, ecological land use strategies **build resilience** to climate variability by improving soil health, water retention, and biodiversity, thus providing **co-benefits** essential for long-term agricultural sustainability and food security ([Pretty et al., 2018](#)). The synergistic integration of diverse biological components allows for **enhanced nutrient cycling, reduced external inputs, and improved adaptation** to climate stressors ([Garritty, 2004](#)).

This section presents five key ecological land use strategies central to carbon-negative farming:

- **Agroforestry**, which incorporates trees into crop and livestock systems;
- **Perennial cropping**, which leverages deep-rooted, long-lived plant species;
- **Integrated crop-livestock systems**, which recycle biomass and nutrients efficiently;
- **Wetland restoration and peatland conservation**, which protect powerful carbon sinks; and
- **Aquaforestry**, which integrates trees with aquatic systems for carbon and ecosystem benefits. Together, these practices **offer scalable, regenerative solutions** that align with both **climate mitigation and ecological restoration goals**, paving the way toward truly sustainable agricultural systems.

2.1. Agroforestry

Agroforestry, the **deliberate integration of trees and shrubs into agricultural landscapes**, is one of the most effective and widely adopted land use strategies for **enhancing carbon sequestration** while delivering numerous ecological and socio-economic benefits. By combining woody perennials with crops and/or livestock on the same unit of land, agroforestry systems mimic natural ecosystems and create **complex, resilient landscapes** that store carbon both **above ground in biomass** and **below ground in soils and roots** ([Nair, 2012](#)).

One of the primary benefits of agroforestry is its **capacity to act as a long-term carbon sink**. Trees in agroforestry systems continuously absorb atmospheric CO₂ through photosynthesis, storing it in **trunks, branches,**

leaves, and roots. At the same time, **leaf litter and root turnover** contribute to the buildup of **soil organic carbon (SOC)**, enhancing the long-term stability of soil carbon pools ([Montagnini & Nair, 2004](#)). According to [Nair et al. \(2009\)](#), “agroforestry has the potential to sequester between **1.1 to 2.2 Pg CO₂ annually**” across global systems, especially in the tropics and subtropics.

Agroforestry is not a one-size-fits-all system; it encompasses several forms, each tailored to ecological conditions and farming needs:

- **Silvopasture** involves the **intentional combination of trees, forage, and livestock**, enhancing carbon sequestration while improving animal welfare and productivity ([Jose & Dollinger, 2019](#)).
- **Alley cropping** entails **planting rows of trees or shrubs alongside crops**, which not only sequester carbon but also provide wind protection, reduce erosion, and improve microclimates.
- **Windbreaks or shelterbelts** are linear plantings of trees that **protect croplands from wind erosion**, contribute to carbon storage, and improve soil moisture retention.

Beyond carbon, agroforestry systems also improve **biodiversity, soil fertility, nutrient cycling**, and **climate resilience**. These systems reduce dependence on synthetic inputs, diversify farm income, and restore degraded lands, making them central to **carbon-negative farming and regenerative agriculture**.

2.2. Perennial Cropping

Perennial cropping systems are increasingly recognized as a cornerstone of carbon-negative agriculture due to their **deep root systems, permanent**

soil cover, and minimal disturbance to soil structure. Unlike annual crops, which require seasonal tilling and replanting, **perennial crops regrow year after year**, allowing them to **continuously sequester carbon in both biomass and soil** ([Glover *et al.*, 2012](#)).

One of the key ecological advantages of perennial crops is their **extensive root systems**, which penetrate deep into the soil, enhancing **soil organic carbon (SOC) accumulation** and stabilizing the soil structure. Deep-rooted perennials build soil carbon at depths beyond the reach of most annual crops, contributing to long-term carbon sequestration and greater resilience against drought and erosion ([Chepkemai *et al.*, 2025](#)). The **year-round ground cover** provided by perennials also reduces soil erosion, suppresses weeds, and moderates soil temperature and moisture regimes, thereby supporting **microbial communities critical to soil health**.

Perennial cropping also helps to **minimize tillage**, which is a major source of CO₂ emissions in conventional agriculture. By reducing the need for repeated soil disturbance, perennial systems **lower fuel use and mechanical inputs** while maintaining **carbon-rich soil aggregates** ([Crews & Rumsey, 2017](#)). Additionally, perennial systems often require **fewer external inputs** like fertilizers and pesticides, further reducing their carbon footprint.

A wide range of **perennial crops** are now being cultivated for both food and fodder. These include:

- **Perennial grains** such as *Kernza* (intermediate wheatgrass), which are being developed to offer both grain yield and deep-rooted soil benefits.
- **Fruit and nut trees** like apples, almonds, and mangoes, which store significant above-ground carbon in their woody biomass.

- **Perennial forage crops** like alfalfa (*Medicago sativa*) and napier grass (*Pennisetum purpureum*), which contribute to **sustainable livestock systems** while enhancing below-ground carbon pools.

As part of a diversified farming system, perennial cropping provides a **low-emission, soil-regenerative alternative** to annual monocultures. It not only supports long-term carbon storage but also improves **ecosystem resilience, biodiversity, and landscape stability**, making it a vital component of carbon-negative farming.

2.3. Integrated Crop-Livestock Systems

Integrated Crop-Livestock Systems (ICLS) are multifunctional agricultural systems where **crop production and livestock rearing are combined in a synergistic manner**. These systems enhance **carbon sequestration, nutrient recycling, and ecological resilience** while reducing greenhouse gas (GHG) emissions and dependency on synthetic inputs ([Lemaire et al., 2014](#)).

A key feature of ICLS is the **recycling of organic residues and animal manure**, which are returned to the soil as natural fertilizers. This practice **enhances nutrient cycling** and boosts **soil organic matter (SOM)**, thereby increasing **soil carbon stocks** over time. As [Aboul Naga et al., \(2020\)](#) noted, “manure applications in integrated systems improve soil quality and sustain long-term productivity, while contributing to climate change mitigation through SOC enhancement.”

Managed grazing in ICLS also contributes significantly to **soil carbon gains**. Rotational grazing and well-regulated stocking densities can promote root biomass, enhance soil microbial activity, and reduce erosion, all of which **facilitate below-ground carbon sequestration** ([Conant et al., 2017](#)). In addition, **pasture-based livestock systems** generally have a

lower carbon footprint than confined animal feeding operations, particularly when paired with **leguminous forage crops** that naturally fix nitrogen, reducing the need for synthetic fertilizers ([Petersen *et al.*, 2006](#)).

By combining multiple enterprises within the same landscape, ICLS allow for **input substitution and diversification**, which reduces reliance on fossil fuels, agrochemicals, and external feed inputs. According to Lemaire *et al.* (2014), “the strategic integration of crops and livestock leads to more efficient land use and promotes environmental sustainability.” Common examples of ICLS include:

- **Mixed farming systems** where crop residues feed livestock, and manure is used for crop fertilization;
- **Agropastoral systems** with rotational grazing on cover-cropped or fallow lands;
- **Silvopastoral systems**, a form of agroforestry that integrates trees, pasture, and livestock on the same land unit.

These systems represent a **closed-loop model of agriculture**, improving **carbon balance, resource-use efficiency, and resilience**, and are particularly valuable in both smallholder and large-scale farming contexts pursuing carbon-negative outcomes.

2.4. Wetland Restoration and Peatland Conservation

Wetlands and peatlands are among the most **carbon-rich ecosystems on the planet**, storing vast amounts of carbon in saturated soils and organic matter. These ecosystems act as **natural carbon sinks**, capable of storing carbon for thousands of years due to their **anaerobic (low-oxygen) conditions**, which significantly slow the decomposition of organic material ([Mitsch & Gosselink, 2000](#)). Wetland restoration and peatland conservation

are, therefore, **critical strategies in carbon-negative farming and climate change mitigation.**

Globally, **peatlands cover just 3% of the Earth's land surface** but store over **30% of the world's soil carbon**, more than all other vegetation types combined ([Joosten *et al.*, 2012](#)). However, when degraded or drained for agriculture or development, peatlands become **major sources of CO₂ and methane emissions**. Rewetting and restoring these areas not only halts these emissions but **reactivates their carbon sequestration function**, making peatland conservation a top priority for climate action ([Leifeld & Menichetti, 2018](#)).

Restoring wetlands through hydrological rehabilitation (e.g., blocking drainage channels, replanting native vegetation) can **reestablish their natural carbon balance**, improve **water retention**, and support **biodiversity recovery**. According to [Mitsch *et al.* \(2015\)](#), “restored wetlands can sequester carbon at rates between **118 and 500 g C m⁻² yr⁻¹**, depending on vegetation type and hydrological conditions.”

In addition to carbon storage, **wetlands and peatlands provide vital ecosystem services** such as **flood regulation, groundwater recharge, water purification**, and **habitat for diverse flora and fauna**. These co-benefits contribute to landscape-level **climate resilience**, particularly in areas vulnerable to extreme weather events or water scarcity.

Key strategies in this domain include:

- **Avoiding the drainage of intact peatlands;**
- **Rewetting degraded peatlands** through controlled water management;
- **Incorporating paludiculture**, or the cultivation of wetland-adapted crops (e.g., cattails, reeds, Sphagnum moss), which enables productive land use without drying the soil.

In the context of carbon-negative farming, **protecting existing wetlands and peatlands is as important as creating new carbon sinks**. Their conservation supports **long-term carbon storage, climate stability, and ecological integrity** at both local and global scales.

2.5. Aquaforestry - Integrating Trees with Aquatic Systems

Aquaforestry is an emerging land-use practice that integrates **woody perennials** such as mangroves or riparian trees into **aquatic farming systems**, creating synergistic **land-water carbon sinks**. This integrated model supports **carbon sequestration** both aboveground (in tree biomass) and belowground (in sediments and root systems), while simultaneously enhancing **aquatic biodiversity, water quality, and system productivity** ([Primavera, 2000](#); [Alongi, 2012](#)).

One of the most recognized forms of aquaforestry is the **integration of mangroves with brackish water aquaculture systems**. Mangroves are known for their **high carbon storage capacity**, sequestering carbon at rates of **174–500 g C m⁻² yr⁻¹** in biomass and soil, making them one of the most effective nature-based solutions for climate mitigation ([Donato *et al.*, 2011](#)). They also play a key role in stabilizing shorelines, reducing nutrient runoff, and providing breeding grounds for fish and crustaceans thus linking **climate mitigation with livelihood enhancement**.

In inland areas, **tree-lined fishponds and riparian buffer zones** with native species (e.g., *Acacia*, *Eucalyptus*, *Bamboo*) help regulate microclimates, **absorb excess nutrients**, and store carbon in leaf litter and sediments. These systems, when properly designed, **reduce methane emissions** from aquaculture by stabilizing nutrient cycles and minimizing anaerobic conditions in pond sediments ([Ahmed *et al.*, 2018](#)).

Aquaforestry also enhances **aquatic biodiversity**, as trees provide **shaded, nutrient-rich microhabitats** that support aquatic insects,

amphibians, birds, and fish. Moreover, the **land-water interface zones**, also referred to as *ecotones*, play an outsized role in **biogeochemical cycling**, nutrient interception, and **long-term carbon storage** ([Schlesinger & Bernhardt, 2013](#)).

In regions like Southeast Asia, the **silvofisheries** model where mangroves are co-cultivated with shrimp or fish has proven both **economically viable** and **ecologically regenerative** ([Primavera & Esteban, 2008](#)). Such systems, when governed by sustainable stocking and harvesting practices, can offer a **climate-resilient and low-emission alternative** to conventional aquaculture.

Aquaforestry is particularly valuable in **coastal and floodplain regions**, where conventional land use is constrained by salinity or inundation. When scaled up, these systems can become powerful components of **blue carbon strategies**, aligning climate action with sustainable livelihoods and ecosystem conservation.

3. Soil Health and Organic Carbon Enrichment

Soil health is the foundation of sustainable agriculture and a key lever in advancing carbon-negative farming systems. Healthy soils not only sustain plant growth but also act as dynamic carbon sinks, helping mitigate climate change by storing atmospheric carbon in stable organic forms. The concept of soil organic carbon (SOC) lies at the core of this process formed through the accumulation and stabilization of organic matter, which also improves water retention, nutrient availability, and microbial functioning ([Lal, 2004](#)). Enhancing SOC through ecologically sound practices contributes to soil fertility, resilience against climatic extremes, and reduced dependence on synthetic inputs, thus fostering circular, regenerative farming models.

This section explores five critical components of soil health management that also serve as mechanisms for organic carbon enrichment in agricultural

systems. These include:

- **Cover Cropping and Crop Rotation**, which maintain soil cover, fix atmospheric nitrogen, suppress weeds, and enhance organic matter while breaking pest and disease cycles;
- **Reduced or No-Till Farming**, aimed at minimizing soil disturbance to preserve soil structure, reduce erosion, and improve microbial activity;
- **Biochar Application**, using pyrolyzed biomass to enhance soil properties and sequester carbon long-term;
- **Composting and Organic Amendments**, which recycle organic waste into humus-rich inputs that enhance soil carbon and microbial biomass; and
- **Use of Biostimulants**, which support plant growth and stimulate beneficial microbial activity, enhancing soil nutrient dynamics with fewer chemical inputs.

Together, these practices contribute to a climate-smart and ecologically resilient soil management system essential for carbon-negative agriculture.

3.1. Cover Cropping and Crop Rotation

Cover cropping and crop rotation are foundational agroecological practices that significantly contribute to soil health and organic carbon enrichment, making them indispensable strategies in carbon-negative farming. Cover crops such as legumes, grasses, or brassicas are grown primarily not for harvest but to cover the soil, preventing erosion, suppressing weeds, and enhancing soil structure. These crops protect the soil surface, reduce compaction, and improve water retention. Crucially, leguminous cover crops (e.g., clover, vetch) fix atmospheric nitrogen through symbiosis with

Rhizobium bacteria, reducing dependency on synthetic fertilizers and promoting nutrient cycling ([Snapp et al., 2005](#)).

Beyond their role as living mulch, cover crops contribute substantial organic residues to the soil upon decomposition, thus increasing soil organic matter (SOM) and enhancing microbial activity and aggregate stability ([SARE, 2012](#)). This organic matter is a key pool of soil organic carbon (SOC), critical for long-term carbon sequestration and fertility. Moreover, cover cropping contributes to allelopathic suppression of weed germination and disrupts weed life cycles without chemical inputs ([Bamford & Entz, 2016](#)).

Complementing cover cropping, crop rotation diversifies the cropping system both spatially and temporally. Rotational practices, particularly those involving cereals, legumes, and deep-rooted crops, reduce the build-up of host-specific pests and diseases by interrupting their reproductive cycles ([Larkin, 2003](#)). This diversity reduces soil nutrient depletion and prevents the emergence of monoculture-associated problems, fostering resilient agroecosystems.

Integrating both strategies not only enhances productivity but also improves the ecological functions of agricultural land, supporting long-term sustainability and climate change mitigation. These practices are synergistic in building soil organic carbon and improving soil biological health, which are critical for resilient food systems in the face of increasing environmental stress.

3.2. Reduced or No-Till Farming

Reduced or no-till farming is a key conservation agriculture practice aimed at minimizing soil disturbance, thereby improving soil structure, enhancing soil organic carbon (SOC), and reducing greenhouse gas emissions. Traditional plowing or tillage disrupts soil aggregates, accelerates organic

matter decomposition, and exposes soil to erosion and moisture loss. In contrast, no-till systems maintain a protective residue cover on the soil surface, conserving moisture, moderating temperature fluctuations, and reducing erosion risks ([Hobbs *et al.*, 2007](#)).

One of the critical ecological benefits of no-till farming is the promotion of soil aggregation, which enhances water infiltration, root penetration, and microbial habitat stability. Over time, this leads to an increase in beneficial soil microbial biomass and activity, essential for nutrient cycling and carbon stabilization ([Six *et al.*, 2002](#)). The reduced mechanical disturbance also limits oxidation of soil organic matter, allowing for a more stable carbon pool to accumulate in the soil profile.

Additionally, reduced tillage lowers fossil fuel use by decreasing the number of tractor passes and heavy machinery operations required for seedbed preparation. This results in considerable energy savings and a reduction in carbon dioxide emissions associated with on-farm fuel combustion ([West & Marland, 2002](#)). Moreover, by maintaining continuous soil cover with crop residues or cover crops, no-till systems act as a natural barrier against wind and water erosion, particularly in sloped or marginal lands.

When integrated with other soil-enriching practices such as cover cropping and organic amendments, reduced or no-till farming becomes a powerful tool in climate-resilient and carbon-negative agriculture, offering both mitigation and adaptation benefits.

3.3. Biochar Application

Biochar application has emerged as a promising strategy for enhancing soil health and long-term carbon sequestration in carbon-negative farming systems. Biochar is a stable, carbon-rich material produced through the pyrolysis of organic biomass such as crop residues, wood chips, or animal

waste under limited oxygen conditions. This process locks carbon into a highly stable form that can persist in soils for hundreds to thousands of years, making it a powerful tool for long-term carbon storage ([Lehmann & Joseph, 2015](#)).

When applied to soil, biochar significantly improves physical properties by increasing porosity, reducing bulk density, and enhancing soil structure. These changes promote better root penetration, aeration, and microbial colonization. Moreover, biochar enhances the soil's water-holding capacity, which is particularly beneficial in arid and degraded regions where water availability is a limiting factor for crop productivity ([Glaser *et al.*, 2002](#)). Its high surface area and cation exchange capacity also contribute to improved nutrient retention and fertility, reducing leaching losses of essential nutrients like nitrogen and potassium.

From a carbon management perspective, biochar not only stabilizes organic carbon but also creates a habitat that supports beneficial microbial communities involved in nutrient cycling and disease suppression. Studies have shown that biochar-amended soils exhibit increased microbial biomass and enzyme activity, fostering a more resilient and productive soil ecosystem ([Lehmann *et al.*, 2011](#)).

Integrating biochar into farming systems, especially in combination with compost or reduced tillage, can amplify its positive effects by enhancing the synergy between physical, chemical, and biological improvements in soil. Thus, biochar serves a dual role: mitigating climate change through durable carbon sequestration and enhancing soil productivity for sustainable agriculture.

3.4. Composting and Organic Amendments

Composting and the use of organic amendments are foundational practices in carbon-negative farming, offering a sustainable means to recycle organic

waste while enhancing soil health and carbon sequestration. Composting involves the aerobic decomposition of biodegradable organic matter, such as crop residues, animal manure, food waste, and green biomass, into humus-rich compost. This stable organic product improves soil structure, boosts microbial activity, and enriches soil organic matter (SOM), which plays a vital role in long-term carbon retention ([Bernal *et al.*, 2009](#)).

The application of compost to soil increases SOM levels, which enhances soil water-holding capacity, nutrient availability, and cation exchange capacity. It also promotes the proliferation of beneficial microorganisms that support nutrient cycling, suppress soil-borne pathogens, and improve root health ([Oyege *et al.*, 2023](#)). In turn, these biological processes facilitate greater plant productivity with reduced reliance on chemical fertilizers.

Importantly, composting diverts organic waste from landfills, where it would otherwise generate methane, a potent greenhouse gas. By stabilizing carbon in the form of humus, composting not only mitigates emissions but also builds a resilient carbon pool within the soil. When combined with practices like no-till farming or cover cropping, compost further contributes to agroecosystem sustainability and climate mitigation.

Moreover, the localized production and use of compost foster a **circular nutrient economy**, wherein nutrients are cycled within the farm or community system, reducing external input dependency and enhancing food system resilience ([Diacono & Montemurro, 2010](#)). Organic amendments such as farmyard manure, green manure, and vermicompost similarly contribute to this model, supporting regenerative agriculture through natural soil enrichment.

3.5. Use of Biostimulants for Plant and Soil Health

The application of biostimulants represents an innovative and sustainable strategy in carbon-negative farming, offering a holistic approach to enhance

plant vigor, soil health, and nutrient efficiency. Biostimulants are a diverse group of natural substances and microorganisms such as seaweed extracts, humic and fulvic acids, protein hydrolysates, amino acids, and beneficial microbes like *Rhizobium*, *Azospirillum*, and *Trichoderma* that act on plant physiology and the soil ecosystem to improve growth, resilience, and productivity ([du Jardin, 2015](#)).

One of the primary roles of biostimulants is to **enhance nutrient uptake** by improving root architecture and nutrient use efficiency. This is particularly beneficial in nutrient-deficient soils or under stress conditions like drought, salinity, or extreme temperatures, where biostimulants help mitigate negative effects and promote **stress tolerance** ([Rouphael & Colla, 2020](#)). For example, seaweed-based products contain natural plant hormones (e.g., cytokinins, auxins) and polysaccharides that trigger stress-responsive pathways, resulting in improved photosynthesis and water-use efficiency.

Biostimulants also play a critical role in **stimulating beneficial soil microbiota**, including nitrogen-fixing bacteria, phosphate-solubilizing microbes, and mycorrhizal fungi. These microbial communities enhance soil nutrient cycling and contribute to soil aggregation, thereby improving soil structure and long-term fertility ([Calvo et al., 2014](#)). Moreover, the stimulation of microbial activity leads to greater microbial biomass and enzymatic functions, reinforcing soil organic matter stability and carbon sequestration potential.

Importantly, biostimulants reduce the need for synthetic fertilizers and pesticides, **supporting a transition away from chemical-intensive agriculture**. Their use aligns with regenerative and climatesmart farming models by promoting plant growth through biological means, improving the

resilience of cropping systems, and minimizing the carbon footprint of agricultural inputs.

4. Smart Inputs and Resource Optimization

As agriculture faces mounting pressure to feed a growing population while minimizing environmental harm, the adoption of **smart inputs and resource optimization strategies** has become imperative. This section focuses on modern approaches that enhance input use efficiency, reduce waste, and minimize the carbon intensity of agricultural practices. By aligning input application with actual crop needs and environmental conditions, farmers can significantly cut down greenhouse gas (GHG) emissions, conserve natural resources, and maintain productivity with fewer external inputs.

Smart resource management also plays a critical role in reducing indirect emissions associated with energy-intensive inputs such as synthetic fertilizers, pesticides, and water pumping. These approaches not only support **low-carbon farming** but also improve economic sustainability by lowering production costs and enhancing farm resilience under climate variability ([Smith et al., 2007](#)).

The following components illustrate how precision and efficiency can be leveraged across key resource domains:

- **Efficient Water Management**, which focuses on reducing the energy footprint of irrigation and maximizing water productivity through drip systems, mulching, and rainwater harvesting;
- **Precision Agriculture and Smart Technologies**, which utilize satellite imagery, remote sensing, and IoT-based tools for real-time monitoring and optimized input use;

- **Integrated Pest Management (IPM)**, which replaces blanket chemical use with ecologicallybased strategies to manage pests, improve biodiversity, and reduce pesticide-related emissions.

Together, these strategies represent a synergistic shift from input-intensive agriculture to **knowledgeintensive, data-driven systems**, essential for achieving both productivity and sustainability goals in carbon-negative farming.

4.1. Efficient Water Management

Efficient water management is a cornerstone of carbon-negative farming, as it directly impacts both agricultural productivity and the energy footprint of irrigation systems. Traditional irrigation methods, such as flood or basin irrigation, often lead to significant water loss through evaporation, runoff, and percolation, while also consuming large amounts of energy especially where water is pumped from deep aquifers or over long distances. By contrast, modern water-saving technologies and practices reduce water usage and associated carbon emissions, making agricultural systems more sustainable and climate-resilient ([Burney *et al.*, 2010](#)).

Drip irrigation is one of the most effective solutions in this regard. It delivers water directly to the plant root zone with minimal loss, resulting in up to 30-70% water savings compared to conventional methods ([Postel *et al.*, 2001](#)). This targeted delivery reduces the energy required for pumping and limits nitrous oxide emissions by avoiding over-irrigation, which often leads to nutrient leaching. **Mulching**, another efficient practice, helps reduce evaporation, conserve soil moisture, suppress weeds, and moderate soil temperature. Organic mulches, in particular, enhance soil organic matter and contribute to carbon sequestration over time.

Additionally, **rainwater harvesting** through farm ponds, tanks, or rooftop systems helps supplement irrigation while reducing the reliance on fossil-fuel-powered water sources. Stored rainwater can be used during dry spells, thus stabilizing production and improving water use efficiency (WUE) without increasing carbon intensity.

The relationship between **water use efficiency and carbon intensity** is crucial: improved WUE reduces the need for energy-intensive inputs and mitigates emissions associated with pumping, treatment, and conveyance of water. Hence, water-smart agriculture is inherently low-carbon, contributing to both climate mitigation and adaptation.

4.2. Precision Agriculture and Smart Technologies

Precision agriculture and smart technologies are transforming conventional farming into a highly efficient, data-driven system that optimizes resource use, reduces environmental impact, and supports carbonnegative outcomes. These innovations integrate digital tools such as GPS-guided equipment, remote sensing, IoT-based sensors, drones, and satellite imagery to monitor and manage agricultural inputs with pinpoint accuracy. By tailoring practices to the specific needs of crops, soils, and microclimates, precision farming enhances productivity while minimizing resource wastage ([Zhang et al., 2002](#)).

A central feature of precision agriculture is **satellite and sensor-based input management**, which allows real-time monitoring of soil moisture, crop health, nutrient deficiencies, and pest infestations. This enables site-specific application of fertilizers, pesticides, and irrigation, avoiding blanket treatments that lead to overuse and associated greenhouse gas (GHG) emissions. For example, nitrogen fertilizers, when overapplied, contribute to nitrous oxide emissions one of the most potent GHGs. Precision tools

help optimize these applications, thereby mitigating emissions and reducing input costs ([Gebbers & Adamchuk, 2010](#)).

Additionally, these technologies enable **data-driven emissions monitoring and reductions** by providing accurate assessments of input use, crop performance, and carbon footprints across farming operations. Platforms that integrate GIS, AI, and machine learning can model GHG fluxes, track carbon sequestration, and support low-emission decision-making in real-time ([Sishodia et al., 2020](#)). Farmers can also use digital dashboards to generate verifiable data for carbon credit schemes, enhancing access to climate finance.

Overall, precision agriculture is not just about efficiency it is a pathway to regenerative and climate-smart farming. By minimizing the overuse of synthetic inputs and maximizing resource-use efficiency, it aligns economic viability with environmental responsibility.

4.3. Integrated Pest Management (IPM)

Integrated Pest Management (IPM) is a holistic and ecologically sound approach to crop protection that plays a crucial role in reducing agriculture's environmental footprint and advancing carbonnegative farming. Unlike conventional pest control methods that rely heavily on synthetic pesticides, IPM emphasizes the use of **biological, cultural, mechanical, and chemical tools in a coordinated manner** to manage pest populations at acceptable levels without harming the ecosystem ([Deguine et al., 2021](#)).

One of the primary goals of IPM is **reducing reliance on synthetic pesticides**, which are not only energy-intensive to manufacture but also contribute to greenhouse gas emissions during production and application. Excessive pesticide use also degrades soil and water quality and harms non-target organisms, including pollinators and beneficial insects. IPM mitigates

these impacts by encouraging the judicious and need-based use of chemical inputs as a last resort.

IPM strategies promote **ecological and biological pest control** through techniques such as the introduction of natural predators (e.g., ladybugs, parasitic wasps), use of biopesticides, pheromone traps, and habitat manipulation to enhance natural enemy populations. Cultural practices like crop rotation, intercropping, and trap cropping further disrupt pest life cycles and suppress outbreaks without environmental harm (Hatt, and Doring, 2023).

In doing so, IPM enhances **resilience and biodiversity** within agricultural ecosystems. By minimizing chemical disruptions, it fosters a diverse community of soil organisms, insects, and microbes that contribute to pest regulation, pollination, and nutrient cycling. This ecological balance not only makes the system more self-sustaining but also resilient to climate-induced stresses and pest invasions.

Thus, IPM aligns well with the principles of carbon-negative agriculture by reducing emissions, promoting ecosystem health, and supporting long-term sustainability of food systems.

5. Controlled and Renewable Systems

As the agricultural sector seeks pathways to reduce emissions and enhance sustainability, the integration of **controlled environment agriculture (CEA)** and **renewable energy systems** has emerged as a transformative approach. Section IV highlights how innovations in controlled and renewable systems can decouple agricultural production from environmental degradation, reduce the carbon footprint of farms, and improve resource-use efficiency.

Controlled systems allow for **precise regulation of growing conditions**, enabling optimized use of water, nutrients, and energy, while renewable

technologies reduce dependence on fossil fuels. Together, these systems support a **low-emission, high-efficiency model of farming** that is adaptable to diverse geographical and climatic contexts including urban and peri-urban areas.

This section focuses on three key innovations that embody the shift towards carbon-conscious, resource-optimized agriculture:

- **Renewable Energy on Farms**, which involves deploying solar, wind, and biogas systems to replace conventional fossil fuel-based energy for operations such as irrigation, processing, and greenhouse heating;
- **Soilless Farming**, including hydroponics, aeroponics, and aquaponics, which eliminate soil use and enable **precise input control**, reducing emissions, water usage, and land degradation;
- **Production of Microgreens**, which represent a model of ultra-short-cycle, nutrient-rich crop cultivation that is particularly suited to vertical farms and urban settings, offering high returns with minimal environmental impact.

These innovations, when integrated thoughtfully, **redefine agricultural efficiency and resilience**, supporting the global transition toward carbon-negative and climate-resilient food systems.

5.1. Renewable Energy on Farms

The integration of renewable energy on farms is a vital strategy in the transition toward carbonnegative agriculture, offering a clean and sustainable alternative to fossil fuel-based energy systems. Farms traditionally depend on diesel and electricity often generated from non-renewable sources for operations such as irrigation, processing, lighting,

and greenhouse heating. Replacing these with **solar, wind, and biogas systems** not only reduces **greenhouse gas (GHG) emissions** but also cuts long-term energy costs and enhances energy security for rural communities ([Burney *et al.*, 2010](#)).

Solar energy is among the most widely adopted renewable options in agriculture. Photovoltaic (PV) panels are now commonly used to power irrigation pumps, greenhouse systems, and cold storage facilities. Solar-powered drip irrigation, in particular, enhances water-use efficiency while minimizing carbon emissions associated with diesel pumps ([IRENA, 2016](#)). Similarly, **wind turbines** especially small-scale vertical-axis designs can be used in open field farms to generate power for mechanical and electrical operations.

Biogas systems, utilizing farmyard manure and crop residues, provide a closed-loop solution for both waste management and energy generation. Anaerobic digestion not only produces methane-rich biogas for cooking and heating but also generates nutrient-rich slurry that can be used as organic fertilizer, further supporting low-emission farming ([FAO, 2013](#)).

The cumulative effect of renewable energy adoption is a significant **reduction in the farm's carbon footprint**. By minimizing emissions from fuel combustion and enabling circular use of onfarm biomass, these technologies align with broader climate goals and contribute to more resilient and sustainable food systems.

5.2. Soilless Farming

Soilless farming systems such as **hydroponics, aeroponics, and aquaponics** represent a transformative approach to sustainable and carbon-efficient food production. These systems eliminate the need for soil by delivering nutrients directly to plants via water or mist, making them particularly suitable for regions facing soil degradation, water scarcity, or

limited arable land. They offer high productivity per unit area and can be established in **controlled environments** such as greenhouses and vertical farms, allowing year-round cultivation and climate resilience ([Resh, 2022](#)).

Hydroponics involves growing plants in nutrient-enriched water, which enables precise control over nutrient supply and water use. It uses up to **90% less water** than traditional farming, with **minimal nutrient runoff**, thereby reducing water-related energy costs and emissions ([Resh, 2022](#)).

Aeroponics, where plant roots are suspended in air and misted with nutrient solutions, further optimizes water and nutrient efficiency, and promotes faster growth due to improved oxygenation (Barbosa *et al.*, 2015).

Aquaponics integrates hydroponics with fish farming, creating a circular system where fish waste provides nutrients for plants, and plants purify water for the fish, significantly lowering input needs and waste (Love *et al.*, 2015).

These systems are highly **resource-efficient**, enabling dense cultivation in urban or peri-urban areas with **reduced carbon footprints** due to decreased land use, transportation needs, and emissions from mechanized soil management ([Gruda, 2009](#)). The **controlled environments** allow for optimal lighting, humidity, and CO₂ levels, leading to higher yields with less environmental impact. Moreover, soilless systems can be powered by renewable energy sources, further enhancing their contribution to carbon-negative agriculture

5.3. Production of Microgreens

The **production of microgreens**, young, tender greens harvested at the cotyledon or first true leaf stage, offers a highly efficient and climate-smart agricultural practice with strong potential for **carbon-negative farming**. These **ultra-short-cycle crops** are typically harvested within 7 to 21 days of germination, allowing for multiple crop rotations per year, high turnover,

and optimal use of **space, time, and resources** ([Xiao et al., 2012](#)). Their short life cycle means reduced energy inputs, water use, and nutrient demands, contributing to **low overall emissions** and **high resource-use efficiency**.

Microgreens are ideally suited for **urban, vertical, and indoor farming systems**, making them a key component of **controlled environment agriculture (CEA)**. These systems can be integrated into rooftops, greenhouses, and indoor vertical racks with LED lighting, using hydroponic or soilless substrates that further reduce environmental footprints ([Kyriacou et al., 2016](#)). Because they require **minimal land**, produce negligible waste, and can thrive in **energy-optimized environments**, microgreens align well with carbon-reduction strategies in food production, especially in urban settings.

Nutritionally, microgreens are **densely packed with vitamins, minerals, and antioxidants**, often containing **3 to 40 times higher concentrations of nutrients** compared to their mature counterparts ([Xiao et al., 2012](#); [Pinto et al., 2015](#)). This makes them not only efficient in terms of production but also powerful contributors to **nutritional security**, particularly in space-constrained or resourcelimited environments.

Incorporating microgreens into farming portfolios offers a **sustainable and scalable approach** to reduce emissions, enhance urban food sovereignty, and promote health through high-quality plantbased nutrition making them a valuable element in **carbon-negative farming systems**.

6. Conclusion and Way Forward

Carbon-negative farming represents a paradigm shift from emission-intensive agriculture to a regenerative model that actively removes atmospheric carbon while enhancing ecosystem health and productivity. The practices discussed in this chapter, spanning Ecological Land Use

Systems for Carbon Sequestration, Soil Health and Organic Carbon Enrichment, Smart Inputs and Resource Optimization, and Controlled and Renewable Systems, together provide a holistic framework for transforming agriculture into a climate-positive enterprise.

At its core, carbon-negative farming integrates traditional ecological wisdom with modern technological innovations. Ecological land use systems such as agroforestry, perennial cropping, and wetland restoration restore biological carbon sinks while enhancing biodiversity and landscape resilience. Soil health management practices, including biochar application, composting, cover cropping, and minimal tillage, rebuild the organic carbon foundation of agroecosystems, improving water retention, nutrient cycling, and long-term fertility. Meanwhile, precision agriculture, efficient water management, and integrated pest management bring data-driven optimization that minimizes waste and reduces indirect emissions. Finally, controlled and renewable systems such as hydroponics, microgreens cultivation, and solar-powered farms illustrate how production can be decoupled from environmental degradation while ensuring year-round food security.

However, the successful operationalization of carbon-negative farming requires context-specific adaptation. Practices must be tailored to local agroecological zones, resource availability, and socio-economic realities. Farmer participation, indigenous knowledge, and adaptive co-creation of solutions are essential for ensuring scalability and equity. One-size-fits-all models are impractical; instead, localized innovation networks and community-based carbon farming models offer pathways for inclusive climate action.

The way forward lies in building an enabling ecosystem that integrates policy support, financial incentives, and institutional collaboration.

Governments and international agencies should embed carbon-negative strategies within national climate plans, rural development programs, and food system reforms. Mechanisms such as carbon credit markets, green financing tools, and results-based payments can reward farmers for ecosystem services and verified carbon sequestration. Likewise, capacity-building initiatives, farmer field schools, and digital extension platforms are critical for empowering farmers to adopt and manage these innovative practices effectively.

Continuous research and technology development must focus on quantifying carbon fluxes, optimizing sequestration potential, and assessing trade-offs between productivity, biodiversity, and carbon outcomes. Integrating remote sensing, artificial intelligence, and life-cycle assessment tools can enable transparent carbon accounting and support participation in global carbon markets.

In sum, carbon-negative farming offers a transformative pathway toward resilient, regenerative, and climate-smart agriculture. By synergizing ecological integrity, technological innovation, and socioeconomic inclusion, it can redefine the future of food systems—making them not only sustainable but restorative. The transition ahead demands commitment, collaboration, and creative governance, but the outcome promises a resilient planet where agriculture becomes a powerful force for carbon neutrality and climate stability.

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Chapter - 5

Innovative Approaches and Technologies

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1. Introduction

Agriculture, while vital for food security and livelihoods, is a significant contributor to global greenhouse gas (GHG) emissions, accounting for nearly 23% of total anthropogenic emissions when including land use change ([IPCC, 2019](#)). This ecological footprint results primarily from deforestation, methane emissions from rice paddies and livestock, nitrous oxide emissions from fertilized fields, and unsustainable land management practices. As the world strives to meet the targets of the Paris Agreement and stabilize global temperatures, agriculture must transition from being a carbon source to a carbon sink. Carbon-negative farming is an emerging paradigm that aims not just to reduce emissions but to actively remove CO₂ from the atmosphere and sequester it in soils, biomass, and long-lived materials. This transformation is driven by a suite of innovative approaches and technologies, both nature-based and engineered, that enhance carbon sequestration, improve input-use efficiency, and reduce reliance on fossil fuels.

Among the most promising technologies is the production and soil application of biochar, a stable carbon-rich material derived from the pyrolysis of biomass. Biochar can sequester carbon for centuries while improving soil structure and nutrient retention ([Lehmann & Joseph, 2015](#)). Similarly, enhanced rock weathering (ERW), which involves applying finely ground silicate rocks to croplands, accelerates natural carbon capture through mineral carbonation processes, offering substantial potential for

gigaton-scale carbon removal (Beerling *et al.*, 2020). In parallel, agroforestry systems, the deliberate integration of trees and shrubs into agricultural landscapes, enhance above and belowground carbon storage while delivering co-benefits such as biodiversity conservation and resilience to climate extremes ([Nair *et al.*, 2010](#)). The role of deep-rooted perennial crops, which promote subsoil carbon sequestration, is increasingly recognized for their potential in stabilizing carbon in deeper soil layers less prone to disturbance ([Kell, 2012](#)). Biological amendments also play a pivotal role. The application of microbial biostimulants and organic inputs such as compost and manure enhances microbial carbon use efficiency, promotes aggregation, and extends carbon residence time in soil ([Compant *et al.*, 2010](#)).

Technological innovations are central to operationalizing carbon-negative farming. Precision agriculture tools, including satellite imagery, remote sensing, and soil sensors, help minimize overuse of water and fertilizers, key drivers of emissions while maintaining productivity ([Gebbers & Adamchuk, 2010](#)). Smart irrigation systems automate water delivery based on crop need, reducing energy and water footprints, whereas machine learning and AI-driven analytics offer predictive insights into carbon fluxes, enabling real-time decision-making for carbon-smart farming. In high-tech agricultural systems, Controlled Environment Agriculture (CEA), such as vertical farming and hydroponics, demonstrates potential to grow crops with minimal land, water, and GHG emissions. When coupled with renewable energy sources, these systems move toward complete decarbonization ([Al-Chalabi, 2015](#)).

Further at the cutting edge are synthetic biology and gene editing technologies like CRISPR, which are being explored to engineer crops and microbes with enhanced carbon-fixing capabilities, nitrogen-use efficiency,

and stress tolerance, ushering in new frontiers in sustainable agriculture ([Doudna & Charpentier, 2014](#)). Lastly, integrating renewable energy systems such as solar irrigation, biogas digesters, and biomass gasifiers into farms helps reduce dependence on fossil fuels, contributing to net-zero and negative emission outcomes ([FAO, 2019](#)). Collectively, these approaches form a multidimensional strategy for reimagining agriculture as a climate solution. This chapter delves into each of these innovations, exploring their mechanisms, current applications, limitations, and future potential in driving carbon-negative transformations in global agriculture.

2. Production and application of biochar

Biochar has emerged as a promising tool in the pursuit of carbon-negative farming due to its dual capacity to sequester atmospheric carbon and enhance soil health. Derived from the thermochemical conversion of organic biomass under low-oxygen conditions, a process known as pyrolysis, biochar is a stable, carbon-rich material that can persist in soils for hundreds to thousands of years ([Lehmann & Joseph, 2015](#)). This long-term stability makes it an effective vehicle for locking atmospheric carbon in terrestrial systems, contributing to negative emission outcomes.

2.1. Production of Biochar

The production of biochar involves the thermochemical conversion of biomass through a process known as **pyrolysis**, which is carried out in the absence or limited presence of oxygen. This process transforms organic materials, such as crop residues (e.g., rice husks, wheat straw), forestry waste (e.g., sawdust, bark), animal manure, and even urban green waste, into a carbon-rich solid called biochar, along with by-products like syngas and bio-oil (Schmidt *et al.*, 2023; [Lehmann & Joseph, 2015](#)).

The **pyrolysis temperature**, typically ranging between **300°C to 700°C**, has a critical influence on the physicochemical properties of the resulting biochar. Lower temperatures (<400°C) tend to produce biochar with **higher volatile matter** and **greater nutrient content**, beneficial for plant growth, while higher temperatures (>500°C) generate biochar with **greater stability**, **higher surface area**, and **enhanced carbon sequestration potential** ([Enders *et al.*, 2012](#); [Dayoub *et al.*, 2024](#)). Other influencing factors include **residence time**, **heating rate**, and the **particle size** and **moisture content** of the feedstock ([Roberts *et al.*, 2010](#)).

2.1.1. Types of Pyrolysis Technologies

Pyrolysis can be carried out using a range of technologies, from **low-tech batch systems** to **high-tech continuous reactors**:

- **Traditional and Low-Cost Methods:** Systems like top-lit updraft (TLUD) stoves, pit kilns, and Kon-Tiki flame curtain kilns are cost-effective and appropriate for decentralized, small-scale biochar production in rural or smallholder farming contexts ([Schmidt & Shackley, 2016](#)). These systems are gaining popularity due to their low energy input, ease of construction, and co-benefits like cleaner cooking energy.
- **Intermediate and Industrial Technologies:** More advanced methods include **rotary kilns**, **fixed-bed reactors**, and **fluidized-bed pyrolysis systems**, which allow greater control over temperature and feedstock input. These are used in commercial setups to produce **large volumes of biochar** and capture syngas for **co-generation of electricity or heat** ([Tripathi *et al.*, 2016](#)). In **bioenergy-integrated farming**, the captured energy can be utilized for **drying crops**, **greenhouse heating**, or **electricity needs**,

thereby increasing **resource efficiency and energy self-sufficiency**.

- **Co-Product Utilization:** The gaseous and liquid by-products (syngas and bio-oil) can be combusted for on-site energy or further refined into biofuels, reducing reliance on fossil fuels and contributing to farm-level sustainability ([Lehmann *et al.*, 2006](#); [Tahir *et al.*, 2025](#)).

2.1.2. Carbon-Negative Potential

When feedstocks are sourced sustainably e.g., from crop residues that would otherwise decompose or be burned, biochar production can serve as a carbon-negative process. It not only prevents emissions of CO₂, CH₄, and N₂O from organic matter decay or open burning, but also locks carbon into a highly recalcitrant form, often stable in soils for hundreds to thousands of years (Li, S., & Tasnady, D. (2023; [Feng *et al.*, 2023](#)). The carbon sequestration potential of biochar varies, but life cycle assessments estimate net removal values ranging between 0.4 to 1.8 tonnes of CO₂ equivalent per tonne of biochar, depending on the process efficiency and soil integration strategy ([Saffari *et al.*, 2020](#)).

2.1.3. Environmental Considerations

To maximize climate benefits and minimize unintended impacts, the choice of **feedstock** and **production method** must be aligned with **sustainability criteria**. For instance, using feedstocks with high lignin content produces more stable biochar, while using contaminated materials can lead to toxic by-products. Additionally, **emission control systems** are needed in large-scale operations to prevent the release of volatile organic compounds (VOCs) or polycyclic aromatic hydrocarbons (PAHs) during production (Crombie & Masek, 2015).

2.2. Application of Biochar in Agricultural Systems

Once produced, biochar can be applied to soils directly or integrated into soil fertility management strategies to enhance soil health and productivity. Its porous structure, large surface area, and chemically stable carbon content allow biochar to act as a long-lasting soil amendment that contributes to both agronomic and environmental goals. By improving soil aeration, water retention, and nutrient-holding capacity, biochar is especially valuable in degraded, sandy, or nutrient-deficient soils ([Glaser *et al.*, 2002](#); [Bekchanova *et al.*, 2024](#)). It provides a physical and chemical matrix for soil microorganisms, leading to enhanced microbial colonization and activity.

When co-applied with compost, manure, or organic fertilizers, biochar serves as a synergistic agent, buffering nutrient release and enhancing microbial-driven processes such as nitrogen mineralization, organic matter decomposition, and mycorrhizal interactions (Steiner *et al.*, 2007). This synergistic effect is also observed in compost-biochar blends that improve humification rates and reduce composting time. Biochar's liming effect helps neutralize acidic soils, reducing dependence on synthetic lime and making phosphorus more bioavailable, which is particularly beneficial in tropical and subtropical agroecosystems ([Van Zwieten *et al.*, 2010](#)). In sandy soils, its ability to improve cation exchange capacity (CEC) and water-holding capacity can significantly mitigate drought stress.

The typical application rates of biochar range from 5 to 20 tonnes per hectare, but optimal rates depend on variables such as soil texture, biochar feedstock and pyrolysis conditions, crop species, and local agro-climatic conditions. High-temperature biochars (e.g., >500°C) tend to be more stable and carbon-rich, while low-temperature biochars retain more volatile compounds and may show more immediate agronomic benefits ([Enders *et*](#)

[al., 2012](#)). Site-specific calibration is thus essential for maximizing benefits while minimizing any unintended impacts on soil microbial balance or nutrient dynamics.

Numerous field trials and meta-analyses have documented yield improvements in staple and high-value crops such as maize, rice, wheat, sorghum, and various vegetables ([Jeffery et al., 2011](#); [Liu et al., 2017](#)). These improvements are often more pronounced under low-input or degraded soil conditions, where biochar helps restore key soil functions. For example, rice yield increases of 10-20% have been reported when biochar was integrated with reduced fertilizer doses and alternate wetting and drying (AWD) irrigation in South Asia ([Haider et al., 2017](#)).

From a carbon accounting standpoint, biochar's ability to sequester stable carbon in soils contributes significantly to climate mitigation efforts. Life cycle assessments (LCAs) estimate the carbon removal potential of biochar at 0.5 to 1.8 tonnes of CO₂ equivalent per tonne of biochar applied, depending on pyrolysis conditions, feedstock type, and the extent of avoided emissions ([Woolf et al., 2010](#); Roberts *et al.*, 2010). Moreover, biochar can reduce soil-based greenhouse gas emissions, particularly nitrous oxide (N₂O), by enhancing nitrification efficiency, reducing denitrification, and promoting microbial nitrogen transformations ([Spokas & Reicosky, 2009](#); [Cayuela et al., 2014](#)). This effect is especially valuable in intensively cultivated systems where N₂O emissions are a dominant GHG concern.

In addition to its use in open-field agriculture, biochar is increasingly being integrated into protected cultivation systems, hydroponics, and urban agriculture as a component of soil-less or blended media. Its role in improving water-use efficiency, root health, and crop resilience under

abiotic stress (e.g., drought, salinity) positions biochar as a multifunctional input for climate-resilient agriculture ([Biederman & Harpole, 2013](#)).

2.3. Co-Benefits and Implementation Challenges

Beyond carbon sequestration, biochar offers numerous co-benefits, including improved crop resilience under drought conditions, enhanced nutrient use efficiency, and reduced leaching of agrochemicals. It also acts as a habitat for beneficial soil microbes and serves as a carrier for microbial inoculants, making it a valuable component in regenerative and organic farming systems ([Joseph *et al.*, 2015](#)). However, the widespread adoption of biochar is constrained by several factors:

- High upfront costs of pyrolysis equipment
- Limited farmer awareness
- Variability in biochar quality and performance across contexts
- Lack of standardized regulatory frameworks and carbon market incentives

To unlock its full potential, supportive policies, local production hubs, and inclusion of biochar in carbon credit protocols are essential.

2.4. Future Prospects

In the context of carbon-negative farming, biochar holds significant promise as a scalable negative emissions technology that aligns with both environmental and agricultural sustainability goals. Integration with agroforestry, composting, and renewable energy systems can further enhance its impact. Research and innovation must continue to optimize biochar production methods, tailor biochar formulations to specific soil-

crop systems, and develop decision-support tools for site-specific application.

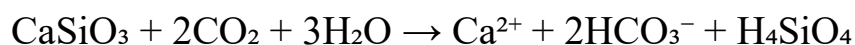
As biochar moves from pilot projects to mainstream agricultural strategies, it could become a cornerstone in the global transition toward low-emission, climate-resilient, and productive food systems.

3. Enhanced Rock Weathering (ERW)

Enhanced Rock Weathering (ERW) is an innovative geoengineering strategy designed to leverage natural biogeochemical processes for climate mitigation and soil restoration. At its core, ERW involves the application of finely ground silicate rocks, such as basalt, dunite (rich in olivine), and other calcium and magnesium-bearing minerals, to croplands to accelerate the chemical weathering process. This geochemical process captures atmospheric carbon dioxide (CO₂) through a series of reactions that form bicarbonates and carbonates, which are then transported to oceans or remain stabilized in soils for centuries to millennia ([Beerling *et al.*, 2018](#); [Hartmann *et al.*, 2013](#)).

3.1. Mechanism of Carbon Sequestration

When silicate rock powders are applied to soils, they undergo dissolution reactions with water and CO₂. A simplified chemical equation for basalt weathering is:



The bicarbonate ions (HCO₃⁻) formed are eventually leached into water bodies, where they contribute to long-term carbon sequestration by forming stable oceanic carbonate minerals. Unlike carbon stored in biomass or soil organic matter, which is subject to potential re-emission, the bicarbonates formed in ERW are resistant to re-release and provide a durable carbon sink ([Taylor *et al.*, 2016](#)).

3.2. Soil Health and Agricultural Co-benefits

Beyond carbon sequestration, ERW offers multiple agronomic benefits. As silicate rocks weather, they release essential macroand micronutrients such as calcium (Ca), magnesium (Mg), potassium (K), iron (Fe), phosphorus (P), and trace elements, thus improving nutrient availability and potentially replacing or supplementing synthetic fertilizers ([Dupla *et al.*, 2024](#)). This makes ERW particularly attractive for resource-constrained farmers aiming to transition to low-input or organic systems. In acidic soils, especially those found in tropical and subtropical regions, ERW helps neutralize pH by consuming hydrogen ions during mineral weathering. This improves root development, microbial diversity, and nutrient uptake efficiency, thereby supporting resilient crop production in regions vulnerable to soil degradation ([Kelland *et al.*, 2020](#); [Kantola *et al.*, 2017](#)).

3.3. Environmental and Climate Co-benefits

One promising, yet underexplored, benefit of ERW is its potential to reduce nitrous oxide (N₂O) emissions. Preliminary studies suggest that rock dust amendments may influence soil microbial communities and denitrification pathways, leading to reduced emissions of this potent greenhouse gas ([Kantola *et al.*, 2017](#)). Furthermore, the physical properties of rock powders, such as their high surface area, can enhance soil water retention, reduce erosion, and improve cation exchange capacity (CEC), contributing to broader agroecological resilience ([Dupla *et al.*, 2024](#)).

3.4. Global Sequestration Potential and Feasibility

Modeling studies estimate that ERW could remove between 2 and 4 gigatonnes of CO₂ annually if applied across suitable global croplands, particularly in warm, humid climates where weathering rates are higher ([Beerling *et al.*, 2018](#)). The potential is highest in countries with large

agricultural areas and access to basaltic rock resources, including India, Brazil, Indonesia, the United States, and parts of sub-Saharan Africa.

Recent pilot studies, such as those conducted by the Leverhulme Centre for Climate Change Mitigation in the UK and the United States, are evaluating the practical field-scale deployment of ERW in combination with regenerative farming practices such as conservation tillage, agroforestry, and cover cropping. These synergistic strategies not only enhance carbon sequestration but also reduce soil disturbance, promote microbial activity, and minimize nutrient losses ([Smith *et al.*, 2016](#)).

3.5. Technological and Operational Challenges

Despite its promise, ERW faces several challenges:

- **Energy Intensity:** Grinding rocks to a fine powder (<100 microns) is energy-intensive. The climate benefit of ERW depends on the use of renewable energy sources or waste heat for milling to ensure a positive carbon balance ([Strefler *et al.*, 2018](#)).
- **Transport Logistics:** Moving bulk quantities of rock powder from mines to fields involves significant costs and carbon emissions. Integrating ERW into existing agricultural logistics systems and exploring **local quarry waste** streams can help mitigate this ([Beerling *et al.*, 2018](#)).
- **Verification and Monitoring:** Accurate measurement, reporting, and verification (MRV) of carbon sequestration through ERW remains a scientific and technical challenge. However, advances in remote sensing, soil spectroscopy, and AI-enabled MRV platforms are being developed to quantify weathering rates and CO₂ drawdown with high precision ([Smith *et al.*, 2016](#)).

3.6. Circular Economy and Policy Implications

The use of rock dust as a **circular input** aligns well with sustainability principles. Quarry fines, often considered waste byproducts in mining and construction, can be repurposed for ERW, reducing environmental liabilities and creating new value chains. Governments and climate finance institutions are beginning to explore policy incentives, carbon credit frameworks, and farmer subsidies to promote ERW as a viable nature-based solution for climate mitigation.

Overall, Enhanced Rock Weathering represents a multi-benefit climate solution with the potential to draw down atmospheric CO₂, revitalize soils, reduce reliance on synthetic inputs, and foster regenerative agricultural systems when appropriately scaled and integrated.

4. Agroforestry: A Multidimensional Strategy for Carbon-Negative Farming

Agroforestry, defined as the intentional integration of trees and shrubs into crop and livestock systems, represents a cornerstone innovation in the pursuit of carbon-negative farming. This approach harnesses the synergistic potential of combining agricultural and forestry practices within the same landscape to optimize ecological, economic, and social outcomes. By creating multifunctional landuse systems, agroforestry not only enhances carbon sequestration above and below ground but also bolsters biodiversity, soil health, and farm resilience ([Nair, 2011](#); [Montagnini & Nair, 2004](#)).

Trees and perennial woody plants within agroforestry systems serve as vital carbon sinks. They store carbon in woody biomass, including trunks, branches, roots, and foliage, and contribute to soil organic carbon pools through leaf litter deposition and root turnover ([Jose, 2009](#)). The magnitude of carbon sequestration varies widely, influenced by system design, species composition, site conditions, and management intensity. Research indicates

that agroforestry systems can sequester between 2.2 and 9.5 Mg CO₂ ha⁻¹ year⁻¹, positioning them as effective climate mitigation tools ([Zomer et al., 2016](#)). Such sequestration rates often exceed those of conventional monocropping systems, underscoring the carbon storage advantage of integrated tree-crop-livestock landscapes.

Beyond carbon capture, agroforestry improves farm microclimates by regulating temperature and humidity, thereby creating more favorable growing conditions ([Mbow et al., 2014](#)). Tree cover reduces wind speed and evapotranspiration, which helps conserve soil moisture and reduces erosion risk, particularly in marginal lands prone to degradation ([FAO, 2013](#)). The root systems of woody plants enhance soil structure, increasing porosity and water infiltration rates, which are critical for drought resilience and nutrient cycling ([Jose, 2009](#); [Rowland et al., 2023](#)). Inclusion of nitrogenfixing species such as leguminous trees adds a further dimension of sustainability by enriching soil nitrogen content naturally, reducing dependence on synthetic fertilizers and associated greenhouse gas emissions ([Garritty et al., 2010](#)).

Economically, agroforestry diversifies farm income streams by providing timber, fruits, nuts, fodder, fuelwood, and non-timber forest products (NTFPs), thus reducing farmers' vulnerability to market and climate fluctuations ([Mbow et al., 2014](#)). This diversification not only supports rural livelihoods but also incentivizes long-term land stewardship, which is essential for sustainable landscape management. The integration of livestock in silvopastoral systems further generates benefits such as shade for animals, improved forage quality, and reduced heat stress, enhancing overall productivity ([Montagnini & Nair, 2004](#)).

Recent technological advances have greatly enhanced the monitoring and quantification of agroforestry's benefits. Remote sensing, geographic

information systems (GIS), and drone-based platforms now allow precise estimation of carbon stocks and ecosystem services at landscape scales, facilitating better management and verification for carbon credit schemes ([Rajput et al., 2025](#)). These tools underpin emerging carbon markets and payment for ecosystem services (PES) programs that financially reward farmers for carbon sequestration and biodiversity conservation, making agroforestry an economically attractive climate solution ([Awazi et al., 2025](#)).

Agroforestry also plays a crucial role in climate adaptation by enhancing ecosystem resilience to extreme weather events. The increased structural complexity and vegetation diversity buffer crops and soils from temperature extremes, flooding, and droughts, while promoting biodiversity that supports pest and disease control ([FAO, 2013](#)). Furthermore, agroforestry can contribute to landscape-level connectivity, facilitating wildlife movement and genetic exchange, thereby reinforcing ecosystem stability ([Silva et al., 2025](#)).

In the context of sustainable development goals (SDGs), agroforestry aligns closely with multiple targets, including climate action (SDG 13), zero hunger (SDG 2), and life on land (SDG 15), by fostering systems that are both productive and restorative. The multifunctionality of agroforestry makes it an exemplary model of climate-smart agriculture that simultaneously addresses mitigation, adaptation, and rural development objectives.

Despite its numerous benefits, scaling agroforestry adoption faces challenges such as tenure insecurity, initial establishment costs, knowledge gaps, and policy barriers ([Garrity et al., 2010](#)). Addressing these issues requires integrated policies that promote secure land rights, extension

services, financial incentives, and participatory approaches involving local communities.

In conclusion, agroforestry is a multidimensional and scalable strategy that embodies the principles of carbon-negative farming. By delivering substantial carbon sequestration alongside enhanced biodiversity, soil fertility, and socio-economic resilience, agroforestry systems offer a vital pathway toward sustainable land management and climate change mitigation. Supporting agroforestry through research, technology, and policy frameworks will be essential to harness its full potential in global efforts to achieve carbon neutrality and food security.

5. Deep-Rooted Perennials: A Biological Engine

Deep-rooted perennial crops are emerging as a biological cornerstone of carbon-negative farming due to their unique ability to capture atmospheric carbon and deposit it deep into the soil profile. In contrast to shallow-rooted annual crops that dominate modern agriculture, perennials such as switchgrass (*Panicum virgatum*), miscanthus (*Miscanthus × giganteus*), and intermediate wheatgrass (commercially known as Kernza) maintain living root systems throughout the year. These extensive root networks continuously contribute organic matter to subsoil layers that are typically beyond the reach of conventional crops and are more stable in terms of long-term carbon storage ([Paustian et al., 2016](#)).

One of the key mechanisms behind their carbon sequestration potential is rhizodeposition, the exudation of sugars, amino acids, and other organic compounds from living roots into the surrounding soil. These compounds feed soil microbial communities and enhance the formation of microbial necromass one of the most stable forms of soil organic matter ([Teixeira et al., 2022](#); [Zhou et al., 2023](#)). Furthermore, the dense and deep root systems of these perennials help to create and stabilize **soil aggregates**, which

physically protect carbon molecules from microbial degradation, effectively increasing the **mean residence time** of carbon in the soil ([Poeplau et al., 2021](#)). Quantitative studies confirm the superior carbon storage potential of perennial crops. For example, DeHaan *et al.* (2010) demonstrated that *intermediate wheatgrass* (*Kernza*) could sequester up to 1.1 Mg C ha⁻¹ yr⁻¹ in soil layers below 30 cm, a region often depleted of carbon due to the repeated tillage and shallow rooting of annual systems. Deep soil carbon is particularly valuable because it is less vulnerable to microbial decomposition and surface disturbances, meaning it can remain stored for centuries ([Lynch & Wojciechowski, 2015](#); Rumpel & Kogel-Knabner, 2011).

In addition to carbon sequestration, deep-rooted perennials offer a suite of co-benefits for climate resilience and ecological sustainability. These include:

- **Improved soil structure and water infiltration**, which buffer farms against drought and flooding.
- **Reduced nitrate leaching** and improved nutrient retention, especially in leachable sandy or degraded soils ([Culman et al., 2013](#)).
- **Decreased erosion and wind loss** due to year-round ground cover.
- **Lower input requirements**, including reduced fertilizer and pesticide use, making them economically and environmentally favorable ([Glover et al., 2010](#)).

Perennial systems are particularly effective on degraded, sloped, or marginal lands, where conventional agriculture often fails. On such lands, they restore lost organic matter, rebuild soil microbial communities, and facilitate the re-establishment of healthy soil functions ([Labeyrie et al.,](#)

[2021](#)). The regenerative potential of these crops makes them central to land restoration strategies under both national and international frameworks such as the UN Decade on Ecosystem Restoration and 4 per 1000 Initiative.

Recent progress in plant breeding, genomics, and biotechnology has enabled the rapid domestication and yield improvement of previously wild perennial species. Kernza, developed by The Land Institute, is now being tested and cultivated as a commercial grain crop across several regions in North America and Europe ([Ryan *et al.*, 2018](#)). This perennial grain offers dual services: a food source and a climate solution, making it attractive to farmers, consumers, and policymakers alike. Furthermore, deep-rooted perennials can be strategically integrated into diversified farming

Furthermore, deep-rooted perennials can be strategically integrated into diversified farming systems, including agroforestry, intercropping, and rotational systems. Such integration can magnify their carbon and ecological benefits. For instance, rotational systems that alternate deep-rooted perennials with legumes or cover crops can maintain high productivity while enhancing soil nitrogen levels, carbon stocks, and biological diversity ([Drinkwater & Snapp, 2007](#)).

Despite their promise, several barriers exist to the widespread adoption of perennial crops. These include lower initial grain yields compared to annuals, lack of processing infrastructure, limited market development, and policy incentives favoring conventional monocultures ([Glover *et al.*, 2010](#)). However, with targeted investments in research, subsidies, and value chain development, deep-rooted perennials could revolutionize sustainable agriculture by providing lasting climate and soil health solutions.

As such, Deep-rooted perennials represent a biologically driven, ecologically sound, and low-input strategy for long-term soil carbon sequestration. Their deep rooting systems, year-round soil cover, and

rhizodeposition processes make them uniquely suited to stabilize carbon in subsoil layers while delivering multiple ecosystem services. As the world seeks scalable and verifiable carbon-negative farming solutions, these crops offer a promising path forward blending environmental stewardship with food system innovation.

6. Microbial Biostimulants and Organic Amendments

Microbial biostimulants and organic amendments are gaining increasing attention as biologically driven solutions for carbon-negative farming. These interventions enhance plant performance, rejuvenate soil ecosystems, and significantly promote the sequestration of soil organic carbon (SOC). When strategically combined, they not only improve soil fertility and crop productivity but also contribute to the development of resilient agroecosystems that function as long-term carbon sinks.

6.1. Microbial Biostimulants: Engineered Allies for the Rhizosphere

Microbial biostimulants include a range of beneficial soil microorganisms such as arbuscular mycorrhizal fungi (AMF), plant growth-promoting rhizobacteria (PGPR), and symbiotic nitrogen-fixing bacteria. These microorganisms play a central role in enhancing carbon dynamics by stimulating root development, increasing photosynthetic efficiency, and facilitating the transformation of labile organic carbon into more stable soil fractions ([Rouphael & Colla, 2020](#)).

AMF, in particular, form mutualistic relationships with the roots of most terrestrial plants. They increase the absorptive surface area of roots, thereby improving nutrient and water uptake. This enhanced nutrient access improves plant biomass accumulation and, in turn, raises the carbon flux into the soil via root exudates and rhizodeposition ([Smith & Read, 2008](#)).

Moreover, AMF secrete glomalin-related soil proteins (GRSPs), particularly glomalin, which contribute significantly to soil aggregate formation and stabilization of carbon in protected microenvironments ([Rillig *et al.*, 2001](#); [Wilson *et al.*, 2009](#)). These soil aggregates not only increase soil porosity and water retention but also physically protect organic matter from microbial decomposition, thereby increasing the longevity of stored carbon.

PGPR, such as species from the genera *Azospirillum*, *Bacillus*, and *Pseudomonas*, influence the soil carbon pool via multiple pathways. They enhance nutrient solubilization (e.g., phosphorus and iron), fix atmospheric nitrogen, and produce phytohormones that stimulate root growth, increasing root surface area and carbon exudation ([Bhattacharyya & Jha, 2012](#); [Vessey, 2003](#)). These exudates act as energy sources for microbial biomass, which contributes to microbial necromass a dominant and persistent form of soil organic matter ([Cotrufo *et al.*, 2013](#)). PGPR also play roles in suppressing soil pathogens and reducing plant stress, indirectly enhancing net primary productivity and further increasing soil carbon inputs ([Berendsen *et al.*, 2012](#)).

6.2. Organic Amendments: Renewable Inputs for Soil Carbon Enhancement

Organic amendments such as compost, vermicompost, green manures, and farmyard manure (FYM) provide external carbon inputs and substrates for microbial metabolism. These materials supply both labile and stable carbon forms, contributing to short-term microbial activity and long-term humus formation ([Lal, 2004](#)). For example, compost application has been shown to enhance microbial carbon use efficiency (CUE), thereby converting more plant and microbe-derived carbon into stable soil organic matter ([Ryals & Silver, 2013](#); [Sokol *et al.*, 2019](#)).

Incorporation of organic amendments improves soil structure, enhances cation exchange capacity, buffers soil pH, and increases moisture retention factors that collectively create a conducive environment for soil microbes and plant roots. Over time, repeated applications of organic inputs accelerate soil carbon accumulation and build biologically enriched, self-sustaining systems ([Diacono & Montemurro, 2010](#)). Green manures, particularly those from leguminous cover crops, provide an added benefit by **fixing atmospheric nitrogen**, further reducing reliance on synthetic fertilizers.

6.3. Synergistic Effects and Soil Function Restoration

The combination of microbial biostimulants with organic amendments can lead to **synergistic effects**. Microbes decompose complex organic matter more efficiently when stimulated by fresh organic inputs, while the enhanced microbial diversity fosters functional redundancy and resilience in the soil microbiome ([Bender *et al.*, 2016](#)). These interactions accelerate nutrient cycling, reduce greenhouse gas emissions (especially nitrous oxide), and stabilize SOC in both particulate and mineral-associated forms.

Such integrated strategies are particularly promising in degraded and carbon-depleted soils, where microbial inoculants restore microbial functional groups, and organic amendments provide the raw materials for rebuilding soil organic matter pools ([Gattinger *et al.*, 2012](#)). Importantly, these interventions also reduce the environmental footprint of agriculture by decreasing the need for synthetic agrochemicals and improving nutrient-use efficiency.

6.4. Emerging Biotechnologies and Commercialization

Recent advances in microbial biotechnology and synthetic ecology are enabling the development of customized microbial consortia, designed to

function under specific soil, crop, and climatic conditions ([Backer et al., 2018](#)). These consortia are formulated to be more competitive, stress-tolerant, and functionally diverse, ensuring reliable field performance. Moreover, novel bioformulations are being integrated into carbon farming protocols and verified carbon offset schemes, making them economically attractive to farmers and stakeholders.

Managing soil as a living and dynamic system, where microbial processes are central to soil health and carbon regulation, marks a paradigm shift in agricultural science. This holistic understanding supports the transition toward biologically intensive, climate-resilient, and regenerative farming systems that function as active agents in climate mitigation.

Finally, microbial biostimulants and organic amendments form a powerful, symbiotic toolkit for carbon-negative agriculture. By catalyzing microbial activity, enhancing nutrient dynamics, and stabilizing carbon within the soil matrix, these inputs offer a scientifically grounded and environmentally sound pathway for **scaling regenerative practices**. As innovations in microbial biotechnology continue to advance and synergistic strategies are better understood, these interventions will play a critical role in **building climate-resilient soils** and achieving global carbon neutrality goals.

7. Digital Agriculture Technologies

Digital agriculture technologies play a pivotal role in advancing carbon-negative farming by improving input efficiency, reducing greenhouse gas (GHG) emissions, and enhancing data-driven decision-making. These technologies encompass tools like precision agriculture, smart irrigation systems, and advanced data analytics integrated with machine learning. Together, they enable optimized resource use, increase productivity, and support long-term environmental sustainability.

7.1. Precision Agriculture

Precision agriculture (PA) employs a suite of technologies, including GPS-guided equipment, drones, variable rate technology (VRT), and remote sensors, to manage variability in the field and apply inputs (fertilizers, water, seeds, and pesticides) more efficiently and site-specifically. This not only enhances productivity but significantly reduces the environmental footprint of farming practices. PA contributes to carbon-negative farming by minimizing excessive input use, which reduces nitrous oxide (N₂O) emissions from fertilizers and fuel emissions from machinery ([Gebbers & Adamchuk, 2010](#)). For example, site-specific nitrogen application reduces emissions of N₂O, a greenhouse gas with nearly 300 times the global warming potential of CO₂. Additionally, PA allows for optimized tillage practices, including no-till or strip-till systems, which reduce soil disturbance and promote carbon retention ([Robertson *et al.*, 2013](#)).

7.2. Smart Irrigation Systems

Water use efficiency is a major concern in agriculture, and smart irrigation systems can significantly reduce both water and energy use. These systems include drip irrigation integrated with soil moisture sensors, automated weather-based controllers, and real-time monitoring platforms. Smart irrigation prevents overwatering, reduces leaching of nutrients, and decreases emissions associated with water pumping and fertilizer loss. Sensor-based irrigation has shown potential to reduce water use by 20- 40% and simultaneously lower energy consumption, which directly supports carbon reduction ([Evelt *et al.*, 2012](#)). Furthermore, integration with renewable energy (e.g., solar-powered pumps) further enhances its role in carbon-negative farming ([Daccache *et al.*, 2014](#)).

7.3. Advanced Data Analytics and Machine Learning

The integration of big data analytics and machine learning (ML) models enables real-time farm monitoring, predictive modelling, and early-warning systems for pests, diseases, and weather events. These tools assist farmers in making data-driven decisions that optimize input use, prevent crop failure, and enhance sustainability. ML algorithms can analyze historical yield data, soil characteristics, and climatic variables to predict the best input levels and timings, thus enhancing carbon-use efficiency and minimizing unnecessary emissions. Moreover, decision support systems built on ML frameworks help design low-carbon cropping systems and monitor carbon fluxes in real time ([Kamilaris *et al.*, 2017](#)). For instance, deep learning tools can forecast optimal harvesting time to reduce post-harvest losses and energy used in storage, while ML-enabled platforms track soil organic carbon levels to inform soil management strategies aimed at carbon sequestration ([Liakos *et al.*, 2018](#)).

7.4. IoT and AI-Based Decision Support Systems

The integration of Internet of Things (IoT) and Artificial Intelligence (AI) in agriculture enables real-time monitoring and predictive decision-making, critical for advancing carbon-negative farming. IoT devices, such as soil sensors, drones, and weather stations, collect field-level data on temperature, humidity, nutrient levels, and crop growth. These data streams are processed by AI models to deliver actionable insights on irrigation scheduling, fertilizer application, and pest management. This leads to precision input use, reducing nitrous oxide emissions from fertilizers and conserving water and energy ([Wolfert *et al.*, 2017](#)). Moreover, AI can forecast crop performance and monitor soil organic carbon trends, supporting adaptive and low-emission farm practices ([Liakos *et al.*, 2018](#)). When integrated into Decision Support Systems (DSS), these technologies

enhance resource efficiency, lower GHG emissions, and strengthen farm resilience under climate stress.

7.5. Remote Sensing and Drones

Remote sensing technologies, including satellite imagery and Unmanned Aerial Vehicles (UAVs or drones), play a transformative role in carbon-negative farming by enabling high-resolution monitoring of crops, soil, and vegetation. These tools facilitate site-specific management by providing data on crop health, chlorophyll content, canopy temperature, and soil moisture variability. Such insights help optimize irrigation, fertilization, and harvest timings, minimizing input waste and associated greenhouse gas emissions ([Zhang & Kovacs, 2012](#)). Drones equipped with multispectral and thermal sensors can also assess biomass and monitor changes in soil organic carbon over time, supporting carbon sequestration tracking and land-use planning ([Sankaran *et al.*, 2015](#)). By reducing the need for manual scouting and enhancing input efficiency, remote sensing technologies contribute to both environmental sustainability and improved farm productivity, aligning with carbon-negative farming objectives.

7.6. Variable Rate Technology (VRT)

Variable Rate Technology (VRT) enables the precise application of inputs such as fertilizers, seeds, and pesticides based on spatial variability within a field. Using data from GPS, sensors, and remote sensing, VRT allows site-specific input management, reducing over-application and enhancing resource use efficiency. This precision significantly lowers nitrous oxide (N₂O) emissions from fertilizers, a major contributor to agricultural greenhouse gases, and promotes better soil health through balanced nutrient use ([Bongiovanni & Lowenberg-DeBoer, 2004](#)). By aligning input delivery with crop needs and soil characteristics, VRT contributes to carbon-

negative outcomes through reduced emissions, improved yield efficiency, and conservation of resources like energy and water. When integrated with other digital agriculture tools, VRT supports sustainable intensification, making it a key innovation in climate-smart and regenerative farming systems ([Sharma *et al.*, 2025](#)).

7.7. Blockchain for Carbon Tracking and Incentives

Blockchain technology offers a transparent, secure, and decentralized digital ledger system ideal for tracking carbon flows and verifying carbon sequestration in agricultural systems. By recording data immutably across supply chains, blockchain supports accurate monitoring, reporting, and verification (MRV) of greenhouse gas reductions and soil carbon improvements ([Tripoli & Schmidhuber, 2018](#)). This enhances trust among stakeholders and enables the issuance of carbon credits based on verifiable environmental outcomes. Smart contracts can automate incentive payments to farmers who adopt regenerative practices, linking field-level action to global carbon markets ([Varma *et al.*, 2024](#)). Such systems prevent double-counting of emissions reductions and foster accountability, making blockchain a powerful enabler of climate-smart finance in carbon-negative farming. When integrated with IoT and AI, blockchain-based MRV platforms offer real-time carbon accounting, thus facilitating transparency and market-based rewards for sustainable agriculture.

8. Controlled Environment Agriculture (CEA): Vertical and Hydroponic Farming

Controlled Environment Agriculture (CEA) represents a transformative shift in agricultural production systems aimed at optimizing plant growth by precisely controlling environmental parameters such as temperature, humidity, light intensity, CO₂ levels, and nutrient delivery. This highly

engineered cultivation model contributes directly and indirectly to carbon-negative farming by increasing productivity per unit area, enhancing input-use efficiency, and minimizing emissions through reduced dependency on land, water, and chemical inputs ([Beacham *et al.*, 2019](#)).

Two widely adopted CEA approaches, **vertical farming** and **hydroponics**, are particularly impactful in promoting climate-resilient and carbon-negative food systems. Vertical farming involves cultivating crops in vertically stacked layers, often within climate-controlled facilities equipped with LED lighting, air filtration, and automated nutrient delivery systems. This vertical integration maximizes space usage, reduces land footprint, and eliminates soil degradation. Studies indicate that vertical farms can reduce water usage by over 90% compared to traditional farming and nearly eliminate the use of pesticides and herbicides ([Kalantari *et al.*, 2017](#); [Banerjee & Adenaeuer, 2014](#)). These systems are particularly suited for urban agriculture, allowing food to be grown closer to consumers, thereby significantly reducing food miles and associated carbon emissions.

Hydroponics, a soilless method where plants grow in a water-based, nutrient-rich solution, is central to many vertical farming setups and standalone CEA operations. It offers substantially higher yield per unit area, with precise nutrient control that minimizes fertilizer losses and prevents environmental runoff ([Treftz & Omaye, 2016](#)). When integrated with **closed-loop nutrient recycling** and **CO₂ enrichment**, hydroponic systems not only reduce greenhouse gas emissions but also enhance photosynthetic efficiency and crop productivity ([Tao *et al.*, 2021](#)). The addition of renewable energy sources, such as solar panels, biogas systems, and geothermal heating, can make these systems nearly or entirely self-sustaining, thus offsetting their high initial energy demands ([Al-Kodmany, 2018](#); [Graamans *et al.*, 2018](#)).

In addition to hydroponics, aeroponics and aquaponics are also emerging as sustainable variants of CEA. Aeroponics uses a fine mist to deliver nutrients directly to plant roots, using even less water than hydroponics, while aquaponics integrates fish farming with plant production in a mutually beneficial cycle. These symbiotic systems mimic natural ecosystems and improve resource efficiency, reducing waste and enhancing carbon use effectiveness ([Goddek *et al.*, 2015](#); [Yep & Zheng, 2019](#)).

CEA also plays a role in indirect carbon sequestration by preventing deforestation and reducing pressure on arable land. By enabling intensive production in non-arable or urban locations, it conserves ecosystems and avoids emissions associated with land-use change ([Despommier, 2011](#)). Moreover, some studies suggest that integrating biochar substrates, microbial consortia, and CO₂ capture from indoor air in CEA systems could directly enhance soil-like carbon retention within soilless systems, opening new avenues for carbon sequestration even in artificial environments ([Velmourougane *et al.*, 2022](#); [Rajaseger *et al.*, 2023](#)).

Despite criticisms regarding energy use, life-cycle assessments show that CEA systems, when powered by renewables and managed efficiently, can achieve net-negative emissions over time while offering year-round, high-quality, and resilient food production in the face of climate uncertainties ([Benke & Tomkins, 2017](#); [Barbosa *et al.*, 2015](#)). As climate change disrupts open-field agriculture, CEA provides a scalable, technology-driven solution for sustainable food security and carbon-neutral urban ecosystems.

9. Synthetic Biology and Gene Editing: Emerging Frontiers in Carbon Farming

Synthetic biology and gene editing are revolutionizing agricultural science by offering unprecedented capabilities to redesign biological systems for enhanced sustainability and carbon sequestration. These cutting-edge

technologies are central to the evolution of carbon-negative farming, enabling precise and strategic modifications in plants and microorganisms to optimize carbon capture, reduce greenhouse gas emissions, and enhance overall ecosystem resilience ([Rothan *et al.*, 2019](#)).

Gene editing tools such as CRISPR-Cas9, TALENs, and ZFNs (zinc finger nucleases) are being utilized to develop climate-smart crops with enhanced photosynthetic efficiency, drought tolerance, nutrient-use efficiency, and improved root biomass, all of which contribute significantly to carbon sequestration in soils ([Long *et al.*, 2015](#); [Chen *et al.*, 2019](#)). For example, targeted modifications to the RuBisCO enzyme and photorespiratory bypass pathways have demonstrated up to a 40% increase in carbon assimilation and crop biomass in model plant systems like tobacco, paving the way for similar interventions in staple crops such as rice, wheat, and maize ([South *et al.*, 2019](#)).

Furthermore, editing root system architecture (RSA) such as increasing root length, density, and exudation promotes deeper carbon input into subsoils where it is more stable and less susceptible to microbial respiration. Enhanced RSA also fosters beneficial interactions with soil microbial communities, supporting long-term soil carbon formation and storage ([Kellermeier *et al.*, 2013](#); [Lynch, 2019](#)).

Synthetic biology also offers innovative pathways to reprogram soil microbiota. Genetically engineered microorganisms can be designed to fix atmospheric nitrogen more efficiently, synthesize stable soil organic compounds, and reduce emissions of nitrous oxide (N₂O) a greenhouse gas with over 300 times the warming potential of CO₂ ([Johns *et al.*, 2016](#); [Naranjo *et al.*, 2020](#)). Engineered strains of *Azospirillum*, *Rhizobium*, and *Actinobacteria* have already shown promise in enhancing plant growth and carbon dynamics under field conditions.

Mycorrhizal fungi, critical to carbon cycling in terrestrial ecosystems, are another frontier of intervention. Synthetic enhancement of arbuscular mycorrhizal (AM) fungi or ectomycorrhizal networks could significantly improve rhizodeposition, carbon allocation, and aggregate stability, contributing to more persistent forms of soil organic carbon ([Rillig *et al.*, 2001](#); [Sokol *et al.*, 2022](#)).

In addition, synthetic biology is spearheading the development of bioengineered photosynthesis systems, including artificial carbon-concentrating mechanisms (CCMs) and synthetic carboxylases, which can mimic or surpass natural CO₂ fixation pathways. These systems can be incorporated into C3 plants to emulate C4-like efficiencies, leading to more effective carbon capture from the atmosphere ([Kubis *et al.*, 2019](#); Erb *et al.*, 2012). Advanced platforms are even exploring biohybrid systems, integrating biological modules with carbon capture and storage (CCS) infrastructure in agroecosystems.

Importantly, synthetic biology is not limited to enhancing carbon capture, it is also being used to reduce emissions indirectly. Crops engineered for lower fertilizer demand, faster growth cycles, or enhanced resistance to pests can lower dependence on energy-intensive agrochemicals and reduce emissions from production, application, and transport ([Chen *et al.*, 2019](#); [Zhang *et al.*, 2018](#)).

Despite some ethical and regulatory challenges, the strategic deployment of synthetic biology and gene editing in agriculture offers immense potential to transition agriculture from a net carbon source to a carbon sink. By amplifying natural processes and integrating biological systems with digital and climate technologies, these innovations serve as powerful levers for creating regenerative, resilient, and truly carbon-negative food systems.

10. Renewable Energy Integration in Farming System

The integration of renewable energy systems into agriculture marks a pivotal shift towards carbonnegative farming. Traditional agricultural operations rely heavily on fossil fuels for irrigation, mechanization, greenhouse heating, post-harvest processing, and transportation leading to substantial greenhouse gas (GHG) emissions ([Lal, 2020](#)). Replacing fossil-derived energy with clean alternatives like **solar, wind, biogas, and small hydropower systems** can drastically reduce these emissions while enhancing energy security and resilience, particularly in rural and off-grid farming contexts.

10.1. Solar Energy: Powering Decentralized and Sustainable Agriculture

Solar power is arguably the most accessible and scalable renewable energy source for farmers. Photovoltaic (PV) systems can be deployed at various scales from small household panels to large solar farms to power everything from irrigation pumps and cold chains to farm machinery and greenhouse climate control (IRENA, 2016).

A notable innovation is **Solar-Powered Irrigation Systems (SPIS)**, which utilize PV panels to drive water pumps, replacing diesel-based systems. SPIS not only reduces emissions but also minimizes fuel costs, water losses, and maintenance ([Closas and Rap, 2017](#)). For instance, studies in South Asia and Sub-Saharan Africa have shown that SPIS can reduce carbon emissions by over 30% and increase net farm income (IRENA, 2016; [Closas and Rap, 2017](#)).

Furthermore, **agrivoltaics** the co-location of crops and solar panels represents a multifunctional land-use strategy that simultaneously produces food and energy. Research shows that agrivoltaics can enhance water-use efficiency, moderate crop canopy temperatures, and maintain comparable yields to conventional open-field farming ([Barron-Gafford et al., 2019](#);

[Majumdar & Pasqualetti, 2018](#)). This synergy is particularly valuable in arid and semi-arid climates where water conservation is critical.

10.2. Wind Power: Harnessing Natural Flows for On-Farm Energy

Wind energy, though site-specific, is a promising option in areas with favorable wind speeds. **Small and medium-scale wind turbines** can supply power for farm operations such as grain milling, lighting, and refrigeration. When integrated with storage systems and/or hybrid solar setups, wind power can ensure 24/7 energy availability ([Abdolmaleki and Bello Bugallo, 2021](#)). Some European farming cooperatives and U.S. rural initiatives have successfully deployed community wind farms that share the energy and financial benefits among local agricultural stakeholders.

10.3. Biogas: Circular Economy and Methane Mitigation

Biogas systems use anaerobic digestion to convert organic waste such as livestock manure, food residues, and crop biomass into methane-rich gas and digestate. The gas can be used for cooking, heating, and electricity generation, while the digestate serves as a nutrient-rich organic fertilizer.

Biogas thus supports **energy generation, GHG reduction, and nutrient recycling** in a closed-loop model ([Lansing *et al.*, 2008](#); [Holm-Nielsen *et al.*, 2009](#)).

Importantly, biogas systems mitigate **methane emissions** from unmanaged organic waste a critical benefit, given that methane has a global warming potential 28 times higher than CO₂ over a 100-year timeframe ([IPCC, 2021](#)). Studies show that well-managed biogas systems can reduce farm-level GHG emissions by 50-80% ([Surendra *et al.*, 2014](#)).

10.4. Synergies with Controlled Environment Agriculture (CEA)

Renewable energy is particularly vital for energy-intensive **Controlled Environment Agriculture (CEA)** systems, including greenhouses, vertical farms, and hydroponics. These systems demand continuous power for lighting, ventilation, nutrient management, and climate regulation. Integrating renewable energy sources such as solar and biogas not only reduces their carbon footprint but also stabilizes operational costs over time ([Kalantari et al., 2017](#); [Graamans et al., 2018](#)).

Some innovative models combine **rooftop solar panels with vertical farms**, generating electricity for LED lighting and nutrient circulation while reducing dependency on the grid. Others employ **battery storage or thermal mass systems** to buffer renewable energy intermittency, ensuring uninterrupted production.

10.5. Policy and Financial Instruments to Accelerate Adoption

The broader transition to renewable-powered farming depends not only on technological availability but also on policy incentives, financing mechanisms, and capacity building. Programs offering subsidies, carbon credits, and performance-based incentives are crucial to enable adoption, especially among smallholders ([FAO, 2022](#)). Public-private partnerships and decentralized renewable energy cooperatives also facilitate access to capital and technical support for farmers adopting clean energy solutions.

10.6. Strategic Role in Carbon-Negative Farming

When coupled with carbon sequestration techniques such as biochar application, agroforestry, regenerative grazing, and conservation tillage renewable energy systems contribute to **net-negative emissions** in agricultural landscapes. These synergies form the basis of **carbon-smart**

agriculture, where emissions are not only minimized but actively reversed through atmospheric CO₂ drawdown.

11. Conclusion and Way Forward

The transition to carbon-negative farming demands an integrated approach that leverages both ecological principles and advanced technologies. Digital innovations such as precision agriculture, variable rate technology (VRT), smart irrigation systems, AI-driven analytics, and IoT-enabled monitoring enable data-informed, resource-efficient decision-making. These tools enhance productivity while minimizing greenhouse gas emissions through optimized input use and adaptive management. Controlled Environment Agriculture (CEA), vertical and hydroponic systems, and renewable energy integration further contribute to carbon-use efficiency, supporting sustainable and climate-resilient food production systems.

Complementing these technological solutions are biological innovations that enhance carbon sequestration and soil health. Practices like biochar application, enhanced rock weathering, agroforestry, and the use of deep-rooted perennials offer robust, long-term carbon drawdown strategies. Biological solutions such as microbial biostimulants, organic amendments, and compost teas play a crucial role in improving soil carbon dynamics, nutrient cycling, and ecosystem resilience. Additionally, emerging fields like synthetic biology and gene editing offer transformative potential in designing crops and microbial systems optimized for carbon capture and environmental sustainability.

Together, these innovations represent a paradigm shift toward regenerative, climate-smart agriculture. By combining nature-based solutions with digital and biotechnological advancements, carbon farming can evolve into a scalable, measurable, and impactful approach to

addressing climate change, enhancing food security, and building resilient agroecosystems.

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Chapter - 6

Case Studies and Lessons from the Field

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1. Introduction

The escalating global climate crisis poses an existential threat to ecosystems, livelihoods, and food security. The Intergovernmental Panel on Climate Change (IPCC) warns that limiting global warming to 1.5°C requires not only deep emissions reductions across all sectors but also the deployment of negative emission technologies and practices ([IPCC, 2022](#)). Among these, the agricultural sector holds both the challenge and the promise. As a significant emitter of greenhouse gases, contributing about 24% of total anthropogenic GHG emissions when including land use change, agriculture must undergo a systemic transformation ([Smith *et al.*, 2014](#)).

Traditional farming methods, especially those reliant on synthetic inputs, intensive tillage, and monoculture systems, have depleted soil carbon stocks, degraded biodiversity, and heightened vulnerability to climate shocks ([Lal, 2020](#)). In contrast, carbon-negative farming presents a paradigm shift, one where agriculture not only reduces emissions but also actively removes carbon dioxide from the atmosphere and sequesters it in soils, biomass, and bio-products. Practices such as regenerative agriculture, agroforestry, biochar application, conservation tillage, and nutrient cycling innovations have emerged as promising approaches that enhance soil organic carbon while promoting ecological resilience ([Paustian *et al.*, 2016](#)).

This chapter aims to document and analyze a set of successful, real-world interventions in carbon-negative farming across different geographies, scales, and farming systems. The goal is to illustrate how these practices have been effectively implemented, what measurable outcomes they have produced, and what lessons they offer for replication and policy design. These case studies and success stories demonstrate that carbon-negative farming is not a theoretical ideal, it is already being practiced with tangible results.

2. Selection Criteria for Case Studies

The case studies featured in this chapter are selected to represent a diverse, scalable, and impactful portfolio of carbon-negative farming interventions. Six streamlined criteria guided their selection:

2.1. Geographic and Agroecological Diversity

Cases span varied agro-climatic zones, from arid Rajasthan to tropical Kerala and temperate UK, covering both Global South and North. This ensures insights across distinct ecological, socio-economic, and institutional contexts ([FAO, 2017](#); [Regmi & Paudel, 2024](#)).

2.2. Diverse Scales and Stakeholders

The interventions range from smallholder-led practices (e.g., ZBNF in India) to large-scale initiatives (e.g., regenerative grazing in Australia), involving public schemes, community efforts, and publicprivate partnerships ([Amadu *et al.*, 2020](#); Wongpiyabovorn *et al.*, 2022).

2.3. Varied Intervention Typologies

Selected practices encompass diverse intervention typologies, including agroecological methods such as Zero Budget Natural Farming (ZBNF) and

silvopasture; technological solutions like enhanced weathering; carbon-targeted techniques including biochar application and alternate wetting and drying (AWD); integrated systems such as integrated organic farming systems (IOFS) and composting; and landscape approaches like reforestation and grazing restoration ([Altieri et al., 2015](#); [Lal, 2020](#); [IPCC, 2022](#));).

2.4. Multi-Dimensional Impact

Each case demonstrates clear outcomes across multiple dimensions, including carbon metrics such as soil organic carbon increases and greenhouse gas mitigation; economic viability through yield improvements and input cost savings; ecological co-benefits like enhanced biodiversity and improved water efficiency; and social inclusion aspects including gender equity and community empowerment ([Bossio et al., 2020](#); [Raveloaritiana & Wanger, 2024](#)).

2.5. Innovation and Replicability

Interventions offer scalable solutions through low-cost technologies, traditional-modern knowledge integration, or strong community ownership, enabling adaptation across diverse contexts ([Gemtou et al., 2024](#)).

2.6. Institutional and Policy Integration

Strong alignment with policies (e.g., MGNREGA, organic farming missions) and multi-actor collaboration underpin long-term viability and access to finance and technical support ([Wongpiyabovorn et al., 2022](#)).

3. Need for a Common Evaluation Framework

Carbon-negative farming encompasses a wide range of practices, ranging from agroforestry and biochar application to regenerative cropping systems

and advanced composting. While individual success stories are valuable for inspiration, the lack of a standardized evaluation framework hampers the ability to compare, replicate, and scale interventions across different agroecological zones and socio-economic contexts. A common evaluation framework is therefore essential for:

3.1. Consistency Across Case Studies

Without a shared set of metrics or criteria, the success of carbon-negative farming initiatives is often reported in inconsistent ways some focus on carbon sequestration, others on crop yield or economic benefits. This variation limits comparative learning and policy alignment ([Bossio *et al.*, 2020](#)).

3.2. Enhanced Credibility and Scientific Rigor

Structured evaluation frameworks lend scientific validity to reported outcomes. They help differentiate anecdotal results from those that are measurable, repeatable, and verifiable, particularly important for informing carbon markets and climate finance mechanisms ([IPCC, 2022](#)).

3.3. Alignment with Carbon Accounting Standards

A common framework ensures compatibility with existing measurement, reporting, and verification (MRV) protocols and carbon accounting tools such as IPCC Tier methods, COMET-Farm, or Cool Farm Tool, enabling projects to link with national inventories or international carbon credit systems ([Raveloaritiana & Wanger, 2024](#)).

3.4. Policy and Investment Decision Support

Policy makers and funding agencies require evidence-based insights to prioritize interventions that deliver co-benefits (e.g., biodiversity

conservation, soil health, rural livelihoods). A unified framework provides comparative analysis, helping direct public and private investments more effectively ([Amadu *et al.*, 2020](#)).

3.5. Replication and Scaling Up

A standardized evaluation protocol supports the scaling up of successful models. If practices are assessed using a consistent set of indicators, it becomes easier to determine where and how these can be replicated or adapted in other contexts ([Gemtou *et al.*, 2024](#)).

3.6. Stakeholder Transparency and Engagement

Common evaluation metrics foster transparency and build trust among farmers, project developers, regulators, and carbon buyers. This is particularly relevant in emerging carbon marketplaces, where third-party validation is often required ([Wongpiyabovorn *et al.*, 2022](#)).

3.7. Key Elements of a Common Framework

While the actual indicators may vary based on context, a robust framework typically includes:

- **Environmental metrics:** Soil organic carbon (SOC), GHG emissions, biodiversity indices.
- **Economic metrics:** Cost-benefit ratios, income change, market access.
- **Social metrics:** Labor intensity, gender impact, food security outcomes.
- **Technical metrics:** Scalability, ease of adoption, local compatibility.
- **Temporal metrics:** Duration and sustainability of carbon storage.

4. Framework for Evaluating Carbon-Negative Interventions

As the global agricultural sector seeks climate solutions, there is growing emphasis on identifying and evaluating interventions that can achieve net negative carbon outcomes. Carbon-negative farming refers to a suite of agricultural practices that result in the net removal of atmospheric CO₂, going beyond carbon neutrality. This involves sequestering more carbon than is emitted throughout the production cycle, typically in soils, biomass, or long-lasting organic materials, and reducing other greenhouse gases like methane (CH₄) and nitrous oxide (N₂O). A rigorous framework for evaluating carbon-negative interventions is essential to ensure scientific credibility, economic viability, and policy relevance. This chapter presents such a framework by defining key metrics and outlining major categories of interventions based on existing research and field practices.

4.1. Definition of Carbon-Negative Farming

Carbon-negative farming comprises agricultural strategies that result in net carbon dioxide removal (CDR) from the atmosphere, either by enhancing natural sinks (like soil and vegetation) or by creating long-term carbon stores (e.g., biochar). These practices often also reduce emissions of other potent greenhouse gases like methane and nitrous oxide, making them multidimensional in their climate benefits. In contrast to carbon-neutral systems, which aim for a zero net balance between emissions and removals, carbon-negative systems aim for a net-negative carbon balance, where removals exceed emissions across the life cycle of production.

4.2. Key Metrics for Evaluation

To systematically evaluate carbon-negative farming practices, the following core metrics are considered:

- **Carbon Sequestration Rate (t CO₂e/ha/year):** Quantifies how much atmospheric carbon is removed and stored in soil or biomass annually. Tools such as COMET-Farm, RothC, or Cool Farm Tool can aid in estimation.
- **GHG Emission Reduction (% or t CO₂e/year):** Measures the reduction of direct and indirect emissions from agricultural activities, including CH₄ from livestock and N₂O from fertilizer application.
- **Economic Viability:** Assessed through cost-benefit analysis, return on investment (ROI), and financial feasibility for farmers. This includes consideration of inputs, labor, carbon credit potential, and market incentives.
- **Scalability and Replicability:** Evaluates the ease of adoption across different contexts (e.g., climatic zones, land sizes, cropping systems) and the presence of enabling institutions and infrastructure.
- **Co-benefits:** Includes biodiversity enhancement, water use efficiency, soil health improvement, and socio-economic resilience, indicators that align with regenerative and sustainable agriculture goals.

While specific indicators may vary across interventions and regions, a robust evaluation framework typically incorporates five overarching dimensions:

- **Environmental Metrics:** Includes indicators such as soil organic carbon (SOC), greenhouse gas emissions (CO₂, CH₄, N₂O), and biodiversity indices.

- **Economic Metrics:** Focus on cost-benefit ratios, net income change, return on investment, and access to markets or carbon finance.
- **Social Metrics:** Capture aspects such as labor intensity, gender inclusion, rural livelihoods, and food security outcomes.
- **Technical Metrics:** Evaluate scalability, ease of adoption, technological requirements, and compatibility with local farming systems.
- **Temporal Metrics:** Consider the duration, permanence, and long-term sustainability of carbon sequestration and emission reductions.

4.3. Types of Carbon-Negative Interventions

Carbon-negative interventions encompass a diverse set of practices aimed at drawing down atmospheric CO₂ while enhancing ecosystem services and agricultural productivity. These strategies vary in approach, ranging from regenerative soil management to technological innovations like biochar, yet share the common goal of reversing emissions through sustainable land use.

- **Regenerative Agriculture:** Regenerative practices such as no-till farming, cover cropping, crop rotation, and managed grazing improve soil structure, increase microbial activity, and enhance carbon inputs into the soil. These systems can sequester between **1–4 t CO₂e/ha/ year**, depending on soil type and management ([Lal, 2020](#)). Regenerative agriculture also builds resilience to drought and enhances farm biodiversity.
- **Biochar and Compost Integration:** Biochar, produced from pyrolysis of crop residues or organic waste, acts as a **stable carbon sink**, remaining in the soil for centuries. When combined with compost, it improves nutrient cycling, water retention, and

microbial activity. Studies show that biochar application can result in sequestration rates of **5–10 t CO₂e/ha/year**, with added benefits to soil fertility ([Lehmann & Joseph, 2015](#)).

- **Agroforestry and Silvopasture:** Agroforestry involves the deliberate integration of trees with crops or livestock systems. Trees absorb CO₂ and store it in woody biomass and soils. Silvopasture systems also enhance carbon storage while improving livestock productivity and shade resilience. Agroforestry systems can sequester up to **6–8 t CO₂e/ha/year**, with significant biodiversity and socio-economic benefits ([Nair *et al.*, 2010](#)).
- **Enhanced Rock Weathering:** This emerging technique involves applying finely ground silicate rocks (like basalt) to cropland, accelerating natural chemical processes that capture CO₂. Enhanced weathering can provide co-benefits like improved pH and nutrient availability. Although still under evaluation, models estimate **0.5–3 t CO₂e/ha/year** of sequestration potential depending on mineral type and application rates ([Beerling *et al.*, 2020](#)).
- **Methane Mitigation in Livestock Systems:** Livestock are a major source of methane emissions, primarily from enteric fermentation and manure. Interventions include dietary additives (e.g., seaweed, nitrates), improved manure management, rotational grazing, and genetic selection. Some feed additives have shown **30–60% reductions in methane emissions**, representing a critical path to carbon-negative livestock systems ([Hristov *et al.*, 2013](#)).
- **Precision and Digital Agriculture for Carbon Savings:** Precision agriculture technologies like GPS-guided equipment, variable-rate nutrient application, and real-time monitoring optimize input use and minimize emissions. Digital tools reduce fossil fuel use, cut

fertilizer overuse, and monitor carbon sequestration in real-time. When widely adopted, precision farming can reduce emissions by **15–30%** compared to conventional practices ([Lapidus *et al.*, 2022](#)).

Together, these interventions represent a **diverse toolkit** of carbon-negative farming options. The following chapters will showcase specific examples where these practices have been applied successfully, their quantified outcomes, and lessons learned for broader implementation.

5. Case Studies Portfolio

To explore the real-world application of carbon-negative and climate-resilient farming, this chapter presents selected case studies from India and abroad. These illustrate how diverse farming systems and landscapes, across varying agroecological settings, crops, and socio-economic contexts, have adopted solutions such as no-till farming, biochar, agroforestry, and enhanced weathering. Each case highlights the context, intervention, outcomes, and scalability, offering practical, evidence-based insights for researchers, practitioners, and policymakers advancing climate-smart agriculture.

1. Direct Seeded Rice (DSR) - India
2. Zero Budget Natural Farming (ZBNF) - Andhra Pradesh
3. Biochar Use in Tribal Paddy Fields - Odisha
4. Community Agroforestry under MGNREGA - Jharkhand
5. Enhanced Rock Weathering - Tamil Nadu
6. Silvopasture in Arid Rajasthan
7. Integrated Organic Farming Systems (IOFS) - Sikkim
8. Regenerative Grazing - Kenya
9. Agroforestry Cocoa Systems - Peru

10. No-Till + Cover Cropping - Iowa, USA

11. Biochar Integration in Organic Farming - Germany

Collectively, these cases demonstrate that context-specific approaches, grounded in local knowledge and supported by science and policy, can deliver impactful and scalable climate solutions in agriculture.

5.1. Direct Seeded Rice (DSR) for Climate-Smart Cultivation

- **Title of the Study:** *Direct Seeded Rice (DSR) in Northwestern India: A Low-Carbon Alternative to Conventional Paddy Cultivation*
- **Context and Background:** In water-scarce regions of Punjab, Haryana, and western Uttar Pradesh, traditional puddled rice farming is highly water- and energy-intensive, contributing to methane emissions, soil degradation, and falling groundwater tables. As an alternative, DSR involves direct sowing of seeds into non-puddled fields, minimizing water use, methane emissions, and labor needs.
- **Intervention Description:** DSR replaces transplanting with mechanized or manual seeding of dry or pre-germinated seeds, combined with laser leveling, herbicide-based weed control, and optimized irrigation (e.g., Alternate Wetting and Drying). It aligns with conservation agriculture, requiring 15–25% less water and 40–50% less labor than conventional systems. » **Institutional Support**

Adoption in Punjab and Haryana has been promoted through coordinated efforts from state governments, agricultural universities (e.g., PAU), ICAR institutes, and CIMMYT. Subsidies for DSR machines, field trials,

extension services, and support from agritech firms (e.g., custom hiring centers) have accelerated scaling to over 0.7 million ha by 2023.

- **Outcomes and Impacts**

- **Carbon Mitigation:** Methane emissions reduced by 30–50%; soil carbon enhanced by 0.2–0.4 Mg C ha⁻¹ year⁻¹; nitrous oxide emissions minimized with proper N management ([Bossio *et al.*, 2020](#); [IPCC, 2022](#)).
- **Economic Benefits:** Reduced irrigation and labor lower cultivation costs by INR 4,000–6,000/ha, increasing profitability by 10–20% ([Raveloaritiana & Wanger, 2024](#)).
- **Ecosystem Services:** Improved water use efficiency (15–35%), better soil structure, enhanced microbial biodiversity, and groundwater conservation ([Lal, 2020](#)).
- **Social and Institutional Impacts:** Eases labor shortages, especially benefiting women-led farms. KVKs, cooperatives, and hiring centers enhance knowledge sharing and machine access. Farmer training hubs promote local engagement ([Gemtou *et al.*, 2024](#)).

- **Innovation and Replicability**

DSR integrates zero tillage, laser leveling, and digital tools (e.g., nutrient/weed management apps), making it replicable in similar rice-wheat systems across Asia and Africa. Enabling policies and capacity-building programs support scale-up.

- **Challenges and Limitations**

Higher weed incidence due to lack of puddling, herbicide dependence, and limited suitability in poorly drained soils are key challenges.

Smallholder adoption is hindered by lack of access to machinery and DSR-adapted rice varieties in some regions.

- **Lessons Learned and Key Takeaways**

DSR demonstrates that with proper support and integration of climate-smart practices (e.g., AWD, residue retention), rice cultivation can reduce emissions, conserve resources, and maintain profitability. Policy incentives and targeted farmer training are vital for scaling its adoption.

5.2. Zero Budget Natural Farming (ZBNF), Andhra Pradesh: A Holistic Model for Carbon- Negative Agriculture

- **Title of the Study**

Zero Budget Natural Farming (ZBNF) in Andhra Pradesh, India: Scaling Agroecology for Climate Mitigation and Rural Prosperity

- **Context and Background**

Andhra Pradesh's conventional agriculture faces critical issues, soil degradation, high input costs, chemical overuse, and climate vulnerability. In response, the state adopted Zero Budget Natural Farming (ZBNF) in 2016, based on Subhash Palekar's agroecological model emphasizing low-cost, chemical-free, and farmer-led practices. The state-run Rythu Sadhikara Samstha (RySS) spearheaded the program to restore ecological balance and enhance rural livelihoods.

- **Intervention Description**

ZBNF eliminates the use of synthetic inputs by relying on on-farm, biological resources such as *Jeevamrutha* (a microbial inoculant made from cow dung and urine), *Beejamrutha* (seed treatment), mulching, and *Waaphasa* (soil aeration through minimal irrigation). These practices reduce input costs, enhance soil microbial activity, and restore soil health. The farming model is particularly well-suited to resource-poor smallholders and aligns with agroecological principles.

- **Institutional Support**

With the goal of transitioning 6 million farmers by 2026, the state invested ~USD 240 million from NABARD, BMGF, and Azim Premji Philanthropy. Over 800,000 farmers across 13 districts adopted ZBNF by 2023. Key support mechanisms include trained Village Resource Persons (VRPs), Farmer Field Schools (FFS), and partnerships with FAO, GIZ, and others. Digital platforms track climate and farm data.

- **Outcomes and Impacts**

Climate Mitigation: SOC increased by 0.2–0.5 Mg C ha⁻¹ yr⁻¹; GHG emissions (methane, N₂O) reduced by 20–25% in rice-pulse systems ([Bossio et al., 2020](#); [IPCC, 2022](#)).

Economic Benefits: Input cost savings of 50–70% led to ₹30,000–50,000/ha higher net profits. Yields were stable or higher in pulses and vegetables (4–11%), though cereals saw initial dips. Farmers accessed premium organic markets via FPOs.

Ecosystem Services: Improved microbial soil health, water-use efficiency (15–25%), biodiversity, and partial reversal of land degradation, notably in Anantapur and Chittoor.

Social Impact: ZBNF promoted gender inclusion via 30,000+ women VRPs. Farmer-led clusters and participatory governance enhanced knowledge sharing and local ownership.

- **Innovation and Replicability**

ZBNF revives traditional practices with modern facilitation, suited to semi-arid, rainfed, and degraded regions. Its success has prompted replication in other Indian states and international recognition by FAO as a scalable agroecological model.

- **Challenges and Limitations**

Yield dips during transition, limited indigenous cattle availability, weak market access in some areas, and scientific skepticism due to limited long-term data hinder wider adoption. Institutional inertia also remains a barrier.

- **Lessons Learned and Key Takeaways**

Peer learning, local leadership, and farmer trust are critical to scaling ZBNF. Success depends on supportive policies, digital monitoring, and fair certification systems. ZBNF illustrates how agroecology can simultaneously enhance carbon sequestration, economic resilience, and ecological restoration.

5.3. Biochar Use in Tribal Paddy Fields, Odisha

- **Title of the Study**

Biochar Use in Tribal Paddy Fields, Odisha: Enhancing Soil Health and Climate Resilience

- **Context and Background**

Tribal regions in Odisha (e.g., Koraput, Rayagada, Malkangiri) face soil degradation, low productivity, and climate vulnerability. Traditional upland paddy cultivation on marginal soils suffers from nutrient loss and erratic rainfall. Reviving the indigenous practice of charring biomass, biochar emerged as a sustainable amendment to improve soil health and climate resilience.

- **Intervention Description**

Biochar was produced from rice husk, forest litter, and crop residues using low-cost kilns and applied at 2–5 t/ha, either directly or via compost. This aimed to restore fertility, increase SOC, and reduce methane emissions by improving soil aeration and microbial activity.

- **Implementation and Institutional Support**

NGOs like Living Farms and Sambhav, with OTELP, CRRI, and UAS-Bangalore, supported implementation. Training sessions helped farmers adopt safe production practices. Women's SHGs mobilized biomass and led distribution and education efforts.

- **Outcomes and Impacts**

- **Carbon Sequestration:** SOC increased by 15–25%, sequestering ~1.5–2.8 t CO₂e/ha/ year; methane emissions fell 20–35%.
- **Economic Benefits:** Paddy yields rose by 10–20% (to 1.8–2.0 t/ha); fertilizer use declined by ~30%, boosting profits by ₹3,500–6,000/ha.

- **Ecosystem Services:** Soil water retention improved 12–18%; microbial activity and erosion resistance increased ([Lal, 2020](#)).
- **Social Impact:** Women-led SHGs strengthened local capacity; community trust in extension services improved ([Gemtoui *et al.*, 2024](#)).
- **Innovation and Replicability**

The model's reliance on local biomass, traditional kilns, and compost integration offers a low-cost, scalable approach. Successful replication is underway under OTELP-Plus and NRLM in other tribal belts.

- **Challenges and Limitations**

Labour-intensive production, inconsistent biochar quality, and limited mechanization slowed uptake. Market access for surplus biochar remains weak, and integration into state soil health initiatives is needed for scale.

- **Lessons Learned and Key Takeaways**

Biochar offers a viable carbon-negative strategy in marginal systems when rooted in local knowledge. Gender-inclusive participation, standardization, and monitoring are key to scaling and integration into carbon policy frameworks.

5.4. Community Agroforestry under MGNREGA, Jharkhand

- **Title of the Study**

Community Agroforestry under MGNREGA in Jharkhand: A Climate-Resilient Livelihood Model for Degraded Landscapes

- **Context and Background**

Jharkhand, with a high tribal population and forest dependency, faces severe land degradation, erratic rainfall, and rural poverty. In response, agroforestry under MGNREGA was initiated to restore ecosystems, enhance livelihoods, and reduce migration by promoting tree-based systems on degraded community and private lands.

- **Intervention Description**

Mixed-species plantations (mango, guava, moringa, neem, bamboo) were combined with soil and water conservation measures like trenches and bunds. Agri-horti and silvopasture models enabled seasonal intercropping, fostering carbon sequestration alongside food and fodder production. Communitybased agroforestry initiatives in Jharkhand under MGNREGA have engaged local tribal populations, especially women, in afforestation and livelihood-enhancing plantations on degraded lands. These efforts contribute not only to carbon sequestration and ecosystem restoration but also to rural employment and socio-economic empowerment.

- **Implementation and Institutional Support**

Led by JSRES under MGNREGA, in convergence with Forest Department, PRADAN, and CInI. Gram Panchayats facilitated site selection, planning, and monitoring. CRPs and GIS-based tools supported implementation and ensured transparency.

- **Outcomes and Impacts**

- **Carbon Mitigation:** SOC increased from 0.45% to 0.60%; biomass sequestration estimated at 4–6 t CO₂e/ha/year.

Intercropping with legumes helped lower N₂O emissions ([Bossio et al., 2020](#); [IPCC, 2022](#)).

- **Economic Benefits:** Short-term gains of ₹10,000-₹15,000/ha/year from intercropping; long-term returns from timber and fruits projected at ₹50,000-₹80,000/ha/year by year four ([Lhamtshok, 2022](#)).
- **Ecosystem Services:** Green cover rose by ~35%, reducing erosion by 40–50% and improving local microclimates and biodiversity ([Lal, 2020](#)).
- **Social Outcomes:** Women-led SHGs were central to plantation upkeep. Gram Sabhas and capacity-building improved governance and local planning ([Hossain et al., 2024](#)). » **Innovation and Replicability**

This model illustrates how MGNREGA can integrate ecological restoration with rural employment. Its success hinges on local institutions, convergence with other schemes (e.g., NRLM, Forest Rights Act), and use of tools like participatory micro-planning and GIS.

- **Challenges and Limitations**

Survival rates varied (60–70%) due to water stress and maintenance gaps. Wage delays under MGNREGA, tenure insecurity, and lack of market linkages for tree products limited broader adoption.

- **Lessons Learned and Key takeaways”**

MGNREGA-based agroforestry offers a scalable, inclusive nature-based solution for carbon-negative farming. Gram Sabha leadership, SHG

involvement, and CRP capacity building are essential for sustained impact and replicability.

5.5. Enhanced Rock Weathering (ERW) in Tamil Nadu

- **Title of the Study**

Enhanced Rock Weathering for Climate-Smart Agriculture in Tamil Nadu: A Natural Climate Solution for Carbon Removal and Soil Regeneration

- **Context and Background**

In interior Tamil Nadu districts like Dharmapuri, Salem, and Erode, declining soil fertility and rainfed farming have compounded climate vulnerabilities. The region's acidic red and lateritic soils are low in organic matter, limiting crop productivity. ERW applying crushed silicate rocks like basalt was piloted to improve soil health and sequester atmospheric CO₂ through accelerated natural weathering.

- **Description of the Intervention**

Enhanced Rock Weathering (ERW) involves the application of finely crushed silicate rocks, such as basalt, onto agricultural soils. The process accelerates natural weathering reactions that capture atmospheric CO₂ and transform it into stable bicarbonates. This method also enhances soil health by releasing essential nutrients like calcium and magnesium.

- **Implementation and Institutional Support**

Led by Tamil Nadu Agricultural University (TNAU), with technical support from IIT-Madras and the University of Sheffield. Funding came from Leverhulme Trust and CSR arms of cement and mining firms. Krishi Vigyan Kendras (KVKs) supported farmer outreach, demos, and capacity building.

- **Outcomes and Impacts**

- **Carbon Sequestration:** 4.5–6.0 t CO₂e/ha/year; SOC increased by 0.15–0.25%; 15% drop in N fertilizer use reduced N₂O emissions ([Bossio *et al.*, 2020](#); Sharma *et al.*, 2024).
- **Economic Benefits:** Yield gains of 12–18% in finger millet and 9–14% in groundnut; reduced input costs led to net income increases of ₹8,000–₹12,000/ha ([Lhamtshok, 2022](#)).
- **Soil and Ecosystem Improvements:** Soil pH improved from ~5.5 to ~6.5; basalt added calcium, magnesium, and micronutrients; enhanced moisture retention supported resilience.
- **Social Impact:** Women farmers in SHGs contributed to soil testing and on-farm trials; ERW “champions” enabled peer learning and adoption ([BAIF, 2023](#)).

- **Innovation and Replicability**

ERW using quarry waste basalt promotes circular economy and was integrated into the Soil Health Card scheme. With similar soil-lithology, the model is replicable across drylands in Odisha, Jharkhand, and the Deccan Plateau.

- **Challenges and Limitations**

Barriers included low initial awareness, fragmented supply chains, and a lag in visible carbon gains (1–3 years). Absence of MRV frameworks restricted carbon market integration.

- **Lessons Learned and Takeaways**

ERW offers co-benefits of carbon sequestration and soil rehabilitation. Success depended on local materials, scientific backing, and institutional convergence. Embedding ERW into national soil and climate programs could scale adoption sustainably.

5.6. Silvopasture Development in Rajasthan's Arid Zones

- **Title of the Study**

Silvopasture Development in Rajasthan's Arid Zones: Restoring Grazing Commons and Enhancing Carbon Resilience

- **Context and Background**

In the arid districts of western Rajasthan (Jodhpur, Barmer, Jaisalmer), degraded common lands and overgrazing have reduced biomass productivity to 0.25–0.40 t/ha and weakened pastoral livelihoods. With annual rainfall between 170–280 mm, community-driven silvopasture interventions were launched to restore ecosystem health and livestock systems through participatory planning.

- **Description of the Intervention**

Silvopasture systems in Rajasthan's arid districts cover ~10 ha plots, interplanting drought-resistant native trees, *Hardwickia binata*,

Colophospermum mopane, and Prosopis cineraria, with perennial grasses like Cenchrus ciliaris. Supported by soil and water conservation measures (fencing, trenches, bunds), these systems enhance ecological resilience. Livestock grazing is managed via rotational and cut-and-carry methods to prevent overgrazing and sustain biomass. Co-developed with local communities, these silvopastoral landscapes sequester carbon, improve soil fertility, and support traditional livestock such as camels and goats vital to pastoral livelihoods.

- **Implementation and Institutional Support**

ICAR-CAZRI led the initiative alongside local NGOs and Gram Panchayats. The “Mozer framework” guided species selection, aligning ecological suitability with community needs. By-laws were developed to govern access, maintenance, and benefit sharing. Demonstration plots facilitated knowledge dissemination.

- **Outcomes and Impacts**

- **Carbon Sequestration:** Biomass productivity increased to 1.6–4.6 t/ha within two years. Over 19 years, total carbon sequestration reached ~5.4 Mg C/ha, slightly higher than pasture (5.3 Mg C/ha) and agri-horti systems (5.5 Mg C/ha) (AGRIS). SOC improved by 36–60% over tree- or pasture-only systems.
- **Economic Benefits:** Compared to annual cropping, silvopasture showed higher profitability with a ~3-year payback and >30% IRR over 10 years. However, intensive sheep grazing models were less viable in extremely dry zones.

- **Ecosystem Services:** Enhanced canopy and root systems improved moisture retention, reduced erosion, and increased microbial activity. Edible forage species rose from 1524% to 55–73%.
- **Social and Institutional Outcomes:** Community-formulated by-laws improved governance and equity. Participatory monitoring built ownership and improved compliance with conservation practices.
- **Innovation and Replicability**

The model integrates native species, conservation practices, and local governance making it replicable across ~1 million hectares of degraded arid commons. It offers a scalable model through partnerships with CAZRI, forest departments, and Panchayats.

- **Challenges and Limitations**

Silvopasture success depends on rainfall reliability; droughts limit biomass growth and tree survival. Institutional capacity and sustained community engagement remain constraints for widespread adoption.

- **Lessons Learned and Takeaways**

Silvopasture offers ecological, economic, and social co-benefits. Core enablers include community participation, species-site matching, and investment in basic conservation infrastructure. It is a viable pathway for carbon-negative land restoration in arid India.

5.7. Integrated Organic Farming Systems (IOFS) in Sikkim

- **Title of the Study**

Integrated Organic Farming Systems in Sikkim: A Holistic Model for Carbon-Negative, Biodiverse, and Resilient Agriculture

- **Context and Background**

Sikkim, declared India's first fully organic state in 2016, faces challenges of fragmented landholdings, steep slopes, and fragile ecosystems in the Eastern Himalayas. To combat soil erosion, chemical dependency, and climate vulnerability, Integrated Organic Farming Systems (IOFS) were introduced. The Integrated Organic Farming System (IOFS) integrates crops, livestock, forestry, and horticulture with organic nutrient and pest management to close nutrient cycles and boost resilience at the household scale. IOFS model in Sikkim integrates multiple components including cereals, vegetables, livestock, aquaculture, and water harvesting structures like Jalkunds to enhance sustainability, productivity, and climate resilience.

- **Description of the Intervention**

IOFS involves multicomponent organic models customized for local agroecological zones, combining organic cereals, vegetables, and spices with backyard livestock, agroforestry, and on-farm inputs like vermicompost and bio-pesticides. Rainwater harvesting and polyhouse cultivation are used in higher altitudes. Pilots were launched across Sikkim under the National Mission on Sustainable Agriculture and scaled through the Sikkim Organic Mission.

- **Implementation and Institutional Support**

Led by the Sikkim Organic Mission with technical backing from ICAR institutes and State Agricultural Universities, IOFS received funding

through RKVY, NMSA, and PKVY schemes. Farmer clusters trained via ATMA and KVKs, with women's Self-Help Groups (SHGs) and cooperatives playing key roles in participatory planning and demonstrations.

- **Outcomes and Impacts**

- **Carbon Sequestration:** SOC improved from ~0.7% to 1.2–1.4% over four years, corresponding to 3.5–5.0 t CO₂e/ha/year sequestration through organic amendments and agroforestry. Eliminating synthetic inputs reduced embedded GHG emissions; better manure and fodder management lowered methane ([Bossio et al., 2020](#); [Albrecht et al., 2023](#)).
- **Economic Outcomes:** Economic Outcomes: Crop yields increased by around **15 %** after switching to certified organic farming, with input costs dropping by **20–25 %**; net household incomes in high-value spice farms rose significantly due to premium prices for crops like organic ginger ([Jamir et al., 2022](#)).
- **Ecosystem Services:** IOFS enhanced soil fertility, moisture retention, and reduced runoff on slopes. Biodiversity was supported through agroforestry and restoration of forest-edge lands ([Lal, 2020](#)).
- **Social Outcomes:** Social Outcomes: Women-led SHGs are increasingly leveraged through the *Krishi Sakhi Convergence Programme*, implementing over 30,000 Krishi Sakhis drawn from SHGs; these women lead capacity-building, participatory training in soil-health management,

and act as para-extension resource persons in their communities (MoA & FW/DAY-NRLM, 2024)..

- **Innovation and Replicability**

Sikkim's IOFS offers a replicable model for hilly, smallholder systems across Northeast India and the Western Ghats, emphasizing on-farm inputs and closed nutrient loops. The model aligns well with climate finance, including carbon credits, and has gained FAO and UN recognition for sustainable mountain agriculture.

- **Challenges and Limitations**

Initial yield drops during transition led to dropouts. Ongoing scientific support for pest and nutrient management was crucial. Limited market access and weak MRV infrastructure constrained economic gains and carbon credit integration.

- **Lessons Learned and Takeaways**

Multi-component IOFS enhances resilience and productivity while supporting biodiversity. Success depends on strong institutional support, active community participation, and women's leadership. IOFS stands out as an effective nature-based carbon farming approach in mountainous agroecosystems.

5.8. Regenerative Grazing on Degraded Rangelands - Kenya

- **Title of the Study**

Restoring Kenya's Degraded Rangelands through Regenerative Grazing and Community-Led Land Stewardship

- **Context and Background**

Kenya's arid and semi-arid lands (ASALs), covering over 80% of the country, support pastoralist communities reliant on livestock. Overgrazing, deforestation, and erratic rainfall in regions like Laikipia, Baringo, and Samburu have degraded grasslands, reducing productivity, biodiversity, and increasing climate vulnerability. Traditional rotational grazing was disrupted by land fragmentation and population pressure, leading to compacted soils and elevated greenhouse gas (GHG) emissions.

- **Description of the Intervention**

Regenerative grazing mimics natural herd movements through rotational grazing in small paddocks, allowing pasture recovery. Native grasses like *Cenchrus ciliaris* and *Chloris roxburghiana* were reseeded, stone bunds and contour planting controlled erosion, and silvopastoral elements (Acacia trees) provided shade and fodder. Water harvesting improved moisture availability. Pastoralist communities formed grazing cooperatives for equitable resource management. The Northern Rangelands Trust (NRT), Savory Institute, and NGOs such as the Zeitz Foundation supported training and implementation.

- **Implementation and Institutional Support**

NRT and the Savory Institute led holistic management training, participatory land-use planning, and monitoring. County governments facilitated land tenure clarity and governance. Funding and technical support came from USAID, SIDA, DFID, ILRI, and Mpala Research Centre, which aided research on carbon flux and livestock productivity.

- **Outcomes and Impacts**

- **Carbon Sequestration/GHG Mitigation:** Agroforestry systems in India led to soil organic carbon (SOC) stocks increasing by about **25%** compared to conventional systems; tropical forages and improved legumes/supplements reduced enteric methane emissions by **10–25%** under smallholder grazing systems (Ku-Vera *et al.*, 2022; [Agroforestry Meta-Analysis, 2023](#)).
- **Economic Outcomes:** Livestock productivity rose 20–30%, lowering feed and veterinary costs. Carbon credits could generate USD 15–25/ha/year. Women’s groups diversified incomes via seed collection and dairy production.
- **Ecosystem Services:** Enhanced soil aggregation, moisture retention, and microbial activity improved land productivity ([Lal, 2020](#)). Vegetation cover restoration reduced runoff by 15–20%, aiding hydrological resilience. Biodiversity revived, including native grasses and wildlife corridors. Over 45,000 ha of rangeland were restored.
- **Social and Institutional Outcomes:** Social and Institutional Outcomes: Local grazing committees reinforced governance and conflict resolution; women were actively involved in managing seed and fodder nurseries, and over 1,500 pastoralists were trained in rangeland ecology and rotational grazing under participatory programmes ([UNCCD, 2024](#)).

- **Innovation and Replicability**

This low-cost, community-led model blends indigenous knowledge with holistic grazing, showing strong potential for replication in ASAL regions like Ethiopia, Sudan, and Rajasthan. Integration with carbon markets and payment for ecosystem services (PES) enhances financial sustainability.

- **Challenges and Limitations**

Land tenure conflicts delayed grazing block formation. Carbon certification monitoring was costly, especially in remote areas. Initial pastoralist resistance required sustained behavior change. Extreme droughts necessitated adaptive management and fodder reserves.

- **Lessons Learned and Key Takeaways**

Sustainable land restoration hinges on community ownership, trust-building, inclusive governance, and incentives. Regenerative grazing is scalable in resource-poor contexts when grounded in local knowledge. Carbon finance supports but requires strong institutional frameworks and MRV systems. Women's active participation significantly boosts resilience and income diversification.

5.9. Agroforestry Cocoa Systems - Peru

- **Title of the Study**

Agroforestry Cocoa Systems for Climate Mitigation and Livelihoods in the Amazonian Highlands, Peru

- **» Context and Background**

Peru's Amazonian regions, notably San Martín, Ucayali, and Huánuco, have suffered extensive deforestation due to illegal coca cultivation and shifting agriculture. This caused biodiversity loss, soil degradation, and increased greenhouse gas (GHG) emissions from slash-and-burn practices. Cocoa (*Theobroma cacao*), a shade-tolerant perennial, offers a climate-resilient alternative when grown in agroforestry systems with native timber and fruit trees.

- **Description of the Intervention**

The project transformed degraded pastures and monocultures into diversified cocoa agroforestry systems. Cocoa was interplanted with timber species (e.g., *Cedrela odorata*, *Swietenia macrophylla*), fruit trees (banana, citrus), and leguminous cover crops. The system emphasized organic practices using compost and biofertilizers, avoiding synthetic agrochemicals. GIS and soil mapping guided site selection. Smallholder cooperatives (e.g., ACOPAGRO), NGOs like Pur Projet and Rainforest Foundation, and private partners such as Nestlé and UNDP's Green Commodities Program collaborated in implementation.

- **Implementation and Institutional Support**

The Ministry of Agriculture and Peru's National Cocoa Plan (2013–2023) provided governmental backing, complemented by international support from FAO, UNDP, and USAID's Alternative Development Program. Carbon finance was accessed via Plan Vivo-certified reforestation projects, alongside premium organic and fair-trade market linkages. Research and extension were led by the National Agrarian University of La Molina and CATIE, focusing on training, trials, and soil carbon monitoring.

- **Outcomes and Impacts**

- **Carbon Sequestration / GHG Mitigation:** Soil organic carbon (SOC) increased by 15–20% over five years, with carbon sequestration rates of 5–7 t CO₂e/ha/year through biomass ([Bossio *et al.*, 2020](#)). Methane and nitrous oxide emissions remained low due to reduced fertilizer use and perennial species dominance.
- **Economic Outcomes:** Cocoa yields stabilized at approximately 800–1,000 kg/ha, with farmer incomes increasing by 20–30% due to organic and fair-trade premiums. Input costs declined through enhanced nutrient cycling, and stable market access was secured via buyers like Alter Eco and Ethiquable ([Fairtrade International, 2021](#)).
- **Ecosystem Services:** The system improved soil health, nutrient cycling, microbial activity, and reduced erosion. Canopy and mulch layers enhanced water use efficiency. Biodiversity increased with more functional plant and animal species, and over 15,000 ha of degraded land were restored between 2012–2022 ([Lal, 2020](#)).
- **Social and Institutional Outcomes:** Women-led cooperatives promoted gender equity in processing and marketing. Participatory training improved farmer skills in pruning, composting, and shade regulation. Over 3,500 households engaged in decision-making and benefit-sharing. Intercropping with fruits and legumes enhanced food security ([FAO, 2023](#)).

- **Innovation and Replicability**

Innovations included farmer-led carbon monitoring via smartphone apps and blockchain for cocoa traceability, increasing transparency and engagement. The model is replicable in humid tropical regions like Colombia and Ecuador with local adaptations.

- **Challenges and Limitations**

Challenges involved maintaining pruning and management skills, high establishment costs (~\$1,000/ ha), and shifting from coca to cocoa farming culturally. Price volatility in global cocoa markets also threatened economic sustainability.

- **Lessons Learned and Key Takeaways**

Cocoa agroforestry offers a scalable carbon-negative solution for tropical deforested landscapes. Success requires sustained incentives, strong technical support, and institutional collaboration. Integration of carbon finance, premium markets, and community participation ensures lasting impacts beyond donor funding.

5.10. No Till + Cover Cropping in Corn-Soy Rotations - Iowa, USA

- **Title of the Study**

Reducing GHG Emissions via No Till and Multi-Species Cover Cropping in Corn-Soybean Rotations, Iowa, USA

- **Context and Background**

The U.S. Midwest's fertile mollisols support intensive corn-soybean monocropping, which, under conventional tillage, causes soil erosion, nutrient runoff, and loss of soil organic carbon (SOC). Since the 1950s, tillage-based corn-soy systems have left soils bare between crops, worsening environmental degradation and reducing resilience to climate extremes.

- **Intervention Description**

The intervention promotes carbon-negative practices by combining annual no-till planting with diverse cover crops during fallow periods. Typical species include legumes (e.g., crimson clover), grasses (rye, oats), and brassicas. This reduces soil disturbance, promotes nitrogen fixation, builds SOC, and improves water retention. Key stakeholders are farmers linked through networks like Practical Farmers of Iowa, USDA NRCS, agronomic consultants, and carbon-market organizations such as Carbon180.

- **Implementation and Institutional Support**

The USDA NRCS encourages cover cropping via programs like the Conservation Stewardship Program (CSP) and Environmental Quality Incentives Program (EQIP). Iowa State University and Practical Farmers of Iowa facilitate research and outreach through trials and peer learning. Carbon180 and Field to Market assist with carbon accounting using COMET-Farm. Financial incentives include cost-sharing for seeds and equipment and access to carbon credit pilots and voluntary markets.

- **Outcomes and Impacts**

- **Carbon Sequestration and GHG Mitigation:** SOC increased by 0.2–0.4% per decade, with net GHG mitigation of 1.5–2.2 t CO₂e/ha/year (Smith *et al.*, 2020; Bossio *et al.*, 2020). Reduced synthetic nitrogen use lowers N₂O emissions; methane emissions remain minimal.
- **Economic Benefits:** Crop yields remain stable or improve, with some reporting 5–8% higher corn yields due to better moisture retention. Input costs fall by 10–15%, boosting profitability by 5–10%. Carbon markets offer additional revenue streams ([Cammara, 2025](#))
- **Ecosystem Services:** Soil structure, microbial biomass, and infiltration improve, reducing erosion ([Lal, 2020](#)). Cover crops enhance drought resilience and biodiversity, aiding ecological recovery.
- **Social Outcomes:** Farmer networks enable peer learning and innovation dissemination. Though farms are mainly male-managed, benefits extend to families, supporting household resilience ([American Farmland Trust, 2023](#)).

• **Innovation and Replicability**

Technologies like precision seeders, roller-crimpers, and tailored cover blends, combined with carbon accounting platforms, enable successful adoption. These practices are replicable in similar temperate regions such as Argentina, Ukraine, and China.

• **Challenges and Limitations**

Technical challenges include managing cover crops in wet springs and upfront costs for seeds and equipment. Cultural reliance on tillage and

herbicides slows adoption. Reliable carbon monitoring requires robust data and modeling.

- **Lessons Learned and Key Takeaways**

Long-term commitment is essential as benefits accrue slowly. Early adopter networks foster trust and knowledge sharing. Combining no-till with cover cropping yields synergistic benefits. Carbon programs must be accessible and farmer-friendly to broaden uptake.

5.11. Biochar Integration in Organic Farming - Germany

- **Title of the Study**

Biochar-Amended Organic Farming for Soil Carbon Sequestration in Brandenburg, Germany

- **Context and Background**

Brandenburg, northeastern Germany, has sandy, nutrient-poor soils and low rainfall (~550 mm), making it prone to drought and fertility decline (Gross *et al.*, 2024). The region's agriculture, increasingly organic under EU CAP incentives, faces challenges like inefficient nutrient cycling and limited soil carbon inputs. This spurred interest in biochar as a carbon-negative soil amendment.

- **Intervention Description**

The intervention involved annually applying 5–10 t/ha of pyrogenic biochar, co-composted with farmyard manure, to certified organic crop rotations of legumes and grains under minimum tillage with winter cover

crops. Key players included organic farmer cooperatives, biochar suppliers, research institutions such as the Thünen Institute and Universität Hohenheim, and NGOs like TerraBoGa (Bogunovic *et al.*, 2023).

- **Implementation and Institutional Support**

Led by the Thünen Institute and funded by Germany's BMEL, the EU LIFE Programme, and EIPAgri, the project included farmer field schools and extension services delivering practical biochar training. Compliance with European Biochar Certificate (EBC) standards and EU fertiliser regulations (2019/1009) ensured product quality and regulatory alignment.

- **Outcomes and Impacts**

- **Carbon Sequestration and GHG Mitigation:** Compost-biochar amendments increased soil organic carbon by 0.3–0.7% over four years, reducing CO₂e emissions by 3.4–5.6 t/ha annually, including lower N₂O emissions via improved nitrogen efficiency ([Gross *et al.*, 2024](#)).
- **Economic Benefits:** Synthetic input costs dropped by 20%, net farm income rose 1015%, supported by yield stability and premium organic markets ([Jaufmann *et al.*, 2025](#)). Farmers also earned carbon credits certified under the EBC.
- **Ecosystem Services:** Soil moisture retention improved by up to 15% during droughts, biodiversity especially soil fauna and mycorrhiza increased, and cropping systems showed greater climate resilience ([Lal, 2020](#)).
- **Social and Institutional Outcomes:** Over 150 farmers trained through programs led by the [Ecologic Institute \(2023\)](#), with strong collaboration among farmers,

researchers, and policymakers fostering participatory innovation ([Ecologic Institute, 2025](#)).

- **Innovation and Replicability**

Key innovations included low-cost mobile pyrolysis units for on-farm biochar production and cooperative compost, biochar hubs reducing logistics costs. These models are replicable in semi-arid temperate zones with sandy soils, such as Poland, the Czech Republic, and northern India.

- **Challenges and Limitations**

High upfront pyrolysis equipment costs, farmer skepticism, and gaps in emissions trading system regulations complicated adoption and carbon credit monetization.

- **Lessons Learned and Key Takeaways**

Co-composted biochar outperformed raw biochar in improving soil health. Regulatory alignment was crucial for uptake. Broad stakeholder engagement ensured successful adaptation and scaling, demonstrating that tailored carbon-negative farming enhances yields, resilience, and mitigation.

6. Cross-case Analysis and Lessons Learned

The diversity of agroecological zones, socio-economic contexts, and intervention mechanisms across the documented case studies reveals not only the **versatility** of carbon-negative farming approaches but also their **context-specific enablers and constraints**. A synthesis of findings across these cases highlights several key **cross-cutting themes and lessons** relevant for practitioners, policymakers, and researchers.

6.1. Adaptive Technology Adoption and Local Contexts

One of the most consistent lessons is the need to adapt carbon-negative practices to local agroclimatic and socio-cultural realities. For instance, Direct Seeded Rice (DSR) adoption in Punjab was successful due to strong extension support, localized training, and alignment with water-saving imperatives ([Singh et al., 2023](#)). In contrast, Zero Budget Natural Farming (ZBNF) in Andhra Pradesh thrived by building on traditional knowledge systems and promoting low-cost, farmer-led innovation ([Chandran, 2021](#)).

This reinforces that no one-size-fits-all solution exists. Practices like biochar application, while showing strong carbon sequestration potential, require adaptation in terms of feedstock selection, pyrolysis technology, and soil compatibility, as demonstrated in both Odisha's tribal farming context and the structured organic systems in Germany ([Lehmann & Joseph, 2015](#); [Bellè et al., 2022](#))

6.2. Institutional Support and Policy Alignment

Institutional and policy support emerged as a determinant of scalability and sustainability. The ZBNF initiative scaled rapidly due to state-level policy backing, convergence with rural employment schemes, and farmer collectives ([APCNF, 2021](#)). Similarly, the silvopastoral systems in Rajasthan's arid zones were sustained through community-led watershed management institutions and government dryland greening policies ([Chavan et al., 2021](#))

In contrast, areas with fragmented or weak institutional ecosystems often faced challenges in practice adoption, even when technical benefits were evident. This indicates that policy alignment, financial incentives, and institutional coherence are essential catalysts.

6.3. Co-benefits Drive Farmer Motivation

Although carbon sequestration is a central goal, most farmers in the studied cases were primarily motivated by short-term co-benefits such as improved soil health, reduced input costs, higher net returns, or climate resilience.

For example, DSR was adopted not due to its climate mitigation potential but because it significantly reduced water and labor needs, especially under shrinking water tables ([Chavan *et al.*, 2021](#)). Similarly, biochar application in Odisha improved soil moisture retention, crop yield, and organic matter content, thereby improving food security in tribal regions ([Mohanty *et al.*, 2021](#)). The alignment of carbon benefits with immediate farm-level gains enhances adoption likelihood.

6.4. Need for Robust MRV and Carbon Finance Mechanisms

One of the most significant constraints across the cases was the absence of reliable Measurement, Reporting, and Verification (MRV) systems. Many promising carbon-negative practices lack empirically validated GHG reduction baselines, making them ineligible for carbon credit markets.

The German case of biochar integration in organic farming stands out as a rare example where certified life-cycle carbon assessments enabled integration into EU carbon trading frameworks ([European Biochar Certificate, 2023](#)). This illustrates the need to invest in robust MRV tools, open data platforms, and third-party verifications to make carbon-negative practices economically viable through market instruments.

6.5. Community Engagement and Knowledge Co-creation

Community engagement and participatory innovation were critical success factors. In Andhra Pradesh, ZBNF utilized a farmer-to-farmer extension model, resulting in greater trust, reduced dependency on external inputs, and shared ownership of the transition process (Andhra Pradesh Community Managed Natural Farming, 2025). Similarly, silvopastoral

systems in Rajasthan's arid zones were sustained through community-led watershed management institutions and government dryland greening policies (Dookia, 2025).

This shows that community-centric design and knowledge co-production, rather than top-down prescription, is more effective in sustaining behavioral and practice shifts.

6.6. Barriers and Constraints

Despite the benefits, **barriers persist** across contexts. Key constraints include:

- Lack of access to technical knowledge (DSR, biochar)
- Weak extension systems and fragmentation in policies (ZBNF, silvopasture)
- High initial costs or lack of subsidies (biochar, organic certification)
- Inadequate data for carbon markets (all cases except Germany)

These highlight the need for integrated support systems, public-private partnerships, and climatesmart extension frameworks.

7. Conclusion and Way Forward

The case studies presented in this chapter collectively demonstrate that carbon-negative farming is no longer a theoretical aspiration but a practical and evolving reality across diverse agroecological, institutional, and socio-economic contexts. From smallholder systems in India to large-scale regenerative enterprises abroad, these interventions reveal that sustainable carbon sequestration can be achieved through context-appropriate, community-centered, and science-informed strategies. Each model be it Zero Budget Natural Farming in Andhra Pradesh, biochar integration in Odisha and Germany, or regenerative grazing in Kenya proves that aligning

ecological restoration with livelihood improvement is both feasible and scalable.

A recurring insight from these examples is that local adaptation, institutional support, and socio-economic co-benefits are the decisive factors driving adoption. Farmers are motivated less by carbon metrics and more by immediate benefits such as higher soil fertility, reduced input costs, and climate resilience. Therefore, successful scaling of carbon-negative farming hinges on framing carbon as a *co-benefit* of sustainable agriculture rather than as its sole objective. Policy and programmatic approaches must thus integrate climate goals within broader frameworks of food security, livelihood enhancement, and natural resource restoration.

The cross-case synthesis underscores that participatory governance, farmer networks, and inclusive knowledge systems are foundational to success. Community-led institutions, such as SelfHelp Groups (SHGs), cooperatives, and Gram Sabhas, played a transformative role in sustaining interventions from ZBNF and MGNREGA-based agroforestry in India to cooperative-led cocoa agroforestry systems in Peru. Empowering these local collectives ensures that the carbon-negative transition remains socially equitable and resilient over time.

Going forward, four strategic directions emerge:

- 1. Institutional Integration and Policy Convergence:** Integrating carbon-negative farming within existing schemes such as MGNREGA, NMSA, PKVY, and NRLM can provide financial, technical, and social scaffolding for scale-up. Alignment with Nationally Determined Contributions (NDCs) and soil health missions will further mainstream these practices into national climate commitments.

2. **Robust MRV and Carbon Finance Mechanisms:** Establishing cost-effective, transparent systems for Measurement, Reporting, and Verification (MRV) is vital to access emerging carbon markets and climate finance. Open-access data platforms, farmer-centric monitoring tools, and third-party verification can enhance credibility and ensure equitable benefit-sharing.
3. **Capacity Building and Knowledge Exchange:** Farmer-to-farmer learning networks, digital advisory systems, and participatory research models should be prioritized. Universities, KVKs, and NGOs can play pivotal roles in bridging scientific knowledge with traditional practices, ensuring that innovations are both credible and locally relevant.
4. **Inclusive and Ethical Carbon Transitions:** Carbon-negative farming must advance with ethical integrity protecting land rights, promoting gender equity, and safeguarding biodiversity. The benefits of carbon finance and ecosystem restoration should reach smallholders, women, and marginalized communities to ensure a just transition toward sustainable food systems.

In essence, the way forward lies in transforming carbon-negative farming from isolated success stories into mainstream agricultural policy and practice. This requires multi-level collaboration—linking grassroots innovations with enabling governance, transparent finance, and robust research. As the world moves toward net-zero and beyond, the lessons distilled from these case studies illuminate a path where agriculture serves as both a climate solution and a driver of equitable rural prosperity. By investing in this transition, nations can simultaneously address climate change, biodiversity loss, and livelihood insecurity—turning farms into active agents of planetary restoration.

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Chapter - 7

Challenges and Solutions of Carbon-Negative Farming

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1 Introduction

The urgent need to mitigate climate change has prompted a global shift in agriculture from merely reducing greenhouse gas (GHG) emissions to actively removing atmospheric carbon dioxide (CO₂). This transition has given rise to the concept of carbon-negative farming, a holistic approach that integrates sustainable land management practices with the goal of net carbon sequestration in soils and vegetation. Unlike conventional systems that are often carbon-intensive due to synthetic inputs, excessive tillage, and monoculture practices, carbon-negative farming seeks to reverse emissions trends by enhancing natural carbon sinks ([Lal, 2020a](#)).

However, the widespread adoption of carbon-negative farming is not without challenges. At the core lie technical barriers, such as limited understanding of the soil-carbon dynamics across different agroecological zones and the lack of standardized metrics for measuring carbon sequestration ([Paustian *et al.*, 2016](#)). Many farmers face economic constraints, particularly in resource-limited settings, where upfront investment in regenerative practices such as agroforestry, cover cropping, compost application, or biochar incorporation may not yield immediate financial returns ([Smith *et al.*, 2008](#)). Moreover, there is often institutional inertia, with inadequate policy incentives, lack of extension support, and

poor market access for carbon credits further slowing adoption ([Bossio *et al.*, 2020](#)).

Social and cultural dimensions also play a role. Farmers may be reluctant to change traditional practices due to uncertainty about results, perceived risks, or the absence of successful demonstration models ([Schreefel *et al.*, 2020](#)). Furthermore, the fragmented nature of landholdings, particularly in developing countries like India, limits the scalability and monitoring of carbon-negative interventions.

Despite these challenges, a range of innovative solutions is emerging. Scientific advancements in soil microbiology, carbon modeling, and precision agriculture are improving our ability to track and manage soil carbon ([Oldfield *et al.*, 2019](#)). Economic tools such as carbon markets, result-based financing, and green subsidies can help bridge the investment gap ([FAO, 2019](#)). Policy frameworks are gradually evolving to support climate-resilient and carbon-sequestering practices through integrated climate-smart agricultural strategies. Strengthening knowledge systems, farmer training, and participatory research are also critical to empower local communities and ensure context-specific adoption ([Pretty & Bharucha, 2014](#)).

Thus, addressing the challenges of carbon-negative farming requires a multi-pronged strategy that combines science, policy, finance, and grassroots engagement. Only through such systemic approaches can agriculture transform from a net emitter into a force for climate restoration and ecological regeneration.

2 Key Challenges and Corresponding Solutions

While the vision of carbon-negative farming is both scientifically promising and ecologically essential, its practical implementation reveals a complex landscape of interrelated challenges. These barriers are multifaceted,

spanning economic, institutional, technical, and environmental domains, and significantly influence the feasibility, adoption, and scalability of regenerative practices. Building a resilient, carbonsequestering agricultural system therefore requires a nuanced understanding of these challenges and the development of context-specific, targeted solutions.

1. High Initial Costs
2. Knowledge and Awareness Gaps
3. Measurement and Verification
4. Policy and Incentive Barriers
5. Market Access and Economic Viability
6. Climatic and Soil Variability

2.1 High Initial Costs

Adopting carbon-negative farming practices often requires significant upfront investments in regenerative inputs, infrastructure, monitoring tools, and training. These initial costs can be a major barrier, especially for smallholders and resource-limited farmers, potentially discouraging widespread adoption. Addressing both the financial burdens and structural limitations is essential to make carbonnegative farming economically viable and scalable.

Challenges

One of the most immediate and visible challenges to adopting carbon-negative farming practices is the high initial cost associated with transitioning from conventional methods. Carbon-negative agriculture often requires investment in organic amendments like compost, vermicompost, or biochar, establishment of agroforestry systems, adoption of no-till or conservation tillage technologies, or installation of soil carbon monitoring infrastructure. These expenses are typically front-loaded, while the financial

benefits, such as increased soil fertility, reduced input costs, and potential income from carbon credits, accrue gradually over time. This mismatch between short-term costs and long-term gains creates a significant financial barrier, especially for smallholder and marginal farmers who operate on thin profit margins ([Lal, 2020b](#)).

Another important challenge is the lack of access to affordable credit or startup capital. Many small-scale farmers, particularly in developing regions, lack formal financial records or collateral, making them ineligible for traditional bank loans ([Pretty & Bharucha, 2014](#)). Moreover, conventional financial institutions often have limited understanding or trust in regenerative farming models, further restricting the flow of finance to these areas. In addition, the limited availability of affordable regenerative inputs, such as cover crop seeds, microbial biofertilizers, or biochar, also contributes to higher operational costs. For farmers in remote or underserved areas, transportation and procurement costs further add to this burden ([FAO, 2019](#)).

A less visible but equally important barrier is limited financial literacy and institutional support. Many farmers may not be aware of the long-term economic benefits of carbon-negative farming, nor do they have access to training on how to assess investment risks, access grants or subsidies, or participate in emerging carbon markets (Schreefel *et al.*, 2019). The absence of a strong institutional framework that promotes and supports the financial aspects of regenerative farming results in low adoption rates, despite increasing awareness of its environmental benefits.

Solutions

Overcoming the financial challenges of carbon-negative farming requires multi-level intervention, combining public policy, market mechanisms, and local institutional support. One of the most effective strategies is the

provision of targeted subsidies or financial incentives to lower the initial cost burden. Governments can play a key role by realigning existing agricultural subsidies to support carbon-sequestering practices, such as subsidizing compost, biochar, or agroforestry seedlings instead of chemical fertilizers ([Smith *et al.*, 2008](#)).

Another promising solution is access to carbon finance through voluntary carbon markets. Farmers who adopt practices that demonstrably sequester carbon can be rewarded with carbon credits, which are sold to companies or entities looking to offset their emissions. When aggregated at the community or cooperative level, this can create new income streams and incentivize long-term practice change ([Bossio *et al.*, 2020](#)). However, to fully benefit from these mechanisms, robust and affordable measurement, reporting, and verification (MRV) systems must be in place.

In addition, the development of **low-interest green credit schemes** or **micro-financing programs** specifically designed for carbon-negative agriculture can play a transformative role. Financial institutions, in partnership with governments and development agencies, can create risk-sharing mechanisms or guarantee funds that reduce the risk for lenders while empowering farmers with capital ([FAO, 2019](#)).

Public-private partnerships (PPPs) can also play a crucial role by sharing the cost of infrastructure development, supporting supply chains for regenerative inputs, and investing in training and capacitybuilding. For example, PPPs can help establish decentralized composting units or rural biochar production facilities, reducing input costs for local farmers ([Pretty & Bharucha, 2014](#)).

Finally, increasing **financial and investment literacy** through farmer field schools, extension networks, and rural development programs is critical. Farmers need to understand how to evaluate returns on investment,

manage regenerative input costs, and leverage incentives effectively. Involving rural banks, cooperatives, and non-governmental organizations in this process helps bridge the gap between financial services and on-ground practice.

2.2 Knowledge and Awareness Gaps

The successful implementation of carbon-negative farming hinges on informed decision-making and a sound understanding of regenerative principles. However, widespread gaps in knowledge, technical expertise, and awareness, particularly among smallholder and rural farmers, pose significant hurdles. Bridging these gaps is vital to ensure effective adoption, sustained practice, and community-level impact.

Challenges

One of the most persistent barriers to the large-scale adoption of carbon-negative farming practices is the lack of knowledge and awareness among farmers, extension agents, policymakers, and other key stakeholders. These gaps span multiple domains, from basic understanding of soil carbon dynamics to more applied knowledge on the implementation, monitoring, and long-term benefits of regenerative techniques. In many cases, farmers are unaware of the potential of practices such as conservation tillage, cover cropping, agroforestry, biochar application, and composting to not only enhance soil health but also sequester atmospheric carbon ([Amelung *et al.*, 2020](#)).

The challenge is particularly acute among smallholder and resource-constrained farmers, who often rely on traditional knowledge or inherited farming practices and have limited exposure to scientific innovations. Moreover, climate-related concepts such as carbon sequestration, greenhouse gas mitigation, or ecosystem services may be too abstract or

disconnected from the farmers' daily realities. This disconnect is further compounded by the lack of locally adapted, practical knowledge resources and demonstration models that would help translate abstract concepts into actionable practices ([Schreefel *et al.*, 2020](#)).

In addition, knowledge transfer systems in many regions are weak or fragmented. Public extension services are often understaffed or under-resourced, and private advisory services may be too expensive or unavailable in remote areas ([FAO, 2019](#)). There is also a notable absence of capacity-building programs tailored specifically to carbon-negative farming. Existing training platforms generally focus on productivity, pest control, or fertilizer use, with limited emphasis on sustainable practices that contribute to carbon sequestration. Furthermore, even when knowledge exists, it may not reach farmers in formats they can easily understand or trust, due to issues of language, literacy, or digital exclusion ([FAO, 2025](#)).

Solutions

To address these challenges, a multi-pronged knowledge-building approach is essential. First, **investments** must be made in participatory training models that include hands-on learning through field schools, farmer-led demonstrations, and peer-to-peer mentoring. Research has shown that when farmers are directly involved in the co-creation and testing of innovations, adoption rates increase significantly ([Pretty & Bharucha, 2014](#)). Second, extension systems need to be revitalized and reoriented to include carbon literacy and agroecological principles as core components of their curricula. This includes training of trainers, curriculum development, and integration of climate-smart agriculture into university and vocational education.

Another critical solution is the use of digital knowledge platforms to disseminate region-specific best practices, carbon accounting tools, and decision-support systems. Mobile-based advisory services and farmer

helplines can also be leveraged to overcome geographical barriers and reach underserved populations ([Vermeulen *et al.*, 2012](#)). Further, partnerships between research institutions, NGOs, and community-based organizations can foster decentralized learning networks that empower local champions and farmer innovators.

Finally, awareness campaigns and policy support are needed to normalize and incentivize carbon-negative farming as a credible and economically viable climate solution. Governments can play a key role by launching media campaigns, organizing national workshops, and integrating carbon farming into mainstream agricultural discourse. Creating enabling environments that link knowledge dissemination with incentives, such as carbon credits, subsidies, or awards, will reinforce behavioral change.

2.3 Measurement and Verification

Effective **Measurement, Reporting, and Verification (MRV)** systems are essential for assessing the impact of carbon-negative farming practices, quantifying soil carbon sequestration, and validating outcomes for carbon credit mechanisms. However, the complexity and variability of biological systems, combined with the lack of standardized protocols and affordable technologies, pose significant obstacles in this domain.

Challenges

A major challenge in carbon-negative farming is the lack of accessible, accurate, and cost-effective methods for measuring soil organic carbon (SOC) changes over time. Traditional soil carbon measurement involves destructive sampling and laboratory analysis (e.g., dry combustion or wet oxidation methods), which can be labor-intensive, expensive, and time-consuming ([Paustian *et al.*, 2019](#)). These methods may not be feasible for

smallholder farmers or large-scale landscape-level monitoring due to cost and logistical constraints.

Another critical issue is temporal and spatial variability in soil carbon levels, which can fluctuate depending on factors such as climate, soil type, land use history, and management practices. This variability complicates the establishment of reliable baselines and makes it difficult to distinguish between natural carbon fluctuations and those induced by farming interventions ([Bossio *et al.*, 2020](#)). In addition, there is limited capacity in many countries to design and operate robust MRV frameworks, especially at local and community levels.

Furthermore, inconsistent or non-standardized protocols for monitoring carbon sequestration across regions hinder the comparability of data and limit the credibility of carbon credit claims. Many carbon markets and climate finance mechanisms require third-party validation and transparent documentation, but the lack of harmonized standards can lead to disputes or exclusion of projects from formal markets ([Okoli *et al.*, 2024](#)). Smallholders in particular face challenges in navigating complex documentation requirements for verification.

Finally, integration of co-benefits, such as biodiversity enhancement, water conservation, and improved soil health, into MRV systems is still underdeveloped. This limits the holistic valuation of regenerative practices and reduces incentives for farmers who contribute positively across multiple ecological dimensions ([Smith *et al.*, 2019](#)).

Solutions

To overcome these challenges, a multipronged strategy is required, involving technological innovation, institutional capacity building, and harmonization of standards. First, there is growing potential for low-cost, non-invasive tools such as remote sensing, near-infrared spectroscopy

(NIRS), in-situ sensors, and mobile apps integrated with AI to enhance the accuracy and affordability of carbon measurement (Meng *et al.*, 2024). These digital and geospatial technologies can complement or partially replace traditional soil sampling methods, especially for scaling measurements across diverse agroecosystems.

Second, standardized and simplified MRV protocols need to be developed, especially for smallholder contexts. International organizations, such as FAO and the Verified Carbon Standard (VCS), are working to develop methodologies that balance scientific rigor with practical applicability in developing regions ([FAO, 2019](#)). These tools must be context-specific, user-friendly, and aligned with the realities of farmers on the ground.

Third, community-based MRV (CMRV) models have shown promise by engaging local stakeholders directly in data collection and monitoring. These participatory approaches improve trust, reduce costs, and ensure that indigenous knowledge and local context are considered in verification frameworks ([Murthy *et al.*, 2017](#)). Moreover, training extension workers and farmers to use mobile data collection tools can democratize monitoring processes.

To incentivize accurate reporting, carbon finance systems must integrate performance-based rewards tied to verifiable outcomes. Linking MRV outputs to tangible benefits, such as payments for ecosystem services (PES), certification, or climate-smart subsidies, can motivate adoption and compliance. Equally important is capacity building at institutional levels, including national MRV registries, satellite data interpretation hubs, and decentralized laboratories to support carbon accounting.

Finally, the development of integrated MRV platforms, which combine carbon measurements with other sustainability indicators, will allow for the

co-tracking of carbon, biodiversity, and resilience benefits. This integrated approach enhances transparency and supports holistic climate adaptation and mitigation planning ([Sanderman *et al.*, 2017](#)).

2.4 Policy and Incentive Barriers

The successful adoption of carbon-negative farming relies heavily on enabling policy environments and supportive incentive structures. However, current agricultural policies and financial systems in many regions are misaligned with the goals of regenerative agriculture. Addressing this mismatch is crucial to remove institutional roadblocks and create favorable conditions for widespread implementation.

Challenges

One of the most persistent impediments to the adoption of carbon-negative farming is the absence of supportive policies and financial incentives that align with regenerative agricultural principles. In many regions, agricultural policies are still rooted in the Green Revolution paradigm, which emphasizes high-input, yield-maximizing practices. These policies often subsidize synthetic fertilizers, chemical pesticides, and large-scale monoculture systems, inadvertently disincentivizing sustainable land-use transitions that focus on carbon sequestration and ecosystem restoration ([Pretty & Bharucha, 2014](#)).

A critical challenge is the lack of formal recognition and integration of carbon-negative farming practices within national agricultural and climate strategies. Without legal definitions, protocols, or policy frameworks that recognize carbon farming as a climate mitigation strategy, farmers are unable to access support mechanisms such as subsidies, tax relief, or participation in carbon credit markets ([Schreefel *et al.*, 2020](#)). This policy vacuum results in uncertainty and discourages investment in regenerative

approaches. The challenges and proposed solutions to enhance market access and economic viability of carbon-negative farming are outlined in [Table 7.1](#). In addition, weak inter-ministerial coordination often hampers the development of coherent and cross-sectoral strategies that integrate agriculture, environment, and finance. For example, while climate departments may support carbon sequestration goals, agricultural ministries may prioritize conventional productivity gains, resulting in fragmented policy landscapes ([FAO, 2021](#)).

Table 7.1 Challenges and Solutions for Market Access and Economic Viability in Carbon-Negative Farming

Category	Challenges	Solutions
Market Recognition & Rewards	• Lack of markets that value ecosystem services (e.g., carbon sequestration, biodiversity) • Market rewards based on yield, not environmental outcomes • Inconsistent price premiums for regenerative produce	• Develop local and regional value chains focused on regenerative products • Promote regenerative and carbon certification schemes • Support digital platforms and eco-labeling to connect producers with conscious consumers

Category	Challenges	Solutions
Farmer Profitability	• Premiums often absorbed by intermediaries • Niche markets offer limited scalability • Lack of post-harvest infrastructure (cold storage, processing, logistics), especially for smallholders	• Invest in rural infrastructure (collection centers, cold storage) • Strengthen farmer cooperatives and producer organizations for bulk marketing • Facilitate direct-to-consumer or institutional (e.g., public procurement) market access

Category	Challenges	Solutions
Carbon Credit Market Access	• Limited access to voluntary carbon markets • High transaction and certification costs • Lack of aggregators and technical support • Complexity of MRV systems and carbon pricing volatility	• Simplify access to carbon markets through result-based finance and mobile MRV platforms • Encourage carbon aggregators or cooperatives for smallholders • Implement successful models from global pilot programs (e.g., Australia, Africa) • Provide technical and financial support for registration and certification

Category	Challenges	Solutions
Policy & Economic Incentives	• Absence of consistent financial incentives • Limited support for climate-smart supply chains • Lack of stable income or price guarantees	• Introduce tax breaks, input subsidies, and long-term contracts for regenerative producers • Encourage public and institutional procurement of regenerative products • Promote green labeling, stable pricing, and fiscal support for transitioning to carbonnegative practices

Furthermore, most current policy and incentive systems are poorly tailored to the needs of smallholder and marginalized farmers, who form the backbone of food systems in developing countries. These farmers often lack the capacity to navigate complex application procedures or to meet stringent compliance requirements necessary to access financial support or carbon markets ([Lal, 2020a](#)).

Solutions

To address these barriers, governments must reform agricultural policy frameworks to actively support carbon-negative practices. This involves a

shift from conventional subsidies to “green subsidies” that reward practices such as agroforestry, cover cropping, conservation tillage, organic inputs, and holistic grazing. For example, transitioning fertilizer subsidies to support compost and biofertilizer use can reduce emissions while enhancing soil health ([FAO, 2021](#)).

Another key solution is the development of robust and standardized carbon farming protocols that can be embedded into national and regional policies. These protocols should define eligible practices, monitoring requirements, verification methodologies, and mechanisms for benefit-sharing. Such standardization can foster trust, transparency, and accountability, enabling farmers to participate in voluntary and compliance carbon markets. Countries like Australia, through its Emissions Reduction Fund, and the U.S., through its COMET-Farm tool, have made progress in this direction ([California Department of Food and Agriculture, 2021](#)).

Public-private partnerships (PPPs) can also play a catalytic role by bringing together government bodies, research institutions, agri-tech companies, and farmer cooperatives to design innovative financial models and incentive mechanisms. For instance, carbon credit pre-financing models or ecosystem service payments can provide upfront capital for regenerative transitions ([Schreefel *et al.*, 2020](#)).

Lastly, integrating carbon-negative farming into broader rural development and climate resilience policies such as Nationally Determined Contributions (NDCs) under the Paris Agreement can help anchor long-term support and attract international climate finance. Policy coherence, participatory governance, and farmer-centric designs are essential for the effective rollout of incentive systems that truly support transformation at scale (Lal, 2020).

2.5 Market Access and Economic Viability

For carbon-negative farming to be sustainable in the long term, it must offer viable economic returns and reliable market pathways. However, farmers adopting regenerative practices often face difficulties in accessing premium markets, monetizing ecosystem services, or achieving consistent income streams. Improving market structures and creating fair economic incentives are essential for scaling up these environmentally beneficial practices.

Challenges

One of the major challenges facing carbon-negative farming is the lack of well-established and accessible markets that reward ecosystem services, such as carbon sequestration or biodiversity enhancement. Most agricultural markets remain structured around yield and short-term productivity rather than long-term environmental benefits, making it difficult for regenerative farmers to capture the full economic value of their practices ([Niles *et al.*, 2015](#)).

Additionally, price premiums for organically or regeneratively grown products are often inconsistent, limited to niche markets, or absorbed by intermediaries rather than reaching farmers. For smallholders and marginal farmers, the lack of infrastructure, such as collection centers, cold storage, or processing units, further exacerbates the challenge, increasing post-harvest losses and reducing profitability ([FAO, 2020](#)).

Another issue is the absence of mechanisms to economically reward carbon sequestration or reduced emissions through farming. Although voluntary carbon markets are emerging, many farmers, especially in developing countries, lack access to certification systems, registries, or aggregators who can help them generate and sell carbon credits ([Smith *et al.*, 2019](#)). Moreover, transaction costs, measurement complexity, and price volatility in carbon markets discourage participation, particularly among small-scale producers. The economic and market-related challenges of

carbon-negative farming, along with actionable solutions, are summarized in [Table 7.2](#). The table highlights gaps in ecosystem service markets, infrastructure, carbon credit access, and policy incentives, and outlines targeted measures to support farmers in realizing economic returns from climate-positive practices.

Table 7.2 Market Access and Economic Viability Challenges and Solutions in Carbon-Negative Farming

Key Area	Challenges	Solutions
Ecosystem Service Markets	• Lack of established markets to reward ecosystem services like carbon sequestration or biodiversity • Current markets prioritize short-term yield over long-term sustainability	• Develop local and regional value chains for regenerative products • Promote ecosystem service-based certifications and green labeling • Create digital marketplaces for direct access to conscious consumers

Key Area	Challenges	Solutions
Price Premium & Value Chain	• Inconsistent premiums for regenerative or organic products • Intermediaries absorb profits • Infrastructure gaps (cold storage, processing) increase post-harvest losses and reduce profitability	• Support rural infrastructure (e.g., collection centers, processing units) • Strengthen farmer cooperatives to reduce transaction costs and increase bargaining power • Encourage public procurement of regenerative produce
Carbon Credit Access	• Limited access to carbon markets • High certification and transaction costs • Lack of registries, aggregators, and support for smallholders • Volatile carbon pricing and complex MRV processes (Smith <i>et al.</i>, 2020)	• Simplify carbon market entry through result-based finance and community aggregators • Use mobile MRV platforms for smallholders • Replicate successful programs like Australia's Carbon Farming Initiative or African pilot projects

Key Area	Challenges	Solutions
Policy and Economic Incentives	• Lack of consistent incentives or subsidies for regenerative practices • No stable long-term contracts or price signals • Limited government support for climate-smart value chains	• Provide tax incentives, subsidies for regenerative inputs • Develop climate-smart procurement and contracting systems • Encourage long-term market linkages and green labeling

Solutions

To enhance market access and ensure economic viability, multiple strategies must be implemented. Firstly, developing supportive infrastructure, such as local value chains, regenerative certification schemes, and digital marketplaces, can help farmers reach premium markets and obtain better prices for their produce ([FAO, 2020](#)). Strengthening farmer cooperatives and producer organizations can also enhance bargaining power, reduce transaction costs, and facilitate bulk marketing of regenerative products.

Secondly, expanding access to carbon markets through simplified and inclusive frameworks is critical. Initiatives like result-based finance, community carbon aggregators, and mobile-based MRV (monitoring, reporting, and verification) platforms can reduce entry barriers for smallholder farmers ([Schilling, 2023](#)). Programs such as the “Carbon Farming Initiative” in Australia and pilot carbon farming projects in Africa have shown that when smallholders are supported in aggregating and

monetizing their sequestration efforts, they can benefit financially while improving soil health and resilience ([Thamo & Pannell, 2016](#)).

Furthermore, governments and financial institutions should promote public procurement of regenerative produce, green labeling, and incentives for climate-smart supply chains. Creating consistent price signals and long-term contracts can offer market stability, while tax incentives or subsidies for regenerative inputs can reduce production costs and improve farm profitability ([Springmann et al., 2018](#)).

2.6 Climatic and Soil Variability

Climatic and soil variability represent critical factors influencing the success and sustainability of carbon-negative farming systems. These variations encompass differences in temperature, precipitation, humidity, and soil properties such as texture, structure, fertility, and microbial diversity. Such heterogeneity affects carbon sequestration potential, crop productivity, and the overall resilience of agroecosystems. Understanding and managing these variabilities are essential for optimizing carbon capture, enhancing soil health, and ensuring long-term climate mitigation benefits from farming practices (Lal, 2020; [Smith et al., 2016](#)). The challenges posed by climatic and soil variability in carbon-negative farming, along with corresponding mitigation strategies, are summarized in [Table 7.3](#).

Table 7.3 Challenges and corresponding solutions related to climatic and soil variability in carbon-negative farming systems.📄

Category	Challenges	Solutions

Category	Challenges	Solutions
Climatic Variability	• Unpredictable weather patterns (droughts, floods, heat waves) • Shifting growing seasons and temperature extremes • Reduced biomass and photosynthetic rates	• Climate-resilient cropping systems (e.g., drought-tolerant cultivars, diversified rotations) • Agroforestry for climate buffering • Cover crops and mulching to conserve moisture and reduce erosion

Category	Challenges	Solutions
Soil Variability	• Differences in texture, pH, fertility, organic matter, and microbial diversity • Poor soil structure affecting carbon stabilization • Uneven moisture retention and SOC mineralization	• Organic amendments (compost, manure, biochar) to improve soil structure and microbial activity • Precision agriculture tools (sensors, remote sensing) for localized soil management

Category	Challenges	Solutions
Combined Impacts	• Inconsistent carbon sequestration outcomes across farms or regions • Difficulty in carbon accounting and scalability • One-size-fits-all policies ineffective	• Adaptive management and site-specific interventions • Modeling and decision-support tools integrating climatic and soil data • Landscape-level planning to harness variability for ecosystem-scale resilience

Challenges

Climatic variability, characterized by unpredictable weather patterns, temperature extremes, droughts, floods, and shifting growing seasons, poses significant risks to carbon-negative farming. These fluctuations can disrupt plant growth cycles, reduce biomass production, and impair soil carbon inputs, thus limiting carbon sequestration capacity ([Porter *et al.*, 2014](#)). For instance, prolonged drought stress reduces photosynthetic rates and organic residue return to soils, directly impacting soil organic carbon (SOC) dynamics ([Deng *et al.*, 2021](#)).

Soil variability adds another layer of complexity. Differences in soil texture, nutrient status, organic matter content, pH, and microbial communities can lead to inconsistent carbon sequestration outcomes across fields or regions ([Paustian *et al.*, 2016](#)). Poorly structured or degraded soils may have reduced capacity to stabilize organic carbon, thereby undermining

efforts for carbon storage ([Lal, 2004](#)). Moreover, variability in soil moisture regimes influences microbial decomposition rates and SOC mineralization, further complicating carbon management ([Schimel *et al.*, 2007](#)).

Together, climatic and soil variability increase the uncertainty of carbon accounting in farming systems and challenge the scalability of carbon-negative practices. This heterogeneity necessitates tailored management strategies rather than uniform prescriptions, complicating extension and policy support ([Smith *et al.*, 2016](#)).

Solutions

To address climatic and soil variability in carbon-negative farming, adaptive management approaches and site-specific practices are imperative. Climate-resilient cropping systems that include droughttolerant cultivars, diversified crop rotations, and agroforestry can buffer against climatic extremes and stabilize biomass inputs for carbon sequestration ([Altieri *et al.*, 2015](#)). Incorporating cover crops and mulching helps maintain soil moisture and reduce erosion, mitigating adverse climatic impacts ([Haruna & Black, \(2020\)](#)).

Improving soil health through organic amendments like compost, biochar, and manure enhances soil structure, nutrient cycling, and microbial activity, which collectively improve carbon stabilization even in variable soil conditions ([Lehmann *et al.*, 2011](#); [Schmidt *et al.*, 2011](#)). Precision agriculture tools, such as soil sensors and remote sensing, enable monitoring of soil variability and help tailor interventions to localized needs ([Gebbers & Adamchuk, 2010](#)).

Furthermore, modeling and decision-support systems that integrate climatic forecasts and soil data allow farmers and policymakers to anticipate risks and optimize carbon-negative practices accordingly ([Paustian *et al.*, 2016](#)). Promoting landscape-level planning that

incorporates diverse soil types and microclimates can enhance overall ecosystem carbon storage and resilience ([Smith *et al.*, 2016](#)).

In summary, effectively managing climatic and soil variability through adaptive, knowledge-driven practices is fundamental to realizing the full potential of carbon-negative farming. These approaches not only enhance carbon sequestration but also improve productivity, biodiversity, and system resilience under changing environmental conditions.

3 Conclusion and Way Forward

Carbon-negative farming offers a transformative approach to mitigating climate change by actively drawing down atmospheric carbon while enhancing soil health and agricultural resilience. However, the path to its widespread implementation is fraught with complex, interrelated barriers. These include high initial costs, technological and knowledge gaps, climatic and soil variability, policy and incentive barriers, limited market access, and socio-economic constraints faced particularly by smallholder and resource-poor farmers. The analysis reveals that high upfront investments in infrastructure, inputs, and capacity building act as a major deterrent to adoption. Technological limitations, such as inadequate access to precision tools, monitoring systems, and region-specific innovations, further hamper implementation. Environmental variability, including erratic weather patterns and soil degradation, challenges the consistency and scalability of carbon-sequestration practices. Moreover, policy incoherence, weak institutional support, and limited financial incentives fail to adequately support carbon-negative farming, leaving farmers without the structural backing necessary for longterm change. Lastly, poor access to premium carbon markets and sustainable value chains restricts the economic viability of such practices. Despite these challenges, targeted solutions exist. Financial mechanisms like subsidies, carbon credit access, and blended

finance models can alleviate cost burdens. Investment in farmer-centric research, digital tools, and participatory extension can close knowledge and technology gaps. Climate-resilient cropping systems, integrated nutrient management, and soil regeneration techniques are crucial for environmental adaptation. Importantly, enabling policies, supportive institutional frameworks, and result-based incentive schemes, such as Payments for Ecosystem Services (PES), can provide long-term viability and adoption incentives. Linking farmers to carbon markets, ecolabels, and regenerative value chains will enhance both profitability and sustainability.

To advance carbon-negative farming, a coordinated approach is needed that addresses financial, technical, and institutional barriers. This includes designing inclusive funding models, such as grants, microcredit, and result-based carbon financing, for smallholders, and strengthening research-extensionfarmer linkages to promote location-specific innovations. Developing climate-smart agronomic practices tailored to local soil and climate conditions, alongside enabling policies that embed carbon farming within national climate and rural agendas, is crucial. Transparent and farmer-accessible carbon markets supported by digital MRV systems will ensure accountability and financial returns. Additionally, promoting cooperative models, agroecological education, and institutional support will empower farmers as active contributors to climate solutions. Together, these actions can transform carbon-negative farming from concept to reality, enhancing both environmental sustainability and rural livelihoods.

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Chapter - 8

The Future of Carbon-Negative Farming

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1 Introduction

Carbon-negative farming represents a transformative approach to agriculture that seeks to reverse the traditional paradigm of farming as a source of greenhouse gas emissions. Instead, it aims to turn agriculture into a net sink of atmospheric carbon dioxide (CO₂) by adopting practices that actively remove and store more carbon than they emit. These practices not only mitigate climate change but also enhance ecosystem services, improve soil health, and build resilient food systems. As climate change accelerates, with agriculture contributing roughly 23% of total anthropogenic greenhouse gas emissions through activities such as deforestation, soil degradation, livestock rearing, and excessive use of synthetic fertilizers ([IPCC, 2019](#)), the need to reimagine agriculture through a carbon-negative lens becomes increasingly urgent.

Carbon-negative farming includes a diverse suite of strategies such as conservation tillage, cover cropping, agroforestry, organic amendments like compost and biochar, and integrated crop-livestock systems that enrich soil organic carbon (SOC) while reducing emissions. These regenerative and climatesmart practices not only contribute to climate mitigation but also improve productivity, biodiversity, and water retention capacities of soils ([Lal, 2020](#); [Paustian *et al.*, 2016](#)). With growing international commitments to achieve net-zero emissions, particularly under the Paris Agreement, carbon-negative farming is now recognized as a crucial component of global climate action (Smith *et al.*, 2020).

However, modern agriculture faces significant challenges. Although it has achieved remarkable increases in food production over the past century, it has also become a major driver of environmental degradation. Unsustainable land management practices, excessive dependence on synthetic inputs, monoculture cropping systems, and large-scale land use changes have led to declining soil fertility, water scarcity, and biodiversity loss ([FAO, 2017](#)). At the same time, agriculture remains one of the sectors most vulnerable to the impacts of climate change. Increasingly frequent extreme weather events, such as droughts, floods, heatwaves, and pest outbreaks, are already threatening crop yields and jeopardizing the livelihoods of millions of farmers, especially in climate-sensitive regions like South Asia and Sub-Saharan Africa ([Wheeler & von Braun, 2013](#)).

The current trajectory of global food systems, if left unchecked, is incompatible with both environmental sustainability and global climate targets. Studies show that even if fossil fuel emissions are reduced significantly, the agricultural sector alone could consume up to 70% of the remaining carbon budget required to limit global warming to 1.5°C ([World Resources Institute, 2019](#)). This stark reality underscores the need for a fundamental shift in agricultural policy and practice one that prioritizes carbon sequestration, emission reduction, and ecological regeneration as integral components of food production.

Adopting a future-oriented approach is therefore critical. This involves moving beyond short-term, input-intensive solutions toward long-term, systems-based transformations. A forward-looking strategy in agriculture integrates innovative technologies, regenerative principles, and inclusive governance to build resilient, low-carbon, and equitable food systems. Carbon-negative farming offers a pathway toward this transformation by

addressing multiple global challenges simultaneously, climate change, land degradation, food insecurity, and rural poverty (Rockstrom *et al.*, 2017).

Moreover, the future of agriculture must be guided by intergenerational responsibility. The decisions made today regarding land use, soil management, and resource efficiency will determine whether future generations inherit a livable planet. As the Food and Land Use Coalition aptly states, “The next revolution in agriculture must be regenerative, inclusive, and climate-smart, transforming farms into carbon sinks and centers of ecological regeneration” ([FOLU, 2019](#)). Embracing this vision is not merely an option but an imperative in the face of escalating climate threats and shrinking natural resources.

2 Evolution of Carbon-Negative Agricultural Practices

The concept of carbon-negative farming, while emerging as a modern climate solution, is deeply rooted in historical agricultural paradigms. Traditional farming systems across civilizations were inherently regenerative, relying on crop rotations, composting, mixed farming, and diversified agroecosystems that maintained soil fertility and sequestered carbon in biomass and soil. The rise of industrial agriculture in the 20th century, characterized by monocultures, heavy tillage, and synthetic inputs, disrupted this balance, contributing to widespread soil degradation and greenhouse gas emissions. In response, the organic farming movement emerged in the mid-20th century, emphasizing natural nutrient cycles, minimal chemical input, and soil health ([Lampkin, 2002](#)). This laid the foundation for regenerative agriculture, which builds upon organic principles but places a stronger emphasis on actively restoring soil carbon stocks, enhancing biodiversity, and increasing system resilience. More recently, climate-smart agriculture (CSA) has integrated these ecological principles with technological innovation to develop practices that increase

productivity, enhance resilience to climate change, and reduce emissions ([FAO, 2013](#)). As [Smith *et al.* \(2020\)](#) assert, “climate-smart and regenerative approaches offer the potential to simultaneously mitigate climate change, support food security, and restore degraded ecosystems.”

Equally significant is the wealth of ecological knowledge embedded in indigenous and traditional farming systems, many of which were inherently low-carbon and sustainable. These systems practiced for centuries by communities in Asia, Africa, and the Americas employed techniques such as agroforestry, intercropping, mulching, seasonal fallowing, and integrated livestock management that preserved soil carbon and biodiversity. For example, India’s Zabo system in Nagaland and the Barahnaja (twelve-grain) system in the Himalayan region are time-tested models of carbon-efficient polycultures (Altieri & Nicholls, 2004). Such practices exemplify what [Pretty *et al.* \(2011\)](#) refer to as “resource-conserving agriculture”, which harnesses local ecological processes and knowledge while minimizing external inputs. These indigenous systems provide valuable insights for designing context-specific, low-input, and carbon-negative farming solutions in the face of climate uncertainty. As the IPCC (2019) acknowledges, “the inclusion of traditional knowledge and practices is essential for the success of climate-resilient land management.”

3 Technological and Biological Innovations

The future of carbon-negative farming is being shaped by rapid advances in both **technology and biological sciences**, offering unprecedented tools to measure, manage, and mitigate agricultural emissions while improving productivity and sustainability. These innovations support real-time decision-making, precise input use, enhanced carbon sequestration, and ecosystem restoration, key components in the shift from conventional to regenerative agriculture. As farming systems become more complex and

climate risks intensify, **data-driven, bio-enhanced, and controlled-environment technologies** provide critical leverage points for reducing emissions and drawing down atmospheric carbon dioxide (CO₂).

As such, the following technological and biological tools form the foundation for next-generation carbon-negative farming systems:

1. Precision agriculture, AI, and IoT for decision-making and carbon monitoring
2. Remote sensing, drones, and big data platforms
3. Bio-based innovations: microbial inoculants, carbon-sequestering crops, and soil biotechnologies
4. Advanced amendments: biochar, compost, enhanced weathering
5. Controlled-environment agriculture and net-negative food production systems

3.1 Precision agriculture, AI, and IoT for decision-making and carbon monitoring

Precision agriculture employs GPS-enabled equipment, sensors, and analytics to apply water, fertilizers, and pesticides only where needed, reducing overuse and minimizing emissions. When combined with **artificial intelligence (AI)** and the **Internet of Things (IoT)**, these systems can predict soil conditions, monitor crop health, and calculate the **carbon footprint** of individual farming practices in real-time. According to [Wolfert et al. \(2017\)](#), “smart farming technologies provide the ability to control field variability and optimize resource efficiency,” which is essential for reducing emissions and increasing carbon-use efficiency. AI-integrated carbon dashboards and digital carbon farming tools are also enabling farmers to **track carbon sequestration progress**, automate compliance

with carbon credit protocols, and improve transparency in carbon reporting ([AgroCares, 2023](#); [van der Voort *et al.*, 2023](#)).

3.2 Remote sensing, drones, and big data platforms

Remote sensing through satellites and drones allows for landscape-scale carbon assessment, vegetation indexing, and early detection of stress conditions. These tools are now widely used for mapping soil organic carbon, biomass estimation, and verifying carbon offsets. High-resolution imagery combined with machine learning algorithms helps estimate carbon fluxes, identify carbon-rich zones, and support monitoring, reporting, and verification (MRV) protocols for carbon farming initiatives. [Li *et al.* \(2023\)](#) note that “remote sensing enables cost-effective and scalable approaches for evaluating ecosystem carbon dynamics,” especially in large or remote agricultural landscapes. Integrated with big data analytics, this spatial information is now being used by governments and private firms to build carbon registries and incentive platforms.

3.3 Bio-based innovations: microbial inoculants, carbon-sequestering crops, and soil biotechnologies

Carbon-rich amendments like biochar and compost are widely recognized for their role in long-term carbon storage and soil fertility improvement. Biochar, a stable form of carbon produced through pyrolysis, can sequester carbon for hundreds to thousands of years while improving nutrient retention and water holding capacity ([Lehmann & Joseph, 2015](#)). Compost not only provides organic matter but also supports microbial activity and nutrient cycling. Meanwhile, enhanced weathering the application of finely ground silicate rocks to soils offers a novel approach to capture CO₂ through mineral carbonation while replenishing soil nutrients ([Beerling *et*](#)

[al., 2020](#)). These amendments collectively offer co-benefits for climate mitigation, crop yield, and soil regeneration.

3.4 Advanced amendments: biochar, compost, enhanced weathering

Carbon-rich amendments like **biochar and compost** are widely recognized for their role in **long-term carbon storage and soil fertility improvement**. Biochar, a stable form of carbon produced through pyrolysis, can sequester carbon for hundreds to thousands of years while improving nutrient retention and water holding capacity ([Lehmann & Joseph, 2015](#)). Compost not only provides organic matter but also supports microbial activity and nutrient cycling. Meanwhile, enhanced weathering the application of finely ground silicate rocks to soils - offers a novel approach to capture CO₂ through mineral carbonation while replenishing soil nutrients ([Beerling *et al.*, 2020](#)). These amendments collectively offer co-benefits for climate mitigation, crop yield, and soil regeneration.

3.5 Controlled-environment agriculture and net-negative food production systems

Controlled-environment agriculture, including vertical farming, hydroponics, aquaponics, and closedloop greenhouses, represents a growing sector of climate-smart food production with potential to achieve net-negative emissions. By using renewable energy, water recycling, and zero-emission technologies, CEA systems can drastically reduce the carbon footprint of food production while enabling year-round yields. Some advanced CEA models also integrate carbon capture and utilization (CCU) systems to remove CO₂ from indoor environments and repurpose it for algal biomass or other uses ([Benke & Tomkins, 2017](#)). While the initial energy investment may be high, the shift toward solar-powered and modular units

is rapidly increasing their sustainability profile. As noted by [Beacham *et al.* \(2019\)](#), “future food systems based on CEA can become integral to climate mitigation if designed with carbon-negative principles in mind.”

4 Integration with Renewable Energy and Circular Bioeconomy

The future of carbon-negative farming hinges not only on regenerative agricultural practices and biological innovations but also on the integration of clean energy systems and circular economy principles. Conventional agriculture is heavily reliant on fossil fuels for irrigation, mechanization, processing, and transportation - contributing significantly to greenhouse gas emissions. Moreover, linear resource flows in current agri-food systems, from input use to waste disposal, result in inefficiencies, nutrient losses, and environmental degradation. By contrast, decarbonized, circular agri-systems aim to minimize external inputs, eliminate waste, and close energy and nutrient loops, aligning agriculture with planetary boundaries.

Integrating **renewable energy sources** and developing **circular bioeconomies** in agriculture not only reduces emissions but also enhances energy independence, resource efficiency, and system resilience. The following subsections explore the core components of this integration:

1. Solar, wind, and bioenergy in farming operations
2. Circular systems: nutrient loops, waste valorization, and biorefineries
3. Development of low-emission, carbon-negative agri-value chains

4.1 Solar, wind, and bioenergy in farming operations

The use of solar panels, wind turbines, and bioenergy systems in farming has expanded rapidly, offering farmers clean alternatives to diesel and grid

electricity. Solar energy powers irrigation pumps, greenhouse heating, drying units, and cold storage, drastically lowering operational emissions. For instance, solar-powered drip irrigation in India and Sub-Saharan Africa has enhanced both energy access and carbon efficiency in smallholder systems ([Burney *et al.*, 2010](#)). Similarly, wind energy is increasingly used in highland farms to supplement energy needs for grain milling and water pumping.

In addition to solar and wind, bioenergy derived from crop residues, animal waste, and organic biomass can be converted into biogas or bioethanol. These biofuels not only serve as on-farm energy sources but also reduce methane emissions from unmanaged manure. According to [Wieruszewski & Mydlarz, 2022](#)), “agricultural biogas systems offer significant climate mitigation potential, especially when integrated with nutrient recycling and organic waste treatment.” Such systems support energy self-sufficiency while contributing to circularity in carbon flows.

4.2 Circular systems: nutrient loops, waste valorization, and biorefineries

In a circular bioeconomy, waste is not discarded but repurposed as a valuable resource. Agricultural residues, food waste, and livestock manure can be transformed into organic fertilizers, compost, or feedstock for biorefineries, thus closing nutrient and energy loops. Nutrient circularity reduces dependency on synthetic fertilizers, which are energy-intensive to produce and major contributors to nitrous oxide emissions.

Innovative systems such as anaerobic digestion, vermicomposting, and black soldier fly bioconversion are being employed to convert organic waste into high-value products, including biofertilizers and protein-rich animal feed. In the European Union and elsewhere, integrated biorefineries are emerging that co-produce bioenergy, bio-based chemicals, and soil

amendments from agricultural biomass ([Oxfam International et al., 2015](#); [Kourmentza et al., 2020](#)). These models contribute to multi-functional carbon-negative farming, where waste streams are reintegrated to enhance farm productivity, reduce emissions, and create new economic opportunities. By reimagining waste as a resource, circular farming systems not only reduce environmental impact but also add value to the farm economy ([FAO, 2018](#)).

4.3 Development of low-emission, carbon-negative agri-value chains

Achieving carbon-negative outcomes requires interventions beyond the farm gate. This includes the decarbonization of supply chains, transport, storage, packaging, and processing, through renewable energy, climate-friendly logistics, and eco-design. Lifecycle assessments reveal that post-harvest stages can account for up to 30-50% of food system emissions, depending on the commodity and context ([Poore & Nemecek, 2018](#)). Thus, greening the entire value chain is critical.

Initiatives such as low-carbon food labeling, carbon farming certification, and blockchain-based traceability are helping align markets with climate goals. Furthermore, companies are exploring carbon insetting, offsetting emissions within their own supply chains, by supporting carbon sequestration practices among their supplier farmers ([Giles, 2025](#)). Developing these climate-aligned value chains not only helps meet emissions targets but also enhances market access and brand value for producers practicing regenerative agriculture. Sustainable value chains are not only essential for climate goals but also a pathway for inclusive and profitable rural development ([WBCSD, 2021](#); [Galvez, 2022](#)).

5 Carbon Accounting, Markets, and Incentives

As agriculture becomes central to climate mitigation efforts, credible carbon accounting and market-based incentives are essential to scale carbon-negative farming. Accurate quantification of soil carbon sequestration and greenhouse gas (GHG) reductions is critical for validating environmental benefits, enabling carbon trading, and accessing climate finance. This demands robust, transparent, and scalable Monitoring, Reporting, and Verification (MRV) systems to track on-farm carbon performance.

Traditional carbon measurement approaches were costly, manual, and time-consuming, limiting smallholder participation in carbon markets. However, technological advances in digital MRV and remote sensing, coupled with emerging carbon standards and blockchain-enabled platforms, are revolutionizing how soil carbon and emissions are tracked and monetized. The following subsections explore these developments in detail:

1. Advances in carbon monitoring, reporting, and verification (MRV)
2. Digital MRV and blockchain-enabled transparency
3. Carbon credit standards (Verra, Gold Standard, FAO's EX-ACT)
4. Access to carbon finance and emerging carbon credit markets

5.1 Advances in carbon monitoring, reporting, and verification (MRV)

Carbon MRV involves the systematic measurement and documentation of carbon fluxes and stocks to ensure transparency, credibility, and traceability. New approaches leverage satellite imagery, modeling algorithms, machine learning, and soil sensors to estimate changes in carbon stocks with greater precision and reduced costs ([Bossio *et al.*, 2020](#)). These systems can differentiate between carbon removals and emissions from various land-use and management practices across temporal and spatial scales.

For example, the Cool Farm Tool, COMET-Farm (USDA), and FAO's EX-ACT Tool provide farm-level estimations of carbon footprints using region-specific emission factors and crop management data ([Bernoux *et al.*, 2010](#)). Such tools are gaining traction in MRV frameworks, especially for large-scale soil carbon projects under voluntary and compliance markets. "MRV systems that are scientifically robust and practically feasible are vital for scaling climate-smart land use" (Smith *et al.*, 2020).

5.2 Digital MRV and blockchain-enabled transparency

Digital MRV platforms use cloud-based data collection, artificial intelligence, and geospatial analytics to enable real-time, low-cost carbon tracking for farmers. These systems automate the integration of satellite imagery, weather data, soil health indicators, and farm records into dynamic models of carbon sequestration. For instance, platforms like OpenTEAM, Agrible, and CIBO provide scalable solutions for remote MRV of regenerative practices.

Complementing this, blockchain technology is being deployed to enhance data integrity, traceability, and trust in carbon markets. Blockchain-based registries store tamper-proof carbon credit data, ensuring the legitimacy of credits and avoiding double counting. According to [Merlo *et al.*, \(2025\)](#), blockchain can increase transparency and accountability in decentralized carbon credit systems. These innovations reduce transaction costs and enable even smallholder farmers to participate in global carbon finance mechanisms.

5.3 Carbon credit standards (Verra, Gold Standard, FAO's EX-ACT)

A variety of carbon credit certification standards guide how soil carbon and emission reduction projects are validated and monetized. Each uses specific

methodologies for baseline estimation, additionality, leakage, and permanence.

Verra's Verified Carbon Standard (VCS) includes methodologies for agricultural soil carbon, agroforestry, and improved grazing practices.

The **Gold Standard** emphasizes sustainable development co-benefits along with carbon sequestration, promoting projects with social, economic, and environmental gains.

FAO's **EX-ACT tool** (Ex-Ante Carbon-balance Tool) supports pre-assessment of GHG impacts of land-use projects and is often used in international development settings ([Bernoux et al., 2010](#)).

Verra's Verified Carbon Standard (VCS) provides standardized methodologies which set detailed procedures for quantifying greenhouse gas reductions or removals, ensuring transparency, technical rigor, baseline definition, additionality, monitoring, and independent verification. These frameworks help generate Verified Carbon Units (VCUs) which can be traded in voluntary or regulated markets, thereby improving confidence in carbon credit projects including soil carbon initiatives ([Verra. \(2023; Pudasaini et al., 2024\)](#)).

5.4 Access to carbon finance and emerging carbon credit markets

Accessing **carbon finance** can incentivize farmers to adopt climate-positive practices. Carbon credit revenues can offset initial costs of regenerative inputs, monitoring, and certification. New initiatives such as the LEAF Coalition, Nori, and Soil Carbon Initiative aim to link farmers with buyers willing to pay for verified sequestration outcomes.

Voluntary carbon markets are growing rapidly, valued at over \$2 billion in 2023, driven by corporate net-zero commitments and ESG (Environmental, Social, Governance) mandates ([Ecosystem Marketplace,](#)

[2023](#)). Programs such as Indigo Ag and Regen Network have launched farmer-friendly carbon platforms, where producers earn credits by sequestering carbon through cover cropping, reduced tillage, or organic amendments. Incentivizing climate-smart farming through market-based mechanisms can accelerate the transition to sustainable agri-food systems” ([Smith *et al.*, 2020](#)).

However, challenges remain in ensuring equity, accessibility, and permanence, particularly for smallholders in the Global South. Blended finance, public-private partnerships, and capacity-building are critical to overcome these barriers and ensure inclusive participation in carbon markets.

6 Policy Frameworks and Governance

The transition to carbon-negative farming requires more than just innovation at the farm level it demands robust, multi-level governance frameworks that create enabling environments for sustainable transformation. Without supportive policies, financial incentives, and institutional coherence, carbon-sequestering practices will remain fragmented and underutilized. Governments, multilateral bodies, and regional alliances play a central role in shaping and accelerating the deployment of carbon-negative agriculture through targeted legislation, investment mechanisms, and global agreements.

This section explores how national and international policy roadmaps, regulatory support, and climate agreements are aligning agriculture with climate goals, and what further steps are needed for wide-scale adoption of carbon-negative practices.

1. National and global policy roadmaps to support carbon-negative agriculture

2. Regulatory mechanisms, subsidies, and climate-smart incentives
3. Integration into Nationally Determined Contributions (NDCs) and food-climate policies

6.1 National and global policy roadmaps to support carbon-negative agriculture

Policy roadmaps and national strategies are crucial in steering agricultural systems toward climate neutrality and beyond. Several countries have begun embedding carbon farming into their agricultural policies. For instance, the European Union's Common Agricultural Policy (CAP) now includes an "eco-schemes" mechanism, which incentivizes practices such as cover cropping, agroforestry, and organic farming to enhance soil carbon sequestration ([European Commission, 2021](#)). Similarly, Australia's Emissions Reduction Fund allows farmers to earn credits for carbon farming, while India's National Mission for Sustainable Agriculture (NMSA) includes soil health management and water-use efficiency as core components for sustainable intensification.

At the global level, frameworks such as the Koronivia Joint Work on Agriculture under the UNFCCC recognize the potential of agriculture to contribute to both mitigation and adaptation. Yet, many national action plans still lack concrete pathways for soil carbon accounting and regenerative transitions. "Policy must actively support ecosystem-based mitigation strategies in agriculture to align with net-zero goals" ([Smith *et al.*, 2020](#)).

6.2 Regulatory mechanisms, subsidies, and climate-smart incentives

Direct policy instruments, such as subsidies, tax credits, carbon pricing, and green procurement, can drive behavioral change among producers. For

example, California's Healthy Soils Program offers cost-sharing to farmers for implementing composting, cover cropping, and reduced tillage, thereby supporting measurable increases in soil carbon ([CDFA, 2022](#)). Similarly, Brazil's Low Carbon Agriculture Plan (ABC Program) provides concessional loans to support climate-smart technologies like integrated crop-livestock systems and bio-inputs. In many countries, however, current subsidies still favor high-emission inputs like synthetic nitrogen fertilizers and fossil-fuel-based irrigation, which counteract carbon-negative efforts. Aligning subsidies with ecological outcomes is critical.

“Shifting from perverse subsidies to positive incentives for regenerative practices is a key policy challenge” ([OECD, 2019](#)). Moreover, carbon pricing systems whether in the form of carbon taxes or emissions trading schemes can further enhance the competitiveness of carbon-negative farming if agriculture is appropriately included in their scope.

6.3 Integration into Nationally Determined Contributions (NDCs) and food-climate policies

Nationally Determined Contributions (NDCs) under the Paris Agreement represent each country's commitment to reduce greenhouse gas emissions and adapt to climate change. While many NDCs mention agriculture, only a fraction explicitly reference soil carbon or carbon sequestration practices ([FAO, 2021](#)). Increasing the visibility of carbon-negative farming in NDCs could unlock international finance and technical support for climate-smart agriculture.

Some promising examples include New Zealand's Climate Change Response (Zero Carbon) Amendment Act, which incorporates emissions targets for biological methane and sets frameworks for land-sector mitigation. Likewise, Rwanda's NDC integrates agroecology and afforestation programs to sequester carbon while enhancing resilience.

Food systems governance is also evolving. The UN Food Systems Summit (2021a&b) called for aligning food policy with climate goals by fostering agroecological transitions, reducing food waste, and supporting smallholders. Integrating agriculture more fully into climate dialogues such as at COP summits will be essential to elevate carbon-negative farming on the global stage. “A stronger linkage between food systems and climate policy is needed to ensure sustainable, low-emission agriculture” ([Tubiello et al., 2021](#)).

7 Capacity Building and Knowledge Systems

The long-term success of carbon-negative farming hinges not only on technology and policy but also on the capacity of farmers, institutions, and society to understand, adapt, and innovate. Bridging knowledge gaps and strengthening human capital are essential to ensure the uptake of carbon-sequestering practices at scale. Farmers, especially smallholders, often lack access to reliable climate information, soil management knowledge, and market signals related to carbon. Meanwhile, extension systems, research institutions, and civil society organizations play a pivotal role in knowledge co-creation and dissemination. Building a responsive and inclusive knowledge ecosystem is therefore fundamental to empowering stakeholders, fostering behavioral change, and anchoring sustainable transitions.

1. Farmer education and carbon literacy
2. Role of extension, NGOs, cooperatives, and youth
3. Institutional frameworks for training, research, and knowledge exchange

7.1 Farmer education and carbon literacy

Carbon literacy among farmers is a foundational requirement for implementing regenerative and climate-positive practices. Carbon literacy refers to the understanding of how farming activities influence greenhouse gas emissions and soil carbon dynamics, along with the ability to act accordingly ([Yata et al., 2023](#)). Through participatory education models, farmers can learn how to integrate biochar, cover crops, reduced tillage, composting, and agroforestry into their systems.

Programs such as Farmer Field Schools (FFS) and Climate-Smart Agriculture Training Modules, developed by FAO and partners, have demonstrated success in enhancing climate literacy and adaptive capacity ([FAO, 2017](#)). In India, initiatives under the National Innovations in Climate Resilient Agriculture (NICRA) program by ICAR have trained thousands of farmers on carbon farming, drought mitigation, and weather-based advisories. Equipping farmers with the tools to understand carbon dynamics is critical for landscape-scale transformation” ([Wollenberg et al., 2016](#)).

7.2 Role of extension, NGOs, cooperatives, and youth

The transformation toward carbon-negative systems is a collective endeavor requiring robust extension services, active participation of civil society, and the engagement of youth and producer cooperatives. Traditional extension services, however, often remain under-resourced and focused on productivity rather than sustainability goals. A paradigm shift toward climate-smart extension is needed, one that integrates carbon metrics, environmental monitoring, and socio-ecological resilience. NGOs and farmer cooperatives are also emerging as critical intermediaries. Organizations like BAIF Development Research Foundation and Sustainable Agriculture Network (SAN) have demonstrated success in promoting low-emission practices and carbon accounting through farmer groups and community-managed resource centers ([BAIF, 2020](#)).

The engagement of local organizations and youth movements can accelerate the cultural shift towards carbon-negative agriculture” ([IPES-Food, 2021](#)). Youth-led agritech startups are increasingly contributing to the transformation through innovations in carbon monitoring, regenerative inputs, and value chain traceability. Incubation platforms such as NAARM’s a-IDEA and TNAU’s ABI are supporting young entrepreneurs working on climate-friendly agri-solutions.

7.3 Institutional frameworks for training, research, and knowledge exchange

Institutional capacity building is key to mainstreaming carbon-negative practices through research, curricula, and knowledge exchange platforms. Agricultural universities, technical institutions, and research councils must reorient their focus from input-intensive agriculture to systems that promote carbon sequestration, circularity, and ecosystem services. For example, the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS) has developed global training modules on climate-smart agriculture that integrate carbon metrics ([CCAFS, 2019](#)). National Agricultural Research Systems (NARS), including institutions under ICAR, are gradually incorporating regenerative farming into their research agenda.

Inter-institutional collaboration and international knowledge hubs, such as the 4 per 1000 Initiative and GACSA (Global Alliance for Climate-Smart Agriculture), provide platforms for cross-border learning, data sharing, and collaborative research. “Institutional innovation must match technological innovation to enable a just and effective agro-ecological transition” ([Garnett *et al.*, 2015](#)).

8 Scaling and Agro-ecological Adaptation

Scaling up agro-ecological practices is essential for achieving sustainable and carbon-negative agricultural systems at regional and national levels. Agro-ecological adaptation involves tailoring farming approaches to the specific biophysical, cultural, and socio-economic contexts of a region, ensuring that ecological sustainability is maintained while improving productivity and resilience. A major challenge lies in translating successful local innovations into broader policies and programs without losing their context-specific relevance and efficacy. This calls for climate-smart scaling strategies that integrate traditional knowledge, scientific research, and inclusive development models (Gliessman, 2015; [Anderson et al., 2020](#)).

As climate variability and land degradation intensify, it becomes crucial to develop location-specific strategies, supported by regional models and case studies, and to ensure the participation of marginalized and climate-vulnerable communities. These three aspects form the cornerstone of a robust framework for agro-ecological scaling and adaptation. The following sub-sections provide insights into three essential pillars for effectively scaling agro-ecological interventions:

1. Regional models and replicable case studies
2. Climate- and soil-specific adaptation strategies
3. Inclusion of marginalized and climate-vulnerable communities

8.1 Regional models and replicable case studies

Scaling agroecological farming practices requires strong evidence from real-world applications. Regional models and replicable case studies act as powerful tools for building farmer confidence, guiding policy, and demonstrating the socio-economic and environmental benefits of agroecology. These models integrate landscape-level assessments, local cropping systems, and community-based resource management strategies.

For instance, the System of Rice Intensification (SRI), initially developed in Madagascar, has been adapted and scaled in India, Southeast Asia, and Africa with modifications suited to regional conditions (Uphoff, 2007). Similarly, the Push-Pull technology developed by the International Centre of Insect Physiology and Ecology (ICIPE) in East Africa has been scaled successfully through participatory approaches, benefiting over 150,000 smallholder farmers ([Khan *et al.*, 2016](#)). Such case studies help identify enabling conditions like supportive policies, extension services, and local leadership that can guide replication in similar agroecological zones.

8.2 Climate- and soil-specific adaptation strategies

Agroecological adaptation must be rooted in local biophysical realities. Diverse agroecosystems demand flexible strategies tailored to specific climatic zones, soil types, and resource availability. These strategies include:

- **Use of stress-tolerant crop varieties** adapted to local conditions (e.g., drought-resistant millets or saline-tolerant rice).
- **Conservation agriculture practices** such as minimum tillage and mulching to retain soil moisture and improve carbon sequestration in drylands ([Thierfelder *et al.*, 2017](#)).
- **Agroforestry systems** that provide shade, reduce wind erosion, enhance microclimates, and improve soil fertility.
- **Biofertilizers and microbial amendments** that enhance nutrient cycling and soil health under varying pH and organic matter conditions.

Such context-driven interventions are essential for climate resilience and must be backed by soil mapping, weather forecasting, and farmer-led

experimentation ([Altieri & Nicholls, 2017](#)).

8.3 Inclusion of marginalized and climate-vulnerable communities

Climate-resilient agricultural transitions must be inclusive to be effective and just. Marginalized communities, including smallholder farmers, indigenous peoples, women, and landless laborers, are often the most vulnerable to climate change yet possess valuable traditional knowledge and adaptive capacity. Agroecological scaling must ensure:

- **Equitable access to resources** (land, seeds, credit, and training).
- **Participatory planning processes** that involve these communities in co-designing adaptation strategies.
- **Support for indigenous farming knowledge**, which often aligns with sustainable and regenerative principles.
- **Capacity building for women and youth**, as they are key agents of change in rural settings ([FAO, 2019](#)).

Projects like India's National Rural Livelihoods Mission (NRLM) and Andhra Pradesh's Community Managed Natural Farming (CMNF) initiative have demonstrated the potential of collective action and decentralized governance in enabling inclusive transitions to agroecology ([Pretty *et al.*, 2018](#)).

9 Market Development and Consumer Engagement

The success of carbon-negative and climate-resilient farming hinges not only on production-level innovations but also on the development of enabling markets and active consumer participation. Market development ensures that sustainably produced goods gain visibility and value, while consumer engagement drives demand for environmentally responsible

choices. As the global food system accounts for over 30% of greenhouse gas emissions, empowering consumers and incentivizing market actors to support low-carbon agricultural products is a critical step toward climate mitigation ([Springmann *et al.*, 2018](#)).

Emerging market mechanisms, such as eco-labeling, carbon certification, and climate-positive branding, have begun to shift both production and consumption patterns. In tandem, public-private partnerships (PPPs) and private sector innovation play an important role in value chain development, consumer education, and upscaling climate-resilient products. Together, these strategies form a cohesive framework for market transformation that rewards sustainability and supports smallholder transitions to carbon-negative agriculture. To operationalize a carbon-negative food system, it is essential to create an ecosystem that values sustainable products, raises consumer consciousness, and leverages collaboration across public and private sectors. The following sub-sections elaborate on key components of this transformation.

1. Promoting climate-positive labels and certified carbon-neutral produce
2. Enhancing consumer awareness and sustainable food choices
3. Leveraging private sector and public-private partnerships (PPPs)

9.1 Promoting climate-positive labels and certified carbon-neutral produce

Eco-labels and certification schemes serve as key instruments to communicate the climate performance of agricultural products to consumers and markets. Labels such as “carbon-neutral,” “climate-positive,” or “regeneratively farmed” not only incentivize farmers to adopt low-emission practices but also offer premium pricing opportunities.

For example, the “Climate Neutral Certified” label, managed by Climate Neutral (a non-profit), requires companies to measure, reduce, and offset *all* greenhouse gas emissions associated with their products ([Dering 2019](#)). Similarly, programs like FairCarbon and Regen Network offer blockchain-backed verification of soil carbon sequestration and ecological regeneration.

Such initiatives provide traceability, enhance market confidence, and can be integrated into broader climate accounting frameworks ([Wiesmeier et al., 2020](#)). However, challenges remain in standardizing metrics, ensuring transparency, and minimizing greenwashing, which calls for robust verification and third-party monitoring (Barbato and & Strong, 2023).

9.2 Enhancing consumer awareness and sustainable food choices

Consumer preferences are powerful levers for sustainability. Educating consumers about the environmental footprints of food and promoting behavior change toward low-carbon diets is essential for building resilient food systems. This includes reducing food waste, opting for seasonal and local produce, and supporting climate-smart products. Studies show that carbon labeling on food items can influence purchasing decisions and reduce the overall carbon footprint of diets ([Vanclay et al., 2011](#)). Public awareness campaigns, school-based nutrition education, and digital platforms (e.g., food carbon footprint calculators) are effective tools to encourage informed choices.

Additionally, social media and influencer-driven advocacy are emerging as key channels for building momentum around climate-conscious food behaviors ([Coman et al., 2025](#)). For long-term impact, such efforts must be inclusive, culturally relevant, and supported by clear messaging backed by science.

9.3 Leveraging private sector and public-private partnerships (PPPs)

Private sector actors, including agribusinesses, retailers, food brands, and logistics firms, have significant influence over agricultural value chains and can accelerate the adoption of carbon-negative practices. When aligned with public sector goals, public–private partnerships (PPPs) can mobilize capital, drive innovation, and ensure last-mile connectivity for smallholder farmers. For instance, Unilever’s Sustainable Agriculture Code supports regenerative sourcing from farmers worldwide, while PepsiCo and Danone are investing in soil health initiatives to reduce Scope 3 emissions ([PepsiCo, 2023](#)). In India, the Paramparagat Krishi Vikas Yojana (PKVY) and Bioeconomy PPPs are examples of how policy-led partnerships can boost organic and agroecological markets.

PPPs can also support infrastructure for certification, supply chain traceability, rural entrepreneurship, and digital marketplaces. However, successful PPPs require transparent governance, risk-sharing mechanisms, and alignment of commercial interests with environmental outcomes ([FAO, 2021](#)).

10 Risk Management and Ethical Considerations

While carbon-negative and climate-resilient farming offer promising solutions to mitigate climate change and restore degraded ecosystems, they also bring a set of ethical and operational risks that must be acknowledged and addressed. As new technologies, carbon markets, and sustainability standards proliferate, there is a growing concern over the potential misuse, inequitable access, and unintended consequences associated with such interventions.

Critical questions arise around land ownership, carbon rights, corporate accountability, and power asymmetries, especially in the Global South.

Moreover, without careful governance, there is a risk that climate-smart agriculture becomes a tool for elite accumulation, marginalizing smallholders and indigenous communities. Therefore, ethical frameworks and risk management strategies must be integral to any carbon-negative farming agenda ([Schroeder & McDermott, 2014](#); [Dooley & Kartha, 2018](#)). These concerns necessitate a closer look at key ethical and operational risks inherent in the transition.

1. Risks of technological overdependence and land competition
2. Ensuring equity, transparency, and integrity in carbon claims
3. Preventing greenwashing and ensuring genuine impact

10.1 Risks of technological overdependence and land competition

The drive for carbon sequestration and yield optimization often leads to a strong reliance on digital tools, precision farming, biotechnology, and large-scale agroforestry plantations. While such technologies can improve efficiency, they may exclude smallholders due to high costs, lack of infrastructure, or limited digital literacy ([FAO, 2021](#)).

Moreover, large-scale afforestation or carbon farming projects risk triggering land grabs and displacement especially in regions with weak land tenure systems. Programs incentivized by carbon credits may prioritize tree planting or biomass over food security, threatening smallholder livelihoods and local ecosystems ([Baka, 2013](#); [Parsons, 2024](#)). A balance must be struck between innovation and inclusion, ensuring that technological adoption is context-sensitive, participatory, and culturally appropriate.

10.2 Ensuring equity, transparency, and integrity in carbon claims

Carbon offset markets have become central to climate action, yet they remain fragmented and poorly regulated, often lacking uniform methodologies and verification protocols. This can lead to opaque carbon claims, where corporations or countries declare emissions reductions that are either exaggerated, untraceable, or based on flawed accounting ([Schneider & La Hoz Theuer, 2019](#)). Ensuring equity and transparency requires:

- **Robust MRV (Monitoring, Reporting, and Verification)** systems.
- **Participatory carbon accounting** involving farmers and local communities.
- Clear **benefit-sharing arrangements**, especially where communal land and labor contribute to carbon sequestration.

Frameworks like the Voluntary Carbon Market Integrity Initiative (VCMI) and Article 6 of the Paris Agreement aim to bring greater transparency and accountability to carbon trading and claims ([CMI, 2024](#); [UNFCCC, 2021b](#)).

10.3 Preventing greenwashing and ensuring genuine impact

As climate narratives gain traction in business and marketing, there is a growing trend of greenwashing where entities overstate or falsely claim environmental benefits to enhance brand image or investor appeal. In agriculture, this may include vague claims of “climate-smart” or “regenerative” practices without measurable impacts or independent verification ([Hickel & Kallis, 2020](#)). To prevent greenwashing and promote genuine transformation, it is essential to:

- Require **science-based targets** and impact assessments.

- Promote **third-party certification and open data platforms**.
- Foster **multi-stakeholder governance**, including civil society, in oversight processes.

Transparency in carbon claims builds consumer trust, avoids reputational risks, and ensures that carbon-negative farming contributes meaningfully to climate goals.

11 Long-term Monitoring, Evaluation, and Accountability

The credibility and effectiveness of carbon-negative and climate-resilient agriculture depend not only on implementation but also on rigorous, long-term monitoring, evaluation, and accountability (M&E&A) systems. These systems are vital to assess the real-world outcomes of interventions on soil carbon stocks, biodiversity, water quality, yields, and farmer livelihoods. Without such mechanisms, it becomes difficult to verify impact, improve practices over time, or ensure that policies and investments are aligned with sustainability goals.

Moreover, in a global context where carbon trading, climate finance, and environmental policy are rapidly evolving, transparent and science-based reporting is essential to gain trust, attract support, and maintain environmental integrity. Embedding adaptive feedback loops and data-sharing platforms into agricultural programs helps transform climate-smart interventions from pilot projects into scalable, accountable systems ([Bossio et al., 2020](#); [Sanderman et al., 2017](#)). To achieve this, three core components must be developed:

1. Designing impact metrics for carbon, soil, biodiversity, and socio-economic outcomes
2. Feedback systems for continuous improvement

3. Transparent reporting for national and global benchmarking

11.1 Designing impact metrics for carbon, soil, biodiversity, and socio-economic outcomes

Effective long-term monitoring begins with defining standardized and context-specific metrics that reflect both biophysical and socio-economic dimensions of sustainable agriculture. These include:

- **Carbon sequestration indicators** such as changes in soil organic carbon (SOC), biomass carbon, and GHG emission reductions per hectare.
- **Soil health metrics** including bulk density, microbial activity, aggregate stability, and nutrient availability.
- **Biodiversity measures** at genetic, species, and ecosystem levels, especially in agroforestry and mixed cropping systems.
- **Socio-economic indicators** such as income diversification, farmer resilience, gender equity, and food security.

Emerging frameworks like FAO's SHARP tool (Self-evaluation and Holistic Assessment of climate Resilience of farmers and Pastoralists) and the Cool Farm Tool enable participatory and science-based data collection ([FAO, 2020](#); [Hillier *et al.*, 2011](#)). These tools are evolving to incorporate satellite data, AI-driven analytics, and community-led monitoring for precision and inclusivity.

11.2 Feedback systems for continuous improvement

A static evaluation approach limits innovation and responsiveness. Instead, adaptive feedback loops must be embedded in project design, allowing real-

time data to inform management practices, policy shifts, and extension services.

- **Digital dashboards and mobile apps** can connect farmers, researchers, and policymakers for near-instant updates and responses.
- **Participatory monitoring frameworks**, where farmers assess their own fields using simple tools, empower local ownership and learning.
- **Iterative learning systems**, common in agroecological transitions, ensure that evolving challenges like climate variability or pest outbreaks are addressed dynamically ([Altieri & Nicholls, 2020](#)).

These feedback mechanisms promote adaptive management and strengthen institutional learning over time.

11.3 Transparent reporting for national and global benchmarking

Transparent reporting of agricultural climate outcomes supports accountability to multiple stakeholders including communities, national governments, and international donors. It is also essential for countries to meet their Nationally Determined Contributions (NDCs) under the Paris Agreement. Standardized reporting frameworks include:

- IPCC guidelines for agriculture, forestry, and land use (AFOLU).
- UNFCCC's Enhanced Transparency Framework (ETF) for emissions and mitigation tracking.
- Voluntary Carbon Standards (e.g., Verra, Gold Standard) which demand credible data for carbon claims.

Public platforms such as FAOSTAT, Global Soil Partnership, and LandPKS support data transparency and open access. Open reporting fosters global benchmarking and helps scale successful models while flagging underperforming initiatives ([Smith et al., 2020](#)).

12 Vision 2050: Transforming Global Agriculture

By 2050, the world must feed nearly 10 billion people while reversing the escalating crises of climate change, biodiversity loss, and soil degradation. Transforming agriculture into a **climate-resilient, regenerative, and carbon-negative** system is therefore a defining global mission of the 21st century.

The **Vision 2050** framework charts a long-term pathway toward agricultural systems that are productive, sustainable, and equitable. It aligns with the **IPCC's net-zero goal** and the **UN Sustainable Development Goals**, particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land), emphasizing that food production and planetary health must advance together.

12.1 Global Scenarios and Emission Impact

Scenario modeling reveals that large-scale adoption of regenerative and nature-positive practices could dramatically reshape global food systems.

[Griscom et al. \(2017\)](#) estimate that natural climate solutions, including agroforestry, improved grazing, cover cropping, and organic amendments, could sequester up to **23.8 Gt CO₂e per year**, representing **9–13 % of the total mitigation potential required by 2050**. Likewise, [Project Drawdown \(2020\)](#) projects that applying regenerative approaches on **1–2 billion ha** could cumulatively mitigate **22.3 Gt CO₂e** while improving food security.

A worldwide transition to regenerative farming can therefore:

- Reduce dependence on synthetic fertilizers and associated nitrous-oxide emissions.
- Increase resilience to droughts, floods, and heat stress.
- Reconnect landscapes through biodiversity corridors and soil restoration.

These projections illustrate that agricultural regeneration is not only compatible with productivity but essential for climate stability and ecological renewal.

12.2 Strategic Roadmaps and Cooperation Frameworks

Delivering Vision 2050 demands coordinated national and global action framed by clear milestones:

- **By 2030:** Integrate climate-smart extension services, reform harmful input subsidies, promote soil-health incentives, and operationalize national carbon registries.
- **By 2040:** Develop regional agroecological zoning, scale low-carbon value chains, and embed carbon farming within national climate policies.
- **By 2050:** Achieve net-zero emissions in agriculture and land use while regenerating degraded ecosystems and embedding climate literacy in rural economies.

Collaborative mechanisms such as the **Koronivia Joint Work on Agriculture (KJWA)** under the UNFCCC and the **Coalition of Action for Soil Health (CA4SH)** ([UNFCCC, 2021a](#); WEF, 2023) exemplify international cooperation for knowledge exchange and resource mobilization. Region-specific platforms, like the **African Union's CAADP**, the **EU Green Deal**, and **India's National Mission on Sustainable**

Agriculture (NMSA), demonstrate how regional priorities can align with global sustainability objectives.

12.3 The Ethical Foundation of Regenerative Agriculture

Beyond science and policy, regeneration is a **moral commitment** grounded in intergenerational justice and ecological stewardship. The industrial agricultural paradigm, despite increasing yields, has pushed humanity beyond several planetary boundaries, resulting in soil depletion, biodiversity collapse, and rural distress ([Rockström et al., 2009](#)).

The ethical dimension of regenerative agriculture emphasizes:

- **Restoring dignity** and agency to smallholders and indigenous knowledge systems.
- **Safeguarding the rights of future generations** to live in a stable climate and fertile environment.
- **Redefining prosperity** in harmony with ecological integrity rather than extractive growth.

As **Hans Jonas (1979)** stated in *The Imperative of Responsibility*, humanity must act to ensure “the permanence of genuine human life.” This principle must now guide global agriculture, ensuring that food systems regenerate rather than exhaust the life-support systems of the planet.

13 Conclusion and Way Forward

Carbon-negative farming embodies a new agricultural paradigm one that restores rather than depletes, sequesters rather than emits, and regenerates rather than exploits. It stands at the confluence of scientific innovation, environmental stewardship, and socio-economic transformation.

The path forward requires a **systems approach** linking ecological principles with renewable energy, circular bioeconomy models, and digital

innovation. Advances in **soil-carbon monitoring, bio-based inputs, precision irrigation, and data analytics** now enable accurate quantification of emissions and sequestration. Yet without enabling policies and equitable access, these technologies risk remaining isolated or elite-centric.

Governments, research institutions, and private actors must embed carbon-negative farming into national and international agendas by:

- Integrating **soil-carbon restoration** and **regenerative practices** into **Nationally Determined Contributions (NDCs)**.
- Establishing **transparent MRV (Monitoring, Reporting, and Verification)** systems anchored in digital traceability and farmer participation.
- Redirecting **subsidies and incentives** toward low-emission, circular resource flows. » Expanding **carbon literacy** and **capacity-building** for farmers, youth, and local institutions.

Empowering smallholders with knowledge, technology, and access to **carbon finance** will democratize the benefits of carbon farming and strengthen resilience in vulnerable regions.

The pursuit of net-negative agriculture must uphold food security, land rights, and biodiversity. Regenerative systems should rebuild the ecological foundations of life, soil, water, and genetic diversity, while revitalizing rural economies and cultural landscapes.

Ethical stewardship, participatory governance, and inclusivity must guide all interventions so that agricultural progress enhances both human and planetary well-being.

The transformation from concept to practice demands sustained commitment at all levels:

- **By 2030:** Mainstream regenerative practices and integrate carbon metrics into agricultural policy frameworks.
- **By 2040:** Expand equitable carbon markets, low-carbon value chains, and regional agro-ecological hubs.
- **By 2050:** Realize net-zero, or preferably net-negative, agriculture that unites food security with climate stability.

This collective journey calls for courage, coordination, and shared purpose, from farmers who steward the land to policymakers who shape its future. Agriculture's true measure of success in the Anthropocene will not be yield alone, but its power to **heal the Earth while feeding humanity**.

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Chapter - 9

Soil Health and Carbon Sequestration: The Cornerstone of Carbon-Negative Farming

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1 Introduction

Modern agriculture has delivered remarkable gains in food production, yet it has come at a steep environmental cost. The widespread reliance on synthetic fertilizers, chemical pesticides, monocultures, and intensive tillage has led to widespread soil degradation, loss of organic matter, and disruption of natural nutrient cycles ([Lal, 2004](#); Montgomery, 2007). As a result, soils across the globe have become increasingly compacted, eroded, biologically impoverished, and, most critically, depleted in carbon ([Amundson *et al.*, 2015](#)).

Soils, once a vital reservoir of organic carbon and biodiversity, have gradually transitioned from being net carbon sinks to significant sources of greenhouse gas emissions, particularly carbon dioxide (CO₂) and nitrous oxide (N₂O). According to recent estimates, agriculture and land use change contribute up to 24% of global anthropogenic greenhouse gas emissions, with a large fraction stemming directly from unsustainable soil management practices ([IPCC, 2019](#)).

In response to this challenge, carbon-negative farming emerges as a transformative paradigm, one that not only aims to minimize emissions but also to remove atmospheric carbon and store it safely in terrestrial ecosystems. At the heart of this approach lies the restoration and stewardship of soil health, a dynamic system of physical structure, biological diversity, and chemical balance that governs the productivity and resilience of

agroecosystems ([Doran & Zeiss, 2000](#); [FAO, 2020](#)). Soil plays a dual role in the climate equation.

- It acts as a source of carbon when mismanaged, releasing CO₂ through the oxidation of organic matter and erosion ([Lal, 2003](#)).
- It functions as a sink when managed regeneratively, drawing carbon from the atmosphere via plant photosynthesis and storing it in the form of stable soil organic matter (SOM) and microbial residues ([Lehmann & Kleber, 2015](#); Janzen *et al.*, 2021).

Enhancing soil organic carbon (SOC) is thus not only a powerful climate mitigation strategy but also a foundation for long-term agricultural sustainability. Improved soil health enhances water retention, nutrient cycling, disease resistance, and overall crop productivity, co-benefits that are critical in the face of increasing climate variability and land degradation ([Kibblewhite *et al.*, 2008](#); [Oldfield *et al.*, 2020](#)).

This chapter explores how soil health and carbon sequestration intersect at the core of carbon-negative farming systems. It presents the scientific principles, mechanisms, and best practices that allow soils to transition from degraded and carbon-depleting states to regenerative and carbon-sequestering ecosystems. By adopting nature-based solutions grounded in soil ecology, farmers can become vital stewards of the planet's climate and custodians of food system resilience ([Smith *et al.*, 2008](#); Bossio *et al.*, 2020).

2 Understanding Soil Health

Soil health refers to the ongoing capacity of soil to function as a living, dynamic ecosystem that supports plant growth, maintains environmental quality, and promotes the health of all living organisms ([Doran & Zeiss, 2000](#); [FAO, 2020](#)). Unlike the traditional view of soil as an inert medium for crop production, soil health emphasizes its biological vitality, structural

integrity, and ecological functionality. A healthy soil system performs multiple interrelated functions, including nutrient cycling, water purification, climate regulation, and habitat provision for soil organisms ([Kibblewhite *et al.*, 2008](#); Lehmann *et al.*, 2020). The key indicators of soil health include the following interconnected physical, chemical, and biological properties:

1. Soil structure and aggregation
2. Organic matter content
3. Microbial diversity and activity
4. Nutrient cycling efficiency
5. Water retention and infiltration capacity

2.1 Soil Structure and Aggregation

Soil structure refers to the arrangement of soil particles (sand, silt, clay) into aggregates or “peds.” Well-aggregated soils have stable crumb-like structures that allow for better root penetration, air exchange, and water infiltration ([Bronick & Lal, 2005](#)). Stable aggregates resist erosion and create pore spaces for microbial life. Practices such as no-till farming, cover cropping, and organic amendments improve aggregation by promoting microbial glues like glomalin, secreted by arbuscular mycorrhizal fungi, and root exudates that bind particles together ([Wright & Upadhyaya, 1998](#); [Six *et al.*, 2004](#)).

2.2 Organic Matter Content

Soil organic matter (SOM) consists of decomposing plant and animal residues, microbial biomass, and humic substances. SOM is the engine of soil fertility, influencing nutrient supply, cation exchange capacity (CEC), pH buffering, and soil structure ([Lehmann and Kleber, 2015](#); [Lal, 2016](#)). Soils rich in organic matter exhibit improved tilth, higher nutrient and water-holding capacity, and enhanced biological activity. Increasing SOM through

composting, crop residue retention, and reduced tillage is central to improving soil health and carbon sequestration (Chivenge *et al.*, 2011).

2.3 Microbial Diversity and Activity

Soil is teeming with life, a single teaspoon of healthy soil can contain billions of microorganisms. These include bacteria, fungi (especially mycorrhizae), actinomycetes, protozoa, and nematodes, which form complex food webs that mediate organic matter decomposition, nutrient cycling, and pathogen suppression (van der Heijden *et al.*, 2008; Fierer *et al.*, 2017). High microbial diversity increases soil resilience to stress and improves nutrient availability through symbiotic relationships, such as mycorrhizal associations. Practices that minimize chemical overuse and promote biological inputs e.g., biofertilizers and compost teas, help maintain microbial richness and ecological functionality ([Larkin, 2015](#)).

2.4 Nutrient Cycling Efficiency

Soil health depends on the efficient cycling of nutrients such as nitrogen (N), phosphorus (P), potassium (K), sulfur (S), and micronutrients. These must be available to plants in bioavailable forms without excessive loss through leaching or volatilization. Biological processes, including biological nitrogen fixation, mineralization, and mycorrhizal-mediated uptake, are essential to nutrient dynamics ([Drinkwater & Snapp, 2007](#); [Richardson *et al.*, 2009](#)). A biologically active soil maintains nutrient balance and synchrony with plant demand, reducing reliance on synthetic fertilizers and preventing nutrient runoff into water bodies ([Fontaine *et al.*, 2024](#)).

2.5 Water Retention and Infiltration Capacity

Healthy soils act like a sponge, absorbing, storing, and gradually releasing water. Good soil structure, high organic matter, and continuous ground cover

increase infiltration and reduce surface runoff and evaporation ([Hudson, 1994](#); [Franzluebbers, 2002](#)). This improves drought resilience and ensures sustained plant growth. In contrast, degraded soils are compacted and hydrophobic, leading to crusting, poor infiltration, and erosion. Water-smart practices, like mulching, contour farming, and perennial cover, are essential components of regenerative agriculture and climate-smart farming systems ([Bossio *et al.*, 2020](#)).

The synergy among these attributes determines the overall health of a soil. Critically, soil organic carbon (SOC) acts as a unifying factor, supporting microbial life, enhancing structure, facilitating nutrient cycling, and increasing water holding capacity. Thus, any strategy aimed at carbon-negative farming must prioritize the restoration and maintenance of these fundamental soil health parameters through regenerative, low-input, and biologically driven practices ([Lal, 2020](#); [Oldfield *et al.*, 2020](#)).

3 Soil Organic Carbon (SOC): Forms and Functions

Soil Organic Carbon (SOC) is the carbon component of organic compounds in soil, derived from decomposing plant residues, root exudates, animal manures, and microbial biomass. It forms the backbone of soil organic matter (SOM) and plays a critical role in maintaining soil fertility, microbial life, nutrient cycling, water retention, and overall soil health ([Lal, 2004](#); [Lehmann & Kleber, 2015](#)).

Importantly, SOC is not homogeneous, it exists in different fractions or “pools” with distinct chemical compositions, turnover rates, and stability. These pools interact with biological and environmental factors and must be considered in designing effective carbon sequestration strategies under carbon-negative farming systems ([Schmidt *et al.*, 2011](#); Cotrufo *et al.*, 2013).

Understanding the characteristics and functions of each SOC pool, namely, labile, stable, and recalcitrant carbon, is essential for their targeted

management within sustainable farming frameworks.

1. Labile Carbon (Active Pool)
2. Stable Carbon (Slow Pool)
3. Recalcitrant Carbon (Passive Pool)

3.1 Labile Carbon (Active Pool)

This is the most dynamic and bioavailable fraction of SOC, consisting primarily of recently deposited organic materials like fresh plant residues, microbial biomass, and root exudates. Labile carbon has a short turnover time, ranging from days to a few years and is rapidly decomposed by soil microorganisms ([Gregorich *et al.*, 2001](#)). While it does not contribute significantly to long-term carbon storage, it is essential for:

- Fueling microbial activity and soil enzyme processes
- Driving nutrient mineralization and cycling
- Supporting immediate plant nutrient availability

Due to its sensitivity, land management practices such as intensive tillage and fallowing can quickly deplete this pool ([Six *et al.*, 2002](#)). Maintaining a continuous input of organic matter through cover crops and crop residues is key to sustaining labile carbon and overall biological functioning (Sparling *et al.*, 1998).

3.2 Stable Carbon (Slow Pool)

Stable SOC refers to organic materials that are chemically complex and physically protected, often incorporated into microaggregates or bound to clay and mineral surfaces. This includes humic and fulvic substances, which can persist in soil for decades to centuries ([Christensen, 2001](#)). Stable SOC contributes significantly to:

- Long-term nutrient supply and fertility
- Improved soil structure and aggregate stability
- Enhanced water-holding capacity and drought resilience
- Buffering soil pH and increasing cation exchange capacity (CEC)

Strategies like reduced tillage, compost addition, and diversified cropping improve humification and microbial transformation of fresh inputs into this pool ([Blanco-Canqui & Lal, 2004](#); [Cotrufo *et al.*, 2013](#)).

3.3 Recalcitrant Carbon (Passive Pool)

Recalcitrant SOC is the most chemically resistant and long-lived form of organic carbon in soil. This includes black carbon, such as biochar, soot, and charred organic matter, which can persist for hundreds to thousands of years ([Schmidt & Noack, 2000](#); [Lehmann, 2007](#)). Key features of recalcitrant carbon include:

- Exceptional resistance to microbial degradation
- Serves as a long-term carbon sink for climate mitigation
- Improves soil physical properties, such as porosity and structure
- Enhances chemical functions, including nutrient retention and pH regulation

Biochar, produced through pyrolysis of biomass, is a promising amendment that increases recalcitrant carbon while also benefiting soil fertility, microbial diversity, and water dynamics ([Lehmann *et al.*, 2011](#)).

Integration into Carbon-Negative Farming: The goal of carbon-negative farming is not only to increase total Soil Organic Carbon (SOC), but to enhance its stability and longevity by directing more carbon into the stable and recalcitrant pools. These fractions resist microbial decomposition and physical erosion, making them ideal targets for long-term climate mitigation

(Paustian *et al.*, 2016). By strategically managing these SOC pools, especially through practices that favor stable and recalcitrant carbon forms, carbon-negative farming systems can significantly boost long-term carbon storage and soil resilience. Key practices include:

- **Agroforestry and perennial systems:** Deep-rooted plants provide continuous carbon inputs and improve soil aggregation ([Lorenz & Lal, 2014](#)).
- **Reduced tillage:** Helps preserve soil aggregates and minimize the loss of physically protected SOC ([West & Post, 2002](#)).
- **Organic amendments:** Compost introduces diverse labile carbon, while biochar enhances stable carbon fractions ([Jeffery *et al.*, 2011](#)).
- **Cover cropping and crop diversification:** Encourage microbial processing and contribute to the formation of stable soil aggregates ([Kong *et al.*, 2005](#)).

Understanding the dynamics of SOC pools is fundamental to climate-smart agriculture. While labile carbon fuels immediate microbial and nutrient processes, the stable and recalcitrant pools underpin long-term carbon storage, ecosystem resilience, and climate regulation. By integrating this knowledge, carbon-negative farming emerges as a powerful strategy to reverse soil degradation and mitigate climate change, empowering farmers to become stewards of the climate and restorers of soil health.

4 Mechanisms of Carbon Sequestration in Soil

Carbon sequestration in soil is the process by which atmospheric carbon dioxide (CO₂) is captured through photosynthesis, transferred into plant biomass, and eventually stored in the soil in organic or inorganic forms. (Lal, 2004; Paustian *et al.*, 2016). This carbon enters the soil system primarily through:

- Plant roots (biomass and root sloughing)
- Aboveground plant litter and residues
- Root exudates (sugars, amino acids, and secondary metabolites)
- Microbial residues (decomposed microbial biomass)
- Organic amendments (e.g., compost, manure, biochar) ([Cotrufo *et al.*, 2013](#))

Once in the soil, the persistence of this carbon depends on how well it is stabilized or protected from microbial decomposition. The three primary mechanisms through which soil organic carbon is stabilized and sequestered over time are described below:

1. **Aggregation:** Physical Protection of Organic Matter in Soil
Aggregates
2. **Mineral Association:** Adsorption onto Clay and Silt Particles
3. **Chemical Transformation:** Conversion into Humus and Humic Substances

4.1 Aggregation: Physical Protection of Organic Matter in Soil Aggregates

Soil aggregation occurs when soil particles bind together into larger units or clusters, known as aggregates, which protect organic matter by isolating it from microbial enzymes and oxygen (Six *et al.*, 2002). This physical inaccessibility significantly reduces decomposition rates.

- Microaggregates (20-250 μm) are especially effective in encapsulating labile carbon in fine-textured soils ([Tisdall & Oades, 1982](#)).
- Aggregates reduce carbon loss by minimizing erosion and surface runoff ([Bronick & Lal, 2005](#)).

- Glomalin (a glycoprotein produced by arbuscular mycorrhizal fungi) plays a key role in stabilizing aggregates ([Wright & Upadhyaya, 1998](#)).

Practices that improve aggregation, such as reduced tillage, cover cropping, and retention of crop residues, promote SOC stabilization through this mechanism ([Blanco-Canqui & Lal, 2004](#)).

4.2 Mineral Association: Adsorption onto Clay and Silt Particles

Mineral-associated organic matter (MAOM) refers to organic compounds that bind tightly to soil minerals, particularly clays and oxides of iron and aluminium (Kleber *et al.*, 2007). These chemical and electrostatic interactions make the carbon less bioavailable to microbes, thereby increasing its residence time from decades to centuries (Lehmann & Kleber, 2015). The following key points highlight the processes and factors influencing the formation and stability of MAOM:

- Clay-rich and fine-textured soils have greater capacity for long-term carbon stabilization ([Hassink, 1997](#)).
- The formation of MAOM is favored by low disturbance systems (e.g., no-till farming) and the gradual decomposition of organic inputs ([Kogel-Knabner & Amelung, 2013](#)).
- MAOM is believed to be the dominant mechanism for long-term SOC storage, especially in temperate and tropical soils ([Schmidt *et al.*, 2011](#)).

This mineral-carbon complex is crucial for long-term carbon persistence in soil and is a key target in carbon sequestration strategies.

4.3 Chemical Transformation: Conversion into Humus and Humic Substances

Organic materials undergo chemical transformation through microbial and enzymatic decomposition, resulting in the formation of complex, stable compounds known as humic substances. Humic acids, fulvic acids, and humin constitute the major fractions of humic substances ([Stevenson, 1994](#)).

These compounds are chemically resistant to further breakdown and can persist in the soil for decades or even centuries. This process is sometimes referred to as humification. The humification process is enhanced under moderate moisture, a balanced C:N ratio, and diverse microbial activity ([Lehmann *et al.*, 2020](#)). Humic substances not only sequester carbon but also improve soil structure, buffer pH, and enhance nutrient retention, making this process essential to both soil health and climate mitigation ([Piccolo, 2001](#)).

Integrated Role in Carbon-Negative Farming: The above three mechanisms, aggregation, mineral association **and** chemical transformation, act in a complementary and interconnected manner to enhance soil's capacity to store carbon for the long term. In carbon-negative farming systems, these pathways are strategically promoted through sustainable practices such as reduced tillage, organic amendments, cover cropping, and diversified rotations ([Lal, 2004](#); [Paustian *et al.*, 2016](#); [Smith *et al.*, 2020](#)). These practices:

- Encourage the formation of stable soil aggregates that **physically protect organic matter** from microbial decomposition (4.1). ([Six *et al.*, 2002](#))
- Enhance the **adsorption of organic matter onto clay and mineral surfaces**, reducing its bioavailability (4.2). ([Kleber *et al.*, 2007](#); [Lehmann & Kleber, 2015](#))

- Support the **biochemical conversion of plant residues into recalcitrant humic compounds**, which persist for decades to centuries (4.3).(Kögel-Knabner, 2002; [Lehmann & Kleber, 2015](#)).

Together, these processes **increase the size and longevity of soil carbon pools**, thereby enabling farming systems to **sequester more carbon than they emit**, a hallmark of carbon-negative agriculture ([Smith *et al.*, 2020](#); [Bossio *et al.*, 2020](#)).

5 Practices Enhancing Soil Carbon Sequestration

Adopting sustainable land management practices that increase organic inputs and reduce carbon losses is vital for enhancing soil organic carbon (SOC) and mitigating climate change. Such practices also contribute to soil fertility, biodiversity, water regulation, and climate resilience ([Lal, 2004](#); [Paustian *et al.*, 2016](#)). The following six evidence-based practices form the cornerstone of soil carbon-building strategies in carbon-negative agriculture.

Core practices and their contributions to soil carbon enhancement.

1. Conservation Tillage and No-Till Farming
2. Cover Cropping and Green Manuring
3. Crop Rotation and Diversification
4. Application of Organic Amendments
5. Biochar Addition
6. Silvopasture and Agroforestry

Table 9.1 Comparative Impact of Soil Practices on Carbon Sequestration Rates.

Soil Practice	CSR	Key Benefits	Considerations / Challenges

Soil Practice	CSR	Key Benefits	Considerations / Challenges
No-Till / Conservation Tillage	0.2 - 1.0	Reduces soil disturbance, improves aggregation, lowers erosion	May require specialized equipment; possible initial yield lag
Cover Cropping	0.3 - 1.2	Increases biomass input, improves soil microbial activity	Seed cost; requires proper management to avoid pests
Crop Rotation and Diversification	0.2 - 0.8	Enhances microbial diversity and nutrient cycling	Requires planning and crop market access
Organic Amendments (Compost/Manure)	0.5 - 2.0	Adds stable organic matter, enhances fertility and microbes	Source availability; risk of nutrient leaching if overapplied
Biochar Application	1.0 - 3.0 (long-term storage potential)	Very stable carbon pool, improves soil water and nutrient retention	High initial cost; requires knowledge of correct application
Agroforestry / Silvopasture	1.5 - 4.0 (includes above- and belowground carbon)	Sequesters carbon long-term, enhances biodiversity and resilience	Land tenure issues; longer-term investment and planning
CSR-Carbon sequestration rate (Mg C ha ⁻¹ year ⁻¹)			

The table (9.1) highlights the relative effectiveness of key soil management strategies in enhancing SOC levels. It provides quantitative context for understanding how certain regenerative and conservation

practices compare in their carbon sequestration potential, allowing for informed decision-making in carbon-negative farming design.

5.1 Conservation Tillage and No-Till Farming

Conservation tillage, particularly no-till farming, represents a fundamental shift from conventional plowing practices by minimizing mechanical soil disturbance. In no-till systems, seeds are directly sown into undisturbed soil and residues from previous crops are retained on the surface. Reduced tillage may involve shallow cultivation but avoids complete inversion of soil layers. These practices are central to carbon-negative agriculture, as they help retain soil organic carbon (SOC) and reduce carbon emissions through various interlinked mechanisms. One of the most important outcomes is the reduction in soil aeration, which limits oxygen exposure and slows down microbial decomposition of organic matter. According to [West & Post \(2002\)](#), no-till significantly reduces the rate of SOC oxidation by limiting microbial respiration, thereby decreasing carbon loss to the atmosphere.

Another major advantage of no-till farming lies in its ability to preserve soil aggregates. Tillage disrupts the physical structure of soil, breaking apart aggregates that serve as protective enclosures for organic matter. In contrast, no-till systems maintain the integrity of micro- and macro-aggregates, which shield SOC from microbial attack and enhance its physical stabilization ([Six et al., 2000](#)). Furthermore, the relatively undisturbed soil environment promotes biological activity, including the proliferation of earthworms, fungal hyphae, and other beneficial organisms. These soil biota facilitate the formation of aggregates and secrete stabilizing compounds such as glomalin, which contribute to the biological stabilization of carbon ([Lal, 2004](#)). At the same time, the presence of surface residues reduces erosion and runoff, preserving carbon-rich topsoil and improving soil moisture retention and

infiltration. These combined effects maintain the integrity of carbon pools, as shown by Blanco-Canqui & Lal (2008).

Importantly, no-till farming is often practiced in combination with cover cropping, crop rotation, and residue management, which enhances its benefits for carbon sequestration and soil health. The integration of continuous organic inputs with minimal disturbance results in more effective carbon buildup than any single practice alone, thus creating a resilient, multifunctional carbon sink. Over time, these practices contribute to measurable SOC gains, particularly in the upper 30 cm of soil. For instance, a meta-analysis by [Angers & Eriksen-Hamel \(2008\)](#) found that long-term no-till practices increased surface SOC stocks by 15-20% compared to conventional tillage systems. These findings highlight the long-term potential of conservation tillage to sequester atmospheric CO₂ in soils and support climate-smart, carbon-negative agriculture.

5.2 Cover Cropping and Green Manuring

Cover cropping and green manuring are essential regenerative practices for enhancing soil organic carbon (SOC) and improving agroecosystem sustainability. Cover crops, such as legumes (e.g., clover, vetch), grasses (e.g., rye, oats), and brassicas (e.g., mustard), are typically grown during fallow periods or intercropped with cash crops. Green manures, on the other hand, are cover crops that are grown specifically to be incorporated into the soil at a certain growth stage to enrich soil fertility. These practices introduce both above- and below-ground biomass, significantly boosting the input of labile organic matter (readily decomposable carbon) as well as precursors to more stable organic fractions. For instance, studies by Kuo *et al.* (1997) have shown that cover crops increase both particulate organic matter and mineral-associated carbon fractions, thereby supporting both short-term and longer-term SOC accumulation.

The presence of live roots from cover crops during fallow periods stimulates microbial activity in the rhizosphere through the continuous release of root exudates, sugars, amino acids, and other low-molecular-weight compounds that act as energy sources for soil microbes ([Lynch & Whipps, 1990](#)). This biological stimulation accelerates nutrient cycling and promotes the microbial transformation of organic matter into more stable humic substances, a process essential for medium-term carbon sequestration. Moreover, cover crops play a significant protective role in maintaining soil integrity. By covering the soil surface, they reduce erosion, improve water infiltration and retention, and limit nutrient leaching, which collectively enhance soil structure and help preserve carbon-rich topsoil ([Snapp *et al.*, 2005](#)).

Certain cover crops, particularly leguminous species, offer the added benefit of biological nitrogen fixation, converting atmospheric nitrogen into forms usable by plants and reducing the need for synthetic fertilizers ([Drinkwater *et al.*, 1998](#)). The incorporation of green manures not only enriches soil fertility but also reduces reliance on synthetic fertilizers, thereby indirectly lowering greenhouse gas emissions linked to their production. When returned to the soil, green manures accelerate humification processes, strengthen soil aggregation, and enhance the stabilization of soil organic carbon over medium timescales ([Park & Lee, 2025](#); [Li *et al.*, 2025](#)). Similarly, cover crops contribute substantial above- and below-ground biomass, increasing both particulate and mineral-associated organic carbon pools that support short- and long-term carbon sequestration ([Hu *et al.*, 2023](#); [Zhang *et al.*, 2022](#)). Altogether, cover cropping and green manuring represent integrated strategies that align with the principles of carbon-negative farming, simultaneously enhancing soil carbon storage and ecosystem resilience

5.3 Crop Rotation and Diversification

Crop rotation and diversification represent key strategies for enhancing soil organic carbon (SOC) sequestration through improved root dynamics and microbial activity. By alternating crops across seasons and integrating diverse species, farmers can introduce varying root architectures that penetrate different soil layers. This diversity facilitates deeper carbon deposition and improves soil porosity and nutrient cycling. For instance, the inclusion of deep-rooted crops such as alfalfa or perennial legumes enhances carbon inputs not only to surface layers but also into subsoil horizons that are typically less disturbed and offer greater stability for long-term carbon storage ([Congreves *et al.*, 2014](#)).

Additionally, diverse cropping systems promote heterogeneous microbial communities that are capable of transforming and stabilizing organic matter in a variety of ways. Microbial richness contributes to functional redundancy, meaning that even under environmental stress, carbon-cycling processes continue effectively ([Tiemann *et al.*, 2015](#)). Rotation systems also interrupt pest and pathogen life cycles, reducing the reliance on agrochemicals that can disrupt soil biology ([Altieri, 1999](#)). Over time, this integrated approach not only sequesters carbon but also enhances ecosystem resilience, productivity, and sustainability. [Smith *et al.* \(2008\)](#) emphasized that diversified rotations, especially those incorporating legumes and cover crops, result in significantly higher SOC in both topsoil and subsoil compared to monoculture systems.

5.4 Application of Organic Amendments

The application of organic amendments, such as compost, farmyard manure, vermicompost, and crop residues, is a cornerstone of regenerative agriculture and carbon-negative farming. These materials contribute to SOC buildup by directly adding carbon-rich substances to the soil and by stimulating

microbial activity, which enhances carbon cycling and stabilization. Organic inputs improve the labile (easily decomposed) and stable (long-lived) fractions of SOC, leading to a balanced and persistent carbon pool. For example, [Bhattacharyya *et al.* \(2010\)](#) reported significant increases in microbial biomass and SOC content with the use of organic manures, which also provided secondary benefits such as nitrogen mineralization and micronutrient supply.

In addition to increasing the quantity of organic matter, these amendments contribute to the formation of humus through microbial-mediated decomposition processes. [Bhogal *et al.* \(2009\)](#) found that compost and manures significantly enhanced the formation of stable humic substances in long-term field trials. The improvements in soil structure and porosity that result from organic matter applications also help soils retain more water and nutrients, increasing crop resilience and reducing leaching losses ([Diacono & Montemurro, 2010](#)). When integrated with conservation tillage and cover cropping, organic amendments produce synergistic effects on both carbon sequestration and crop productivity ([Liu *et al.*, 2014](#)).

5.5 Biochar Addition

Biochar represents a powerful tool in carbon-negative farming due to its high stability, porous structure, and beneficial effects on soil properties. Produced via pyrolysis of organic biomass under low-oxygen conditions, biochar contains a significant portion of recalcitrant carbon that resists microbial degradation and can persist in soils for hundreds to thousands of years. [Lehmann \(2007\)](#) documented how this persistent carbon form serves as a long-term carbon sink, effectively locking carbon away from the atmosphere.

Beyond stability, biochar enhances soil fertility by increasing cation exchange capacity (CEC), which improves nutrient retention and reduces fertilizer losses. [Lehmann *et al.* \(2011\)](#) showed that biochar application

enriched soils with essential nutrients and boosted microbial populations, especially beneficial fungi like mycorrhizae and nitrogen-fixing diazotrophs. These effects are particularly pronounced in nutrient-depleted and sandy soils, where biochar improves water retention and aeration ([Jeffery *et al.*, 2011](#)). When co-applied with compost or manure, biochar not only enhances carbon sequestration but also improves plant growth and nutrient use efficiency. [Agegnehu *et al.* \(2016\)](#) demonstrated that integrated use of biochar and organic amendments resulted in increased SOC levels and higher crop yields under various cropping systems.

5.6 Silvopasture and Agroforestry

Silvopasture and agroforestry systems combine trees or shrubs with agricultural crops and/or livestock, creating multilayered ecosystems that are highly efficient at sequestering carbon both above and below ground. These systems mimic natural forest ecosystems by integrating deep-rooted woody perennials that store carbon in biomass while simultaneously improving soil health. [Nair *et al.* \(2009\)](#) highlighted that such systems sequester carbon not only in tree trunks and roots but also enhance SOC through litter deposition and root turnover.

The canopy and root structures of agroforestry systems provide protective cover to the soil, reducing erosion, moderating microclimates, and improving moisture retention. This results in more stable and resilient soil ecosystems that are less prone to carbon loss ([Lorenz & Lal, 2014](#)). Additionally, these systems increase biodiversity and support a rich network of soil organisms, leading to improved nutrient cycling and enhanced carbon storage. [Jose \(2009\)](#) noted that agroforestry improves the ecological complexity of farmland, supporting stable soil food webs essential for long-term soil productivity and carbon stabilization.

Beyond environmental benefits, agroforestry provides economic resilience through diversified income sources, timber, fruits, fodder, and livestock, all within a single integrated system. [Montagnini and Nair \(2004\)](#) emphasized the dual benefits of these systems in terms of sustainability and profitability, making them a compelling strategy for carbon-negative farming in both tropical and temperate regions.

6 Soil Microbiome and Carbon Sequestration

The **soil microbiome** is the biological engine behind carbon cycling in terrestrial ecosystems. These communities of bacteria, archaea, fungi, actinomycetes, protozoa, and viruses regulate the decomposition of organic matter and the transformation of carbon into stable forms. Unlike passive physical or chemical processes, microbial activity directly determines whether carbon is respired back into the atmosphere as CO₂ or incorporated into stable soil organic carbon (SOC) pools through various biochemical pathways ([Fierer, 2017](#); [Liang *et al.*, 2019](#)). The efficiency and direction of these microbial processes are influenced by numerous factors including soil type, climate, land management, plant-microbe interactions, and resource availability ([Schmidt *et al.*, 2011](#); [Lehmann & Kleber, 2015](#)).

Soil microbes play dual roles in the carbon cycle. On one hand, they are decomposers, mineralizing organic residues and releasing CO₂; on the other, they contribute to long-term sequestration through biochemical transformation and the generation of microbial necromass, which can become chemically and physically protected within soil matrices. This duality underscores the importance of microbial regulation in balancing carbon inputs and outputs, a process central to any carbon-negative agricultural strategy ([Cotrufo *et al.*, 2013](#)).

This functional duality of microbes, as both decomposers and carbon stabilizers is reflected in multiple mechanisms by which they influence carbon

dynamics, including the formation of microbial necromass, the activity of specific microbial guilds, and the management practices that enhance their biomass and diversity. These processes not only contribute to soil carbon storage but also generate co-benefits that improve soil structure, fertility, and resilience, making the microbiome a cornerstone of climate-smart, carbon-negative farming systems.

1. Microbes as Carbon Processors
2. Microbial Necromass: The Hidden Carbon Sink
3. Key Microbial Players in Carbon Stabilization
4. Practices That Enhance Microbial Biomass and Diversity
5. Co-Benefits of a Healthy Soil Microbiome

6.1 Microbes as Carbon Processors

Soil microorganisms decompose organic materials such as crop residues, root exudates, leaf litter, and manure, through the secretion of extracellular enzymes that break down complex organic molecules into simpler compounds ([Schimel & Schaeffer, 2012](#)). This decomposition process plays a dual role: it releases nutrients such as nitrogen (N), phosphorus (P), and sulfur (S), making them available for plant uptake, and it releases carbon dioxide (CO₂) through microbial respiration. However, microbial activity also produces biomass and cellular debris that can contribute to long-term carbon stabilization. These microbial by-products are foundational to the formation of stable soil organic carbon (SOC), acting as precursors to humic substances and mineral-associated organic matter ([Cotrufo *et al.*, 2013](#); [Buckeridge *et al.*, 2022](#)).

6.2 Microbial Necromass: The Hidden Carbon Sink

Microbial necromass, remnants of dead microbial cells, forms a substantial and persistent fraction of soil organic carbon (SOC). Unlike fresh organic

inputs, microbial necromass can become chemically bound to mineral surfaces or physically occluded within soil aggregates, rendering it highly stable and resistant to decomposition ([Mambelli *et al.*, 2011](#); [Liang *et al.*, 2019](#)). This transformation from living microbial biomass to necromass represents a critical pathway through which carbon is sequestered for the long term.

6.3 Key Microbial Players in Carbon Stabilization

Several groups of soil microbes are particularly effective in stabilizing carbon. Arbuscular Mycorrhizal Fungi (AMF) form symbiotic relationships with plant roots and release glomalin, a sticky glycoprotein that binds soil particles into aggregates and contributes to long-term carbon storage ([Rillig *et al.*, 2002](#)). Actinobacteria are another crucial group; these filamentous bacteria are excellent decomposers of complex polymers such as lignin and cellulose and are instrumental in promoting humification processes that stabilize organic matter ([Lacombe-Harvey *et al.*, 2018](#)). Rhizobacteria, which live in the rhizosphere, enhance root exudation and microbial turnover, indirectly boosting SOC accumulation by increasing microbial biomass and nutrient cycling ([Berendsen *et al.*, 2012](#)). The relative abundance and activity of these functional groups can significantly influence whether carbon is mineralized and lost as CO₂ or sequestered in stable soil fractions.

6.4 Practices That Enhance Microbial Biomass and Diversity

To harness the full potential of soil microbes for carbon sequestration, agricultural practices must foster microbial abundance, diversity, and habitat stability. Key strategies include the regular addition of organic matter through compost, green manures, and crop residues, which provide carbon substrates for microbial growth ([Liu *et al.*, 2014](#)). Reducing the use of synthetic fertilizers and pesticides is also crucial, as these inputs can harm beneficial

microbes, including nitrogen-fixers and mycorrhizal fungi ([Turbé *et al.*, 2010](#)). Minimizing soil disturbance through reduced or no-till systems preserves microbial habitats and allows fungal networks to thrive. Increasing plant diversity via crop rotations, intercropping, and agroforestry expands microbial niches and promotes functional redundancy within the microbial community ([Tiemann *et al.*, 2015](#)). Finally, the use of cover crops and keeping living roots in the soil throughout the year ensures a continuous supply of root exudates to maintain active microbial populations, even in the off-season ([Wortman *et al.*, 2012](#)).

6.5 Co-Benefits of a Healthy Soil Microbiome

Beyond carbon sequestration, a robust and diverse soil microbiome offers numerous ecological and agronomic benefits. It enhances nutrient cycling by decomposing organic matter and mobilizing essential nutrients, reducing reliance on chemical fertilizers (van der Heijden *et al.*, 2008). Beneficial microbes also improve disease resistance by outcompeting pathogens, producing antimicrobial compounds, and activating plant immune responses ([Van Wees *et al.*, 2008](#)). Furthermore, microbial activity contributes to soil aggregation, improving porosity, infiltration, and aeration. Some microbes also help plants withstand abiotic stresses by producing osmoprotectants and plant growth regulators, thereby increasing crop resilience to drought, salinity, and temperature extremes ([Naylor & Coleman-Derr, 2018](#)). Together, these co-benefits underscore the value of a thriving microbiome in building climate-resilient, carbon-negative farming systems.

7 Measuring Soil Carbon Sequestration

Accurate measurement of soil organic carbon (SOC) is critical for evaluating the success of carbon-negative farming practices, monitoring carbon stock changes, and participating in carbon credit verification and trading schemes.

Because SOC is spatially heterogeneous and influenced by climate, soil type, and land use, its quantification involves an integration of field sampling, laboratory analysis, and process-based modeling ([Minasny *et al.*, 2017](#); [Smith *et al.*, 2020](#)). Soil carbon sequestration is measured through a combination of traditional methods and modern tools, which include the following four key approaches:

1. Field Sampling and Baseline Assessment
2. Laboratory Techniques for SOC Analysis
3. Soil Carbon Modeling Tools
4. Emerging Tools and Technologies

7.1 Field Sampling and Baseline Assessment

Establishing a baseline for soil organic carbon (SOC) stock is the critical first step in tracking changes resulting from carbon-negative farming practices. This process begins with systematic soil sampling, typically conducted at standardized depth intervals, such as 0-15 cm, 15-30 cm, and deeper, to capture both surface and subsoil carbon dynamics ([Poeplau & Don, 2013](#)). Sampling should be spatially referenced using GPS coordinates to ensure repeatability and consistency in long-term monitoring. Additionally, it is essential to record soil bulk density (g/cm^3), as this is a key parameter for converting SOC concentrations into stock values expressed per unit area. Best practices for field sampling include:

- Sampling soil at standard depth intervals (e.g., 0-15 cm, 15-30 cm, and >30 cm).
- Using GPS-referenced locations for consistent monitoring over time.
- Measuring bulk density to convert SOC content to stock values.
- Documenting site history, vegetation, and land use to interpret SOC variability.

- Performing sampling at regular intervals (e.g., annually or biannually), depending on monitoring goals and land-use changes.

The SOC stock (Mg C ha^{-1}) is calculated using the formula ([FAO, 2019](#)):

$$\text{SOCstock} = \text{SOCconcentration} \times \text{BulkDensity} \times \text{Depth} \times 10$$

This quantification allows researchers and practitioners to evaluate the effectiveness of management practices in enhancing carbon storage and to meet requirements for carbon accounting frameworks.

7.2 Laboratory Techniques for SOC Analysis

Accurate laboratory analysis is essential for quantifying soil organic carbon (SOC) content and validating field measurements. Two widely used methods are dry combustion and loss on ignition, each varying in precision, cost, and suitability for different applications.

- **Dry Combustion (Elemental Analysis):** Considered the gold standard, this method involves combusting soil samples at 900-1000°C in an oxygen-rich environment, with released CO_2 measured using a CHN or LECO analyzer ([Nelson & Sommers, 1996](#)). Acid pre-treatment is required to exclude inorganic carbon in calcareous soils. It offers high accuracy and is ideal for research and carbon accounting ([Leogrande et al., 2021](#)).
- **Loss on Ignition (LOI):** A cost-effective alternative, LOI involves heating dried soil samples at 360-550°C in a muffle furnace and estimating SOC based on weight loss using a standard conversion factor (1.724) ([Howard & Howard, 1990](#)). While suitable for routine comparisons, it may overestimate SOC due to loss of water from minerals ([Jensen, 2018](#)).

- **Spectroscopic Methods (NIR, MIR):** Near-Infrared (NIR) and Mid-Infrared (MIR) spectroscopy offer rapid, non-destructive analysis of SOC by detecting molecular vibrations of organic compounds in the soil. These methods are fast, cost-efficient after calibration, and suitable for high-throughput analysis, though they require robust reference datasets and calibration models ([Janik *et al.*, 2007](#); [Viscarra Rossel & Webster, 2012](#)).

7.3 Soil Carbon Modeling Tools

In addition to field and laboratory measurements, soil carbon dynamics are increasingly assessed using simulation models. These process-based tools help predict long-term changes in soil organic carbon (SOC) under varying land use, management, and climate conditions. By integrating biological, physical, and environmental variables, these models support decision-making for sustainable land management and carbon accounting.

- **RothC Model:** Developed for temperate regions, RothC simulates SOC turnover in the top 30 cm of soil based on inputs such as climate, soil texture, organic matter additions, and land management practices ([Coleman & Jenkinson, 1996](#)). It is widely used for assessing SOC changes in agricultural and grassland systems.
- **Century Model:** A comprehensive model that simulates the long-term cycling of carbon, nitrogen, phosphorus, and sulfur across diverse ecosystems, including croplands, grasslands, and forests (Parton *et al.*, 1987). It is especially valuable for studying the effects of land-use changes, fertilization, and tillage on SOC dynamics over decades.
- **COMET-Farmml:** An online decision-support tool developed by the USDA and Colorado State University, COMET-Farm estimates

greenhouse gas (GHG) emissions and carbon sequestration at the farm level across the United States ([Paustian *et al.*, 2019](#)). It supports farmers and policymakers in carbon accounting, offset generation, and climate-smart agriculture planning.

7.4 Emerging Tools and Technologies

Recent technological advancements are significantly enhancing the accuracy, efficiency, and scalability of soil organic carbon (SOC) monitoring. Remote sensing technologies, including UAV drones equipped with multispectral and hyperspectral cameras, now allow non-invasive and rapid estimation of SOC across large and often inaccessible landscapes ([Mulder *et al.*, 2011](#)). These tools capture reflectance data that correlate with organic matter content, offering a cost-effective alternative to extensive ground sampling.

Additionally, the integration of machine learning algorithms with satellite imagery and large-scale soil databases is revolutionizing SOC mapping. These data-driven models can predict SOC with greater spatial resolution and reliability, especially in data-scarce regions ([Padarian *et al.*, 2019](#)). Complementing these innovations, Digital Soil Mapping (DSM) and Soil Information Systems (SIS) provide platforms for collecting, modeling, storing, and sharing SOC data. These systems play a crucial role in developing national SOC inventories, supporting sustainable land-use planning, and informing climate policies ([Arrouays *et al.*, 2017](#)).

In summary, accurate measurement and modeling of soil organic carbon (SOC) are vital for evaluating carbon sequestration and supporting climate-smart land management. Integrating field sampling, laboratory analysis, modeling tools, and emerging technologies ensures robust carbon accounting across spatial and temporal scales.

8 Co-benefits of Soil Carbon Sequestration

In addition to its role in mitigating climate change, soil carbon sequestration delivers a suite of important co-benefits that enhance agricultural sustainability, soil functionality, and environmental quality. By increasing soil organic carbon (SOC), these benefits manifest across hydrological, biological, and nutrient-related dimensions, making carbon sequestration a holistic tool for ecosystem restoration and climate-resilient farming. The key co-benefits include:

1. Water Infiltration and Drought Resilience
2. Soil Fertility and Productivity
3. Biodiversity and Pest Suppression
4. Reduction in Nutrient Leaching and Runoff

8.1 Water Infiltration and Drought Resilience

Soil organic carbon (SOC) is a critical factor influencing soil structure, porosity, and water dynamics, thereby playing a pivotal role in improving water infiltration and moisture retention. SOC enhances the formation of stable soil aggregates, largely due to microbial exudates like glomalin, an adhesive glycoprotein secreted by arbuscular mycorrhizal fungi, which improves soil porosity and pore connectivity ([Rillig *et al.*, 2002](#)). This aggregation facilitates better infiltration of rainwater and reduces surface crusting, especially in degraded soils.

Moreover, higher levels of SOC significantly increase the soil's field capacity and plant-available water, which is particularly beneficial in sandy or coarse-textured soils prone to rapid drainage ([Hudson, 1994](#)). During drought conditions, soils enriched with organic matter retain moisture for longer durations, thereby delaying the onset of plant stress and wilting ([Hudson, 1994](#)). In addition to sustaining crops under dry spells, enhanced infiltration and reduced runoff also help mitigate soil erosion and flash

flooding, both of which are becoming more prevalent due to increased rainfall variability under climate change scenarios ([Bronick & Lal, 2005](#)). Collectively, these hydrological benefits position SOC as a cornerstone of climate-resilient agricultural systems. These water-related benefits make SOC central to climate-resilient agriculture.

8.2 Soil Fertility and Productivity

Soil organic carbon (SOC) acts both as a vital source and regulator of essential nutrients for plant growth. As organic matter decomposes, it releases key nutrients such as nitrogen (N), phosphorus (P), sulfur (S), and various micronutrients in forms that are readily available to plants ([Weil & Brady, 2017](#)). In addition, SOC enhances the soil's cation exchange capacity (CEC), which improves nutrient retention, an especially important function in highly weathered tropical soils prone to nutrient loss ([Six et al., 2002](#)). The presence of SOC also supports a diverse and active microbial population, which accelerates nutrient mineralization and increases nutrient-use efficiency, thereby optimizing plant nutrition ([Lehmann & Kleber, 2015](#)). Numerous studies have demonstrated that increasing SOC correlates with higher and more stable crop yields, particularly under low-input or resource-limited farming systems ([Pan et al., 2009](#); [Lal, 2020](#)). Therefore, enhancing SOC content is a sustainable and effective strategy to improve soil fertility and productivity over the long term.

8.3 Biodiversity and Pest Suppression

Healthy soils rich in organic carbon support diverse and abundant biological communities, ranging from microorganisms to larger soil fauna such as earthworms and arthropods. This diverse soil microbiome includes antagonistic fungi and bacteria that compete with or directly inhibit soil-borne pathogens, thereby contributing to natural disease suppression (van der

Heijden *et al.*, 2008). High levels of SOC create varied microhabitats and resource availability, fostering populations of earthworms, nematodes, and arthropods that enhance nutrient cycling and act as natural predators of pests ([Brussaard *et al.*, 2007](#)). Additionally, SOC supports critical plant-microbe symbioses, including mycorrhizal associations that improve nutrient uptake and bolster plant resistance against both abiotic and biotic stresses ([Smith & Read, 2008](#)). These complex biological interactions help reduce dependence on chemical pesticides, promoting healthier ecosystems and increasing farm profitability.

8.4 Reduction in Nutrient Leaching and Runoff

Soil organic carbon (SOC) plays a vital role in retaining nutrients within the root zone, thereby mitigating non-point source pollution. Organic matter enhances nutrient binding and retention, which is especially important in soils susceptible to nitrate leaching and phosphorus runoff ([Diacono & Montemurro, 2010](#)). Additionally, improved soil structure and aggregation associated with higher SOC slow water movement through the soil profile, facilitating greater nutrient uptake by plants and reducing losses caused by erosion and leaching ([Palm *et al.*, 2014](#)). These processes contribute significantly to minimizing downstream environmental problems such as eutrophication, harmful algal blooms, and the formation of dead zones in aquatic ecosystems ([Tilman *et al.*, 2002](#)).

In conclusion, soil carbon sequestration not only mitigates climate change but also enhances soil health, water management, biodiversity, and nutrient retention. These co-benefits make it a cornerstone for sustainable and resilient agricultural systems.

9 Policy and Incentives for Soil Carbon

As the global climate crisis intensifies, enhancing soil organic carbon (SOC) has emerged as a crucial climate mitigation and land restoration strategy. SOC sequestration offers a nature-based solution that aligns with agricultural sustainability, ecosystem resilience, and food security goals. Recognizing these benefits, governments, international bodies, and carbon finance mechanisms are increasingly formulating supportive policies and incentives to promote carbon farming and regenerative practices (Paustian *et al.*, 2019). These efforts are reflected in several national and international initiatives, including:

1. Soil Health Card Scheme (India)
2. per 1000 Initiative (Global)
3. Voluntary Carbon Markets (VCMs) for Regenerative Farming
4. Other Supportive Policy Instruments

These mechanisms are crucial for scaling carbon-negative farming, especially in resource-constrained regions.

9.1 Soil Health Card Scheme (India)

Launched in 2015 by the Government of India, the Soil Health Card (SHC) Scheme represents a pioneering effort in data-driven soil management and offers a strong foundation for promoting sustainable agriculture. The scheme provides farmers with field-specific reports on critical soil health indicators, including soil organic carbon (SOC), pH, and macro- and micronutrient levels (GOI, 2017). Based on laboratory analyses, the program delivers customized recommendations for fertilizer use and organic inputs, thereby indirectly encouraging carbon-positive practices such as composting, cover cropping, and reduced tillage.

As of 2020, the SHC initiative has reached over 110 million farmers across the country, significantly increasing awareness of SOC's importance in

enhancing soil fertility and long-term agricultural sustainability ([Kaur et al., 2019](#)). Although not a direct carbon market mechanism, the scheme functions as an enabling infrastructure for future carbon credit programs by providing a potential platform for Monitoring, Reporting, and Verification (MRV) of soil carbon ([Petropoulos et al., 2025](#)). Thus, the SHC scheme not only promotes better soil stewardship but also supports India's Nationally Determined Contributions (NDCs) under the Paris Agreement, laying the groundwork for climate-smart agriculture.

9.2 per 1000 Initiative (Global)

The 4 per 1000 Initiative, launched during COP21 in 2015, presents a global strategy for climate mitigation through soil. It proposes that increasing soil carbon stocks worldwide by just 0.4% (or 4 per 1000) annually could offset a significant portion of anthropogenic CO₂ emissions ([Minasny et al., 2017](#)). The initiative emphasizes the adoption of agroecology, conservation agriculture, agroforestry, and other sustainable land management practices as effective tools for enhancing soil organic carbon (SOC) sequestration.

Since its inception, the initiative has garnered support from over 70 national governments, alongside hundreds of research institutions and civil society organizations, creating a broad and collaborative international network (4p1000, 2024). By bridging the gap between science, policy, and on-ground implementation, it aims to integrate SOC enhancement targets into national climate strategies, land restoration efforts, and carbon finance frameworks. Notably, several countries have already incorporated SOC goals into their Nationally Determined Contributions (NDCs) under the United Nations Framework Convention on Climate Change ([UNFCCC, 2022](#)). The 4 per 1000 Initiative marks a significant milestone in elevating soil carbon to the forefront of global climate policy and sustainable development agendas.

9.3 Voluntary Carbon Markets (VCMs) for Regenerative Farming

The voluntary carbon market (VCM) is emerging as a promising financial mechanism that rewards farmers for enhancing soil organic carbon (SOC) through regenerative practices. By adopting climate-smart methods such as no-till farming, cover cropping, and the application of biochar, farmers can generate measurable increases in SOC and earn carbon credits, which are then sold to corporate or institutional buyers seeking to offset their emissions ([Loke *et al.*, 2022](#)).

Robust protocols developed by leading standards such as Verra's VM0042, the Gold Standard, and the Regen Network provide comprehensive Measurement, Reporting, and Verification (MRV) frameworks to ensure credibility and transparency in quantifying SOC gains ([Gold Standard, 2020](#); [Verra, 2023](#)). Platforms like Indigo Ag and Nori have pioneered digital soil carbon marketplaces, connecting growers directly to buyers of high-integrity, nature-based carbon offsets ([Imvelo Ltd, 2024](#)). Although carbon prices vary across projects and regions, early participants in these markets have received payments ranging from \$15 to \$30 per ton of CO₂-equivalent sequestered, offering a valuable revenue stream, especially for smallholder and low-input farmers ([Baranski & MacFarlane, 2021](#)). When aligned with national climate finance and sustainability goals, VCMs represent a scalable incentive model for transitioning to carbon-negative agricultural systems.

9.4 Other Supportive Policy Instruments

In addition to direct carbon incentive mechanisms, a range of national and international programs are advancing soil carbon restoration through broader agricultural and climate policy frameworks. In India, schemes like the Paramparagat Krishi Vikas Yojana (PKVY) and the Mission on Organic Value Chain Development provide subsidies for composting, biochar

application, and organic inputs, thereby indirectly promoting SOC enhancement ([MoA&FW, 2023](#)). State-level agroecology movements such as Zero Budget Natural Farming (ZBNF) in Andhra Pradesh and the organic farming model of Sikkim further contribute to SOC gains through diverse cropping patterns, minimal soil disturbance, and the exclusion of synthetic chemicals ([Khadse *et al.*, 2017](#)).

Public-private partnerships are also playing a pivotal role; collaborations among institutions like ICAR, the National Remote Sensing Centre (NRSC), and agricultural technology startups are advancing soil carbon monitoring platforms, digital extension tools, and regenerative certification programs ([CABI, 2021](#)). On the global front, initiatives such as the World Bank's Climate-Smart Agriculture (CSA) framework and carbon-integrated development projects supported by the International Fund for Agricultural Development (IFAD) are embedding soil carbon practices within sustainable livelihood models ([World Bank, 2021](#); IFAD, 2022). Collectively, these efforts are aligning soil health improvement, rural resilience, and climate change mitigation under a unified and inclusive policy vision.

10 Challenges and Future Perspectives

While soil health and carbon sequestration lie at the heart of carbon-negative farming, translating these principles into widespread practice faces a number of scientific, economic, institutional, and socio-cultural barriers. Despite mounting evidence supporting the climate and agronomic benefits of increasing soil organic carbon (SOC), farmers often struggle with limited access to technical knowledge, reliable measurement tools, and financial incentives necessary to implement and sustain regenerative practices. In many regions, particularly in the Global South, smallholder farmers face competing land use pressures, inadequate policy support, and weak market linkages for organic or carbon-smart products.

Moreover, the complexity of soil-carbon dynamics, driven by climate, land use history, and microbial interactions, presents challenges for accurately quantifying, verifying, and monetizing SOC gains through carbon markets. The lack of standardized MRV (Measurement, Reporting, and Verification) frameworks and fragmented policy landscapes further hinder the scaling of carbon-farming initiatives.

Looking ahead, the future of carbon-negative farming will depend on technological innovation, robust science-policy integration, and equitable financial models that reward ecosystem stewardship. Emerging tools, such as satellite-based monitoring, AI-powered soil diagnostics, and digital advisory platforms, offer promise for scaling impact. However, success will ultimately hinge on inclusive governance, farmer capacity-building, and aligning global climate goals with local agronomic realities.

1. Measurement Uncertainty and Verification Difficulty
2. Reversibility of Carbon Gains under Drought or Tillage
3. Farmer Adoption and Socio-Economic Constraints

10.1 Measurement Uncertainty and Verification Difficulty

Quantifying changes in soil organic carbon (SOC) across different spatial and temporal scales continues to pose a significant challenge ([Minasny *et al.*, 2017](#); [Paustian *et al.*, 2019](#)). Spatial variability is a major hurdle, as heterogeneity in soil texture, historical land use, and management practices can lead to wide variability in SOC levels even within a single plot. Similarly, temporal fluctuations, including seasonal and interannual changes, necessitate the collection of long-term datasets to accurately detect meaningful trends in SOC ([Smith *et al.*, 2020](#)).

From a technical perspective, while laboratory-based dry combustion methods offer high accuracy, they are cost-intensive and impractical for

large-scale or routine monitoring. Alternative techniques such as Loss-on-Ignition (LOI) and spectroscopic methods like Near-Infrared (NIR) and Mid-Infrared (MIR) spectroscopy offer more scalable solutions but require careful calibration for specific soil types and conditions to ensure reliable results ([FAO, 2021](#)).

Furthermore, in the context of carbon markets, robust Measurement, Reporting, and Verification (MRV) frameworks are essential to uphold the environmental integrity and credibility of tradable carbon credits (Gold Standard, 2023; [Verra, 2023](#)). Addressing these challenges will require continued innovation in digital soil mapping, remote sensing, and the development of machine learning-based carbon prediction models that can improve the accuracy, affordability, and scalability of SOC assessments ([Scharlemann *et al.*, 2014](#); Loke *et al.*, 2022).

10.2 Reversibility of Carbon Gains under Drought or Tillage

Soil carbon sequestration is inherently reversible, and carbon once stored in soils can be rapidly re-emitted into the atmosphere under conditions of poor land management or environmental stress ([Lal, 2004](#); Bradford *et al.*, 2016). Practices like tillage disrupt stable soil aggregates, exposing protected organic carbon to microbial oxidation and increasing susceptibility to erosion. Similarly, drought conditions, exacerbated by climate change, limit plant growth and reduce carbon inputs to the soil, while also accelerating carbon losses through enhanced microbial respiration ([Biederman & Harpole, 2013](#)).

In addition, land-use changes that revert soils to conventional agriculture with intensive inputs and disturbance can undo decades of carbon accumulation within a few seasons. This raises critical concerns about the permanence of SOC gains, a foundational requirement in both scientific evaluations and carbon market accounting. To safeguard long-term carbon

storage, it is imperative to adopt and maintain sustainable, resilient farming practices that can withstand climatic variability and support continued carbon retention in soils ([IPCC, 2019](#)).

10.3 Farmer Adoption and Socio-Economic Constraints

Despite clear scientific evidence supporting the benefits of soil carbon sequestration, widespread farmer adoption is often hindered by a combination of economic, informational, and institutional challenges ([Pretty *et al.*, 2018](#)). Many farmers, particularly in developing regions, face significant knowledge gaps and lack technical skills, with limited awareness of the climate and agronomic advantages of improved soil health. Inadequate access to training and extension services further compounds these issues.

Economic barriers are equally significant. High initial investment costs for carbon-positive inputs such as compost, biochar, and cover crop seeds can be prohibitive especially for smallholder and marginal farmers ([Thierfelder *et al.*, 2015](#)). Moreover, the economic returns from carbon-sequestering practices are often delayed, conflicting with the immediate livelihood needs of rural households.

Additional hurdles include poor access to markets, weak connections to voluntary carbon trading platforms, and the absence of reliable price guarantees. Land tenure insecurity also discourages long-term investment in sustainable land management, undermining the incentive for soil stewardship ([Khadse *et al.*, 2017](#)). To overcome these constraints, it is crucial to empower farmers through improved extension services, affordable credit systems, and inclusive carbon financing mechanisms that align climate goals with local development priorities ([FAO & IFAD, 2022](#)).

11 Future Research and Innovations

As the urgency to mitigate climate change intensifies, advancing soil carbon science and its practical application has become a critical research priority. Emerging frontiers focus on deepening our understanding of carbon dynamics, improving measurement technologies, and developing innovative management practices that maximize soil carbon storage. Integrating these scientific advances with socio-economic insights will be key to scaling carbon-negative farming globally. The following areas highlight some of the most promising directions in this evolving field:

1. Deeper Soil Carbon Pools
2. Microbial-Derived Carbon and Necromass
3. Precision Carbon Farming
4. Biochar and Novel Amendments
5. Socio-Economic and Policy Research

11.1 Deeper Soil Carbon Pools

Most current soil carbon models and sequestration efforts primarily focus on the top 30 cm of soil, yet the subsoil layers below 30 cm often contain larger and more stable carbon reservoirs that remain largely underexplored. Research into deep-rooting plants, perennial cropping systems, and the unique microbial communities residing in subsoils has the potential to unlock new strategies for long-term carbon storage. Understanding how carbon is stabilized at these depths could significantly enhance overall sequestration potential and resilience against disturbances ([Rumpel & Kögel-Knabner, 2011](#)).

11.2 Microbial-Derived Carbon and Necromass

Recent advances reveal that microbial necromass, the remains of dead microbial cells, constitutes a major and stable component of soil organic carbon. Unlike fresh plant residues, microbial necromass is more resistant to

decomposition and contributes to long-term carbon stabilization. By deepening our understanding of soil microbiome composition and function, scientists can develop targeted management practices that enhance microbial biomass production and necromass formation, thereby improving carbon sequestration efficiency ([Kallenbach *et al.*, 2016](#); [Liang *et al.*, 2019](#)).

11.3 Precision Carbon Farming

The integration of cutting-edge technologies such as Geographic Information Systems (GIS), remote sensing, Internet of Things (IoT) sensors, and artificial intelligence (AI)-based decision support tools is transforming soil carbon management. These innovations enable precise, site-specific monitoring of soil carbon dynamics, real-time feedback on soil health, and optimized input use tailored to local conditions. Precision carbon farming allows for more efficient adoption of regenerative practices, reducing costs and maximizing carbon gains at the landscape scale ([Mulla, 2013](#); Stockmann *et al.*, 2015).

11.4 Biochar and Novel Amendments

Biochar, a form of stable charcoal produced from biomass, shows great promise as a soil amendment that can enhance soil organic carbon levels, improve nutrient retention, and increase water-holding capacity. However, there is a need for further research to identify optimal biochar feedstocks, production techniques, and application rates. Additionally, exploring the combined use of biochar with compost or mineral fertilizers may yield synergistic effects that boost soil health and carbon stabilization, thus advancing the practical application of these novel amendments ([Lehmann & Joseph, 2015](#)).

11.5 Socio-Economic and Policy Research

Beyond the scientific and technical aspects, understanding the socio-economic drivers and policy environments is critical to the success of soil carbon initiatives. Research focused on farmer decision-making, incentive structures, and the efficacy of carbon finance mechanisms helps ensure that interventions are both practical and equitable. Integrating socio-economic insights with policy design will support widespread adoption of carbon farming practices and foster sustainable rural development aligned with climate goals ([Phelan, 2024](#)).

12 Conclusion and Way Forward

Soil health and carbon sequestration are fundamental components of carbon-negative farming systems that mitigate climate change while enhancing agricultural productivity and ecosystem resilience. Increasing soil organic carbon improves soil structure, water retention, nutrient cycling, and biodiversity, delivering multiple co-benefits for sustainable food systems. Despite scientific advances and emerging technologies for measuring and managing soil carbon, challenges remain in accurately quantifying sequestration, ensuring permanence, and scaling farmer adoption amid socio-economic constraints. Policy frameworks and market incentives play a vital role in supporting carbon-positive practices.

Soil carbon sequestration represents a promising, nature-based solution for climate mitigation that simultaneously promotes soil fertility and farm resilience. However, realizing its full potential requires overcoming technical, economic, and institutional barriers. Advances in measurement tools, deeper understanding of microbial processes, and precision farming innovations offer pathways to improve efficacy. Equally important are inclusive policies, financial mechanisms, and capacity-building initiatives that empower farmers to adopt sustainable practices. Integrating scientific

knowledge with practical, equitable approaches will be critical to embedding soil carbon strategies in global climate action.

To advance soil carbon sequestration as a core strategy for carbon-negative farming, it is essential to invest in scalable and cost-effective soil organic carbon (SOC) monitoring technologies while standardizing Measurement, Reporting, and Verification (MRV) protocols to ensure transparency and maintain the integrity of carbon credits. Promoting sustainable management practices such as reduced tillage, cover cropping, and the application of organic amendments can significantly improve long-term soil carbon storage. Expanding policy support and financial incentives through inclusive carbon finance schemes, subsidies, and extension services will help lower barriers faced by smallholder and marginalized farmers.

Further, prioritizing interdisciplinary research focused on soil microbiomes and deeper carbon pools beyond the topsoil can unlock new pathways for stable carbon sequestration. Strengthening farmer capacity through enhanced training programs, digital advisory platforms, and participatory knowledge-sharing approaches is critical to increase awareness and adoption of regenerative practices. Additionally, integrating socio-economic considerations by designing policies that address land tenure security, improve market access, and support farmers' livelihood needs will ensure equitable benefits and sustained engagement.

By implementing these integrated strategies, soil health and carbon sequestration can be firmly established as the cornerstone of climate-resilient, carbon-negative farming systems worldwide.

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Chapter - 10

Carbon Accounting and Measurement Tools

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1 Introduction

As global concerns over climate change intensify, driven by rising concentrations of greenhouse gases (GHGs) such as carbon dioxide (CO₂), the need for accurate tracking and management of carbon flows in natural and managed systems has become paramount ([IPCC, 2022](#)). The Agriculture, Forestry, and Other Land Use (AFOLU) sectors hold a unique dual role: they act as both sources of GHG emissions and as vital carbon sinks that sequester and store atmospheric carbon. Understanding these complex carbon dynamics, how much carbon is emitted, absorbed, or stored, is essential for developing effective mitigation strategies, participating meaningfully in carbon markets, and fulfilling international climate commitments such as those outlined in the Paris Agreement ([UNFCCC, 2015](#)).

At the core of this understanding lies carbon accounting, a comprehensive and systematic methodology designed to quantify, monitor, and manage the flow of carbon and other greenhouse gases associated with a specific entity, activity, or system ([WRI & WBCSD, 2004](#)). Whether applied at the scale of individual farms, industrial operations, cities, nations, or global supply chains, carbon accounting involves identifying all significant sources of emissions ranging from fossil fuel use and agricultural practices to land-use changes as well as carbon sinks, including

forests, soils, and oceans that absorb and store CO₂ ([IPCC, 2006](#); [ISO, 2018](#)).

The purpose of carbon accounting is to provide a clear and credible picture of the net carbon balance, often expressed as carbon dioxide equivalent (CO₂e), which represents the combined effect of all relevant GHGs. By systematically measuring emissions, sequestration, and changes in carbon stocks over time, carbon accounting enables stakeholders to make informed decisions and implement strategies that reduce emissions and enhance removals. The objectives of carbon accounting are multifaceted and critical for advancing climate action:

- **Identify Emission Sources and Sinks:** Pinpointing where emissions originate and where carbon is stored allows for targeted mitigation and conservation efforts ([FAO, 2017](#)).
- **Inform Decision-Making:** Providing robust data empowers governments, organizations, and land managers to adopt sustainable practices and climate-smart interventions ([IPCC, 2019](#)).
- **Track Progress:** Establishing measurable baselines and monitoring trends facilitates transparent reporting and evaluation of progress toward emission reduction targets ([UNFCCC, 2015](#)).
- **Support Transparency and Reporting:** Accurate carbon data fosters accountability to stakeholders, investors, regulators, and the broader public ([WRI & WBCSD, 2015](#)).
- **Enable Carbon Markets:** Reliable accounting forms the foundation for developing carbon offset projects, generating verified carbon credits, and engaging in emissions trading systems that incentivize reductions ([Kossoy et al., 2015](#)).
- **Guide Policy and Regulation:** Evidence-based accounting informs the design of effective climate policies and realistic targets at local,

national, and global levels ([OECD, 2018](#)).

In a world increasingly shaped by climate imperatives, carbon accounting translates abstract environmental goals into measurable, actionable outcomes. It ensures that emissions and sequestration efforts are quantified consistently and transparently, underpinning effective climate action across sectors and scales. As voluntary carbon markets expand and corporate sustainability commitments grow, rigorous carbon accounting will remain central to bridging the gap between intention and impact ([Hamilton *et al.*, 2017](#)).

2 Key Concepts in Carbon Accounting

To effectively implement and interpret carbon accounting, it is essential to understand the fundamental concepts that underpin how carbon is measured, managed, and reported. These concepts provide the scientific foundation for assessing emissions and removals within ecosystems, agricultural landscapes, and production systems. The following key terms clarify the main components of carbon dynamics and form the basis for all carbon accounting frameworks:

1. Carbon Emissions
2. Carbon Sequestration
3. Carbon Stocks
4. Carbon Fluxes
5. Carbon Footprint

2.1 Carbon Emissions

Carbon emissions arise from multiple sectors that release carbon dioxide (CO₂) and other greenhouse gases (GHGs) such as methane (CH₄) and nitrous oxide (N₂O) into the atmosphere. These emissions are primarily

driven by energy use, land-use changes, and industrial processes. Understanding their sources is essential for developing mitigation strategies and climate policies.

- **Fossil Fuel Combustion:** One of the most dominant contributors is fossil fuel combustion, which involves burning coal, oil, and natural gas for electricity generation, industrial operations, heating, and transportation. These carbon-rich fuels release vast amounts of CO₂ when oxidized. Emissions from vehicles, thermal power stations, aviation, and maritime transport are major examples of this category. According to the International Energy Agency, “the combustion of fossil fuels accounts for approximately 75% of global greenhouse gas emissions and nearly 90% of all carbon dioxide emissions” ([IEA, 2021](#)). Despite growing momentum toward renewable energy, fossil fuels continue to dominate the global energy mix, especially in rapidly developing economies.
- **Agricultural Practices:** Agricultural practices are another significant source of emissions, though they differ by emitting mainly non-CO₂ GHGs such as CH₄ and N₂O. The application of synthetic and organic fertilizers introduces reactive nitrogen into the soil, which drives microbial processes like nitrification and denitrification that emit nitrous oxide. Additionally, enteric fermentation in ruminant livestock such as cattle and sheep produces methane, a potent greenhouse gas with a global warming potential (GWP) over 265 times greater than CO₂ over a 100-year period. Manure management, particularly under anaerobic conditions in storage lagoons or pits, also emits both CH₄ and N₂O, depending on the treatment method. [Smith et al. \(2014\)](#) observe that “agriculture contributes 10-12% of total global anthropogenic GHG

emissions, largely through methane from livestock and nitrous oxide from fertilized soils” . These emissions are particularly high in livestock-intensive and fertilizer-reliant production systems.

- **Deforestation and Land Use Change:** Deforestation and land use change are significant drivers of CO₂ emissions. When forests, wetlands, or grasslands are cleared for agriculture or urban expansion, the carbon stored in biomass and soil is released into the atmosphere. This is especially problematic in tropical regions, where vast areas of forest are cleared for cattle grazing and the cultivation of commercial crops like palm oil and soy. As [Harris *et al.* \(2012\)](#) report, “land use change, especially deforestation, is responsible for about 11% of total anthropogenic GHG emissions globally.” The impact is twofold: not only is carbon released, but the capacity of natural ecosystems to sequester CO₂ is diminished, creating a lasting climate debt.
- **Industrial Processes:** Industrial processes also contribute directly to GHG emissions, independent of fossil fuel combustion. For instance, cement manufacturing emits CO₂ during the chemical transformation of limestone (CaCO₃) into lime (CaO), a process known as calcination. Similarly, chemical production, particularly of nitric acid and ammonia, releases substantial amounts of nitrous oxide. The metallurgical industry, especially aluminum and steel production, emits both CO₂ and high-GWP gases like perfluorocarbons (PFCs). Worrell *et al.* (2018) note that “industrial activities contributed nearly one-fifth of total global GHG emissions in 2016, with emissions from cement, steel, and chemicals being particularly significant.”

- **Waste Management:** Finally, waste management is an often-overlooked but critical source of GHG emissions. Organic matter in solid waste decomposes under anaerobic conditions in landfills, producing methane, while improperly managed wastewater can emit both methane and nitrous oxide. Additionally, the open burning of municipal waste not only emits CO₂ but also produces black carbon, a short-lived climate pollutant that has a high warming potential and contributes to atmospheric heating and glacier melting. These emissions are prevalent in regions with inadequate waste infrastructure and unregulated disposal practices.
- Together, these sectors, energy, agriculture, land-use change, industry, and waste, constitute the major pillars of global GHG emissions. Mitigating their impacts requires sector-specific strategies and coordinated climate governance across scales.

2.2 Carbon Sequestration

Carbon sequestration refers to the process of capturing and storing atmospheric carbon dioxide (CO₂) in natural or artificial reservoirs to reduce the concentration of CO₂ in the atmosphere. It plays a vital role in climate change mitigation by acting as a biological and geochemical counterbalance to emissions. According to [Lal \(2004\)](#), carbon sequestration is “the process of transferring atmospheric CO₂ into long-lived carbon pools and securely storing it so that it is not re-emitted for a considerable period of time.” These carbon pools include vegetation, soil, oceans, and in some cases, geological formations. Enhancing these natural sinks is a practical strategy for offsetting emissions from fossil fuels and other human activities. The major pathways of carbon sequestration include several natural processes and ecosystems that act as effective carbon sinks:

- **Photosynthesis in Plants:** At the core of carbon sequestration is photosynthesis, a biological process where plants capture atmospheric CO₂ and convert it into organic compounds such as carbohydrates. This fixed carbon is stored in plant biomass leaves, stems, branches, trunks, and roots until decomposition or combustion occurs. Forests, in particular, are significant carbon sinks due to their extensive biomass. As [Foley *et al.* \(2005\)](#) note, “terrestrial ecosystems store approximately 2,000 gigatons of carbon, more than three times the amount found in the atmosphere.” Forest restoration, afforestation, and agroforestry are thus critical practices for enhancing carbon storage in vegetation.
- ***Soil Organic Carbon (SOC):*** Soils are the largest terrestrial carbon pool, storing more carbon than the atmosphere and plant biomass combined. Soil organic carbon (SOC) originates from plant litter, root exudates, and microbial biomass, which are broken down and stabilized in the soil matrix. This carbon can remain stored for decades to centuries, especially under conservation practices like no-till farming, cover cropping, and organic amendments. Jobbagy and Jackson (2000) explain that “the vertical distribution of SOC is largely influenced by vegetation type, climate, and land management, with deep-rooted systems contributing significantly to long-term sequestration.” Sustainable soil management thus not only improves fertility but also mitigates climate change.
- ***Wetlands and Peatlands:*** Wetlands and peatlands represent unique ecosystems that are highly efficient at carbon sequestration. Due to their waterlogged, anaerobic soils, organic matter decomposition is significantly slowed, leading to carbon accumulation over thousands of years. These ecosystems store a disproportionate

amount of carbon relative to their area. [Bridgham et al. \(2006\)](#) emphasize that “peatlands, while covering just 3% of the Earth’s land surface, store about one-third of the world’s soil carbon.” However, when drained or disturbed, these systems become major carbon sources, underscoring the need for wetland protection and restoration.

- ***Ocean Sequestration:*** The oceans are the largest carbon sink on Earth, absorbing about one-fourth of anthropogenic CO₂ emissions annually. Carbon enters the ocean via two primary mechanisms: the solubility pump, where CO₂ dissolves in surface waters and is transported to deeper layers, and the biological pump, wherein phytoplankton photosynthesize and transfer carbon through the food web or sedimentation. [Sabine et al. \(2004\)](#) report that “oceans have absorbed roughly 118 ± 19 petagrams of carbon from the atmosphere since the beginning of the industrial era.” While vital for carbon regulation, ocean sequestration is not without risks, such as ocean acidification, which can threaten marine ecosystems.

In essence, enhancing carbon sequestration in plants, soils, wetlands, and oceans is crucial for stabilizing the climate. Natural climate solutions, including reforestation, agroecology, wetland conservation, and regenerative agriculture, offer co-benefits for biodiversity, water security, and rural livelihoods. While sequestration is not a substitute for emissions reduction, it is an essential component of an integrated climate mitigation portfolio.

2.3 Carbon Stocks

Carbon stocks refer to the amount of carbon stored in various components of the Earth’s system at a given point in time. These components, also

known as carbon pools, include soil, vegetation, dead organic matter, sediments, and fossil reserves. Measuring carbon stocks is essential to assess how much carbon a system holds and track changes over time, whether gains through sequestration or losses through disturbance.

The Intergovernmental Panel on Climate Change ([IPCC, 2006](#)) defines carbon stocks as “the quantity of carbon contained in a pool, measured in mass units such as tonnes of carbon (t C) or carbon dioxide equivalent (t CO₂e).” These stocks (soil, vegetation/biomass, and dead organic matter and litter) represent either active sinks or potential sources of carbon depending on whether the system is being degraded or enhanced. The major carbon stocks can be categorized into key pools based on their location and composition, including soil, vegetation, dead organic matter, and other geological or aquatic reservoirs, each of which plays a distinct role in the global carbon cycle:

- ***Soil: Soil organic carbon (SOC)*** constitutes the largest terrestrial carbon pool, holding more carbon than the atmosphere and living vegetation combined. This carbon originates from decomposed plant and animal residues, microbial biomass, and root exudates. The amount of SOC varies significantly by soil type, climate conditions, vegetation cover, and land management practices. According to [Lal \(2004\)](#), “the world’s soils contain about 1,500 to 2,400 billion tonnes of organic carbon to a depth of 1 meter,” making them a key component in global carbon dynamics. Sustainable land use, conservation tillage, and organic amendments can help maintain or enhance this stock.
- ***Vegetation/Biomass:*** Carbon stored in vegetation includes both living biomass (e.g., leaves, stems, trunks, roots) and dead plant material (e.g., fallen branches, crop residues). Forests, grasslands,

and agricultural crops differ widely in their carbon storage potential. For instance, dense tropical forests have high aboveground carbon stocks, while annual crops hold significantly less. [Foley *et al.* \(2005\)](#) note that “terrestrial vegetation stores approximately 500 gigatons of carbon globally,” contributing significantly to short- and medium-term sequestration through photosynthesis. The type, age, and density of vegetation directly influence the size of this carbon pool.

- ***Dead Organic Matter and Litter:*** Dead organic matter, such as litter, woody debris, and partially decomposed residues, also represents a notable carbon pool, particularly in forest and wetland ecosystems. This pool is dynamic, influenced by inputs (plant residues) and outputs (microbial decomposition, fire, erosion). [Harmon *et al.* \(2004\)](#) observed that in temperate forests, “coarse woody debris can account for up to 20% of the total ecosystem carbon,” highlighting the importance of forest floor dynamics in carbon accounting. Although this pool is often overlooked, it plays a critical role in carbon cycling and soil formation.
- ***Other Pools:*** Additional carbon stocks include sedimentary carbon (e.g., in lakes, riverbeds, and ocean floors) and fossil carbon, stored in coal, oil, and natural gas reserves. While sediments act as long-term sinks, fossil fuels are inert stocks that, once extracted and burned, contribute to net carbon emissions. The [IPCC \(2006\)](#) emphasizes that fossil reserves are among the largest geological carbon pools, storing an estimated 4,000 gigatons of carbon, much of which has been mobilized during the industrial era.

2.4 Carbon Fluxes

Carbon fluxes refer to the movement of carbon between different reservoirs or pools, such as the atmosphere, vegetation, soil, and oceans, over a specified period. These fluxes represent the rates at which carbon is transferred and are typically measured in terms like tonnes of carbon per hectare per year ($\text{t C ha}^{-1} \text{ yr}^{-1}$) or grams of carbon per square meter per year ($\text{g C m}^{-2} \text{ yr}^{-1}$). The concept is central to understanding ecosystem carbon dynamics, evaluating net carbon budgets, and modeling climate change feedbacks. According to Schlesinger & Bernhardt (2013), “carbon fluxes provide a dynamic view of the carbon cycle, indicating not only where carbon is stored, but how actively it is being exchanged between pools and the atmosphere.” Monitoring these exchanges enables identification of carbon sources (net emitters) and carbon sinks (net absorbers) within managed and natural systems. The key processes driving carbon movement across ecosystems include photosynthetic uptake, respiration, soil CO_2 efflux, and carbon losses through harvest or disturbances, each playing a critical role in shaping the net carbon balance:

- **Photosynthetic Uptake:** One of the most important carbon fluxes is the uptake of atmospheric CO_2 by plants during photosynthesis. Through this process, carbon is fixed into organic compounds that form the biomass of leaves, stems, roots, and fruits. This flux represents a net carbon input into terrestrial ecosystems. [Foley *et al.* \(2005\)](#) emphasize that “photosynthesis is the primary gateway through which carbon enters the terrestrial biosphere, driving both plant growth and subsequent carbon cycling.” The global gross primary production (GPP) is estimated to fix around 120 gigatons of carbon annually. Photosynthetic uptake is influenced by light, temperature, water availability, atmospheric CO_2 concentration, and nutrient status.

- ***Respiration and Decomposition:*** After carbon is fixed in plant tissues, a portion is returned to the atmosphere through autotrophic respiration (from the plants themselves) and heterotrophic respiration (from decomposers such as microbes and fungi). [Davidson & Janssens \(2006\)](#) note that “ecosystem respiration often releases more than half of the fixed carbon back into the atmosphere, reflecting both plant metabolic needs and microbial decomposition of organic matter.” The balance between carbon input via photosynthesis and loss through respiration determines the net ecosystem carbon balance (NECB). In warm and moist ecosystems, respiration rates can be especially high, reducing net carbon sequestration.
- ***Soil CO₂ Efflux:*** Soil respiration or soil CO₂ efflux, refers to the carbon dioxide released from soil as a result of microbial decomposition of organic matter and root respiration. This flux represents one of the largest components of terrestrial carbon emissions. [Bond-Lamberty & Thomson \(2010\)](#) estimate that global soil respiration contributes approximately 68-75 gigatons of CO₂ per year to the atmosphere. “Soil CO₂ efflux is driven by soil temperature, moisture, and substrate availability, and can serve as an early indicator of ecosystem carbon responses to environmental change.” This flux is particularly relevant in agricultural and forested systems, where land-use practices can either accelerate or reduce soil carbon losses.
- ***Harvest or Disturbance Losses:*** When biomass is harvested (e.g., for food, timber, or biofuel), or disturbances like fire, deforestation, and storms occur, significant amounts of stored carbon are removed or released, either directly into the atmosphere or out of the local

carbon cycle. [Houghton \(2003\)](#) describes these anthropogenic and natural disturbances as “key drivers of carbon flux variability,” particularly in forested ecosystems. Harvested biomass results in carbon losses unless it is stored in long-lived products (e.g., timber). Disturbances such as fire can result in immediate emissions, while others like logging may cause gradual losses through decomposition. These losses must be accounted for in **carbon budgets**, particularly when assessing the long-term carbon sequestration potential of ecosystems.

2.5 Carbon Footprint

The **carbon footprint** is a widely used metric that quantifies the total greenhouse gas (GHG) emissions caused directly and indirectly by a person, organization, process, or product, and is usually expressed in carbon dioxide equivalent (CO₂e). The concept allows stakeholders to understand the climate impact of different actions or systems, including those in agriculture, industry, energy, and consumption. [Wiedmann & Minx \(2008\)](#) define the carbon footprint as “a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product.” It is an essential tool in carbon accounting, sustainability reporting, and climate change mitigation planning.

- **Direct Emissions:** Direct emissions are those that originate from sources owned or directly controlled by an entity. In agriculture, this includes (i) On-farm fuel combustion (tractors, irrigation pumps), (ii) Methane from livestock (enteric fermentation), (iii) Nitrous oxide from fertilizer application, and (iv) GHG emissions from biomass burning or on-site processing. According to the

Greenhouse Gas Protocol developed by WRI and WBCSD (2004), these are categorized under Scope 1 emissions: “Direct GHG emissions occur from sources that are owned or controlled by the company.” In a farm context, this includes diesel fuel use, manure decomposition, and emissions from machinery.

- ***Indirect Emissions:*** Indirect emissions originate from external sources linked to the consumption of goods and services by an entity, yet occur outside its direct operational control. These are categorized as Scope 2 and Scope 3 emissions. Scope 2 emissions refer to indirect emissions from the generation of purchased electricity, steam, heat, or cooling such as the electricity used for irrigation pumps or greenhouse lighting. Scope 3 emissions encompass all other indirect emissions across an organization’s value chain, both upstream and downstream, including those from the manufacturing of fertilizers and pesticides, electricity used in post-harvest cooling, transportation of inputs and produce, and embedded emissions in equipment or packaging materials. As explained by WRI and WBCSD (2004), indirect emissions are “a consequence of the activities of the company, but occur at sources owned or controlled by another entity.” In many sectors, especially agriculture and food systems, Scope 3 emissions constitute the majority of the total carbon footprint.
- ***Lifecycle Emissions:*** Lifecycle emissions encompass the total greenhouse gas (GHG) emissions associated with a product or process throughout its entire life cycle from raw material extraction and manufacturing to use and final disposal or recycling. Known as a cradle-to-grave assessment, it accounts for emissions often overlooked when evaluating only one stage. For example, the

lifecycle emissions of plastic packaging include those from petroleum extraction, production, transportation, and incineration or landfill (Zamagni *et al.*, 2012). To enable comparison across different GHGs like methane (CH₄) and nitrous oxide (N₂O), emissions are expressed as carbon dioxide equivalents (CO₂e) based on their global warming potential (GWP) over 100 years ([IPCC, 2019](#)). For instance, CH₄ has 2834 times the warming potential of CO₂.

3 Carbon Measurement Methods

Carbon measurement refers to the systematic quantification of carbon stocks and fluxes across various ecological and anthropogenic pools, including the atmosphere, vegetation (biomass), soils, and harvested products. This quantification is crucial for understanding the carbon dynamics of natural and managed systems and is performed using a combination of direct and indirect methods (Smith *et al.*, 2020). Accurate and reliable carbon measurement underpins a wide range of climate-related initiatives and policies. It is essential for:

- Monitoring ecosystem services and evaluating their role in carbon sequestration and climate regulation ([IPCC, 2019](#))
- Verification and issuance of carbon credits in compliance or voluntary carbon markets ([FAO, 2017](#))
- Preparation of national greenhouse gas (GHG) inventories and the design of evidence-based mitigation strategies ([IPCC, 2006](#)).

Each of the two approaches, direct (empirical) and indirect (model-based), has its own strengths, limitations, and specific contexts of application, as outlined below.

3.1 Direct Measurements

Direct measurements involve empirical, field-based techniques that physically sample or observe components of the carbon cycle. These methods are designed to provide **site-specific, high-accuracy data** on carbon stocks and fluxes, often serving as ground-truth references for model calibration and verification. Though resource-intensive and often limited in spatial coverage, direct measurements are critical for **precise estimation** of carbon in key pools such as soil, biomass, and atmosphere. The following are commonly used direct measurement techniques:

3.1.1 Soil Sampling

Soil sampling involves collecting soil cores from different depths and locations within a field or ecosystem to determine soil organic carbon (SOC) content ([Lal, 2004](#)). These samples are brought to a laboratory where carbon content is analyzed by:

- **Dry Combustion Method:** The soil sample is combusted at high temperatures, and the released CO₂ is measured to determine organic carbon percentage. This method is highly accurate and widely used ([Nelson & Sommers, 1996](#)).
- **Chemical Methods:** Wet chemical oxidation methods (e.g., Walkley-Black method) estimate organic carbon but may underestimate total SOC compared to combustion ([Walkley & Black, 1934](#)).

This method provides a direct, site-specific measure of carbon stored in the soil, crucial for tracking changes over time, assessing soil health, and verifying carbon sequestration efforts ([FAO, 2017](#)).

3.1.2 Biomass Measurement

Biomass measurement quantifies the amount of carbon stored in living plant material, both aboveground (stems, leaves, branches) and belowground (roots) ([Brown, 2002](#)). Methods include:

- **Field Sampling:** Trees or plants are measured for diameter, height, and volume. Biomass is estimated using allometric equations that relate these physical measurements to biomass weight ([Chave *et al.*, 2005](#)).
- **Harvest Method:** Vegetation is harvested and weighed, then dried to calculate dry biomass ([Pearson *et al.*, 2005](#)).
- **Remote Sensing:** Satellites, drones, or aerial imagery use vegetation indices and LiDAR data to estimate biomass over large areas with spatial precision (Asner *et al.*, 2012). Since plant biomass is primarily composed of carbon (about 45-50% of dry weight), this measurement is a key indicator of carbon stocks in forests, croplands, and grasslands ([IPCC, 2006](#)).

3.1.3 Gas Flux Measurement

Gas flux measurement techniques directly capture and quantify the exchange of greenhouse gases (CO₂, CH₄, N₂O) between soil/plants and the atmosphere ([Livingston & Hutchinson, 1995](#)). Common approaches:

- **Closed or Static Chambers:** Transparent or opaque chambers are placed on soil or plant surfaces to trap gases for a short period. Gas samples are collected and analyzed by gas chromatography or infrared gas analyzers ([Parkin & Venterea, 2010](#)).
- **Open Chambers and Eddy Covariance Systems:** Measure gas exchange continuously and over larger spatial scales ([Baldocchi, 2003](#)).

- **Infrared Gas Analyzers (IRGA):** Measure CO₂ concentration changes in the chamber in real-time ([Luo & Zhou, 2006](#)).

These measurements provide insight into emission rates, respiration, and the impact of management practices on GHG fluxes ([Smith *et al.*, 2020](#)).

3.2 Indirect or Modeling Approaches

Indirect measurements rely on **model-based estimations, statistical relationships, and remote sensing interpretations** to infer carbon quantities and fluxes without physical sampling. These methods are particularly suited for **large-scale or long-term assessments**, where direct measurements may be impractical or cost-prohibitive. Although they may involve greater uncertainty compared to direct approaches, they are essential for **scaling up carbon assessments**, informing policy frameworks, and estimating regional or national carbon budgets. Indirect methods are often integrated with direct data for improved accuracy and validation. The following are key indirect methodologies commonly used to estimate carbon stocks and fluxes across diverse systems and scales:

3.2.1 Emission Factors

Emission factors are standardized coefficients that estimate the average emissions associated with a unit of activity ([IPCC, 2006](#)). For example:

- Kilograms of CO₂ emitted per liter of diesel burned.
- Methane emissions per head of cattle per day.

These factors are developed based on extensive measurements and literature and are often provided by institutions like the IPCC. They allow quick estimation of emissions when direct measurement is not feasible, supporting GHG inventories and reporting ([WRI & WBCSD, 2004](#)).

3.2.2 Remote Sensing

Remote sensing involves the use of satellite or aerial imagery and sensors to gather data about the Earth's surface without physical contact ([Asner, 2009](#)). Applications include:

- **Vegetation Indices (e.g., NDVI):** Quantify vegetation health and density to estimate biomass and carbon stocks ([Pettorelli *et al.*, 2005](#)).
- **LiDAR (Light Detection and Ranging):** Provides 3D structural data of forests and crops to estimate biomass volume ([Lefsky *et al.*, 2002](#)).
- **Hyperspectral Imaging:** Differentiates plant species and assesses carbon content more precisely ([Ustin *et al.*, 2004](#)).

Remote sensing enables carbon stock assessment over large, inaccessible, or heterogeneous areas and supports temporal monitoring of land-use changes and carbon sequestration ([Goetz *et al.*, 2009](#)).

3.2.3 Process-Based Models

Process-based models simulate carbon cycling by integrating environmental data, soil properties, crop types, and management practices ([Parton *et al.*, 1994](#)). Examples include:

- **DNDC (DeNitrification-DeComposition Model):** Models soil carbon and nitrogen cycles, predicting GHG emissions and SOC changes (Li *et al.*, 1992).
- **Century Model:** Simulates long-term soil organic matter dynamics and nutrient cycling ([Parton *et al.*, 1987](#)).
- **DayCent Model:** Daily time-step version of Century for detailed ecosystem modelling ([Del Grosso *et al.*, 2005](#)).

These models use input data such as temperature, precipitation, soil texture, crop rotation, and fertilizer use to estimate carbon fluxes and stocks, allowing scenario analysis and forecasting under different management or climate conditions ([Ogle et al., 2010](#)).

4 Carbon Accounting Frameworks & Standards

To ensure consistency, comparability, and credibility in quantifying greenhouse gas (GHG) emissions and removals, several internationally recognized carbon accounting frameworks and standards have been developed ([WRI & WBCSD, 2004](#); [IPCC, 2006](#); [ISO, 2018](#)). These frameworks provide the methodological foundation for measuring, reporting, and verifying emissions across different sectors, activities, and geographies. They serve as essential tools for organizations, governments, and projects aiming to manage their carbon footprints and contribute to climate goals ([BSI, 2008](#)). The most widely used frameworks include the ***Greenhouse Gas Protocol (GHG Protocol)***, ***ISO 14064 standards***, and sector-specific guidelines such as those developed by the ***Intergovernmental Panel on Climate Change (IPCC)***.

These standards guide users in defining organizational and operational boundaries, selecting appropriate emission factors, and applying principles of transparency, accuracy, completeness, consistency, and relevance ([ISO, 2018](#); [IPCC, 2019](#)). As climate action becomes a global priority, adherence to robust carbon accounting standards has become critical for enabling effective climate policy, carbon trading mechanisms, and sustainability ([FAO, 2017](#)).

Several established frameworks and standards guide the systematic measurement, reporting, and verification of greenhouse gas emissions and removals across various sectors and scales. Key among these are:

1. **IPCC Guidelines:** The Intergovernmental Panel on Climate Change provides global protocols for GHG inventories, including agriculture and forestry ([IPCC, 2006](#); [2019](#)).
2. **GHG Protocol:** The Greenhouse Gas Protocol provides standards and tools for carbon accounting at corporate and project levels ([WRI & WBCSD, 2004](#)).
3. **ISO 14064:** International standards for quantifying and reporting GHG emissions and removals ([ISO, 2018](#)).
4. **PAS 2050:** Specification for assessing product carbon footprints ([BSI, 2008](#)).

4.1 IPCC Guidelines

The Intergovernmental Panel on Climate Change (IPCC) provides internationally recognized guidelines for national greenhouse gas inventories. These guidelines are crucial for countries to systematically quantify and report their GHG emissions and removals in a consistent and transparent manner, particularly under the United Nations Framework Convention on Climate Change (UNFCCC) ([IPCC, 2006](#)).

- **Scope:** The guidelines cover all sectors, including energy, industrial processes, agriculture, land use, land-use change and forestry (LULUCF), and waste.
- **Agriculture & Forestry:** The IPCC Guidelines provide detailed methodologies for estimating emissions from livestock, soil management, fertilizer use, crop production, biomass burning, deforestation, afforestation, and forest management ([IPCC, 2019](#)).
- **Tiered Approach:** They offer different tiers (Tier 1, Tier 2, Tier 3) for emission estimation, ranging from default emission factors and

activity data (Tier 1) to country-specific data and advanced modeling approaches (Tier 3) ([IPCC, 2006](#)).

- **Updates:** The guidelines are periodically updated to reflect the latest science and improve accuracy (e.g., the 2006 IPCC Guidelines, with supplements and the forthcoming 2019 Refinement). The IPCC Guidelines serve as the global reference for governments in compiling national GHG inventories and are the backbone for international climate negotiations and reporting.

4.2 GHG Protocol

The GHG (Greenhouse Gas) Protocol is a widely adopted corporate and project-level standard for measuring, managing, and reporting greenhouse gas emissions ([WRI & WBCSD, 2004](#)).

- **Developed by:** The World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD).
- **Scope:** It includes standards for:
 - **Corporate Accounting and Reporting:** Defines organizational boundaries, scopes of emissions (Scope 1 - direct emissions, Scope 2 - indirect emissions from purchased energy, and Scope 3 - other indirect emissions across the value chain).
 - **Project Accounting:** Guidance for quantifying emission reductions from climate projects, such as renewable energy or reforestation.
 - **Tools and Guidance:** Provides practical tools and calculation methods for companies and organizations to develop GHG inventories aligned with international standards.

- **Use Case:** It's the foundation for most corporate sustainability reports, carbon disclosure projects, and voluntary carbon markets ([CDP, 2022](#)).

By following the GHG Protocol, organizations can transparently track their emissions, identify reduction opportunities, and credibly report their climate impact.

4.3 Iso 14064

ISO 14064 is an international standard series developed by the International Organization for Standardization (ISO) specifically for greenhouse gas accounting and verification ([ISO, 2018](#)).

- Parts of ISO 14064:
 - **Part 1:** Specification with guidance at the organization level for quantification and reporting of GHG emissions and removals.
 - **Part 2:** Guidance for quantifying, monitoring, and reporting GHG projects, important for carbon offset projects.
 - **Part 3:** Requirements for validating and verifying GHG assertions, ensuring credibility and transparency.
- **Applicability:** ISO 14064 standards are applicable globally across industries, governments, and projects, providing consistent requirements that support comparability and credibility.
- **Benefits:** Helps organizations establish robust GHG inventories, implement emission reduction projects, and undergo third-party verification to assure stakeholders of data reliability. ISO 14064 is often integrated into corporate sustainability strategies and used for

compliance with emissions trading schemes and voluntary carbon markets.

4.4 Pas 2050

PAS 2050 (Publicly Available Specification 2050) is a standard developed by the British Standards Institution (BSI) to assess the life cycle greenhouse gas emissions of goods and services, commonly referred to as product carbon footprints ([BSI, 2008](#)).

- **Focus:** It provides a consistent method to evaluate the total GHG emissions associated with all stages of a product's life cycle, including raw material extraction, manufacturing, distribution, use, and disposal.
- **Goal:** To enable businesses to identify emission hotspots in their products and work on reducing their environmental impact.
- **Application:** Used by companies to support product labeling, supply chain management, and consumer information.
- **Alignment:** PAS 2050 is aligned with ISO standards on life cycle assessment (ISO 14040 and 14044) and complements corporate-level standards like the GHG Protocol.

By applying PAS 2050, organizations can measure the carbon footprint of individual products, providing transparency and fostering sustainable consumption choices.

5 Carbon Accounting in Agriculture

Agriculture plays a dual role in the climate system, acting as both a significant source and a potential sink of greenhouse gas (GHG) emissions ([Smith *et al.*, 2014](#); [IPCC, 2019](#)). Emissions arise predominantly from methane (CH₄) released through enteric fermentation and flooded rice

fields, nitrous oxide (N₂O) from nitrogen-rich soils, and carbon dioxide (CO₂) due to land-use changes and fossil fuel use in farm operations ([Lal, 2004](#); [IPCC, 2019](#)). Accurately accounting for these emissions and carbon removals is essential for guiding climate change mitigation strategies in the agricultural sector. However, the sector's inherent complexity, driven by biological processes, spatial variability, and climatic sensitivity, poses significant measurement challenges (Ogle *et al.*, 2010).

To address these complexities, several standardized frameworks and tools have been developed, including the IPCC Guidelines, the GHG Protocol's Agricultural Guidance, and decision-support tools such as the Cool Farm Tool and EX-ACT ([Hillier *et al.*, 2011](#); [FAO, 2017](#)). These platforms help streamline emissions estimation across different farming systems, practices, and inputs. Robust carbon accounting in agriculture not only informs sustainable land management and climate-smart agriculture but also supports the development of carbon markets and targeted policy interventions at multiple governance levels ([FAO, 2017](#); Hamilton *et al.*, 2017).

The core components of agricultural carbon accounting include the quantification of emissions and sequestration across various aspects of the farming system. These components are outlined below:

1. **Soil Organic Carbon (SOC):** Monitoring SOC change is critical as it acts as a major carbon sink ([Lal, 2004](#); [Smith *et al.*, 2014](#)).
2. **Crop and Livestock Emissions:** Account for CO₂, methane (CH₄), and nitrous oxide (N₂O) emissions from cultivation, fertilizer application, enteric fermentation, and manure management ([IPCC, 2019](#); [Ogle *et al.*, 2010](#)).
3. **Carbon Credits:** Quantified sequestration can be converted into carbon credits for trading or incentive programs ([Kossoy *et al.*](#),

[2015](#); Hamilton *et al.*, 2017).

5.1 Soil Organic Carbon (SOC)

Soil Organic Carbon is one of the largest terrestrial carbon pools and plays a pivotal role in the global carbon cycle ([Lal, 2004](#)). SOC consists of decomposed plant and animal residues, microbial biomass, and humus, which stores carbon in stable forms over long periods ([Jobbágy & Jackson, 2000](#)).

- **Importance:** Monitoring changes in SOC is crucial because it reflects soil health, fertility, and productivity, while also serving as a major carbon sink that can offset atmospheric CO₂ emissions ([Lal, 2004](#)).
- **Measurement:** SOC is assessed through soil sampling and laboratory analysis. Long-term monitoring allows detection of gains or losses in carbon stocks due to agricultural practices such as tillage, crop rotation, cover cropping, and organic amendments ([FAO, 2017](#)).
- **Management Impact:** Practices like reduced tillage, agroforestry, organic farming, and biochar application enhance SOC sequestration by minimizing soil disturbance and increasing organic inputs ([Lal, 2004](#); [Smith *et al.*, 2014](#)).
- **Climate Role:** Increasing SOC improves carbon sequestration capacity, reduces GHG emissions, and contributes to climate change mitigation while boosting resilience against drought and erosion ([Smith *et al.*, 2014](#)).

5.2 Crop and Livestock Emissions

Agriculture is a significant source of greenhouse gases beyond CO₂, including methane (CH₄) and nitrous oxide (N₂O), both having higher global warming potentials ([IPCC, 2019](#)).

- **Crop Emissions**

- **Fertilizer Application:** Synthetic nitrogen fertilizers and organic manures release N₂O through nitrification and denitrification processes in soil ([IPCC, 2019](#)).
- **Rice Cultivation:** Flooded rice paddies produce methane due to anaerobic decomposition ([IPCC, 2019](#)).
- **Soil Management:** Tillage and crop residue management affect soil respiration and CO₂ release ([Lal, 2004](#)).

- **Livestock Emissions**

- **Enteric Fermentation:** Ruminant animals (cattle, sheep) produce methane during digestion, representing a major source of agricultural CH₄ ([Smith *et al.*, 2014](#)).
- **Manure Management:** Decomposition of manure in storage or fields emits both methane and nitrous oxide depending on aerobic or anaerobic conditions ([IPCC, 2019](#)).
- **Accounting:** Quantifying these emissions involves activity data (number of animals, fertilizer use, crop area) combined with emission factors or detailed process-based models ([Ogle *et al.*, 2010](#)).
- **Mitigation Options:** Improved feed quality, manure management, precision fertilization, and adoption of low-emission rice varieties help reduce emissions intensity ([Smith *et al.*, 2014](#)).

5.3 Carbon Credits

Carbon credits translate agricultural carbon accounting into actionable climate and economic benefits. Each credit represents one metric tonne of CO₂-equivalent (CO₂e) reduced, avoided, or sequestered through verified mitigation activities ([Kossoy et al., 2015](#); Hamilton et al., 2017). These credits can be traded in **compliance** or **voluntary** carbon markets, linking sustainable farming practices with climate finance mechanisms established under the UNFCCC and the Paris Agreement ([UNFCCC, 2015](#)).

Agricultural Potential:

Agriculture offers vast opportunities for carbon credit generation through practices that enhance soil carbon, reduce CH₄ and N₂O emissions, and increase biomass carbon storage. *Examples:* Conservation tillage, cover cropping, agroforestry, improved manure and nutrient management, and biochar use ([Lal, 2004](#); [Nair et al., 2009](#)).

MRV Framework (Measurement, Reporting, Verification): Ensures transparency and credibility.

- *Measurement:* Quantifies carbon gains or emission reductions.
- *Reporting:* Documents methods and outcomes using standard templates.
- *Verification:* Independent third-party audit for certification ([FAO, 2017](#)).

Market Mechanisms:

- *Compliance Markets:* Operate under regulatory systems (e.g., EU ETS).
- *Voluntary Markets:* Driven by corporate net-zero or sustainability goals ([Kossoy et al., 2015](#)).

Benefits:

- Financial incentives for farmers through carbon payments.
- Promotion of climate-smart and sustainable land management.
- Support for national and global mitigation targets and SDGs ([Smith et al., 2014](#)).
- **Co-Benefits:** Enhanced soil health, biodiversity, water conservation, and rural livelihoods ([Hamilton et al., 2017](#)).

6 Challenges in Carbon Measurement

Accurate carbon measurement is essential for credible carbon accounting, yet it faces several challenges. These include variability in emission sources, limited data availability, lack of standardized methodologies across sectors, and technical limitations in measuring soil carbon and non-CO₂ gases like methane and nitrous oxide ([IPCC, 2019](#); [Ogle et al., 2010](#)). Addressing these challenges is vital for ensuring reliable reporting, policy development, and climate action.

Several technical and environmental factors hinder the precision and reliability of carbon measurement across ecosystems and practices, including:

1. Spatial variability in soils and vegetation complicates sampling.
2. Temporal dynamics require long-term monitoring.
3. Measurement of soil carbon changes can be slow and subtle.
4. Uncertainty in emission factors and modeling assumptions.

6.1 Spatial Variability in Soils and Vegetation

- **Heterogeneity Across Landscapes:** Soil properties such as texture, organic matter content, moisture, and microbial activity vary widely

even within small geographic areas. Similarly, vegetation types, density, and biomass can differ dramatically due to microclimate, land use, and management ([Ogle et al., 2010](#)).

- **Implication for Sampling:** This spatial variability means that soil or biomass samples taken at one point may not represent the larger area accurately. To capture true carbon stocks or fluxes, extensive and well-distributed sampling is required ([Lal, 2004](#)).
- **Cost and Labor Intensive:** Increasing sample numbers to account for spatial variability raises the cost and labor of fieldwork and analysis ([Ogle et al., 2010](#)).
- **Remote Sensing Limitations:** While remote sensing helps cover large areas, resolution limits and ground-truthing challenges can reduce precision, especially in heterogeneous or mixed landscapes ([Asner, 2009](#)).

6.2 Temporal Dynamics Require Long-Term Monitoring

- **Seasonal and Annual Fluctuations:** Carbon pools and fluxes fluctuate seasonally for example, plant growth varies with weather, and soil respiration rates change with temperature and moisture ([Davidson & Janssens, 2006](#)).
- **Long-Term Trends:** Detecting meaningful changes in soil organic carbon or biomass stocks often requires monitoring over several years or decades due to the slow pace of carbon accumulation or loss ([Lal, 2004](#)).
- **Short-Term Disturbances:** Events such as droughts, floods, land use changes, or management interventions can cause rapid, sometimes transient, changes in carbon levels that need to be distinguished from long-term trends ([IPCC, 2019](#)).

- **Sustained Effort:** Long-term studies demand consistent methodologies, funding, and institutional commitment to ensure data comparability and reliability over time ([Ogle et al., 2010](#)).

6.3 Measurement of Soil Carbon Changes Can Be Slow and Subtle

- **Low Rate of Change:** Soil organic carbon typically changes gradually, often at rates of a few grams per kilogram per year, making it challenging to detect statistically significant changes over short periods ([Lal, 2004](#)).
- **Sampling and Analytical Errors:** Variability in sampling depth, lab methods, and natural heterogeneity can mask subtle SOC changes ([Nelson & Sommers, 1996](#)).
- **Depth Complexity:** Carbon changes may occur at different soil depths, requiring deep and repeated sampling to fully assess total SOC stocks ([FAO, 2017](#)).
- **Time Lag:** Management practices like conservation tillage or cover cropping may take years before significant SOC increases are measurable ([Lal, 2004](#)).

6.4 Uncertainty in Emission Factors and Modeling Assumptions

- **Generalized Emission Factors:** Many emission factors are derived from global or regional averages and may not reflect site-specific conditions like climate, soil type, crop variety, or management, leading to inaccuracies ([IPCC, 2006](#)).
- **Model Limitations:** Process-based models rely on assumptions, simplifications, and input data quality. Variations in

parameterization or missing data can result in significant uncertainty in carbon stock or flux estimates ([Ogle *et al.*, 2010](#)).

- **Measurement Error Propagation:** Small inaccuracies in input data (e.g., fertilizer use, livestock numbers) can amplify uncertainty in final emission estimates ([Ogle *et al.*, 2010](#)).
- **Verification Challenges:** The variability and complexity of biological systems make verification of modeled or estimated emissions difficult, particularly in decentralized farming systems ([Hamilton *et al.*, 2017](#)).

Addressing these challenges requires integrating multiple measurement methods, improving modeling approaches, investing in long-term monitoring networks, and developing context-specific emission factors and protocols ([FAO, 2017](#); [IPCC, 2019](#)).

7 Recent Innovations and Tools

The field of carbon accounting has rapidly evolved with the integration of advanced technologies and digital tools. Innovations such as remote sensing, automated monitoring systems, data analytics, and blockchain are improving the precision, scalability, and transparency of carbon measurements ([Nguyen & Saha, 2024](#); [Zhang *et al.*, 2024](#); [Ghosh *et al.*, 2023](#); [Hultman *et al.*, 2022](#)). These tools are especially valuable in complex environments like agriculture and forestry, where traditional methods face limitations. Key recent innovations and tools transforming carbon measurement and reporting include:

1. Isotope Tracing
2. Automated Soil Respiration Systems
3. Machine Learning

4. Blockchain

7.1 Isotope Tracing

Isotope tracing uses the natural abundance or artificial enrichment of stable carbon isotopes, primarily carbon-12 (^{12}C) and carbon-13 (^{13}C), to track and differentiate sources and pathways of carbon in ecosystems ([Besser, 2022](#); [Kruger et al., 2024](#)).

- **Principle:** Different carbon sources and processes discriminate between isotopes to varying degrees, creating distinct isotopic signatures. For example, plants using the C3 photosynthetic pathway have a different $^{13}\text{C}/^{12}\text{C}$ ratio than those using the C4 pathway.
- **Applications**
 - Distinguishing carbon derived from recent photosynthesis versus older soil organic matter.
 - Tracking carbon flow through soil microbial communities.
 - Identifying sources of soil respiration and methane emissions.
- **Benefits:** Provides precise insight into carbon cycling dynamics, helping to understand sequestration rates, carbon turnover, and the effectiveness of mitigation practices.
- **Challenges:** Requires specialized equipment (e.g., isotope ratio mass spectrometers) and expertise.

7.2 Automated Soil Respiration Systems

These are advanced instruments designed for continuous, real-time monitoring of soil CO_2 efflux, a key indicator of soil microbial activity and carbon flux ([Nguyen et al., 2025](#)).

- **Technology:** Systems typically include soil chambers connected to infrared gas analyzers (IRGA) that measure CO₂ concentration changes continuously or at frequent intervals.
- **Advantages**
 - Capture diurnal and seasonal variations in soil respiration.
 - Provide high-resolution data that improve understanding of how soil carbon dynamics respond to environmental factors like temperature and moisture.
 - Facilitate long-term monitoring with minimal manual intervention.
- **Applications:** Assessing impacts of agricultural practices, climate variability, and land-use changes on soil carbon emissions.
- **Example Systems:** Li-8100A Automated Soil CO₂ Flux System (LI-COR Biosciences).

7.3 Machine Learning

Machine learning (ML) techniques enhance carbon accounting by improving data analysis, pattern recognition, and prediction capabilities, especially when handling complex or large datasets ([Reichstein *et al.*, 2019](#); [Rolnick *et al.*, 2022](#)).

- **Remote Sensing Interpretation:** ML algorithms can process vast satellite and drone imagery data to accurately estimate vegetation biomass, soil properties, and land-use changes.
- **Data Integration:** ML models integrate diverse datasets (climate, soil, management practices) to refine emission factor estimates and carbon stock predictions.
- **Anomaly Detection:** ML can detect outliers or inconsistencies in monitoring data, improving data quality and reliability.

- **Predictive Modeling:** ML enables forecasting of carbon fluxes and stocks under future climate or management scenarios.
- **Benefits:** Enhances accuracy, reduces reliance on simplistic assumptions, and allows scalable monitoring across regions.
- **Challenges:** Requires large, high-quality datasets and expertise in data science.

7.4 Blockchain

Blockchain technology offers a secure, transparent, and decentralized digital ledger system increasingly used in carbon accounting and carbon markets ([Howson, 2019](#); [Zhou & Ahmad, 2022](#); [Qin, 2023](#)).

- **Transparency and Trust:** Blockchain records carbon credit transactions immutably, preventing double counting or fraud in carbon markets.
- **Traceability:** Tracks the origin, ownership, and retirement of carbon credits, ensuring accountability from project inception to credit usage.
- **Smart Contracts:** Automate verification and payment processes based on predefined conditions, streamlining carbon trading.
- **Integration:** Can link with IoT devices and remote sensing data to provide real-time carbon monitoring and reporting.
- **Impact:** Builds stakeholder confidence, encourages wider participation in carbon markets, and promotes environmental integrity.
- **Challenges:** Requires digital infrastructure, regulatory acceptance, and standards for interoperability.

8 Conclusion and Way Forward

This chapter explored the foundational concepts, methodologies, frameworks, and applications of carbon accounting and measurements, emphasizing their critical role in climate change mitigation, policy formulation, and sustainable land management. Carbon accounting involves the systematic quantification of greenhouse gas (GHG) emissions and removals across various carbon pools, soil, biomass, atmosphere, and products, using both direct (empirical) and indirect (model-based) approaches. Direct methods, such as soil sampling, biomass measurement, and gas flux analysis, offer site-specific accuracy, while indirect methods, like emission factor-based estimations, remote sensing, and process-based models, enable large-scale assessments and scenario forecasting. The chapter also discussed the importance of carbon accounting in agriculture, a sector with both high emissions and large mitigation potential. Frameworks such as the IPCC Guidelines, GHG Protocol, and tools like Cool Farm Tool and EX-ACT help standardize data collection and reporting. Finally, the chapter examined how quantified carbon outcomes can be monetized through carbon credits, thus linking accounting to actionable incentives. These credits offer climate mitigation benefits while supporting biodiversity, soil health, and rural livelihoods when rigorously measured, verified, and integrated into carbon markets.

Carbon accounting and measurement form the bedrock of global efforts to manage climate change, enabling transparent reporting, credible mitigation strategies, and meaningful participation in carbon markets. As carbon flows vary across ecosystems and land uses, employing an integrated approach that combines both empirical data and model-based estimations is essential for accuracy and scalability. Agriculture, in particular, represents a challenging yet promising frontier, where improved MRV systems and inclusive frameworks can unlock its mitigation potential.

Furthermore, the integration of digital technologies, such as remote sensing, AI, and GIS, has greatly enhanced the precision and accessibility of carbon accounting across scales. Effective carbon accounting not only informs climate policy and carbon credit generation but also reinforces sustainability, equity, and resilience in land-based systems. Its continued evolution and standardization are central to achieving national targets, international climate commitments, and the Sustainable Development Goals (SDGs).

To strengthen carbon accounting and measurement practices, it is recommended that hybrid approaches combining direct field measurements with model-based estimations be widely adopted to enhance accuracy and scalability. In agriculture, the development of robust, context-specific MRV (Measurement, Reporting, and Verification) systems is essential to account for the sector's complexity and variability. Capacity-building initiatives should be prioritized to equip farmers, practitioners, and local institutions with the knowledge and tools necessary for effective carbon monitoring and participation in carbon credit schemes. Facilitating equitable access to carbon markets, particularly for smallholders, through aggregation models and simplified verification protocols can promote broader inclusion. The integration of digital technologies such as remote sensing, machine learning, and mobile applications should be expanded to enable real-time monitoring and improve data reliability. Carbon accounting should also be embedded into national climate policies, agricultural strategies, and land-use planning frameworks to ensure coherence and effectiveness. Continued research and innovation are needed to refine models and understand carbon dynamics under varying climate and management conditions. Lastly, carbon initiatives should be designed to maximize co-benefits, including

improvements in soil health, biodiversity, water conservation, and rural livelihoods, thereby supporting broader sustainability goals.

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Chapter 11

Economic Viability and Market Mechanisms

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1. Introduction

Carbon-negative farming refers to agricultural systems that result in a net removal of carbon dioxide (CO₂) from the atmosphere, thereby going beyond the goal of carbon neutrality and actively contributing to climate reversal ([Smith *et al.*, 2015](#)). This is achieved through a variety of practices such as agroforestry, regenerative tillage, cover cropping, organic amendments, integrated nutrient management, and biochar application, all of which enhance carbon sequestration in soils and perennial biomass ([Lal, 2018](#); Fuss *et al.*, 2018). These approaches also improve soil health, foster biodiversity, and build ecosystem resilience, making them crucial for both environmental sustainability and agricultural productivity.

The economic viability of carbon-negative farming hinges on its potential to deliver both ecological gains and financial returns. Although these systems may initially require higher investments in knowledge, labor, or technology, they often provide long-term agronomic benefits, such as improved soil fertility, water retention, pest resistance, and enhanced climate resilience. These improvements contribute to greater input-use efficiency, yield stability, and ultimately, increased profitability over time ([Paustian *et al.*, 2019](#); [Lorenzetti & Fiorini, 2024](#)). However, despite these potential gains, the widespread adoption of carbon-negative practices remains constrained by several economic and institutional challenges.

Limited awareness, fragmented policies, lack of incentives, and uncertain returns on investment discourage farmers, especially smallholders, from transitioning to regenerative systems (Cacho *et al.*, 2020).

To bridge this gap between ecological promise and economic reality, market-based mechanisms have gained traction as viable tools for monetizing the environmental benefits of carbon sequestration. One such mechanism is the carbon credit market, wherein farmers can earn tradable credits for each verified tonne of CO₂ they sequester or avoid emitting. These credits can be sold in both voluntary and compliance-based markets, offering an emerging revenue stream for sustainable land management. International standards such as Verra's Verified Carbon Standard and the Gold Standard are leading platforms that certify agricultural carbon projects based on rigorous monitoring, reporting, and verification protocols ([Goldstein *et al.*, 2021](#)). Beyond carbon trading, result-based payment models such as Payment for Ecosystem Services (PES) provide direct financial incentives to farmers for measurable improvements in carbon storage, soil quality, water retention, or biodiversity conservation. These programs, often supported by governments, NGOs, or international donors, reward environmental stewardship and create performance-linked income for landowners ([Wunder *et al.*, 2020](#)). At the same time, corporate offsetting initiatives are becoming a key driver of agricultural carbon projects. Many companies, in pursuit of net-zero emissions targets, are turning to nature-based solutions, including farm-level carbon credits, to offset their residual emissions ([ISUEO, 2021](#)). This trend has catalyzed partnerships between agri-tech firms, farmer cooperatives, and carbon certifiers, expanding the scope and scale of regenerative agriculture.

In parallel, governments and financial institutions are introducing green financing instruments, including low-interest loans, tax exemptions, and

subsidies to encourage farmers to adopt climatesmart and carbon-negative technologies. Meanwhile, multilateral institutions and development banks are increasingly mobilizing climate funds and issuing green bonds focused on sustainable agriculture, thus reducing capital constraints and incentivizing investment in regenerative practices ([FAO, 2025](#); [Climate Bonds Initiative, 2023](#)). Technological innovation is playing a pivotal role in strengthening the credibility and scalability of carbon markets. Advances in remote sensing, digital monitoring systems, machine learning, and blockchain-based registries are revolutionizing how carbon sequestration is quantified and verified. These tools not only lower transaction costs but also ensure transparency, traceability, and stakeholder trust in carbon offset mechanisms ([Vilkov & Tian, 2023](#)). With such infrastructure in place, it becomes increasingly feasible to include small and marginal farmers in carbon finance, thereby democratizing access to emerging green markets.

In essence, carbon-negative farming offers a compelling pathway for addressing climate change while simultaneously advancing soil restoration and rural prosperity. However, unlocking its full potential hinges on the establishment of supportive policy frameworks, robust market systems, and inclusive financial mechanisms that make adoption viable for all farming communities. Realizing this vision demands an integrated strategy, one that synchronizes agricultural policy with climate objectives, leverages cutting-edge technologies for measurement and verification, and ensures that environmental gains are matched by equitable economic returns. As the world increasingly turns to sustainable solutions, carbon-negative agriculture emerges not merely as a mitigation tool, but as a cornerstone of a resilient, low-carbon economy ([Hawken, 2017](#); [IPCC, 2022](#)).

2. Economic Viability of Carbon Negative Farming

The economic viability of carbon-negative farming lies at the intersection of ecological sustainability and financial performance. These practices aim to remove more carbon dioxide from the atmosphere than they emit, offering a potential solution to climate change while simultaneously enhancing agricultural productivity and ecosystem health. However, for widespread and sustained adoption, these systems must prove to be not only environmentally beneficial but also economically attractive, especially for resource-constrained farmers. Unlike conventional agricultural models focused on shortterm returns, carbon-negative farming often requires longer time horizons to realize its full benefits, which may include increased soil organic matter, improved nutrient cycling, greater biodiversity, and higher climate resilience. While these co-benefits offer significant long-term value, they may not immediately translate into profit, posing challenges for uptake in risk-averse or capital-poor farming communities ([Lal, 2018](#)).

Small and medium-scale farmers who comprise the bulk of agricultural producers globally, often lack the financial flexibility to absorb high upfront costs or experiment with unproven techniques. Additionally, the economic returns from carbon sequestration are influenced by numerous variables, including soil type, climate, crop system, labour availability, and access to carbon markets. The uncertainty surrounding carbon offset revenues, fluctuating commodity prices, and the cost of implementing new technologies all contribute to a complex and often unpredictable financial landscape ([Fuss *et al.*, 2018](#); [Lorenzetti & Fiorini, 2024](#)). Understanding these financial dynamics is crucial not only for farmers but also for policymakers, investors, development agencies, and private sector actors, who all play a role in shaping the enabling environment for carbon-negative agriculture. Robust cost-benefit analyses, targeted incentives, risk mitigation strategies, and access to affordable finance are essential

components to de-risk and incentivize adoption (Smith *et al.*, 2015). The following sections delve into the economic dimensions that shape the viability of carbon-negative farming, exploring the costbenefit trade-offs, financial risks and barriers, and the critical role of policy and institutional support mechanisms that can help accelerate the transition toward low-carbon, climate-resilient agriculture.

Cost-Benefit Analysis of Carbon Negative Practices

- Initial investment and operational costs: inputs, equipment, labor, and technology adoption.
- Direct benefits: increased yields, improved soil fertility, reduced input costs (fertilizers, pesticides).
- Indirect benefits: enhanced ecosystem services, resilience to climate extremes, improved water use efficiency.
- Long-term economic returns versus short-term costs.
- Case studies of economically successful carbon-negative farms.

Financial Barriers and Risks

- High upfront costs and limited access to capital for smallholders.
- Uncertainties in carbon sequestration rates and payoff timelines.
- Market price volatility for agricultural products and carbon credits.
- Risk management strategies: diversification, insurance, government support.

Role of Policy Incentives and Subsidies

- Government programs supporting carbon-friendly agriculture (grants, low-interest loans, tax breaks).

- Payment for Ecosystem Services (PES) schemes targeting carbon sequestration.
- Impact of National and International Climate Policies on Farm Economics

2.1 Cost-Benefit Analysis of Carbon Negative Practices

A critical step in assessing the economic viability of carbon-negative farming is understanding the balance between the initial costs of implementation and the economic benefits accrued over time. While these practices may require upfront investments in labor, equipment, and new technologies, they can lead to significant long-term gains through enhanced productivity, soil health, and input savings. Moreover, carbon-negative systems often generate indirect benefits such as improved water efficiency and climate resilience that, while harder to quantify, contribute substantially to farm sustainability and risk reduction. To evaluate this balance effectively, it is important to examine both the tangible and intangible costs and benefits associated with these systems. The key components of such an analysis include:

Initial Investment and Operational Costs

Adopting carbon-negative farming practices often requires upfront investments that can include purchasing specialized equipment (e.g., no-till seeders, drip irrigation systems), acquiring inputs such as biofertilizers or organic amendments, and investing in technology like soil sensors or carbon measurement tools ([FAO, 2025](#)). Labor costs may increase initially as farmers learn and implement new techniques such as cover cropping, agroforestry, or precision nutrient management. These initial capital and operational expenses can be a barrier, especially for small and resource-poor farmers ([Cacho *et al.*, 2005](#)).

Direct Benefits

Despite higher initial costs, carbon-negative farming can lead to several direct economic benefits. Improved soil fertility due to enhanced soil organic matter increases crop productivity and yield stability ([Paustian *et al.*, 2019](#)). The use of organic or bio-based inputs often reduces dependency on costly chemical fertilizers and pesticides, lowering input expenses over time ([Lal, 2018](#)). Healthy soils also contribute to better nutrient and water retention, which can translate into more efficient resource use and lower operational costs ([Lorenzetti & Fiorini, 2024](#)).

Indirect Benefits

Carbon-negative farming delivers broader ecosystem services that have economic value, though often indirect or difficult to quantify. Enhanced biodiversity supports natural pest control and pollination, reducing the need for chemical interventions ([Smith *et al.*, 2015](#)). Soils with higher organic carbon content are more resilient to climate extremes such as droughts and floods, protecting crop yields and farmer incomes ([FAO, 2025](#)). Improved water use efficiency decreases irrigation costs and helps adapt to water scarcity, further contributing to economic stability (Wollenberg *et al.*, 2016).

Long-term Economic Returns versus Short-term Costs

While some carbon sequestration practices may take years to show measurable returns, the long-term economic advantages often outweigh initial expenditures ([Fuss *et al.*, 2018](#)). Practices like agroforestry or conservation tillage build soil health progressively, enhancing farm productivity and reducing input requirements over multiple seasons. This long-term perspective is critical, as the benefits of carbon-negative farming accumulate and compound, ensuring sustained profitability and resilience ([Lal, 2018](#)).

Case Studies of Economically Successful Carbon-Negative Farms

Real-world examples from various regions illustrate that carbon-negative farming can be both ecologically beneficial and economically viable when adapted to local conditions and supported by appropriate policies and market frameworks. In India, the state of Sikkim transitioned to fully organic agriculture by 2016, implementing practices such as composting, green manuring, and intercropping, which have reduced reliance on synthetic inputs and improved crop resilience, resulting in higher net farm incomes and ecosystem restoration ([FAO, 2025](#)). Similarly, Andhra Pradesh's Community Natural Farming initiative promotes zero-budget natural farming techniques like mulching and cover cropping, delivering lower input costs, enhanced soil carbon, and increased profitability for smallholder farmers ([Duddigan & Reddy, 2022](#)).

2.2 Financial Barriers and Risks

Despite the long-term environmental and economic potential of carbon-negative farming, a range of financial barriers and risks can hinder its widespread adoption, particularly among smallholder and resource-poor farmers. Transitioning to practices such as agroforestry, biochar application, cover cropping, or precision agriculture often demands significant initial investment in equipment, inputs, or training. However, the return on these investments may take years to materialize, particularly where carbon sequestration is involved, creating financial uncertainty and deterring adoption. These challenges are further compounded by market unpredictability and limited access to formal credit, insurance, and support systems in many regions. The key points of financial barriers and risks are described here under.

High Upfront Costs and Limited Access to Capital for Smallholders

One of the main challenges facing carbon-negative farming is the significant initial investment required. Many smallholder farmers lack access to affordable credit or financial services to fund new technologies and inputs ([Cacho *et al.*, 2005](#)). Without financial support, these farmers may hesitate to adopt practices perceived as costly or risky.

Uncertainties in Carbon Sequestration Rates and Payoff Timelines

Carbon sequestration rates vary widely depending on soil type, climate, crop species, and management practices, leading to uncertainty about the actual climate benefits and associated financial returns ([Smith *et al.*, 2015](#)). Additionally, the benefits often accrue over a long time horizon, making it difficult for farmers to predict when they will realize economic gains. This uncertainty can deter investment and adoption (Fuss *et al.*, 2018).

Market Price Volatility for Agricultural Products and Carbon Credits

Farmers engaged in carbon-negative agriculture face risks related to fluctuating prices of their crops and potential revenues from carbon credits. Commodity prices can be highly volatile due to market demand, weather events, or geopolitical factors ([ISUEO, 2021](#)). Similarly, carbon credit prices are still evolving, influenced by regulatory changes, market demand, and verification costs, adding uncertainty to income from carbon trading ([Goldstein *et al.*, 2021](#)).

Risk Management Strategies: Diversification, Insurance, Government Support

To mitigate financial risks, farmers can diversify their income streams by integrating multiple crops, livestock, or agroforestry products, reducing dependence on a single commodity ([Wollenberg *et al.*, 2016](#)). Agricultural insurance schemes can protect against crop failure or weather-related losses. Moreover, government programs offering subsidies, technical assistance, or

price supports play a vital role in de-risking carbon-negative farming investments ([FAO, 2025](#)).

2.3 Role of Policy Incentives and Subsidies

Policy incentives and subsidies play a critical role in enhancing the economic viability of carbon-negative farming systems. Given the high upfront costs, delayed financial returns, and market uncertainties associated with sustainable agricultural transitions, public sector intervention becomes essential to encourage adoption, especially among smallholders. Well-designed incentives can reduce financial burdens, reward environmental services, and align farming practices with national and global climate goals. These mechanisms not only improve farmers' profitability but also strengthen the long-term resilience and sustainability of agricultural systems. The following sub-components illustrate how policy support can drive carbon-negative agriculture:

Government Programs Supporting Carbon-Friendly Agriculture

Governments worldwide are increasingly recognizing the importance of incentivizing sustainable and carbon-negative agricultural practices. Programs providing grants, low-interest loans, tax breaks, or cost-sharing arrangements reduce the financial burden on farmers adopting conservation agriculture, organic farming, or agroforestry ([IPCC, 2022](#)). These incentives can stimulate wider adoption by improving economic feasibility ([FAO, 2025](#)).

Payment for Ecosystem Services (PES) Schemes Targeting Carbon Sequestration

PES schemes reward farmers for ecosystem services they provide, such as carbon sequestration, biodiversity conservation, or water purification. By assigning monetary value to carbon stored in soils or biomass, PES

programs offer farmers financial compensation that supplements farm income ([Wunder et al., 2020](#)). Successful PES examples include carbon farming projects under voluntary carbon markets or national climate initiatives (Goldstein *et al.*, 2021).

Impact of National and International Climate Policies on Farm Economics

Climate policies at national and global levels, including carbon pricing, emission reduction targets, and climate finance mechanisms, influence agricultural economics ([IPCC, 2022](#)). Policies that integrate agriculture in climate mitigation commitments can drive investments, create market opportunities, and enhance farmer incomes. Conversely, lack of supportive policies may limit access to carbon markets or create regulatory uncertainties, affecting the economic attractiveness of carbon-negative farming ([ISUEO, 2021](#)).

3. Market Mechanisms Supporting Carbon Negative Farming

As global interest in climate-smart and sustainable agriculture intensifies, market-based mechanisms have increasingly emerged as powerful instruments to provide financial incentives for farmers adopting carbon-negative practices ([FAO, 2021](#); [Goldstein et al., 2021](#)). These mechanisms establish a direct link between environmental stewardship and economic opportunity, enabling farmers not only to reduce emissions but also to generate income by monetizing carbon sequestration, improved soil health, and other ecosystem services ([ISUEO, 2021](#)). Through active participation in voluntary or compliance carbon markets, green finance platforms, or sustainability-linked supply chains, agricultural producers can diversify their revenue streams while aligning their operations with national and global climate goals ([Kreibich et al., 2021](#)). Moreover, such market tools serve a dual purpose: they offer a business case for sustainable land use

while contributing to national commitments under climate agreements like the Paris Accord. However, to be effective and equitable, these systems must be built upon transparent governance structures, standardized carbon accounting methodologies, and inclusive participation frameworks that ensure benefits reach smallholders and marginalized communities ([Hamrick & Gallant, 2018](#)). Building on this foundation, the following subsections explore the core components of these mechanisms, including carbon markets, credit trading systems, green financing options, and the integration of sustainability metrics into agricultural value chains.

Carbon Markets: Voluntary and Compliance

- Overview of carbon markets and their functioning.
- Voluntary carbon markets: motivations, standards, and key players.
- Compliance markets: cap-and-trade systems, regulated carbon pricing.
- How farmers and agribusinesses participate in carbon markets.
- Challenges: verification, additionality, permanence, leakage.

Carbon Credits and Certification

- Definition and generation of carbon credits from agricultural practices.
- Certification standards and protocols (e.g., Verified Carbon Standard, Gold Standard, Climate Action Reserve).
- Measurement, Reporting, and Verification (MRV) systems ensuring credibility.
- Case examples of successful carbon credit projects in agriculture.

Other Market-Based Incentives

- Ecosystem service markets beyond carbon (biodiversity, water quality).
- Green bonds and sustainable investment funds.
- Agroforestry and organic product premiums.
- Corporate social responsibility (CSR) and sustainability commitments driving demand.

3.1 Carbon Markets: Voluntary and Compliance

Carbon markets are central to the monetization of greenhouse gas (GHG) reductions and form a foundational component of market mechanisms that support carbon-negative farming. These markets enable the trading of carbon credits, which represent measurable and verified reductions in GHG emissions or enhancements in carbon sequestration. By participating in carbon markets, farmers and agribusinesses can generate additional income while contributing to climate mitigation objectives. Carbon markets are broadly classified into voluntary markets, where entities choose to offset emissions beyond regulatory requirements, and compliance markets, which are governed by legally binding caps on emissions under national or international schemes. Each system offers unique opportunities and poses distinct challenges for agricultural stakeholders. The sub-components below explore the structure, stakeholders, and implementation aspects of both types of carbon markets:

Overview of Carbon Markets and Their Functioning

Carbon markets are trading platforms where carbon credits, representing one metric ton of CO₂ equivalent emissions reduced or sequestered, are bought and sold ([World Bank, 2020](#)). They incentivize emission reductions by putting a monetary value on carbon sequestration or avoided emissions. The markets function by linking buyers, who want to offset or comply with

emission limits, and sellers, often project developers or farmers generating carbon credits through verified sustainable practices ([Goldstein et al., 2021](#)).

Voluntary Carbon Markets: Motivations, Standards, and Key Players

Voluntary carbon markets enable individuals, companies, and organizations to purchase carbon credits beyond regulatory obligations, driven by motivations such as corporate social responsibility, sustainability commitments, and consumer demand ([Donofrio et al., 2021](#)). These markets operate under recognized standards and protocols, like the Verified Carbon Standard (VCS), Gold Standard, and Plan Vivo, which ensure the quality and credibility of carbon credits ([Verra, 2023](#)). Key players in voluntary markets include project developers, certification bodies, carbon credit brokers, corporate buyers, and NGOs. The flexibility of these markets allows for a wide range of project types, including agriculture, forestry, renewable energy, and waste management ([Hamrick & Gallant, 2018](#)). Voluntary carbon markets have grown rapidly in recent years as businesses increasingly seek to demonstrate climate leadership and respond to evolving consumer preferences (Donofrio et al., 2021).

Compliance Markets: Cap-and-Trade Systems and Regulated Carbon Pricing

Compliance markets are government-regulated frameworks designed to meet legally binding greenhouse gas (GHG) reduction targets and are often embedded within national or regional climate policies ([World Bank, 2020](#)). These markets operate primarily through cap-and-trade systems, where a limit is set on total emissions and allowances are distributed or auctioned. Companies must hold allowances equal to their emissions, incentivizing cost-effective reductions and innovation. Alternatively, carbon pricing mechanisms impose direct taxes or fees on emissions, encouraging

behavioral change by internalizing environmental costs. While traditionally focused on industrial sectors, some compliance markets are beginning to incorporate agriculture, forestry, and land use, allowing farmers to earn credits through soil carbon sequestration, afforestation, or methane reduction ([IPCC, 2022](#)). Notable examples include the European Union Emissions Trading System (EU ETS) and California's Capand-Trade Program, both of which serve as models for regulated carbon trading ([ICAP, 2023](#)). These markets provide structured opportunities for agriculture to contribute to climate mitigation and earn new income streams.

How Farmers and Agribusinesses Participate in Carbon Markets

Farmers generate carbon credits by adopting practices that sequester carbon or reduce emissions, such as agroforestry, conservation tillage, or methane capture from manure ([FAO, 2021](#)). Participation steps include (i) project design and baseline establishment, (ii) implementation of carbon-negative practices, (iii) measurement, reporting, and verification (MRV) of carbon benefits, (iv) registration and certification of credits and (v) selling credits to buyers through brokers or exchanges. Agribusinesses may also purchase credits to meet sustainability goals or support supply chain decarbonisation ([ISUEO, 2021](#)).

Challenges: Verification, Additionality, Permanence, Leakage

Carbon markets face key challenges related to *verification*, *additionality*, *permanence*, and *leakage*. *Verification* ensures carbon reductions are real and measurable, typically through third-party audits (Kreibich *et al.*, 2022). *Additionality* requires demonstrating that benefits wouldn't occur without the project. *Permanence* involves ensuring sequestered carbon remains stored long-term, while *leakage* refers to emissions shifting outside the project boundary. Addressing these issues demands robust protocols and continuous monitoring ([Donofrio *et al.*, 2021](#)).

3.2 Carbon Credits and Certification

Carbon credits represent quantified greenhouse gas reductions or removals that can be traded in carbon markets, providing a financial incentive for adopting sustainable agricultural practices. These credits are generated when verified carbon sequestration or emission reductions occur on farms through activities like improved soil management, agroforestry, or methane capture. To ensure transparency and trust, carbon credits must be certified under recognized standards such as the Verified Carbon Standard, Gold Standard, or Climate Action Reserve. Central to this process are Measurement, Reporting, and Verification (MRV) systems, which rigorously track and validate carbon outcomes. The following sub-sections explore how carbon credits are created, certified, and managed, including examples of successful agricultural projects that have leveraged these mechanisms to generate economic and environmental benefits.

Definition and Generation of Carbon Credits from Agricultural Practices

Carbon credits are quantified units of greenhouse gas (GHG) reductions or removals ([Verra, 2023](#)). In agriculture, they arise from practices like increasing soil organic carbon, better manure management, agroforestry, and improved fertilizer use ([IPCC, 2022](#)). To calculate carbon credits, baseline emission levels are first established, serving as a reference point. Then, the net emission reductions achieved through these sustainable practices are measured against this baseline. This process requires accurate data collection and robust methodologies to ensure that credits represent real, additional, and verifiable climate benefits. Such rigorous accounting builds trust in carbon markets and incentivizes farmers to adopt practices that contribute meaningfully to climate mitigation ([FAO, 2021](#)).

Certification Standards and Protocols

Certification provides credibility to carbon credits by ensuring they meet rigorous environmental and methodological criteria. Major certification standards include (i) Verified Carbon Standard (VCS), a widely adopted global framework covering diverse project types; (ii) the Gold Standard, which emphasizes both carbon reduction and broader sustainable development benefits; and (iii) Action Reserve (CAR), which focuses on high-quality protocols for North American projects ([Goldstein et al., 2021](#)). These standards establish clear methodologies, monitoring guidelines, and validation processes to ensure transparency and consistency across carbon projects ([Verra, 2023](#)). Certification is essential for maintaining trust and integrity in carbon markets and attracting investment in sustainable agriculture.

Measurement, Reporting, and Verification (MRV) Systems Ensuring Credibility

Measurement, Reporting, and Verification (MRV) is a critical process for quantifying carbon benefits and ensuring transparency in carbon markets (Kreibich et al., 2022). *Measurement* involves collecting data on carbon stocks and fluxes through field assessments, modeling, or remote sensing. *Reporting* requires documenting these results following standardized templates and protocols, while *verification* entails independent third-party audits to confirm accuracy and compliance. Together, MRV systems play a vital role in minimizing fraud, enhancing market credibility, and enabling the reliable issuance of carbon credits.

Case Examples of Successful Carbon Credit Projects in Agriculture

Successful carbon credit projects in agriculture demonstrate the potential for climate mitigation and rural development. **Agroforestry initiatives in Central America** have generated carbon credits while enhancing farmer livelihoods (World Bank, 2021). In the United States, **methane capture**

from dairy manure digesters has been certified under the Climate Action Reserve ([Goldstein *et al.*, 2021](#)). **Conservation agriculture projects in Africa**, recognized under VCS protocols, have provided income to smallholders ([Verra, 2023](#)). In India, the **NABARD-supported agroforestry project in Odisha** has delivered both carbon benefits and livelihood gains ([NABARD, 2022](#)), while the **Edelweiss Agri Value Chain Project** in Madhya Pradesh has generated voluntary carbon credits through improved land-use practices (Sharma *et al.*, 2023). These examples illustrate practical benefits and market integration.

3.3 Other Market-Based Incentives

Beyond carbon markets, a range of other market-based incentives are emerging to support sustainable agricultural practices and reward ecosystem stewardship. These mechanisms create additional revenue streams for farmers by monetizing services like biodiversity conservation, water regulation, and sustainable land use. They also align agricultural value chains with broader environmental, social, and governance (ESG) goals. The following sub-sections highlight key forms of such incentives, including ecosystem service markets, green financing tools, price premiums, and corporate sustainability initiatives that are reshaping the economics of climate-resilient farming.

Ecosystem Service Markets Beyond Carbon

Markets are increasingly emerging to compensate farmers for providing valuable ecosystem services beyond carbon sequestration. For instance, biodiversity conservation initiatives offer payments to farmers who preserve habitats or adopt wildlife-friendly farming practices. Similarly, water quality markets provide incentives for reducing nutrient runoff and enhancing watershed health, supporting cleaner and more sustainable water

systems ([Wunder et al., 2020](#)). These ecosystem service markets complement carbon markets and offer farmers diversified income streams, strengthening the financial viability of environmentally responsible agriculture ([FAO, 2021](#)).

Green Bonds and Sustainable Investment Funds

Green bonds are specialized debt instruments designed to raise capital for projects that deliver measurable environmental benefits, including those in sustainable agriculture. These bonds help finance initiatives such as reforestation, soil carbon enhancement, and climate-resilient farming infrastructure. By earmarking funds for eco-friendly outcomes, green bonds attract investors seeking both environmental impact and stable financial returns. In parallel, sustainable investment funds channel private capital into businesses and projects that promote carbon-negative farming, aligning with broader ESG (Environmental, Social, and Governance) goals. These financial instruments are gaining traction globally as tools to scale up climate-smart agriculture ([World Bank, 2020](#); [ISUEO, 2021](#)).

Agroforestry and Organic Product Premiums

Consumers are increasingly willing to pay higher prices for products labeled as organic, agroforestrybased, or sustainably sourced, attributes often associated with carbon-negative practices. This growing market preference allows producers to benefit from price premiums, thereby improving farm incomes and encouraging the adoption of environmentally friendly methods ([Donofrio et al., 2021](#); Kreibich et al., 2022).

Corporate Social Responsibility (CSR) and Sustainability Commitments Driving Demand

Corporations aiming to reduce their environmental impact are actively engaging with suppliers and farmers to implement carbon-negative practices across their value chains. These CSR and sustainability

commitments generate demand for certified carbon credits and responsibly produced agricultural goods, strengthening the role of market mechanisms in climate action ([Hamrick & Gallant, 2018](#); [Goldstein *et al.*, 2021](#)).

4. Economic Modeling and Impact Assessment

Understanding the broader economic implications of carbon-negative farming requires robust modeling and impact assessment tools ([Cristian & Lipski, 2019](#); [IPCC, 2022](#)). Economic modeling helps simulate the potential outcomes of adopting carbon-negative practices under various policy, market, and climate scenarios. These models assess cost-effectiveness, return on investment, risk exposure, and long-term sustainability at farm, regional, and national levels. Impact assessment frameworks further evaluate environmental, social, and economic trade-offs, ensuring that interventions are not only financially viable but also equitable and scalable ([Ravindranath & Murthy, 2021](#)). Together, these tools guide policymakers, investors, and farmers in making informed decisions that balance profitability with climate resilience. Building on this foundation, the following subsections delve into key analytical tools used to evaluate the economic viability of carbon-negative farming.

4.1 Tools for Economic Viability Analysis

- Farm-level financial models evaluating profitability of carbon-negative practices.
- Regional and national economic impact models incorporating carbon sequestration benefits.
- Use of cost-effectiveness analysis to prioritize interventions.

4.2 Social and Economic Co-Benefits

- Employment generation and rural livelihoods improvement.
- Food security and nutrition benefits from sustainable farming.
- Gender and social equity considerations

4.1 Tools for Economic Viability Analysis

Assessing the economic viability of carbon-negative farming is essential for informed decision-making by farmers, policymakers, and investors. Various analytical tools help quantify costs, benefits, and trade-offs at different scales. The following sub-sections outline key tools used to evaluate profitability, economic impact, and cost-effectiveness of carbon-negative interventions.

Farm-Level Financial Models Evaluating Profitability of Carbon-Negative Practices

Farm-level financial models are analytical tools designed to estimate the costs, revenues, and profitability of adopting carbon-negative farming practices at the individual farm scale. These models incorporate variables such as input costs (seeds, fertilizers, labor), operational expenses, yield changes, and potential revenues from crop sales and carbon credits ([Medici et al., 2020](#)). By simulating scenarios, these models help farmers and advisors understand the economic trade-offs involved, identify profitable practices, and optimize resource allocation. Common tools include partial budgeting, enterprise budgets, and dynamic simulation models.

Regional and National Economic Impact Models Incorporating Carbon Sequestration Benefits

Beyond individual farms, regional and national scale economic models assess the broader impact of carbon-negative farming adoption on economies. These models integrate data on agricultural production, employment, carbon sequestration, and environmental services to estimate contributions to GDP, rural incomes, and national emission reduction

targets. Examples include computable general equilibrium (CGE) models and input-output models that capture sectoral interactions ([Mardones & Lipski, 2020](#)). Incorporating carbon sequestration benefits allows policymakers to evaluate the economic returns of climate-smart agriculture programs and justify investments.

Use of Cost-Effectiveness Analysis to Prioritize Interventions

Cost-effectiveness analysis (CEA) compares different carbon-negative farming interventions based on the cost incurred per unit of carbon sequestered or emission avoided. This approach helps identify the most efficient and scalable practices, ensuring limited resources are allocated to interventions yielding the highest climate and economic benefits. CEA can also incorporate co-benefits, such as improved soil health or biodiversity, to provide a more comprehensive prioritization framework for decision-makers.

4.2 Social and Economic Co-Benefits

Carbon-negative farming not only contributes to climate mitigation but also delivers a range of social and economic co-benefits that enhance its overall value, especially in rural contexts. These benefits strengthen community resilience and support inclusive development. The following sub-sections highlight key co-benefits such as job creation, improved food security, and enhanced social equity.

Employment Generation and Rural Livelihoods Improvement

Carbon-negative farming practices often require diversified and intensified labor inputs, creating new employment opportunities in rural areas. Practices such as agroforestry, cover cropping, and organic amendments foster demand for skilled and unskilled labor in planting, maintenance, and monitoring ([Ravindranath & Murthy, 2021](#); [Adekiya, 2023](#)). This can

enhance income stability and reduce rural poverty. Moreover, increased farm productivity and ecosystem health contribute to long-term livelihood resilience ([Ravindranath & Murthy, 2021](#)).

Food Security and Nutrition Benefits from Sustainable Farming

Sustainable, carbon-negative agriculture promotes diversified cropping systems and improved soil fertility, leading to more stable and nutritious food production. Enhanced soil health increases crop yields and nutrient density, contributing to better dietary quality. Resilience to climate shocks ensures food availability during adverse weather events, strengthening household and community food security ([Adekiya, 2023](#)).

Gender and Social Equity Considerations

The adoption of carbon-negative farming can significantly influence social dynamics within rural communities. Ensuring inclusivity is essential to provide women, marginalized groups, and smallholders with equitable access to resources, knowledge, and the financial benefits of carbon farming initiatives. For example, the experiences of community forestry in Nepal and the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) program highlight the importance of participatory and inclusive governance structures in achieving both environmental and social goals ([Agarwal, 2001](#); [Larson *et al.*, 2015](#)). Empowering these groups not only improves adoption rates but also promotes broader social justice. Gender-sensitive policies and programs are critical to addressing persistent barriers, such as insecure land tenure, and limited access to credit, extension services, and capacitybuilding opportunities.

5. Challenges and Opportunities in Market Mechanisms

While market mechanisms offer promising pathways to scale carbon-negative farming, they face significant challenges that can limit

participation and impact ([FT Editorial, 2024](#)). Complexities in carbon accounting, high certification costs, and fragmented market structures particularly hinder smallholder farmers from accessing these opportunities. However, advances in technology such as blockchain, mobile platforms, and remote sensing are beginning to lower these barriers by enhancing transparency, reducing costs, and improving data accuracy ([Cuellar & Johnson, 2022](#); Sustainability-Directory, 2023). Looking ahead, expanding nature-based solution markets and stronger public-private collaborations present opportunities for integrating carbon farming into larger climate finance frameworks, fostering more inclusive and effective market systems. This section examines the key barriers limiting market participation, highlights technological innovations that are improving access, and explores emerging trends shaping the future of carbon-negative farming markets.

5.1 Barriers to Market Participation

- Complexity and cost of carbon accounting and certification.
- Market fragmentation and lack of standardized protocols.
- Smallholder inclusion challenges.

5.2 Technological Innovations Facilitating Market Access

- Digital platforms and blockchain for transparent carbon credit trading.
- Mobile applications for farmer engagement and data collection.
- Remote sensing and AI for monitoring and verification.

5.3 Future Trends and Emerging Markets

- Integration of carbon farming into broader climate finance frameworks.
- Expansion of nature-based solutions markets.
- Role of public-private partnerships and international cooperation.

5.1 Barriers to Market Participation

Farmers and agribusinesses often face significant obstacles when entering carbon markets, limiting widespread adoption of carbon-negative practices. Understanding these barriers is crucial to designing inclusive and effective market systems. The following points explore key challenges such as complex certification processes, fragmented markets, and difficulties faced by smallholders.

Complexity and Cost of Carbon Accounting and Certification

Carbon accounting involves rigorous measurement, reporting, and verification (MRV) to ensure emissions reductions or carbon sequestration claims are credible. This process requires technical expertise, specialized equipment, and compliance with stringent protocols set by certification bodies ([Climatic Change, 2024](#)). For many farmers, especially smallholders, these complexities translate into high transaction costs, limiting their ability to participate effectively in carbon markets (SustainabilityDirectory, 2024). Certification fees, auditing costs, and administrative burdens can further discourage engagement, creating barriers to entry for those who may benefit most.

Market Fragmentation and Lack of Standardized Protocols

Carbon markets are highly fragmented, with multiple voluntary and compliance standards operating in parallel. Each standard may have differing rules, methodologies, and verification requirements ([FT Editorial, 2024](#)). This diversity creates confusion among participants, complicates

credit fungibility, and reduces market liquidity. Without standardized protocols, carbon credits' quality and comparability vary, undermining buyer confidence and potentially depressing prices. Fragmentation also hinders scalability and the integration of carbon farming into larger climate finance systems ([FT Editorial, 2024](#)).

Smallholder Inclusion Challenges

Smallholder farmers, who constitute a large share of agricultural producers globally, face particular obstacles to market participation. Their limited land size, low literacy levels, and lack of access to technology or capital make it difficult to undertake complex carbon accounting or meet certification requirements (SustainabilityDirectory, 2024). Moreover, aggregation of smallholder activities into viable carbon projects demands organizational capacity and trust-building, which are often lacking. Without tailored support mechanisms, smallholders risk exclusion from lucrative carbon markets, exacerbating inequalities ([Climatic Change, 2024](#)).

5.2 Technological Innovations Facilitating Market Access

Advances in technology are transforming how carbon markets operate, improving transparency, efficiency, and farmer engagement. Emerging digital tools enable better data collection, secure transactions, and real-time monitoring. This section highlights innovations like blockchain, mobile apps, and AI-driven remote sensing that facilitate broader market participation.

Digital Platforms and Blockchain for Transparent Carbon Credit Trading

Innovative digital platforms streamline the carbon credit lifecycle, from project registration and MRV to trading and retirement, making market participation more accessible and efficient. Blockchain technology

enhances transparency and trust by creating immutable, tamper-proof ledgers of credit issuance and transactions (SustainabilityDirectory, 2023). This reduces risks of double counting and fraud, ensuring integrity across decentralized systems. Platforms integrating blockchain enable farmers and buyers to connect directly, reducing intermediaries and transaction costs (SustainabilityDirectory, 2023; [Tsai, 2024](#)).

Mobile Applications for Farmer Engagement and Data Collection

Mobile technology empowers farmers by providing easy-to-use tools for data collection, training, and real-time communication. Apps can guide farmers through carbon-friendly practices, record agronomic and environmental data, and facilitate participation in carbon projects ([Sustainability Directory, 2023](#)). These applications help bridge information gaps, enhance accuracy in carbon accounting, and enable large-scale data aggregation essential for project validation. Additionally, mobile payments integrated with apps allow for quicker and more secure financial transactions related to carbon incentives.

Remote Sensing and AI for Monitoring and Verification

Remote sensing technologies, including satellites and drones, enable large-scale, cost-effective monitoring of land use, vegetation cover, and biomass changes. Artificial intelligence (AI) and machine learning algorithms process these vast datasets to detect carbon stock changes and verify compliance with project criteria ([Climatic Change, 2024](#); [West Science, 2023](#)). This reduces reliance on labor-intensive field measurements, lowers verification costs, and improves monitoring frequency and accuracy. AI-driven analytics also support predictive modeling to optimize carbon sequestration strategies.

5.3 Future Trends and Emerging Markets

Carbon markets and related climate finance mechanisms are rapidly evolving, offering new opportunities for integrating carbon farming into larger sustainability frameworks. This section outlines future directions including the growth of nature-based solutions, increased public-private collaboration, and expanding international cooperation that will shape market development.

Integration of Carbon Farming into Broader Climate Finance Frameworks

Carbon farming is increasingly being recognized as a critical component of global climate finance strategies. Integration with broader frameworks such as the Green Climate Fund, national climate action plans (NDCs), and sustainable development financing, will channel more resources into carbon-negative agriculture. This alignment promotes coherence across funding streams, leverages public and private capital, and enhances the impact and scalability of carbon farming initiatives.

Expansion of Nature-Based Solutions Markets

Markets for nature-based solutions (NbS) that address climate change and biodiversity loss are rapidly expanding. Carbon-negative farming is a key NbS, providing multiple co-benefits such as habitat restoration, water conservation, and soil health improvement. Emerging markets are increasingly valuing and monetizing these multiple ecosystem services alongside carbon sequestration, creating diversified revenue streams and enhancing the attractiveness of carbon farming projects ([Griscom *et al.*, 2017](#)).

Role of Public-Private Partnerships and International Cooperation

Public-private partnerships (PPPs) play a vital role in mobilizing investment, technical expertise, and policy support to advance carbon-negative farming markets. Collaboration among governments, NGOs,

agribusinesses, and financial institutions fosters innovation, capacity building, and risk-sharing. International cooperation through platforms like the UNFCCC and regional climate initiatives promotes the harmonization of standards, knowledge exchange, and market connectivity, thereby enhancing the effectiveness and global reach of carbon markets ([OECD, 2020](#)).

6. Policy Recommendations and Strategic Actions

To unlock the full potential of carbon-negative farming and ensure equitable participation in emerging carbon markets, a strong enabling environment is essential ([UNCTAD, 2024](#)). This requires coherent policy frameworks, institutional support, and strategic actions that align environmental goals with economic incentives ([FAO, 2015](#)). Policymakers must address current gaps in regulation, capacity, and infrastructure while fostering innovation and inclusivity. By integrating climate, agricultural, and development priorities, governments and stakeholders can create resilient, farmer-friendly systems that advance both carbon mitigation and sustainable development objectives ([UNCTAD, 2024](#); [FAO, 2015](#)). The following points outline key policy measures and strategic interventions needed to strengthen the institutional, technical, and financial foundations of carbon-negative farming.

1. Strengthening institutional frameworks and regulatory support.
2. Promoting capacity building and technical assistance for farmers.
3. Designing inclusive, transparent, and efficient market mechanisms.
4. Encouraging innovation and investment in carbon-negative agriculture.
5. Aligning carbon markets with sustainable development goals (SDGs).

6.1 Strengthening Institutional Frameworks and Regulatory Support

Robust institutional frameworks are essential to create an enabling environment for carbon-negative farming. Governments need to establish clear policies, legal guidelines, and regulatory mechanisms that support carbon accounting, market participation, and environmental stewardship. This includes developing national carbon strategies, integrating agriculture into climate action plans, and enforcing standards for carbon credit certification ([OECD, 2023](#); [FAO, 2015](#)). Effective institutions also ensure coordination among ministries (agriculture, environment, finance) and between local, regional, and national levels ([UNCTAD, 2024](#)). Regulatory clarity reduces market uncertainties, protects stakeholder rights, and builds investor confidence, thus facilitating the scaling up of carbon-negative agriculture ([OECD, 2023](#)).

6.2 Promoting Capacity Building and Technical Assistance for Farmers

Many farmers, especially smallholders, require training and technical support to adopt carbon-negative practices and participate in carbon markets. Capacity building programs should focus on knowledge transfer about sustainable farming methods, carbon measurement techniques, and market processes ([UNEP-CCC, 2023](#)). Extension services, farmer field schools, and digital learning platforms can play vital roles in disseminating information. Additionally, technical assistance must cover data collection for MRV, business skills for managing carbon projects, and understanding certification requirements ([UNEP-CCC, 2023](#)). Strengthening farmer organizations and cooperatives also enhances collective action and bargaining power ([UNCTAD, 2024](#)). Investing in capacity building

empowers farmers, improves adoption rates, and ensures that carbon farming delivers genuine environmental and economic benefits.

6.3 Designing Inclusive, Transparent, and Efficient Market Mechanisms

Market mechanisms must be designed to be accessible to diverse stakeholders, including smallholders, women, and marginalized groups, to ensure equity and maximize environmental impact ([UNCTAD, 2024](#)). Transparency is critical to maintaining trust among participants, which can be enhanced through clear rules, open data platforms, and third-party verification ([WBCSD, 2023](#)). Efficient mechanisms minimize transaction costs by simplifying processes, leveraging technology, and reducing intermediaries ([UNECA, 2024](#)). Policymakers should foster aggregation models that enable smallscale farmers to pool resources and credits, making market participation viable ([UNCTAD, 2024](#)). Furthermore, harmonizing standards and protocols across regions helps create interoperable markets that can scale. Such inclusive and transparent markets encourage broader participation and promote long-term sustainability.

6.4 Encouraging Innovation and Investment in Carbon-Negative Agriculture

Innovative technologies, business models, and financing instruments are key drivers for advancing carbon-negative farming. Policymakers should incentivize research and development in areas such as improved carbon measurement tools, low-cost sensors, and AI-based monitoring systems ([Kyriakarakos *et al.*, 2024](#)). Supporting start-ups and enterprises developing scalable solutions through grants, tax incentives, or innovation hubs fosters a vibrant ecosystem ([Surana *et al.*, 2020](#)). Investment promotion strategies should attract private capital into carbon farming projects by mitigating

risks via guarantees, blended finance, or impact investing ([OECD, 2023](#)). Public funding can catalyze earlystage initiatives, while partnerships with financial institutions broaden access to credit. Encouraging innovation and investment accelerates technology adoption, improves market efficiency, and enhances climate mitigation outcomes.

6.5 Aligning Carbon Markets with Sustainable Development Goals (SDGs)

Carbon markets and related policies must be aligned with the broader agenda of sustainable development to ensure that climate actions also advance social and economic objectives ([FAO, 2015](#); [UNCTAD, 2024](#)). This includes promoting practices that improve livelihoods, gender equity, food security, and biodiversity conservation, core elements of the SDGs ([FAO, 2015](#); [UNCTAD, 2024](#)). Governments and market regulators should embed SDG criteria within carbon credit certification processes and market incentives ([UNCTAD, 2024](#)). Integrating multi-dimensional sustainability metrics encourages holistic project design and implementation. Moreover, reporting frameworks should capture social and environmental co-benefits alongside carbon outcomes. Aligning carbon markets with SDGs enhances their legitimacy, attracts ethical investors, and ensures that climate mitigation contributes to a just and inclusive green transition.

7. Conclusion and Way Forward

This chapter explores the financial dimensions of carbon-negative farming, emphasizing the critical role of market mechanisms and policy incentives in driving adoption. It reviews key components such as carbon markets both voluntary and compliance along with certification, carbon credits, and Measurement, Reporting, and Verification (MRV) systems that ensure transparency and credibility. The chapter also highlights other market-based

incentives, including ecosystem service payments, green bonds, and consumer-driven premiums. Tools for economic viability analysis and the social cobenefits of carbon farming are discussed, alongside barriers to market participation and technological innovations facilitating access. Future trends focus on expanding nature-based solutions markets and fostering public-private partnerships and international cooperation.

Carbon-negative farming holds significant promise as both a climate mitigation strategy and a pathway to sustainable rural development. However, its widespread economic viability depends on overcoming financial, technical, and social barriers. Robust market frameworks, reliable certification, and transparent MRV systems are essential to build trust and incentivize stakeholders. Integrating diverse market-based incentives and leveraging technological innovations can enhance farmer participation and unlock new revenue streams. Collaborative efforts through policy support and global partnerships will be crucial to scaling these solutions effectively.

To ensure lasting impact, policymakers, investors, and practitioners should prioritize strengthening carbon market infrastructure, simplifying access for smallholders, and promoting innovative technologies. Additionally, expanding incentives beyond carbon alone to include broader ecosystem services and social benefits will enhance the economic attractiveness and sustainability of carbon-negative farming.

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Chapter 12

Policy and Governance for Carbon-Negative Agriculture

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1. Introduction

As the world grapples with the intensifying impacts of climate change, agriculture has emerged as both a contributor to and potential mitigator of greenhouse gas (GHG) emissions. Conventional farming practices, especially those relying on intensive tillage, synthetic fertilizers, and monoculture systems, are estimated to contribute around 20–30% of total global GHG emissions ([Smith *et al.*, 2014](#); [FAO, 2023](#)). Yet, this same sector holds immense potential for carbon drawdown through regenerative practices, organic amendments, agroforestry, improved grazing, and other soil-carbon enhancing strategies. The concept of carbon-negative agriculture, which goes beyond carbon neutrality to achieve net-negative emissions, is increasingly being recognized as a critical pathway for achieving climate goals under the Paris Agreement.

However, realizing the potential of carbon-negative agriculture at scale requires more than just technical innovation or farmer-level change. It necessitates transformative shifts in agricultural policy, institutional governance, and market mechanisms. Policies at the national and international levels influence everything from input subsidies and land-use decisions to extension services and carbon accounting frameworks. Yet many current agricultural policies continue to incentivize

emissionsintensive practices, creating structural barriers to low-carbon transitions ([Searchinger et al., 2020](#); [Ganda, 2023](#)).

In response, a new generation of policy instruments is emerging globally from carbon credit schemes and results-based finance to soil health legislation and climate-smart subsidy programs. For example, the EU's Common Agricultural Policy (CAP) now integrates carbon farming within its climate architecture ([European Commission, 2021](#)), while countries like India are piloting voluntary carbon markets for the agricultural sector through mission-based initiatives like the National Mission on Natural Farming ([MoAFW, 2023](#)).

Good governance is equally essential in shaping the success of these transitions. Governance frameworks must enable participatory decision-making, decentralized institutions, and equity-oriented approaches to ensure that marginalized farmers are not excluded from carbon-benefit sharing. Without clear rules, monitoring protocols, and farmer safeguards, carbon farming risks becoming another form of “green grabbing” ([Fairhead et al., 2012](#)), wherein benefits accrue to external investors while rural communities bear the cost of land-use restrictions.

Moreover, interdisciplinary policy integration is needed, linking agricultural policy with climate, energy, forestry, and water policies. Coherent governance across sectors can enable synergistic outcomes such as enhanced resilience, biodiversity protection, and rural livelihoods. International cooperation, especially in the Global South, will also play a critical role in providing technology transfer, climate finance, and institutional capacity building ([UNFCCC, 2022](#)).

In this chapter, we explore the evolving landscape of policy and governance for carbon-negative agriculture, assess case studies from around the world, and offer a framework for building inclusive, climate-aligned

governance systems. Ultimately, enabling a shift toward carbon-negative farming is not just a matter of science and economics, it is a question of political will, institutional design, and the collective capacity to govern for the common good.

2. Policy Landscape for Carbon-Negative Agriculture

Transitioning toward carbon-negative agriculture demands a multi-scalar, multi-sectoral policy framework, from village-level land-use plans to international climate regimes. Such a framework must align efforts in soil carbon sequestration, biodiversity conservation, nutrient-use efficiency, and low-emission food systems. While agriculture's technical potential as a carbon sink is well established ([Smith *et al.*, 2019](#)), this potential remains underutilized without coherent incentives, robust regulations, and inclusive governance mechanisms. The [IPCC \(2019a\)](#) estimates that agriculture, forestry, and other land use (AFOLU) could deliver up to 30% of the mitigation required to meet the 1.5°C climate target - that is, the global goal of limiting the increase in average global temperatures to no more than 1.5 degrees Celsius above pre-industrial levels (i.e., before the year 1850) - with soil carbon sequestration playing a critical role. Yet, national agricultural and climate policies often prioritize yield maximization and export competitiveness, sidelining environmental concerns ([FAO, 2022](#); [Schulte, 2019](#) [Schulte *et al.*, 2025](#)). Fragmented governance across ministries leads to conflicting policies, such as fertilizer subsidies that counteract soil health efforts ([Kalkuhl *et al.*, 2020a](#)). Emerging models in India and New Zealand demonstrate policy innovation through climate-smart agriculture, soil health programs, and the inclusion of agriculture in emissions trading schemes (MoAFW, 2023; NZ [Ministry for the Environment, 2021](#)). However, to be transformative, these efforts must be embedded in decentralized, participatory systems that prioritize equity and

ecological resilience ([Fairhead *et al.*, 2012](#); [Tengö *et al.*, 2017](#)). The following sections explore how national climate and agriculture policies (2.1) and international agreements and frameworks (2.2) are shaping this evolving policy terrain.

2.1 National Climate and Agriculture Policies

- a. Integration of agriculture in Nationally Determined Contributions (NDCs) under the Paris Agreement.
- b. Examples of national climate-smart agriculture policies supporting carbon sequestration.
- c. Role of agricultural subsidies, input regulations, and extension services in shaping carbonnegative practices.

2.2 International Agreements and Frameworks

- a. Influence of global climate agreements (UNFCCC, Paris Agreement) on agricultural mitigation policies.
- b. Role of international bodies (FAO, CGIAR, IPCC) in setting guidelines and facilitating knowledge exchange.
- c. Impact of Global Sustainable Development Agendas (SDGs) on Policy Formulation

2.1 National Climate and Agriculture Policies

Agriculture plays a pivotal role in national climate strategies, especially in countries vulnerable to climate change. The integration of agriculture into Nationally Determined Contributions (NDCs) under the Paris Agreement marks a shift from treating the sector merely as a source of emissions to recognizing its potential for mitigation through practices such as soil carbon sequestration and agroforestry ([FAO, 2021a](#)). However, the extent and

depth of agricultural commitments vary across nations, influenced by socio-economic priorities, institutional capacities, and political will. Strengthening climate-smart agricultural policies and aligning subsidies and extension systems toward sustainability are key to unlocking carbon-negative transitions.

2.1.1 Integration of Agriculture in Nationally Determined Contributions (NDCs) under the Paris Agreement

The Paris Agreement (2015) requires countries to submit Nationally Determined Contributions (NDCs) outlining their climate mitigation and adaptation commitments (UNFCCC, 2015). Agriculture plays a pivotal role in many NDCs due to its dual impact on greenhouse gas emissions and carbon sequestration potential. More than 140 countries have included agriculture in their NDCs highlighting mitigation strategies, such as improved soil carbon management, agroforestry, and sustainable land use, ([Richards *et al.*, 2021](#); [UNFCCC, 2021](#)). For example, India's updated NDC highlights enhancing soil organic carbon and reducing methane emissions from rice paddies and livestock as priority actions ([Government of India, 2022](#)). This integration signals an increasing recognition of agriculture's critical role in meeting global climate goals and mobilizing investments to promote carbon-negative practices at the national scale.

2.1.2 Examples of National Climate-Smart Agriculture Policies Supporting Carbon Sequestration

Several countries have developed dedicated climate-smart agriculture (CSA) policies that embed carbon sequestration as a core objective. Brazil's Low Carbon Agriculture Plan (Plano ABC) incentivizes farmers to adopt no-till farming, integrated crop-livestock-forestry systems, and biological nitrogen fixation, all contributing to soil carbon build-up ([Nepstad *et al.*, 2014](#)). Similarly, Kenya's Climate-Smart Agriculture Strategy promotes

agroforestry and conservation agriculture to increase carbon stocks and enhance resilience (GoK, 2017). India's National Mission on Sustainable Agriculture (NMSA) emphasizes soil health, climate-resilient cropping, and efficient water use, indirectly promoting carbon sequestration (MoAFW, 2023). These policies often combine regulatory frameworks with financial incentives, technical support, and capacity building, thus providing a comprehensive approach to fostering carbon-negative agriculture.

2.1.3 Role of Agricultural Subsidies, Input Regulations, and Extension Services in Shaping Carbon-Negative Practices

Agricultural subsidies and regulations profoundly influence farmers' input choices and management practices. Reforming subsidy programs to support organic amendments, biofertilizers, or cover cropping can encourage carbon sequestration while reducing synthetic fertilizer use, which is a significant source of nitrous oxide emissions (Smith *et al.*, 2020). Likewise, regulatory frameworks governing pesticide and fertilizer application set standards that indirectly affect soil health and carbon dynamics. Extension services play a critical role in disseminating knowledge and training farmers on carbon-negative practices, bridging the gap between policy and practice ([Hsu *et al.*, 2018](#); Chen & Zhang, 2022). Effective extension approaches integrate participatory methods, farmer field schools, and digital advisory platforms to promote adoption ([Rosenstock *et al.*, 2016](#)).

2.2 International Agreements and Frameworks

The advancement of carbon-negative agriculture is increasingly influenced by international climate agreements and multilateral governance frameworks. Agreements such as the UN Framework Convention on Climate Change (UNFCCC) and the Paris Agreement have repositioned agriculture as not only vulnerable to climate change but also vital to mitigation and adaptation efforts. These frameworks guide national policies,

funding mechanisms, and accountability systems for land-based mitigation (UNFCCC, 2015). In addition, organizations like the FAO, CGIAR, and IPCC play a crucial role in synthesizing science, setting normative frameworks, and facilitating knowledge exchange across nations. Their efforts help align global climate goals with agricultural strategies on the ground. The 2030 Agenda for Sustainable Development and its 17 Sustainable Development Goals (SDGs), particularly SDG 13 (climate action), SDG 2 (zero hunger), and SDG 15 (life on land), underscore the importance of integrated, systems-based policy approaches that support food security, equity, and sustainability (UN General Assembly, 2015; [FAO, 2021b](#)).

2.2.1 Influence of global climate agreements (UNFCCC, Paris Agreement) on agricultural mitigation policies

Global climate agreements such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Paris Agreement have redefined the role of agriculture in climate governance. While earlier COP negotiations focused primarily on emission reductions in energy and industry, the Paris Agreement (Article 2 and 4) explicitly encourages countries to “pursue efforts to limit the temperature increase to 1.5°C” and achieve a balance between greenhouse gas emissions and removals. Agriculture is recognized within Nationally Determined Contributions (NDCs) as both a vulnerable sector and a source of mitigation potential through practices like soil carbon sequestration, agroforestry, and sustainable land management ([FAO, 2021b](#)). Notably, the Koronivia Joint Work on Agriculture, adopted at COP23, institutionalized agriculture as a formal topic of negotiation under the UNFCCC. This decision has opened avenues for scientific guidance, technology transfer, and capacity building

around climate-resilient and low-emission agricultural systems ([UNFCCC, 2017](#); [FAO, 2019](#)).

2.2.2 Role of international bodies (FAO, CGIAR, IPCC) in setting guidelines and facilitating knowledge exchange

International scientific and policy organizations such as FAO, CGIAR, and IPCC are instrumental in shaping carbon-negative agricultural pathways. The IPCC synthesizes the latest scientific findings to inform policymakers; its Special Report on Climate Change and Land ([IPCC, 2019b](#)) highlighted agriculture as both a contributor to climate change and a critical sector for mitigation and adaptation. The FAO provides technical guidelines and global assessments like the Global Soil Organic Carbon Map and the RECSOIL program, which promote carbon farming and climate-smart agriculture ([FAO, 2021c](#)). The CGIAR, through its Climate Change, Agriculture and Food Security (CCAFS) program, supports research and innovation in sustainable intensification, carbon monitoring, and climate information services tailored to smallholders ([CCAFS, 2020](#)). These bodies also facilitate South-South cooperation, enabling knowledge exchange and best practices between developing countries through platforms like the Global Alliance for Climate-Smart Agriculture (GACSA).

2.2.3 Impact of Global Sustainable Development Agendas (SDGs) on Policy Formulation

The 2030 Agenda for Sustainable Development, adopted by all UN Member States in 2015, integrates agriculture into a broader framework of planetary health, equity, and resilience. Several Sustainable Development Goals (SDGs) are directly linked to carbon-negative agriculture:

- SDG 2 (Zero Hunger) calls for sustainable food production systems and resilient agricultural practices.

- SDG 13 (Climate Action) urges urgent action to combat climate change, including landbased mitigation.
- SDG 15 (Life on Land) promotes sustainable land use, afforestation, and restoration of degraded lands.

These goals foster integrated policy-making, wherein climate, food, biodiversity, and land-use objectives are aligned. As a result, countries are increasingly embedding sustainability and carbon sequestration goals into agriculture-related strategies, such as land restoration programs and agroecological transitions (UN General Assembly, 2015; [Sachs *et al.*, 2019](#)).

3. Governance Structures and Institutional Roles

Effective governance is a cornerstone for advancing carbon-negative agriculture, which requires managing the complex interplay of environmental, social, and economic objectives. As land-use and climate policies become increasingly interconnected, governance systems must evolve to facilitate transitions toward sustainable and low-emission agricultural practices. Institutional coordination, across ministries, levels of government, and sectors, is critical to avoid policy fragmentation and ensure synergy between mitigation, adaptation, and food security goals ([Jordan & Lenschow, 2010](#)). The governance of carbon-negative agriculture involves a dynamic combination of multi-level governance, where global, national, and sub-national actors interact, and participatory governance, which promotes the involvement of farmers, Indigenous communities, research institutions, and civil society organizations. These hybrid structures enhance not only policy effectiveness but also legitimacy, ownership, and social learning, all essential for long-term systemic change (Ostrom, 2009; [Newig & Fritsch, 2009](#)).

Recent literature emphasizes that inclusive governance is especially important in climate-smart land use, as top-down mandates without local engagement often result in implementation failures or resistance ([Brandi *et al.*, 2015](#)). In contrast, participatory frameworks that incorporate local knowledge and respect tenure rights have shown promise in accelerating soil carbon restoration, agroforestry adoption, and regenerative farming practices ([Chandra *et al.*, 2018](#)). Institutions also play a key role in mobilizing financial incentives, coordinating capacity-building programs, and creating monitoring, reporting, and verification (MRV) systems for agricultural carbon initiatives ([FAO, 2021d](#); [IPCC, 2019b](#)). Thus, designing robust and responsive governance architectures is not merely a matter of administration, it is a strategic investment in institutional innovation that enables climate-resilient agriculture to scale equitably and sustainably. These governance challenges and opportunities can be better understood by examining two core dimensions: (i) multi-level governance and (ii) participatory governance.

3.1 Multi-level Governance

- a. Roles of local, regional, national, and international institutions in policy implementation and enforcement.
- b. Coordination mechanisms across sectors (agriculture, environment, finance).
- c. Examples of successful governance models integrating carbon-negative farming.

3.2 Stakeholder Engagement and Participatory Governance

- a. Inclusion of farmers, communities, NGOs, private sector, and academia in decision-making processes.

- b. Mechanisms for bottom-up feedback and adaptive governance.
- c. Importance of transparency, accountability, and trust-building.

3.1 Multi-level Governance

Multi-level governance refers to the interaction and distribution of authority across different levels of government and institutions, from local to international, essential for effective climate and agricultural transitions. In the context of carbon-negative agriculture, this layered governance system plays a critical role in aligning global climate ambitions with national development priorities and grassroots realities. Effective coordination between these levels enables better policy coherence, resource allocation, implementation, and accountability mechanisms ([Betsill & Bulkeley, 2006](#)).

3.3.1 Roles of Local, Regional, National, and International Institutions in Policy Implementation and Enforcement

Each level of governance has distinct responsibilities in enabling carbon-negative agriculture. Local governments and institutions are often best positioned to promote context-specific practices like agroforestry, organic amendments, and indigenous land stewardship. Regional and national authorities establish regulatory frameworks, fiscal incentives, and land-use policies. Meanwhile, international institutions provide overarching climate frameworks, such as the Paris Agreement, and facilitate transboundary knowledge exchange and finance. As [Widerberg and Pattberg \(2014\)](#), emphasize, “*Subnational institutions are vital for delivering mitigation outcomes in agriculture, as they possess local legitimacy and implementation capacity often missing at national levels,*” underlining the importance of multi-level coordination for successful policy implementation and on-ground impact.

3.3.2 Coordination Mechanisms Across Sectors (Agriculture, Environment, Finance)

Carbon-negative agriculture operates at the nexus of multiple sectors, requiring governance that fosters inter-sectoral coordination across agriculture, climate, environment, and finance. Integrated policy planning is essential to avoid conflicting objectives, for instance, input subsidies that degrade soil health while promoting sustainability on paper. Mechanisms such as cross-ministerial task forces, shared data systems, and integrated budgeting can strengthen coherence and alignment. As [Nilsson et al. \(2012\)](#) assert, “Policy integration across environmental and agricultural sectors is a prerequisite for addressing land-based emissions effectively,” highlighting the importance of institutional frameworks that support holistic and synergistic approaches

3.3.3 Examples of Successful Governance Models Integrating Carbon-Negative Farming

Several countries have pioneered multi-level governance models that effectively integrate carbon sequestration into agricultural planning. For instance, Ethiopia’s Climate-Resilient Green Economy Strategy operationalizes carbon farming through a strong framework of federal coordination and regional implementation. As [Gebregziabher et al. \(2016\)](#), note, “*Ethiopia has demonstrated the ability of coordinated governance across levels to scale up sustainable land management and carbon sequestration initiatives,*” showcasing the importance of vertical policy alignment. Similarly, India’s National Mission on Sustainable Agriculture (NMSA) serves as a platform for harmonizing central government policies with state-level initiatives focused on agroecology, climate adaptation, and soil carbon enhancement, highlighting the crucial role of institutional coherence across governance scales..

4. Regulatory Instruments and Incentives

The widespread adoption of carbon-negative agricultural practices hinges on the presence of robust regulatory instruments and well-designed incentive structures. Regulatory frameworks provide the legal infrastructure for managing land use, emissions, and resource utilization, while incentive mechanisms create the economic rationale for farmers to adopt practices that sequester carbon and restore ecosystem services. As climate change accelerates, governments and global institutions are increasingly turning to a mix of command-and-control approaches, such as environmental laws and land-use regulations, and market-based instruments, including carbon credits and payments for ecosystem services (PES) ([Kust *et al.*, 2017](#); [World Bank, 2020](#)). These instruments can enhance transparency, ensure compliance, and align private behavior with public climate goals. However, effective implementation often requires overcoming challenges related to institutional capacity, monitoring systems, and equitable access to incentives ([FAO, 2021e](#)). This section explores the dual pillars of legal frameworks (4.1) and economic instruments (4.2) that are shaping the policy environment for carbon-negative agriculture.

4.1 Legal Frameworks and Standards

- Environmental laws regulating emissions, land use, and soil management.
- Standards for carbon accounting, reporting, and certification.
- Enforcement challenges and compliance monitoring.

4.2 Economic Incentives and Market-Based Instruments

- Subsidies, grants, and tax incentives promoting carbon-negative practices.
- Carbon markets and trading schemes integrating agriculture.

- Payment for Ecosystem Services (PES) schemes rewarding carbon sequestration.

4.3 Legal Frameworks and Standards

Legal frameworks and standardized regulations provide the structural backbone for implementing carbon-negative agricultural practices. They define the boundaries of acceptable environmental conduct, ensure uniformity in measuring and reporting greenhouse gas (GHG) mitigation, and establish mechanisms for accountability and enforcement. As agriculture becomes increasingly integrated into national climate action plans and global carbon markets, robust legal instruments are essential to guide land-use decisions, support certification systems, and promote long-term compliance. The credibility and scalability of carbon-negative farming hinge on coherent laws, transparent standards, and strong institutional capacity to monitor and enforce sustainability outcomes ([IPCC, 2019b](#); [FAO, 2021e](#); [World Bank, 2020](#)).

Environmental laws regulating emissions, land use, and soil management

Legal frameworks play a foundational role in steering agricultural systems toward carbon-negative pathways. Environmental laws that regulate greenhouse gas (GHG) emissions, restrict harmful land-use changes (e.g., deforestation, wetland conversion), and promote sustainable soil management are essential tools. For instance, countries like Brazil and India have enacted land-use policies that restrict forest encroachment and mandate afforestation targets, helping mitigate emissions from agriculture and land-use change ([FAO, 2021e](#)). Similarly, the EU's Common Agricultural Policy (CAP) includes cross-compliance requirements linking farm subsidies to environmental performance, such as maintaining permanent pastures and protecting carbon-rich soils ([Pe'er et al., 2020](#)).

Standards for carbon accounting, reporting, and certification

To credibly measure, verify, and reward carbon sequestration in agriculture, standardized protocols are necessary. Legal standards for carbon accounting, such as those developed by the IPCC, the Verified Carbon Standard (VCS), and the Gold Standard, provide methodologies for estimating and certifying emissions reductions and soil carbon gains (IPCC, 2019a; [Verra, 2022](#)). These frameworks underpin carbon markets and enable farmers to earn credits for implementing regenerative practices, such as cover cropping or agroforestry. Transparent reporting and third-party verification are central to building trust and scalability in carbon-negative agriculture.

Enforcement challenges and compliance monitoring

Despite the existence of laws and standards, enforcement often remains a major challenge, especially in developing countries where institutional capacities are limited. Inconsistent monitoring, limited technical infrastructure, and fragmented governance structures hamper compliance ([Kust et al., 2017](#)). Moreover, smallholder farmers may lack awareness or resources to meet complex certification criteria, highlighting the need for inclusive regulatory design. Strengthening legal enforcement mechanisms, through satellite monitoring, digital record-keeping, and capacity building, is critical for ensuring accountability and effective implementation of carbon-related standards ([World Bank, 2020](#)).

4.4 Economic Incentives and Market-Based Instruments

Economic incentives and market-based instruments are critical policy tools for scaling up carbon-negative agriculture. These mechanisms create financial motivations for farmers and land managers to adopt practices that reduce emissions and enhance carbon sequestration such as agroforestry,

cover cropping, and reduced tillage. By assigning value to ecosystem services like carbon storage, governments and private sectors can internalize environmental benefits into market transactions. Instruments such as subsidies, tax breaks, carbon credits, and Payments for Ecosystem Services (PES) help align economic interests with climate goals, thereby accelerating the transition to regenerative and sustainable agriculture. When well-designed, such approaches not only enhance climate resilience but also promote equity, rural livelihoods, and sustainable land stewardship ([Salzman *et al.*, 2018](#); [World Bank, 2020](#); [FAO, 2021e](#)).

Subsidies, Grants, and Tax Incentives Promoting Carbon-Negative Practices

Economic incentives such as subsidies, grants, and tax breaks can significantly lower barriers to adopting carbon-negative agricultural practices. Governments often provide financial support for conservation agriculture, agroforestry, organic farming, and soil health improvement initiatives ([OECD, 2020](#)). For example, the U.S. Environmental Quality Incentives Program (EQIP) offers cost-share payments to farmers implementing conservation measures that increase carbon sequestration ([USDA NRCS, 2021](#)). Tax incentives for renewable energy use and low-emission technologies also encourage sustainable farming investments. Well-targeted economic incentives accelerate the transition by compensating for upfront costs and opportunity losses.

Carbon Markets and Trading Schemes Integrating Agriculture

Carbon markets represent a powerful mechanism for monetizing the carbon sequestration potential of agricultural lands. Both compliance and voluntary carbon markets now increasingly include agricultural projects, allowing farmers to generate carbon credits from practices such as reduced tillage, improved manure management, and agroforestry ([Wollenberg *et al.*, 2016](#)).

These markets create financial flows that reward emission reductions and removals, incentivizing broader adoption of carbon-negative farming. Challenges remain in ensuring additionality, permanence, and avoiding leakage, which standards and rigorous monitoring seek to address.

Payment for Ecosystem Services (PES) Schemes Rewarding Carbon Sequestration

PES schemes provide direct payments to landowners or farmers in exchange for managing land in ways that deliver ecosystem services, including carbon sequestration ([Wunder, 2015](#)). These programs often link agricultural land stewardship to conservation objectives, offering financial incentives for practices that increase soil organic carbon and reduce greenhouse gas emissions. Examples include Mexico's PES program, which compensates smallholders for forest conservation and agroforestry, contributing to climate mitigation and rural livelihoods ([Muñoz-Piña *et al.*, 2008](#)). PES schemes foster voluntary participation and can be integrated with carbon markets to create hybrid incentives for carbon-negative agriculture.

5. Policy Challenges and Governance Gaps

While the momentum for carbon-negative agriculture is growing globally, its widespread adoption remains constrained by several structural and institutional challenges. Key among these are fragmented governance systems, inadequate capacity, and deep-rooted social inequalities. Often, agricultural and environmental policies operate in silos, resulting in overlapping mandates, inconsistent regulations, and missed opportunities for synergy ([Altieri *et al.*, 2020](#)). At the same time, many regions face critical shortfalls in technical expertise, financing, and infrastructure needed to implement climate-smart interventions at scale. Moreover, governance systems frequently overlook equity concerns marginalizing smallholders,

indigenous communities, and women farmers from policy benefits and decision-making processes ([IPCC, 2019b](#); [FAO, 2021e](#)). Addressing these interconnected governance gaps is essential for ensuring the effectiveness, legitimacy, and inclusiveness of carbon-negative farming systems. The following sub-sections examine three key areas of concern:

5.1 Fragmentation and Policy Coherence

- Overlapping mandates and conflicting policies across agencies.
- Challenges in aligning agricultural development and climate mitigation objectives.
- Case examples of policy inconsistencies affecting carbon-negative agriculture.

5.2 Capacity Constraints and Resource Limitations

- Limited technical, financial, and human resources for policy implementation.
- Need for strengthening institutional capacity and infrastructure.
- Gaps in data, monitoring, and evaluation systems.

5.3 Equity, Inclusiveness, and Access Issues

- Addressing barriers faced by smallholders, women, and marginalized groups.
- Land tenure security and access to resources as governance issues.
- Ensuring fair benefit sharing from carbon markets and incentives.

5.1 Fragmentation and Policy Coherence

One of the most persistent governance challenges in advancing carbon-negative agriculture is the fragmentation of institutional mandates and

policy incoherence. Agricultural, environmental, energy, and land use policies are often developed in isolation, leading to contradictions that weaken implementation and blur accountability ([Runhaar *et al.*, 2020](#)). For example, while some policies promote soil carbon sequestration and regenerative practices, others continue to subsidize chemical inputs or encourage land conversion, directly undermining climate objectives. The lack of inter-ministerial coordination, unified goals, and integrated planning tools results in inefficiencies and missed opportunities for crosssectoral synergies. Promoting carbon-negative transitions thus requires not only technical reforms but deep institutional alignment across scales and sectors ([Altieri *et al.*, 2020](#)).

Overlapping mandates and conflicting policies across agencies

Multiple government agencies often share jurisdiction over agriculture, environment, finance, and rural development, leading to overlapping responsibilities and sometimes contradictory policies. For example, while an agricultural ministry might promote intensified crop production using synthetic fertilizers, an environmental agency may advocate for reduced chemical inputs to enhance soil carbon stocks ([Runhaar *et al.*, 2020](#)). Such overlaps create confusion and inefficiencies that weaken climate mitigation efforts in agriculture.

Challenges in aligning agricultural development and climate mitigation objectives

Agricultural policies traditionally prioritize food security, productivity, and economic growth, which may conflict with climate goals requiring emission reductions or land-use restrictions. Balancing these priorities demands integrated planning and clear trade-offs, which are often lacking. Without alignment, mitigation efforts may be sidelined or insufficiently funded (Bharucha *et al.*, 2020).

Case examples of policy inconsistencies affecting carbon-negative agriculture

In some countries, fertilizer subsidies persist despite evidence of their negative impact on soil health and carbon sequestration ([World Bank, 2020](#)). Similarly, policies encouraging land expansion for agriculture may conflict with forest conservation mandates, undermining carbon storage goals. These inconsistencies highlight the need for coherent and cross-sectoral policy frameworks.

5.2 Capacity Constraints and Resource Limitations

Even when policies are in place, weak implementation capacity remains a major barrier to scaling carbon-negative agriculture. Many public institutions, particularly in low- and middle-income countries, face critical shortages of skilled personnel, financial resources, and physical infrastructure required to design, monitor, and enforce climate-smart agricultural programs ([FAO, 2021a](#)). These constraints are often compounded by limited access to reliable data, weak monitoring and evaluation frameworks, and inadequate research-extension linkages. Without targeted investments in institutional capacity, knowledge systems, and operational support, carbon-focused policies risk remaining on paper rather than being translated into field-level change (IPCC, 2019a; [Westermann *et al.*, 2018](#)).

Limited technical, financial, and human resources for policy implementation

Many developing countries lack adequate funding and skilled personnel to implement, monitor, and enforce carbon-negative agriculture initiatives effectively ([FAO, 2021e](#)). Limited budgets restrict extension services, capacity building, and technology transfer needed for farmer adoption of climatesmart practices.

Need for strengthening institutional capacity and infrastructure

Effective governance requires investment in institutional infrastructure such as data systems, training programs, and monitoring tools. Capacity-building at local and national levels is critical to operationalize policies and ensure adaptive management ([Westermann *et al.*, 2018](#)).

Gaps in data, monitoring, and evaluation systems

Reliable data on soil carbon stocks, emissions reductions, and farming practices is often scarce, hampering accurate reporting and verification. Without robust monitoring and evaluation frameworks, assessing policy effectiveness and guiding improvements remains challenging ([IPCC, 2019b](#)).

5.3 Equity, Inclusiveness, and Access Issues

Equity and inclusion are central to the effectiveness and legitimacy of governance systems supporting carbon-negative agriculture. Smallholders, indigenous peoples, and women farmers who often steward significant carbon-rich landscapes frequently face structural barriers to participation in policy processes, access to land and finance, and benefit-sharing mechanisms (Agarwal, 2014; [FAO, 2022](#)). Issues of insecure land tenure, historical marginalization, and limited voice in governance structures reduce their ability to adopt new practices or benefit from carbon markets and incentive schemes. Addressing these disparities is not only a moral imperative but essential for ensuring the scalability and durability of climate mitigation in agriculture. Inclusive governance frameworks that secure rights, recognize traditional knowledge, and share benefits equitably can enhance both environmental and social outcomes ([Locatelli *et al.*, 2022](#)).

Addressing barriers faced by smallholders, women, and marginalized groups

Small-scale farmers, women, and indigenous peoples often face structural barriers including limited land rights, restricted access to credit, and exclusion from decision-making forums. These barriers constrain their ability to participate in carbon-negative agriculture programs and benefit from incentives (Agarwal, 2014; [FAO, 2022](#)).

Land tenure security and access to resources as governance issues

Secure land tenure is fundamental for farmers to invest in long-term soil health and carbon sequestration practices. Unclear or insecure land rights undermine incentives for sustainable management and limit eligibility for carbon finance schemes ([Locatelli *et al.*, 2022](#)).

Ensuring fair benefit sharing from carbon markets and incentives

Carbon market mechanisms and Payments for Ecosystem Services (PES) must incorporate transparent and equitable benefit-sharing arrangements to avoid exacerbating existing inequalities. Inclusive governance frameworks that recognize customary rights and promote participatory decision-making improve social justice and program effectiveness ([Altieri *et al.*, 2020](#)).

6. Emerging Policy Innovations and Best Practices

As the urgency to combat climate change intensifies, policy design for carbon-negative agriculture is undergoing a transformative shift. Traditional top-down models, often fragmented and sectoral, are increasingly seen as inadequate for addressing the complex, interconnected challenges of climate mitigation, agricultural sustainability, and rural livelihoods. In response, a new generation of policy innovations is emerging, characterized by integrated planning, digital tools, and collaborative partnerships that aim to enable systemic change and accelerate the adoption of regenerative agricultural practices.

These innovations reflect a growing consensus that climate solutions must be multi-level, multi-actor, and context-specific, grounded in the socio-ecological realities of farming communities. They draw upon insights from landscape ecology, climate-smart agriculture, and co-production of knowledge to create adaptive governance mechanisms that support not only carbon sequestration but also biodiversity conservation, water management, and livelihood resilience.

6.1 Integrated Landscape Approaches

- Policies promoting landscape-level planning and cross-sectoral collaboration.
- Examples of integrated watershed management supporting carbon sequestration.

6.2 Digital Governance and E-Policy Tools

- Use of digital platforms for monitoring, reporting, and stakeholder engagement.
- Blockchain and transparency tools in governance of carbon credits.

6.3 Public-Private Partnerships and Multi-Stakeholder Initiatives

- Collaborative models mobilizing finance, technology, and expertise.
- Role of certification bodies, NGOs, and community organizations.

6.1 Integrated Landscape Approaches

Integrated Landscape Approaches (ILAs) offer a holistic framework for managing land, water, forests, and agriculture together to balance environmental, social, and economic objectives. These approaches promote

synergies between carbon sequestration, biodiversity, and food security by fostering crosssectoral coordination at the ecosystem level (Sayer *et al.*, 2013; Reed *et al.*, 2016). By integrating various land uses, ILAs help optimize landscape functionality, especially under climate mitigation programs like REDD+ ([Minang *et al.*, 2015](#)). The following sub-sections explore how landscape-level policies are operationalized and present field-based examples where integrated watershed management has supported carbon sequestration outcomes.

- **Policies promoting landscape-level planning and cross-sectoral collaboration**

Modern land-use policies are increasingly recognizing the need for landscape-level planning that moves beyond the traditional, fragmented approach. Such planning fosters cross-sectoral collaboration by integrating agriculture, forestry, water, and biodiversity management to ensure carbon sequestration and ecological resilience. Unlike piecemeal interventions, these policies emphasize systemic interactions within ecosystems and promote institutional arrangements that engage diverse actors in shared land stewardship ([Sayer *et al.*, 2013](#)).

In India, policies such as the National Agroforestry Policy (2014) and the Integrated Watershed Management Programme (IWMP) have embedded landscape-level strategies that align agricultural goals with forest conservation and water security. These initiatives involve convergence between departments like Rural Development, Agriculture, Forests, and Panchayati Raj Institutions, enabling joint action for soil health, biomass regeneration, and climate mitigation (Minang *et al.*, 2015).

Globally, the Landscape Approach has been endorsed by frameworks like the Convention on Biological Diversity (CBD) and the UNFCCC REDD+

mechanism, advocating for multilevel, participatory governance across land-use systems to meet both climate and development goals (Reed *et al.*, 2016).

- **Examples of integrated watershed management supporting carbon sequestration** Integrated watershed management is a prime example of landscape-based carbon-negative planning. These programs focus on restoring ecological functions of entire watersheds by enhancing soil organic carbon, reducing erosion, and improving water infiltration, which directly contribute to long-term carbon sequestration.

India's IWMP, launched in over 6000 micro-watersheds, applies check dams, contour bunding, and vegetative cover restoration to enhance soil moisture and build below-ground biomass. Studies show that these interventions have significantly increased soil organic carbon stocks and reversed land degradation in semi-arid regions ([Wani *et al.*, 2011](#)).

In Ethiopia, the Sustainable Land Management Programme (SLMP), implemented across critical highland watersheds, combines soil bunds, area enclosures, and agroforestry, leading to measurable carbon sequestration and improved livelihoods ([Freeman *et al.*, 2015](#)).

These watershed projects, when nested in broader national carbon accounting systems, serve as verifiable models of climate-smart and socially inclusive land restoration.

6.2 Digital Governance and E-Policy Tools

Digital governance is transforming agricultural and environmental policy by enabling real-time monitoring, data-driven decision-making, and participatory engagement. Advanced tools such as GIS, satellite imaging,

mobile apps, and blockchain enhance transparency, traceability, and accountability in carbon-negative initiatives ([World Bank, 2019, 2020](#)). These innovations are crucial for scaling regenerative practices and integrating farmers into carbon markets with verifiable metrics (Winowiecki & Vagen, 2013). The sections below illustrate how digital platforms are being used for monitoring, reporting, and stakeholder engagement, and highlight the emerging role of blockchain in governing carbon credit systems.

- **Use of digital platforms for monitoring, reporting, and stakeholder engagement** Digital tools are revolutionizing policy design and implementation for carbon-negative agriculture by enabling real-time monitoring, automated reporting, and inclusive stakeholder participation. These platforms allow policymakers and farmers to access geospatial data, verify practices, and co-produce knowledge.

One example is Collect Earth, a tool developed by FAO and Google Earth Engine, which enables stakeholders to assess land-use changes, forest cover, and biomass density using satellite imagery. In India, the Soil Health Card Scheme integrates digital soil testing data and provides tailored nutrient advisories, indirectly enhancing soil carbon ([FAO, 2021](#) g).

Digital MRV (Monitoring, Reporting, and Verification) systems, such as those integrated in Kenya's Vi Agroforestry projects, allow climate finance actors to track carbon sequestration outcomes across thousands of smallholder farms with minimal cost and high precision (Winowiecki *et al.*, 2021).

Moreover, stakeholder platforms like Digital Green and AgNext use mobile-based video extension and AI-driven analytics to bridge the policy-

practice gap by making digital advisory tools accessible to rural communities.

- **Blockchain and transparency tools in governance of carbon credits**

Blockchain technology is emerging as a credible tool in ensuring transparency, traceability, and trust in the governance of carbon credits. It provides a decentralized, tamper-proof ledger that tracks each transaction, from field practice to carbon credit issuance, ensuring data integrity and reducing fraud.

Blockchain-based carbon platforms, such as the Regen Network, are being piloted to support regenerative farming systems by issuing digitally verifiable carbon credits based on remotely sensed and field-validated data ([World Bank, 2020](#)). These credits can then be traded on voluntary carbon markets, with every step documented on the blockchain to maintain auditability.

In India, fintech startups are exploring the use of blockchain to aggregate carbon offsets from smallholder farms and ensure transparent benefit-sharing among communities, certification agencies, and investors. Such systems are critical for building confidence among stakeholders and meeting international standards like those of the Verra VCS and Gold Standard ([Van Noordwijk *et al.*, 2011](#)).

6.3 Public-Private Partnerships and Multi-Stakeholder Initiatives

Public-Private Partnerships (PPPs) and multi-stakeholder initiatives have become vital mechanisms to mobilize finance, innovation, and capacity for scaling carbon-negative agriculture. By bringing together governments,

businesses, NGOs, and communities, these partnerships accelerate the adoption of climate-smart practices while sharing risks and benefits (Pattberg & Widerberg, 2015; FAO & GEF, 2022). They also strengthen institutional frameworks for inclusive and measurable climate action across landscapes. The following discussion outlines successful collaborative models for mobilizing finance and technology, along with the critical roles played by certification bodies, NGOs, and community organizations in implementation and oversight.

- **Collaborative models mobilizing finance, technology, and expertise**

Public-Private Partnerships (PPPs) are essential for scaling carbon-negative agriculture by mobilizing capital, technological know-how, and institutional support. These collaborative models leverage public policy and infrastructure with private sector innovation and market access to de-risk and mainstream regenerative practices.

The Livelihoods Carbon Fund, supported by private companies such as Danone, Schneider Electric, and Hermès, invests in agroforestry and reforestation projects across Asia and Africa. In return, these corporations receive certified carbon offsets, while farmers gain long-term income through trees, soil improvement, and enhanced resilience (Pattberg & Widerberg, 2015).

In India, partnerships under the Paramparagat Krishi Vikas Yojana (PKVY) and National Mission on Sustainable Agriculture (NMSA) have facilitated multi-actor alliances to promote organic farming and conservation agriculture. These programs often include collaboration with digital agritech firms, financial institutions, and farmer producer organizations to operationalize climate goals at scale (FAO & GEF, 2022).

- **Role of certification bodies, NGOs, and community organizations**

Certification agencies, NGOs, and grassroots organizations play an indispensable role in ensuring accountability, inclusiveness, and capacity building in carbon-negative farming initiatives. They act as intermediaries between farmers and markets, help interpret carbon protocols, and build trust among stakeholders.

Initiatives like the Cool Farm Alliance provide open-source tools to assess GHG emissions and soil carbon footprints, which are used by both corporations and NGOs to guide sustainability interventions ([Reed et al., 2016](#)). NGOs such as BAIF Development Research Foundation and Watershed Organisation Trust (WOTR) have implemented landscape-scale agroecological programs with strong carbon and livelihood outcomes in India.

These actors also play a role in third-party verification, helping projects meet the standards set by international frameworks like Gold Standard and Plan Vivo, thereby enhancing credibility and access to carbon markets ([Van Noordwijk et al., 2011](#)). Moreover, community-based organizations ensure that local knowledge, land tenure rights, and gender equity are factored into program design and execution.

7. Recommendations for Strengthening Policy and Governance

To effectively scale carbon-negative agriculture, it is essential to address existing policy and governance shortcomings through targeted reforms. Strengthening the alignment between climate objectives and agricultural development, building institutional capacities, and fostering inclusive decision-making are critical steps. Additionally, robust data systems and transparent processes will enhance accountability, while embracing

innovation and adaptive management will ensure policies remain responsive to changing conditions and stakeholder needs. The following recommendations outline key priorities for creating resilient, equitable, and effective governance frameworks to support the transition toward sustainable, carbon-negative farming systems.

1. Developing coherent and integrated policy frameworks linking climate, agriculture, and rural development.
2. Enhancing institutional capacities at all governance levels.
3. Promoting inclusive governance with equitable participation.
4. Investing in data systems, transparency, and accountability mechanisms.
5. Encouraging innovation, flexibility, and adaptive management approaches.

7.1 Developing Coherent and Integrated Policy Frameworks Linking Climate, Agriculture, and Rural Development

Effective advancement of carbon-negative agriculture requires the development of coherent and integrated policy frameworks that bridge the traditionally siloed domains of climate action, agricultural development, and rural livelihoods ([FAO, 2019](#)). Such integration ensures that mitigation and adaptation objectives reinforce food security and socio-economic growth rather than conflict. Policy coherence can be fostered through cross-sectoral strategies, joint planning platforms, and alignment of goals within Nationally Determined Contributions (NDCs) and rural development agendas ([Petersen *et al.*, 2019](#)). Integrated frameworks reduce policy contradictions, streamline resource use, and create enabling environments for carbon-negative practices to scale sustainably.

7.2 Enhancing Institutional Capacities at All Governance Levels

Strengthening institutional capacity is critical to translate policies into actionable outcomes. This includes building technical expertise for carbon accounting, monitoring, and sustainable farming methods, as well as enhancing administrative capabilities for enforcement and coordination ([Lippper *et al.*, 2014](#)). Capacity development should target local, regional, and national levels, recognizing the importance of decentralized governance in agriculture. Investment in human resources, infrastructure such as soil laboratories and digital monitoring tools, and knowledge exchange platforms can empower institutions to support farmers effectively and ensure compliance with carbon regulations (Smith *et al.*, 2020).

7.3 Promoting Inclusive Governance with Equitable Participation

Inclusive governance ensures that all stakeholders, including smallholder farmers, women, indigenous peoples, and marginalized communities, participate equitably in policy design, implementation, and benefit sharing ([Newig *et al.*, 2023](#)). Participatory approaches enhance legitimacy, responsiveness, and social justice in carbon-negative agriculture programs. Institutionalizing mechanisms for stakeholder consultations, community representation, and gender-sensitive policies helps address disparities in access to resources and decision-making ([World Bank, 2019, 2020](#)). Inclusive governance also reduces risks of elite capture and supports sustainable outcomes by aligning initiatives with local needs and knowledge.

7.4 Investing in Data Systems, Transparency, and Accountability Mechanisms

Robust data systems are foundational for evidence-based policymaking, monitoring progress, and ensuring transparency in carbon accounting and carbon markets ([Friedlingstein et al., 2019](#)). Investments in comprehensive databases, remote sensing, and digital platforms improve the accuracy and timeliness of carbon measurements, enhancing stakeholder confidence. Transparency mechanisms such as publicly accessible registries of carbon credits, and independent third-party verification foster accountability, reducing risks of fraud and greenwashing (WRI & WBCSD, 2015). Strengthening feedback loops and grievance redressal mechanisms ensures continuous improvement and trust in governance frameworks.

7.5 Encouraging Innovation, Flexibility, and Adaptive Management Approaches

Given the dynamic nature of climate, markets, and farming systems, policy frameworks must embrace innovation, flexibility, and adaptive management to remain effective ([Sayer et al., 2013](#)). This involves piloting novel carbon sequestration techniques, digital MRV tools, and financing models, coupled with mechanisms for learning and adjusting policies based on new evidence and stakeholder feedback. Adaptive governance allows timely responses to emerging challenges and opportunities, promoting resilience and sustainability in carbon-negative agriculture ([Reed et al., 2016](#)). Encouraging multiactor partnerships and iterative policy design further supports innovation and flexibility.

8. Conclusion and Way Forward

Policy and governance frameworks play a pivotal role in advancing carbon-negative agriculture by creating enabling environments that align climate mitigation with sustainable agricultural development. Effective policies integrate cross-sectoral objectives, ensuring coherence between agricultural

productivity, rural livelihoods, and environmental stewardship. Governance structures that span local to international levels, and incorporate participatory decision-making, are essential for inclusive and equitable implementation. Regulatory instruments, economic incentives, and marketbased mechanisms together provide the necessary drivers for adoption of carbon sequestration practices. However, challenges such as policy fragmentation, capacity constraints, and equity gaps must be addressed to unlock the full potential of carbon-negative agriculture.

The future of carbon-negative agriculture hinges on collaborative, transparent, and adaptive governance systems that can respond flexibly to evolving scientific knowledge, market conditions, and social contexts. Innovations in digital governance, integrated landscape management, and multistakeholder partnerships demonstrate promising pathways to scale carbon sequestration sustainably. Ensuring inclusive participation and fair benefit sharing will strengthen social legitimacy and resilience. Ultimately, carbon-negative agriculture can serve as a cornerstone in global climate action if supported by robust, coherent, and forward-looking policy and governance frameworks.

To effectively scale carbon-negative agriculture, it is essential to promote integrated policy frameworks that align climate, agricultural, and rural development goals, optimizing synergies while minimizing trade-offs. Building institutional capacity through investments in training, infrastructure, and knowledge systems is equally vital to support effective policy implementation and monitoring. Inclusive governance must be ensured by enabling equitable participation of marginalized communities, women, and smallholders in both decision-making and benefit sharing. Strengthening data systems and ensuring transparency through robust accountability mechanisms can foster trust and support evidence-based

polycymaking. Furthermore, fostering innovation through adaptive, flexible policies and encouraging multi-actor collaboration will promote continuous learning and resilience. Lastly, enhancing coordination among government bodies, the private sector, civil society, and farmers is critical to mobilizing resources and expertise through cohesive, multi-stakeholder partnerships. Collectively, these actions will accelerate the transition toward sustainable, climate-resilient, and carbon-negative agricultural systems.

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Chapter 13

Community and Indigenous Knowledge Systems

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1. Introduction

As the global community confronts the escalating threats of climate change, land degradation, and biodiversity loss, there is a growing recognition of the value of traditional, community-rooted knowledge systems in shaping sustainable solutions ([Altieri & Nicholls, 2004](#); [FAO, 2019](#)). Among these, indigenous and community knowledge systems are particularly noteworthy because they are comprehensive, ecologically based frameworks that have been cultivated through centuries of close relationship with the land. These knowledge systems, often referred to as Traditional Ecological Knowledge (TEK), are not just repositories of ecological insight, but also living practices that support biodiversity conservation, sustainable agriculture, and climate resilience (Berkes *et al.*, 2000).

In the context of carbon-negative farming, which seeks to reduce atmospheric greenhouse gases by enhancing carbon sequestration through soil, vegetation, and agroecosystems, indigenous and community knowledge plays a foundational yet often underappreciated role ([Ghosh, 2011](#)). Across the globe, indigenous peoples and local communities have long employed land management strategies that align closely with the goals of carbon sequestration such as agroforestry, organic farming, rotational grazing, wetland conservation, and water harvesting ([Pretty, 1995](#); [Altieri, 2009](#)). These practices are inherently low-input, biodiversity-friendly, and

often centred around circular resource use, offering viable models for climate-friendly agriculture that modern science is increasingly validating ([Mistry & Berardi, 2016](#)).

Despite their value, these knowledge systems have historically been marginalized or overlooked in formal agricultural and environmental policy ([Agrawal, 1995](#); [Posey, 1999](#)). The spread of industrial agriculture, land tenure insecurity, and socio-political marginalization have contributed to the erosion of traditional practices and ecological wisdom. Yet, in recent decades, there has been a paradigm shift toward recognizing the rights of indigenous peoples, documenting their practices, and integrating them into broader sustainability and climate change agendas, including those articulated under the UN Framework Convention on Climate Change (UNFCCC) and the Convention on Biological Diversity (CBD) ([UNFCCC, 2013](#); [CBD, 2011](#)).

This chapter examines how community and indigenous knowledge systems contribute significantly to carbon-negative farming. Rooted in centuries of observation and adaptive land stewardship, these Traditional Ecological Knowledge (TEK) systems enhance soil organic carbon, support sustainable land use, and maintain ecological balance. Case studies from diverse agro-ecological contexts demonstrate how local communities mitigate climate impacts while sustaining livelihoods ([Kimmerer, 2013](#)). Despite their proven value, these systems often face challenges such as lack of legal recognition, intellectual property concerns, and insufficient integration into formal research and policy frameworks ([Robinson & Wallington, 2012](#)). The chapter advocates for co-production of knowledge, where indigenous wisdom and modern science collaborate to design regenerative, socially just agricultural systems (Tengo *et al.*, 2014). By positioning traditional knowledge as central to climate-resilient agriculture,

it calls for their protection, empowerment, and integration into carbon farming policies and market mechanisms. Embracing TEK ensures carbon.

2. Understanding Indigenous and Community Knowledge Systems

Indigenous and Community Knowledge Systems encompass the time-tested wisdom, skills, and cultural practices developed by local communities through sustained interactions with their natural surroundings. These systems offer a rich, place-based understanding of ecological processes, often emphasizing sustainability, biodiversity, and resilience. Rooted in oral traditions and communal experience, such knowledge systems are dynamic and adaptive, enabling communities to respond to environmental changes and manage resources sustainably over generations. This deep ecological understanding holds particular relevance for contemporary efforts to address climate change through sustainable agriculture. In this context, the following subheadings explore the definitions, key features, and the crucial role of Indigenous and Community Knowledge in promoting carbon-negative farming practices.

1. Definition and Characteristics
2. Relevance to Carbon Negative Farming

2.1 Definition and Characteristics

Indigenous Knowledge (IK) and Community Knowledge (CK) represent deeply rooted, place-based systems of understanding that have evolved over centuries through the lived experiences of indigenous peoples and local communities. Unlike conventional scientific knowledge, which often seeks universal truths through formal experimentation, IK is experiential, holistic, and transmitted through generations via oral traditions, observation, and

cultural practices ([Berkes, 1999](#)). These knowledge systems are dynamic and continually adapting to environmental and social changes ([Agrawal, 1995](#)). At the core of IK is a profound connection with nature one that blends practical resource management with cultural, spiritual, and ecological dimensions. This makes it highly relevant for addressing sustainability, climate adaptation, and agro-ecological resilience in the context of carbon-negative farming.

The defining characteristics of Indigenous and Community Knowledge include the following interconnected elements:

- Place-specific wisdom
- Systems thinking
- Adaptive management
- Intergenerational transmission
- **Place-specific wisdom**

Indigenous Knowledge is intricately tied to the specific landscapes in which it has developed. Generations of observation, experimentation, and interaction with local soil types, water flows, plant phenology, and animal behavior have allowed communities to cultivate an exceptional understanding of their environment. This deep, place-based knowledge enables finely tuned management practices such as timing of sowing, pest prediction, water harvesting, and biodiversity conservation that are tailored to microclimates and ecological niches. Because it is inherently local, IK is highly adaptable to regional variability and offers nuanced solutions that top-down approaches often miss (Berkes *et al.*, 1999).

- **Systems thinking**

These knowledge systems are inherently holistic, viewing land, water, air, plants, animals, and humans as part of a single interdependent web. Rather than isolating variables, indigenous worldviews consider the cumulative and cyclical impacts of human and natural actions. For example, agricultural decisions are often made in relation to lunar cycles, soil health, wildlife migrations, or seasonal rainfall patterns, reflecting an integrated understanding of ecosystem dynamics. This systems-level thinking promotes long-term sustainability by minimizing unintended consequences and reinforcing ecological balance (Altieri, 2004; [Berkes, 2008](#)).

- **Adaptive management**

Indigenous communities have long practiced adaptive management, modifying techniques and strategies based on continuous feedback from nature. Through centuries of trial, error, and refinement, they have developed flexible and resilient practices such as rotational cropping, shifting cultivation, and diversified agroforestry. These methods evolve as environmental conditions change, allowing for real-time adjustments in the face of climate variability, pest outbreaks, or soil depletion. The ability to adapt without reliance on external inputs makes these systems robust under uncertain climate scenarios ([Gadgil *et al.*, 2000](#)).

- **Intergenerational transmission**

The continuity and resilience of Indigenous Knowledge depend heavily on its oral and experiential transmission. Elders, storytellers, and community leaders play a vital role in teaching younger generations through seasonal rituals, local narratives, songs, and apprenticeship. These methods do more than transfer technical skills, they embed ethical values, spiritual beliefs, and a deep sense of responsibility toward nature. This

intergenerational learning maintains the cultural identity of communities while preserving ecologically grounded knowledge that modern educational systems often overlook ([McGregor, 2004](#)).

These characteristics make Indigenous and Community Knowledge an essential complement to scientific approaches in building regenerative, carbon-negative farming systems.

2.2 Relevance to Carbon Negative Farming

Traditional agricultural systems, particularly those practiced by Indigenous communities and smallholder farmers, often embody principles that are inherently sustainable and aligned with carbon-negative goals. These time-tested methods emphasize soil conservation, biodiversity, organic inputs, and integrated land use, resulting in practices that promote carbon sequestration, reduce greenhouse gas (GHG) emissions, and enhance ecosystem services. In contrast to industrial, high-input systems, these approaches work in harmony with nature rather than against it, offering low-cost, climate-resilient models for rural communities worldwide ([Altieri, 1996](#); [Lal, 2004](#)). These traditional practices hold immense relevance for modern-day efforts to mitigate climate change through agriculture. Many of them contribute directly to carbon sequestration by improving soil organic carbon, enhancing aboveground biomass, and reducing fossil fuel reliance. Below are key examples of traditional agricultural practices that support carbon-negative farming outcomes:

- Low tillage or zero tillage methods
- Agroforestry and sacred groves
- Mixed cropping and cover cropping
- Use of organic manures and composting
- Community-managed commons and pasture lands

- **Low Tillage or Zero Tillage Methods**

Reducing or eliminating tillage limits soil disturbance, thereby preserving soil structure, preventing erosion, and retaining organic carbon. Traditional no-till methods, such as those used in India's *Zai pits* and *Himadaan* systems, have shown enhanced moisture conservation and soil fertility. According to [Lal \(2004\)](#), "No-till farming increases soil organic carbon stocks by reducing decomposition rates and encouraging biomass input retention."

- **Agroforestry and Sacred Groves**

Agroforestry systems where trees are integrated with crops and/or livestock are traditional land-use practices found in regions such as Kerala, the Khasi Hills, and parts of Central America. These systems can sequester between 2–9 tonnes CO₂/ha/year depending on species and management ([Montagnini & Nair, 2004](#)). Sacred groves, conserved by Indigenous belief systems, also act as carbon sinks and biodiversity reservoirs ([Bhagwat & Rutte, 2006](#)).

- **Mixed Cropping and Cover Cropping**

Mixed cropping, including intercropping and polyculture, not only improves food security but also contributes to carbon sequestration through enhanced root biomass and reduced input use. Cover cropping suppresses weeds, improves nitrogen fixation (in legume-based systems), and increases soil organic matter. [Altieri \(1999\)](#) notes that "diversified cropping systems improve biological interactions in the soil and support the buildup of stable carbon pools."

- **Use of Organic Manures and Composting**

The application of farmyard manure, green manures, and compost is a cornerstone of traditional farming. These organic amendments feed soil biota, enhance humus formation, and improve soil carbon content. Composting, when done aerobically, emits minimal methane and supports long-term soil carbon storage ([Edwards, 2004](#)).

- **Community-managed Commons and Pasture Lands**

Common lands historically managed by village councils for grazing and resource sharing are often biodiverse and managed through low-impact rotational practices. Such systems, when supported by collective governance, reduce degradation and facilitate regrowth of vegetation, aiding carbon capture in both soil and biomass ([Ostrom, 1990](#); [Pretty, 2007](#)).

These examples illustrate that traditional knowledge and practices offer a rich repository of low-carbon techniques, aligning well with the objectives of carbon-negative farming. Each practice, rooted in ecological principles, holds potential for revitalization, replication, and integration into climate-smart agricultural strategies.

3. Traditional Agricultural Practices Supporting Carbon Sequestration

Traditional agricultural practices, deeply rooted in Indigenous and local community knowledge systems, have long contributed to environmental sustainability, soil regeneration, and climate resilience. These systems are based on millennia of empirical observation, ecological adaptation, and cultural evolution. They are often designed to work with natural processes,

emphasizing closed-loop nutrient cycles, minimal ecological disturbance, and the multifunctionality of landscapes ([Altieri *et al.*, 2015](#)).

Unlike industrialized agriculture, which is often input-intensive and emissions-heavy, traditional systems are typically low in fossil fuel dependence, rich in biodiversity, and enhanced by local knowledge that promotes long-term soil fertility. For instance, Indigenous systems in sub-Saharan Africa, South Asia, and Latin America integrate land use with spiritual values, ensuring protective stewardship of trees, soils, and water ([Garnett *et al.*, 2018](#)). These systems inherently promote carbon sequestration through the accumulation of soil organic carbon (SOC) and aboveground biomass, as well as the reduction of methane and nitrous oxide emissions ([Lal, 2020](#); [Barrios *et al.*, 2020](#)).

Moreover, studies show that Indigenous and traditional lands store about 22% of the world's carbon in tropical and subtropical forest biomes, yet comprise less than 5% of the total land area ([Fa *et al.*, 2020](#)). These systems are increasingly recognized as cost-effective and socially inclusive solutions for climate change mitigation under global initiatives like the UNFCCC and IPCC recommendations (IPBES, 2019). The following subheadings highlight specific traditional practices that contribute significantly to carbon sequestration, ecosystem restoration, and the regeneration of degraded lands.

1. Agroforestry and Tree-Based Farming
2. Organic Amendments and Biochar
3. Pastoralism and Rotational Grazing
4. Sacred Groves and Community Forests

3.1. Agroforestry and Tree-Based Farming

Agroforestry, the intentional integration of trees and shrubs with crops and/or livestock, is a foundational element of many traditional and Indigenous agricultural systems across Africa, Asia, and Latin America. These ecologically diverse systems serve multiple functions: they enhance soil fertility, conserve water, moderate microclimates, and support pollinators and biodiversity. One of their most significant contributions lies in their ability to sequester atmospheric carbon, both in aboveground biomass (stems, leaves, branches) and belowground pools (roots and soil organic carbon). Notable examples include the Chagga homegardens of Mount Kilimanjaro, which mimic natural forest structure while supplying food, fuel, and fodder, and the jhum agroforestry systems of Northeast India, which integrate trees with shifting cultivation in a cyclical manner.

According to [Nair *et al.* \(2010\)](#), agroforestry systems can sequester 1.5–3.5 Mg C ha⁻¹ yr⁻¹ in soil and 2–13 Mg C ha⁻¹ yr⁻¹ in biomass, depending on species selection, planting density, and ecological zone. These rates are often higher than conventional monoculture systems, positioning agroforestry as a climate-smart, carbon-negative strategy that aligns food security with environmental sustainability. Recent research by [Mbow *et al.* \(2014\)](#) also highlights agroforestry's potential in climate change mitigation and adaptation, particularly for smallholders in tropical and subtropical regions.

3.2. Organic Amendments and Biochar

Traditional agricultural systems have consistently relied on organic amendments such as compost, farmyard manure, green manures, and crop residues to replenish soil fertility and maintain ecological balance. These inputs, rich in organic matter, not only supply essential nutrients but also improve soil structure, aeration, microbial diversity, and soil organic carbon (SOC) levels. Over time, their application supports humus formation,

enhances carbon sequestration, and builds resilience against erosion and drought. Practices like composting are often community-based and cyclical, aligning with sustainable waste reuse and low-emission farming.

In addition, biochar, a form of stable carbon-rich charcoal produced by pyrolyzing biomass under limited oxygen, is another traditional technique re-emerging as a potent carbon-negative solution. Inspired by the ancient terra preta soils of the Amazon, biochar application enhances longterm carbon stability, boosts nutrient retention, and improves soil water-holding capacity. According to [Lehmann and Joseph \(2009\)](#), biochar can lock carbon in soils for centuries, while also reducing methane (CH₄) and nitrous oxide (N₂O) emissions, thus contributing to climate change mitigation. Recent studies have reinforced its dual role in carbon storage and soil rehabilitation, especially in degraded lands ([Woolf *et al.*, 2010](#)).

3.3. Pastoralism and Rotational Grazing

Traditional pastoralist communities, such as the Maasai of East Africa, the Mongol herders of Central Asia, and the Raika pastoralists of India, have practiced rotational and seasonal grazing for centuries as a means to sustain livestock without degrading the land. These systems involve strategic movement of herds based on forage availability, climate patterns, and traditional ecological knowledge, thereby allowing degraded pastures to recover naturally. By preventing continuous overgrazing, such practices maintain vegetation cover, protect topsoil, and preserve grassland biodiversity, making them integral to carbon-negative land management.

Grasslands, especially when well-managed, are among the most effective ecosystems for carbon sequestration, particularly in the root zone and soil organic carbon pools. According to [Reed *et al.* \(2015\)](#), rotational grazing can increase soil carbon stocks, reduce erosion, and enhance ecosystem services such as water retention and climate regulation. Moreover, pastoral

systems contribute to livelihood resilience, landscape diversity, and the adaptive capacity of rural communities, especially in arid and semi-arid environments ([Teague *et al.*, 2016](#)).

3.4. Sacred Groves and Community Forests

Sacred groves and community-managed forests represent one of the oldest forms of nature conservation practiced by traditional societies across India, West Africa, Southeast Asia, and beyond. These ecologically rich patches of forest are preserved due to religious, spiritual, or ancestral beliefs, where local customs often prohibit tree felling, hunting, or grazing. As a result, these groves have remained largely undisturbed for centuries, fostering dense vegetation, rich biodiversity, and long-term carbon storage in both biomass and soil. In India alone, there are an estimated 100,000 sacred groves spanning thousands of hectares ([Malhotra *et al.*, 2007](#)), acting as living repositories of traditional ecological knowledge and climate resilience.

Sacred groves function as microclimate regulators, pollinator habitats, and groundwater recharge zones, while simultaneously sequestering atmospheric carbon. Their preservation is often enforced through customary laws and community taboos rather than state intervention, highlighting their role as models of decentralized, community-led carbon stewardship ([Bhagwat & Rutte, 2006](#)). These systems underscore how cultural values and ecological sustainability can coexist, offering important insights for modern conservation and climate strategies.

These traditional agricultural practices exemplify how indigenous ecological knowledge can serve as an effective strategy for carbon sequestration and climate resilience. They not only support environmental goals but also sustain livelihoods, cultural heritage, and community cohesion. Recognizing and integrating these practices into modern carbon

farming initiatives can foster more inclusive, equitable, and ecologically sound approaches to climate mitigation.

4. Case Studies

Case studies offer valuable, grounded insights into how traditional and community-based agricultural systems contribute to carbon sequestration, ecological resilience, and sustainable livelihoods. These localized practices are not theoretical constructs but time-tested responses to environmental challenges, refined over generations through deep observation, cultural adaptation, and ecological feedback ([Pretty *et al.*, 2009](#)). Whether in mountainous terrains, drylands, or tropical forests, traditional communities have developed sophisticated agro-ecological strategies that integrate climate mitigation, biodiversity conservation, and social equity.

These systems demonstrate that carbon-negative farming is not a new paradigm, but rather an intrinsic part of Indigenous and rural lifeways, often predating modern climate discourse. Their success lies in low external input use, enhanced soil organic carbon, and community-driven governance, proving especially relevant in today's efforts to develop climate-smart and regenerative agriculture ([Altieri & Nicholls, 2013](#); [Mbow *et al.*, 2019](#)). Furthermore, many of these systems offer co-benefits such as food security, water regulation, and cultural preservation, emphasizing that carbon sequestration and sustainability can be achieved simultaneously through traditional knowledge.

The following case studies showcase exemplary traditional farming and land-use systems, from forest-integrated farming in Nagaland, India, to diverse agroecosystems in Mesoamerica and nomadic grazing in Mongolia, that embody key principles of carbon stewardship, resilience, and sustainable land management.

1. Zabo Farming System - Nagaland, India
2. Milpa System - Mesoamerica
3. Nomadic Pastoralism - Mongolia
4. Transhumant Pastoralism - Jammu & Kashmir, India

4.1 Zabo Farming System - Nagaland, India

The Zabo system (also known locally as Ruza) is practiced by the Chakhesang community in Kikrüma village, Phek district, Nagaland. The term Zabo means “impounding water” and describes a traditional practice of integrated forest-water-agricultural land management ([Singh *et al.*, 2018](#); [Lairenjam *et al.*, 2025](#)). This system harnesses forested hilltops as catchments, channels rain runoff through compacted water pathways and holding ponds, and passes water through livestock yards, allowing animal manure to enrich downstream terraced paddy fields.

In this top-down, zero-waste design, the water flows by gravity, first collected in silt trapping tanks, then stored in lined ponds, and finally used for irrigating fields while carrying nutrients from cattle dung and urine. Crops like rice, vegetables, and pulses are cultivated alongside paddy-fish culture, yielding 50–60 kg of fish per hectare alongside 3–4 tonnes of paddy, all without synthetic inputs.

By recycling organic waste, conserving soil moisture, and boosting biodiversity, Zabo enhances both crop productivity and ecosystem carbon sequestration, through increased biomass, soil organic carbon, and reduced erosion. Managed collectively through Village Development Boards, the system exemplifies how indigenous ecological knowledge can support climate resilient, carbon-negative farming in rain-shadow landscapes ([Singh *et al.*, 2018](#); [Lairenjam *et al.*, 2025](#)).

This case highlights how a forest-integrated farming system, combining water harvesting, livestock, agroforestry, paddy cultivation, and aquaculture

within a cyclical nutrient flow, concretely embodies the carbon stewardship principles outlined in the earlier sections such as those in Agroforestry (3.1), Organic Amendments (3.2), and Community Forest Conservation (3.4).

4.2 Milpa System - Mesoamerica

The Milpa system, widely practiced by Indigenous peoples across Mesoamerica, including the Maya of southern Mexico and Guatemala, is a rotational, polyculture farming tradition deeply rooted in ancestral ecological knowledge. It revolves around intercropping maize, beans, and squash, collectively known as the “Three Sisters.” Each crop offers complementary benefits: maize provides structural support, beans fix atmospheric nitrogen, and squash acts as a living mulch, suppressing weeds and conserving moisture. This synergy promotes soil fertility, reduces erosion, and minimizes the need for synthetic inputs.

Crucially, Milpa fields are fallowed after a few years of cultivation, allowing soil to regenerate and enhancing belowground carbon sequestration. The diverse root systems and organic inputs contribute to long-term soil organic carbon accumulation and biomass growth. Milpa is not only an agricultural method but a cultural system involving ritual cycles, communal work, and food sovereignty. The spatial arrangement of maize, beans, and squash illustrates this ecological synergy and sustainable land use. Altieri (2004) and [Toledo *et al.* \(2003\)](#) emphasize that Milpa represents a model of agro-ecological intensification and climate-resilient, carbon-negative farming.

4.3 Nomadic Pastoralism - Mongolia

Nomadic pastoralism in Mongolia exemplifies a mobile, low-impact land use system that harmonizes human livelihoods with the ecological rhythms

of vast steppe and grassland ecosystems. Practiced for over 4,000 years by Mongolian herders, this system revolves around the seasonal migration and rotational grazing of yaks, sheep, goats, cattle, and camels across diverse pastures (Fernandez-Gimenez, 2000; [World Bank, 2009](#)). The mobility of herders ensures even distribution of grazing pressure, allowing grasslands time to regenerate, thus maintaining soil structure, root biomass, and overall ecosystem integrity.

Mongolia's grassland soils, rich in organic carbon and perennial root systems, serve as important carbon sinks, sequestering significant amounts of atmospheric CO₂ when managed sustainably ([Sneath, 1998](#); [Shi et al., 2012](#)). This land use model not only prevents overgrazing and desertification but also supports biodiversity, water regulation, and climate resilience in an otherwise fragile, arid environment.

A core strength of Mongolian pastoralism lies in its communal governance, traditional norms and customary laws dictate pasture use, seasonal timing, and conflict resolution, fostering collective responsibility (Fernandez-Gimenez, 2000). These institutions promote social cohesion and adaptive capacity, making pastoral communities more resilient to climatic variability and socio-economic shifts ([Fernández-Giménez, 2000](#); [FAO, 2021](#)). As such, Mongolian nomadic pastoralism offers a powerful model of nature-based carbon stewardship, especially suitable for semi-arid and arid landscapes where conventional agriculture proves unsustainable.

4.4 Transhumant Pastoralism - Jammu & Kashmir, India

The Gujjar-Bakarwal communities of Jammu & Kashmir exemplify a resilient form of transhumant pastoralism, mirroring sustainable grazing systems seen in Mongolia (Fernandez-Gimenez, 2000). Practiced for generations, this system involves seasonal migration of sheep, goats, and cattle from the Jammu plains to alpine pastures (dhoks) in the Pir Panjal and

Greater Himalayas, ranging from 3,000 to 4,300 meters ([Sharma, 2020](#); [Dar, 2023](#)). Each journey, lasting 6-8 weeks, is undertaken by kin-based groups who collectively manage herds to maintain grassland health and support biodiversity and soil carbon retention ([Rural India Online, 2021](#); [Land Conflict Watch, 2022](#)).

Unlike formalized governance in Mongolian pastoralism, Bakarwal migration is guided by customary norms, clan leadership, and shared responsibilities within mobile camps (deras) ([Verma et al., 2019](#)). However, increasing climate variability, forest restrictions, and sedentarization pressures threaten traditional routes and access to grazing lands ([Dar, 2023](#)). Limited veterinary care, education, and transport during migration further challenge their livelihoods ([JKPI, 2023](#); [IDR, 2023](#)).

Despite these hurdles, Gujjar-Bakarwal pastoralism, supporting over 600,000 people and 2 million livestock, remains vital for biodiversity conservation, food security, and climate resilience in the Himalayas ([JKPI, 2023](#); [Land Conflict Watch, 2022](#)). Recent policy initiatives by the J&K government aim to incorporate pastoral voices in sustainable pasture regeneration and land-use planning (Brighter [Kashmir, 2023](#)).

5. Role of Communities in Landscape Stewardship

Communities, particularly Indigenous peoples and rural societies, have historically played a vital role in managing natural landscapes. In many regions, local communities depend directly on forests, pastures, rivers, and agricultural land for their livelihoods and cultural identity. This close relationship has led to the development of diverse ecological knowledge systems and sustainable land-use practices tailored to local conditions. As [Pretty and Smith \(2004\)](#) note, “local people have developed and maintained complex systems of sustainable resource management, often without external support or recognition.” These practices include rotational grazing,

agroforestry, sacred grove protection, and community forest management, all of which enhance both ecological resilience and carbon sequestration.

Recent evidence affirms the value of community involvement in environmental governance. According to [IPBES \(2019\)](#), “biodiversity is declining less rapidly in areas managed by Indigenous peoples and local communities than in other lands.” Traditional ecological knowledge (TEK) embedded in these systems offers effective tools to address climate change and biodiversity loss. Moreover, participatory governance fosters equity, conflict resolution, and long-term stewardship. As [Ostrom \(1990\)](#) emphasized, “when local users are involved in the design, implementation, and enforcement of resource rules, the chances of sustainable outcomes are significantly higher.” Recognizing and empowering communities in landscape management is not only an ethical imperative, it is a critical strategy for building climate-resilient, sustainable ecosystems. The following sub-sections delve deeper into two key frameworks through which communities exercise effective landscape stewardship:

1. Community-Based Natural Resource Management (CBNRM)
2. Local Institutions and Customary Laws

5.1 Community-Based Natural Resource Management (CBNRM)

Community-Based Natural Resource Management (CBNRM) is an approach that devolves the authority for managing natural resources such as forests, grazing lands, wetlands, and wildlife, into the hands of local communities. By empowering people who are directly dependent on these resources, CBNRM encourages sustainable practices, fosters stewardship, and generates local benefits, thereby creating strong incentives for conservation. As highlighted by [Ostrom \(1990\)](#), communities are capable of

managing common-pool resources sustainably when appropriate institutional arrangements and social norms are in place.

CBNRM frameworks have shown remarkable success in various global contexts. In southern Africa, for example, community conservancies have helped restore wildlife populations while generating income through eco-tourism and carbon offset programs ([Fabricius *et al.*, 2001](#)). In Nepal, the community forest user groups (CFUGs) have regenerated degraded forests and increased aboveground biomass, sequestering considerable carbon while improving fuelwood availability and social cohesion ([Kanel & Dahal, 2008](#)).

These initiatives not only contribute to biodiversity conservation but also enhance carbon storage, as community-managed forests often outperform state-managed areas in terms of ecological condition and carbon stock retention. A study by [Chhatre and Agrawal \(2009\)](#) found that forests with higher local involvement in governance had significantly greater carbon storage and forest health compared to centrally managed ones.

5.2 Local Institutions and Customary Laws

Indigenous and rural communities often govern their landscapes through customary institutions and unwritten norms that regulate land use, resource access, conservation behavior, and responsibilities passed down through generations. These customary laws, including taboos, seasonal restrictions, rotational usage, and sacred regulations, are deeply rooted in cultural traditions but also serve practical ecological purposes. For instance, in India's tribal regions, customary rules often restrict the harvesting of specific tree species or prohibit entry into forests during the breeding seasons of wildlife, thus contributing to ecosystem regeneration and biodiversity protection. In West Africa, the traditional technique of Zai, a community-managed soil restoration practice, involves digging planting

pits to retain water and organic matter, revitalizing degraded land and enhancing soil carbon storage ([Reij *et al.*, 2009](#)). Likewise, in several Pacific Island nations, the Ra'ui system imposes rotational closures of coastal and forested areas, allowing ecosystems to recover. As [Johannes \(2002\)](#) notes, these temporary no-take zones are “grounded in traditional ecological knowledge and have proven to be highly effective for conservation.”

Customary governance systems are often more locally legitimate, flexible, and enforceable than externally imposed legal frameworks, especially when maintained through communal consensus and social sanctions. These models align well with the ethos of carbon-negative farming, promoting minimal land disturbance, community resource sharing, and long-term ecosystem health. However, such systems are increasingly threatened by formal policies that fail to recognize or support them, leading to weakened traditional governance and escalating ecological degradation ([Larson & Soto, 2008](#)).

Communities play an indispensable role in landscape-scale stewardship through both modern CBNRM programs and enduring customary governance traditions. Their actions not only conserve biodiversity and water resources but also enhance carbon sequestration, reduce emissions from land-use change, and promote social equity. As climate policy and sustainable agriculture frameworks evolve, the recognition, empowerment, and legal reinforcement of these community-led systems will be central to building inclusive and carbon-negative agricultural landscapes.

6. Challenges in Integration

Despite the well-documented value of Indigenous and Community Knowledge (ICK) systems in promoting ecological sustainability, biodiversity conservation, and carbon sequestration, their meaningful

integration into mainstream climate and agricultural policies remains limited. These challenges are not merely technical, but are embedded in complex sociopolitical, cultural, and institutional dynamics that often marginalize traditional systems of knowledge.

One of the most pressing challenges is the erosion of traditional knowledge, driven by modernization, migration, formal education, and a growing disinterest among youth. As [Altieri and Toledo \(2011\)](#) argue, “traditional agricultural systems are under threat from the expansion of industrial agriculture and homogenized development models,” leading to the gradual loss of place-based wisdom that has sustained ecosystems for centuries.

Additionally, there is a persistent policy disconnect between scientific and traditional knowledge systems. Modern policy frameworks often privilege technological and market-based solutions, sidelining experiential and collective learning rooted in community contexts. [Agrawal \(1995\)](#) observed that “scientific knowledge is institutionalized and often legitimized over Indigenous knowledge, leading to asymmetries in decision-making.”

Another significant barrier is the lack of formal recognition and documentation of Indigenous contributions to environmental stewardship. This invisibility hampers the incorporation of traditional practices into national climate strategies and limits opportunities for benefit-sharing.

Land tenure insecurity further exacerbates the problem, as communities without formal land rights are less likely to invest in long-term carbon-storing practices such as agroforestry or rewilding. According to [Larson *et al.* \(2010\)](#), “unclear or contested land rights weaken incentives for sustainable land management and undermine the authority of customary institutions.”

The following sub-sections explore these critical barriers in greater depth, highlighting how they obstruct the integration of Indigenous and community-based knowledge into climate-resilient and carbon-negative land management strategies:

1. Knowledge Erosion due to modernization, migration, and youth disinterest.
2. Policy Disconnect between scientific and traditional systems.
3. Lack of Recognition and documentation of indigenous contributions.
4. Land Tenure Insecurity undermining long-term investment in carbon-storing practices.

6.1 Knowledge Erosion

The erosion of traditional ecological knowledge (TEK) is a critical and growing concern, primarily driven by modernization, rural-to-urban migration, changing livelihood patterns, and youth disengagement. In many Indigenous and rural communities, ecological knowledge is passed orally through stories, rituals, apprenticeship, and day-to-day experience, rather than through written records or formal institutions. This oral transmission becomes vulnerable when younger generations pursue urban-based education and occupations that disconnect them from land-based livelihoods and local ecosystems.

As [Berkes \(2012\)](#) states, “much of traditional knowledge is place-based, cumulative, and embedded in a way of life that is rapidly disappearing.” The decline in Indigenous languages, which often encode ecological and environmental information, further accelerates this loss. [Reyes-García et al. \(2010\)](#) showed that among the Tsimané people of Bolivia, formal education was negatively correlated with ecological knowledge acquisition,

highlighting a generational knowledge gap induced by institutional and cultural shifts.

6.2 Policy Disconnect

A fundamental barrier to integrating Indigenous and Community Knowledge (ICK) into modern environmental governance is the epistemological divide between traditional and scientific knowledge systems. National agricultural and climate policies continue to prioritize high-input, technology-driven models of development, often disregarding traditional land-use practices as unscientific or anecdotal.

As [Agrawal \(1995\)](#) observed, “the politics of knowledge production privileges scientific knowledge and marginalizes the voices of Indigenous communities.” Extension services and climate adaptation programs are typically implemented through top-down approaches, rarely engaging traditional leaders or accounting for cultural values. Although international commitments like the Paris Agreement encourage community-based adaptation, many Nationally Determined Contributions (NDCs) make minimal mention of traditional farming systems or Indigenous governance ([FAO, 2021](#)).

6.3 Lack of Recognition and Documentation

Despite their substantial contributions to biodiversity, soil fertility, and climate resilience, Indigenous practices remain underrepresented in national and global environmental policy. This is due to a lack of formal documentation, inadequate data collection frameworks, and limited inclusion of Indigenous voices in policy-making.

Traditional practices such as rotational grazing, shifting cultivation, or sacred grove conservation often operate outside formal measurement and reporting systems. [Chhatre et al. \(2012\)](#) argue that “when forest-dependent

communities are excluded from carbon markets, both equity and effectiveness suffer.” The absence of mechanisms to reward or validate these practices, such as MRV (Measurement, Reporting, Verification) systems used in carbon trading, leads to missed opportunities for both climate mitigation and community empowerment. Additionally, there are ethical concerns around documentation, including risks of knowledge appropriation and biopiracy. Without community-led protocols, the formalization of Indigenous Knowledge may lead to exploitation rather than recognition.

6.4 Land Tenure Insecurity

Insecure or contested land tenure is a major impediment to the integration of carbon-negative and climate-resilient practices in Indigenous territories. Customary land rights, while socially legitimate, are often not legally recognized, leaving communities vulnerable to land grabs, deforestation, mining, and other extractive pressures. As [Larson *et al.* \(2013\)](#) note, “communities without formal land titles lack the legal leverage to protect their forests or claim the benefits from ecosystem services.” This insecurity undermines investments in long-term restoration techniques like agroforestry, silvopasture, and soil carbon management central pillars of carbon-negative farming.

Moreover, land tenure security is a prerequisite for participation in Payment for Ecosystem Services (PES) schemes and carbon credit programs. Evidence from countries like Brazil, Nepal, and Mexico shows that formalizing community land rights leads to improved forest governance, reduced deforestation, and enhanced social outcomes ([RRI, 2018](#)).

Addressing the challenges to integrating Indigenous and Community Knowledge into carbon-negative farming is not only a matter of ecological

necessity but also of justice and equity. Efforts must focus on preserving traditional knowledge, bridging policy divides, documenting contributions ethically, and securing land rights. Only then can these invaluable knowledge systems contribute fully to climate-resilient, sustainable agricultural futures.

7. Pathways for Integration with Scientific and Policy Systems

Integrating Indigenous and Community Knowledge (ICK) systems with formal scientific research and policy frameworks is increasingly recognized as a vital strategy for advancing sustainable and climate-resilient development. The convergence of Traditional Ecological Knowledge (TEK) and modern science can yield synergies that foster adaptive land management, enhance ecological monitoring, and empower communities to co-design solutions for climate mitigation and adaptation.

Such integration, however, must go beyond tokenistic inclusion. It requires respectful, equitable partnerships grounded in mutual learning, trust, and long-term engagement. As [Chambers \(1994\)](#) emphasized, “local people are not just beneficiaries or informants, but analysts and actors in their own right.” Bridging these knowledge systems strengthens not only the legitimacy and cultural relevance of climate policies, but also improves their outcomes by incorporating context-specific practices and lived experience.

Recent initiatives in agroecology, ecosystem-based adaptation, and biodiversity conservation have shown that co-produced knowledge, generated through collaboration between researchers, Indigenous experts, and policymakers, can improve environmental governance and promote innovation ([Tengö *et al.*, 2014](#)). Moreover, the Convention on Biological Diversity and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) now formally endorse the

recognition of Indigenous knowledge as complementary to scientific understanding ([IPBES, 2019](#)).

Yet, institutional reforms are necessary to support such integration, including legal recognition of customary practices, inclusion in climate action plans, participatory research frameworks, and mechanisms for benefit-sharing. These pathways must ensure that knowledge holders retain control over how their knowledge is used, credited, and compensated. The following sub-sections explore three key pathways that can enable meaningful integration between traditional custodians of knowledge and formal institutions:

1. Participatory Research and Co-production of Knowledge
2. Policy Recognition and Legal Protection
3. Benefit-Sharing and Incentive Mechanisms

7.1 Participatory Research and Co-production of Knowledge

The co-production of knowledge is a collaborative approach where scientists and local communities jointly generate, test, and refine solutions to environmental and agricultural challenges. This method values local insights alongside scientific analysis, ensuring that innovations are both context-specific and socially acceptable. According to [Chambers \(1994\)](#), “participatory research strengthens both the relevance and uptake of knowledge by aligning inquiry with community priorities.” Successful examples include participatory plant breeding initiatives by the International Institute of Tropical Agriculture (IITA) and Bioversity International, where farmers help select traits for climate-resilient crops while preserving local seed diversity. These initiatives not only empower communities but also maintain genetic resources critical for adaptation ([Ceccarelli & Grando, 2007](#)).

In soil and carbon management, co-experiments with farmers, testing cover crops, agroforestry species, or biochar, have proven valuable in merging traditional practices with agronomic science. Community-led trials often reveal insights on local soil responses, pest cycles, and labor efficiency not captured by standard models ([Tengö *et al.*, 2017](#)). Additionally, collaborative environmental monitoring, such as integrating Indigenous weather indicators with remote-sensing or sensor-based data, can enhance the precision of early warning systems. Long-term trust and shared ownership, fostered through co-production, are essential for scaling up carbon-negative farming practices.

7.2 Policy Recognition and Legal Protection

The formal recognition of Traditional Ecological Knowledge (TEK) in policy is advancing through international agreements, but national implementation often lags behind. Instruments such as the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) and the Convention on Biological Diversity (CBD) emphasize that Indigenous Peoples and Local Communities (IPLCs) are key knowledge holders and stewards of biodiversity. However, in practice, many agricultural and climate policies fail to create institutional pathways for TEK inclusion in extension services, land-use planning, or carbon accounting. According to the [FAO \(2021\)](#), “most NDCs under the Paris Agreement contain little operational guidance on integrating Indigenous knowledge into climate action.”

Promising models are emerging such as Canada’s Indigenous Climate Advisory Committee and Australia’s inclusion of Aboriginal fire management practices in national wildfire strategies. These efforts demonstrate how TEK can enhance adaptive governance. Legal protection must also extend to customary tenure systems and intellectual property

rights, ensuring that communities can practice, transmit, and develop their knowledge without fear of misappropriation. Effective integration into MRV frameworks for REDD+ and PES will require localized indicators and community-driven protocols.

7.3 Benefit-Sharing and Incentive Mechanisms

Indigenous and rural communities manage nearly one-quarter of the world's aboveground forest carbon, yet they receive a fraction of climate finance benefits ([RRI, 2018](#)). Barriers include high certification costs, complex carbon verification requirements, and lack of legal recognition, which exclude communities from direct participation in carbon markets and ecosystem service schemes. To address this, equitable benefit-sharing mechanisms are essential. For instance, community forest enterprises in Mexico generate local employment and reinvest carbon credit revenues into health, education, and forest protection. Similarly, Nepal's community REDD+ projects ensure that women and marginalized groups participate in decision-making and receive fair returns ([RECOFTC, 2013](#)).

Free, Prior, and Informed Consent (FPIC) must be central to all agreements, alongside gender equity, transparent governance, and access to grievance mechanisms. New technologies such as blockchain-based carbon registries are being explored to improve traceability and accountability in benefit distribution ([Schroeder & McDermott, 2014](#)). Simplified MRV protocols and capacity-building tools, supported by NGOs and donors, are also enabling communities to access voluntary carbon markets more effectively. These innovations can unlock financing for regenerative, carbon-negative practices rooted in Indigenous stewardship.

Integrating community and Indigenous knowledge systems into carbon-negative farming requires more than technical fixes, it calls for a transformation in values, institutions, and partnerships. Co-produced

knowledge, robust policy frameworks, and equitable benefit-sharing mechanisms can together bridge the gap between ancestral wisdom and modern sustainability science. This pluralistic approach holds the key to just, resilient, and carbon-sequestering food systems.

8. Conclusion and Way Forward

Communities, especially Indigenous peoples and rural societies, have long been the custodians of complex and place-based knowledge systems that sustain landscapes and promote ecological resilience. These knowledge systems encompass a wide array of sustainable practices from land stewardship and agroforestry to rotational grazing and sacred site conservation that contribute significantly to biodiversity preservation and carbon sequestration. Their intimate connection with the land, cultural traditions, and social structures has enabled them to adapt to environmental variability and maintain ecosystem services critical to global climate goals.

Despite their demonstrated value, Indigenous and community knowledge systems face numerous challenges that hinder their full integration into contemporary scientific and policy frameworks. Modernization, youth disengagement, and migration threaten the intergenerational transmission of traditional knowledge. Policy and institutional barriers, including epistemological divides, inadequate legal recognition, and land tenure insecurity, further marginalize these knowledge holders. Additionally, limited documentation and exclusion from formal benefit-sharing mechanisms restrict the ability of communities to participate equitably in emerging climate finance and carbon markets.

Recognizing the essential role of Indigenous and community knowledge requires concerted efforts to bridge traditional and scientific knowledge systems through respectful, participatory approaches. Co-production of knowledge that involves local communities alongside researchers can

generate more effective and contextually appropriate solutions. Legal reforms should enshrine the rights of Indigenous peoples to their knowledge, land, and governance institutions. Furthermore, mechanisms for fair benefit-sharing must be developed to ensure that communities receive equitable returns for their stewardship of carbon-rich landscapes.

To harness the full potential of community and Indigenous knowledge systems in advancing climate resilience and sustainability, policies must prioritize inclusive governance, support capacity-building, and foster collaborative research. Empowering communities through secure land tenure, recognition in policy instruments, and access to financial incentives will be pivotal in sustaining both cultural heritage and ecological integrity for future generations.

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Chapter - 14

Climate-Resilient Crop Systems

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1. Introduction

The global agricultural landscape is undergoing unprecedented changes driven by climate variability, resource scarcity, and ecological degradation. Climate change, in particular, poses a significant threat to global food security by affecting crop productivity, altering growing seasons, and increasing the frequency and intensity of extreme weather events such as droughts, floods, and heatwaves ([FAO, 2021](#); [IPCC, 2023](#)). These impacts are especially severe in regions that are already vulnerable due to poor infrastructure, limited adaptive capacity, and reliance on rainfed agriculture. In such a context, climate-resilient crop systems have emerged as a vital approach to ensure sustainable and adaptive food production.

Climate-resilient crop systems are designed to withstand and adapt to changing climatic conditions while maintaining or even enhancing productivity, resource efficiency, and ecological sustainability ([Vermeulen *et al.*, 2012](#)). These systems incorporate a combination of technological innovations, traditional knowledge, and ecosystem-based approaches that improve soil health, optimize water use, increase crop diversity, and reduce greenhouse gas emissions. For instance, integrating practices like conservation agriculture, agroforestry, crop diversification, and the use of climate-resilient crop varieties can buffer agricultural systems against climate shocks ([Altieri & Nicholls, 2017](#)).

A growing body of evidence underscores the effectiveness of stress-tolerant cultivars and modern breeding techniques, including marker-

assisted selection and genome editing, in developing crops that can thrive under drought, salinity, and heat stress ([Nelson *et al.*, 2013](#); [Voss-Fels *et al.*, 2019](#)). Coupled with efficient input management and early warning systems, these innovations help farmers make informed decisions and reduce risks associated with climate extremes.

Furthermore, the transition to climate-resilient systems involves enabling socio-political frameworks, capacity building, and inclusive policies that support smallholder farmers and marginalized communities ([Aggarwal *et al.*, 2018](#)). Such transformation requires investments in research, extension services, and institutional coordination to facilitate the scaling of context-specific solutions.

In essence, building climate-resilient crop systems is not only a technological challenge but also a socio-ecological imperative. It represents a paradigm shift from linear, input-intensive agriculture to systems-based, adaptive, and inclusive food production models that align with the goals of sustainable development and climate action.

2. Principles of Climate-Resilient Crop Systems

Climate-Resilient Crop Systems (CRCS) represent a holistic response to the interlinked challenges of climate change, environmental degradation, and food insecurity. These systems are designed not only to sustain agricultural productivity in the face of climatic stresses such as drought, erratic rainfall, heatwaves, and flooding, but also to contribute to long-term ecological restoration and climate change mitigation. As agricultural landscapes become increasingly vulnerable to these shifts, CRCS offer adaptive strategies rooted in both scientific innovation and time-tested ecological principles ([FAO, 2021](#); [IPCC, 2023](#)).

CRCS are founded on the concept of resilience, which refers to the capacity of agroecosystems to absorb shocks, adapt to changing conditions,

and transform in ways that sustain productivity and ecosystem services over time ([Walker *et al.*, 2004](#)). This approach builds upon principles drawn from agroecology, traditional farming wisdom, and climate-smart agriculture, integrating ecological intensification with technological interventions to reduce vulnerability and environmental impact ([Altieri & Nicholls, 2017](#); Aggarwal *et al.*, 2018).

The effectiveness of CRCS lies in enhancing functional diversity and system stability across spatial and temporal scales. This includes practices that promote biological activity in soils, conserve water resources, minimize external inputs, and integrate agro-biodiversity to create robust and self-regulating systems. Below are the core principles that underpin CRCS, each playing a crucial role in enhancing resilience and contributing to carbon-negative agriculture. The core principles of climate-resilient crop systems, including diversity, soil health, water efficiency, ecosystem integration, and low external inputs.

1. **Diversity:** Genetic, species, and system diversity enhances resistance to pests, diseases, and climatic extremes ([Lin, 2011](#)).
2. **Soil Health Management:** Practices like cover cropping, mulching, and composting promote soil structure, water retention, and organic carbon accumulation.
3. **Water Efficiency:** Drought-tolerant varieties, mulching, and deficit irrigation enhance resilience to water stress while reducing emissions.
4. **Ecosystem Integration:** Incorporating trees (agroforestry), livestock, and beneficial insects strengthens resilience and soil carbon pools.
5. **Low External Inputs:** Reduced use of synthetic fertilizers and pesticides lowers nitrous oxide (N₂O) and carbon dioxide (CO₂)

emissions.

2.1 Diversity

A central pillar of Climate-Resilient Crop Systems (CRCS) is the incorporation of diversity at multiple levels, genetic, species, and system-wide, to build resilience, adaptability, and ecological functionality. This multidimensional diversity forms the biological foundation for managing risk, enhancing productivity, and maintaining ecosystem services under conditions of climatic uncertainty. At the genetic level, maintaining and utilizing a wide range of crop genotypes including traditional landraces, locally adapted varieties, and stress-tolerant modern cultivars, helps ensure that at least some genotypes can thrive under adverse conditions such as drought, salinity, or heat stress. Such diversity increases adaptive capacity and facilitates evolutionary responses to novel or extreme environmental pressures ([Ceccarelli, 2014](#); [Jarvis *et al.*, 2011](#)). In-situ conservation of traditional varieties, especially in marginal areas, supports climate adaptation by preserving traits suited for local agro-ecological niches.

At the species level, diversification through intercropping, crop rotations, agroforestry, and polycultures disrupts the life cycles of pests and pathogens, supports beneficial organisms, and enhances nutrient cycling and soil health. For example, legume-cereal intercropping improves nitrogen use efficiency and suppresses soil-borne diseases, while crop rotation breaks pathogen buildup and reduces weed pressure ([Altieri, 1999](#); [Brooker *et al.*, 2015](#)). Such practices reduce reliance on chemical inputs and improve the biological stability of agroecosystems.

System-level diversity, the integration of crops, livestock, trees, aquaculture, and even pollinator habitats, creates a mosaic of functional components that interact to stabilize production and enhance ecosystem services. Integrated systems promote ecological redundancies, meaning if

one component fails (e.g., due to climate shock), others can compensate. This diversification of function is crucial in building resilience to climatic and economic variability ([Herrero *et al.*, 2010](#); [Mbow *et al.*, 2019](#)). As [Lin \(2011\)](#) emphasizes, agricultural biodiversity plays a fundamental role in enhancing ecosystem resilience by promoting functional redundancy, increasing biological interactions, and reducing dependence on synthetic inputs. Empirical studies show that diversified farms are less prone to total crop failure during climate extremes such as droughts, floods, or pest outbreaks, and often demonstrate greater yield stability over time and space ([Kremen & Miles, 2012](#); [Tamburini *et al.*, 2020](#)). Thus, embracing diversity in farming systems not only strengthens ecological integrity but also offers low-cost, nature-based solutions for adaptation and mitigation in a changing climate.

2.2 Soil Health Management

Healthy soils are the cornerstone of both climate resilience and carbon sequestration. A diverse suite of practices such as cover cropping, organic mulching, compost addition, and reduced or minimal tillage, play pivotal roles in improving soil structure, promoting aggregate stability, and enhancing soil organic carbon (SOC) levels. These practices foster improved water infiltration and retention, buffer temperature extremes, and ensure greater nutrient cycling and availability, all of which are vital under the increasing unpredictability of climate conditions ([Solidaridad, 2023](#); [Lal, 2004a](#)). For instance, cover crops, particularly legumes (e.g., *Vicia faba*, *Trifolium spp.*) and brassicas (*Brassica napus*, *Raphanus sativus*), contribute considerable biomass and root exudates that enhance SOC while suppressing weeds and reducing erosion. Leguminous cover crops also fix atmospheric nitrogen, thereby improving soil fertility naturally and reducing the dependence on synthetic nitrogen fertilizers, which are energy-

intensive to produce and emit greenhouse gases during application ([Drinkwater *et al.*, 1998](#); [Poeplau & Don, 2015](#)).

Organic mulching, through plant residues, straw, or wood chips, creates a protective layer over the soil surface that limits moisture loss, suppresses weeds, and provides slow-releasing nutrients as it decomposes. When combined with compost application, this approach significantly boosts microbial biomass and enzymatic activity, crucial for nutrient mineralization and carbon cycling ([Bastida *et al.*, 2006](#)). Composting, in particular, not only recycles organic waste but also serves as a low-emission alternative to synthetic fertilizers, helping cut methane and nitrous oxide emissions from landfills and agricultural fields ([Brown *et al.*, 2008](#)). Reduced tillage or zero tillage practices preserve soil structure and prevent the disruption of carbon-rich aggregates. By minimizing soil disturbance, these practices reduce oxidation of organic matter, helping retain more carbon in the soil profile over time ([West & Post, 2002](#)). Long-term no-till systems have shown higher SOC stocks and improved microbial diversity, which enhances disease suppression, plant-microbe symbiosis, and nutrient availability (Six *et al.*, 2004; [Lehman *et al.*, 2015](#)).

Overall, managing soil health through nature-positive approaches not only improves yield stability under climatic stress but also supports ecosystem services essential for sustainable agriculture and carbon-negative outcomes.

2.3 Water Efficiency

Climate-resilient systems must be designed to efficiently manage water scarcity and variability, particularly as extreme weather events and shifting rainfall patterns intensify. A suite of water-saving practices including organic mulching, drip irrigation, deficit irrigation, and alternate wetting and drying (AWD) in paddy cultivation, play a critical role in enhancing

water use efficiency (WUE) and maintaining crop productivity under stress. Mulching, whether with straw, compost, or biodegradable plastic, reduces evapotranspiration losses, maintains soil moisture, and creates a favorable microclimate for soil microbes. It also enhances carbon storage in surface layers while limiting weed growth and reducing the frequency of irrigation events ([Huang *et al.*, 2024](#)).

Drip irrigation and micro-irrigation systems, when combined with soil moisture sensors or automated scheduling, can improve WUE by 30-70% compared to conventional flood irrigation, particularly in arid and semi-arid regions ([Perry *et al.*, 2009](#)). Deficit irrigation, which involves watering crops below their full water requirement during less sensitive growth stages, can improve water productivity without significantly affecting yields. In paddy systems, AWD has emerged as a proven climate-smart practice. By allowing fields to dry intermittently rather than remaining continuously flooded, AWD reduces water use by up to 30% and methane emissions by as much as 50%, without compromising yield (Bouman *et al.*, 2007; [Richards & Sander, 2014](#)). This method is also increasingly compatible with climate mitigation goals due to its potential for reducing greenhouse gas emissions.

Furthermore, cultivating drought-tolerant crop varieties, bred for early maturity, deep root systems, and osmotic adjustment, enhances resilience under prolonged dry spells and erratic rainfall patterns, while maintaining or even improving yield stability ([Blum, 2011](#)). Water-smart farming, therefore, not only safeguards productivity in rainfed and water-scarce regions but also plays a role in GHG mitigation by reducing emissions from fertilizer leaching, waterlogging, and energy-intensive pumping.

2.4 Ecosystem Integration

Ecosystem integration is a foundational principle of CRCS, aiming to emulate the structure and function of natural ecosystems by integrating trees, animals, beneficial insects, microbes, and biodiversity corridors into agricultural landscapes. This integration increases ecological resilience, stabilizes yields, and enhances carbon sequestration. Agroforestry systems, which interplant woody perennials (trees, shrubs) with annual crops or pastures, offer numerous co-benefits: improved **soil fertility** via nitrogen fixation (e.g., *Gliricidia*, *Leucaena*), enhanced microclimate regulation, reduced soil erosion, and increased aboveground and belowground carbon storage ([Nair et al., 2009](#); [Mbow et al., 2014](#)). Tree roots stabilize soils, intercept rainfall, and foster beneficial mycorrhizal associations that improve nutrient uptake. Integrating livestock into cropping systems not only contributes manure for composting, reducing the need for external fertilizers, but also supports nutrient cycling, land diversification, and economic resilience through multiple income streams. Livestock-crop systems can close nutrient loops while reducing environmental externalities associated with confined animal operations ([Herrero et al., 2010](#)).

The role of beneficial insects including pollinators and natural enemies of pests, is enhanced by maintaining flowering plants, hedgerows, or wild refugia around farm borders. These support biological pest control, reducing pesticide reliance and preserving biodiversity ([Gurr et al., 2017](#)). Similarly, integrating soil microbial inoculants and mycorrhizal fungi promotes root health, nutrient availability, and carbon stabilization in soil aggregates. By emulating natural ecosystems, integrated systems are better equipped to withstand environmental shocks, such as drought, floods, and pest outbreaks, while maintaining productivity and continuously sequestering carbon both in biomass and soil pools.

2.5 Low External Inputs

A defining feature of climate-resilient and carbon-negative farming systems is their reduced dependence on external chemical inputs, especially synthetic fertilizers and pesticides. The overuse of nitrogenous fertilizers contributes substantially to nitrous oxide (N₂O) emissions a greenhouse gas nearly 300 times more potent than CO₂ on a 100-year scale ([IPCC, 2014](#)). Reducing these inputs is both an ecological imperative and an economic necessity. CRCS promote the use of organic amendments such as compost, vermicompost, farmyard manure (FYM), biofertilizers (e.g., *Azospirillum*, *Rhizobium*, *Phosphobacteria*), and biopesticides derived from botanical extracts (*Neem*, *Trichoderma*, *Bacillus subtilis*). These improve soil health, nutrient release, and biological control while minimizing environmental harm ([Glick, 2012](#)).

By closing nutrient loops within the farm for example, recycling crop residues, composting kitchen or animal waste, and returning biomass to the soil CRCS reduce leakage of nutrients, lower GHG emissions, and enhance system autonomy from volatile global input markets ([Tittonell & Giller, 2013](#)). Moreover, such low-input approaches reduce the energy footprint associated with the manufacturing, packaging, and long-distance transport of agrochemicals. For instance, producing 1 kg of synthetic nitrogen fertilizer requires an average of 87.9 MJ of energy, often from fossil fuels ([Woods et al., 2010](#)). Substituting these with locally available bio-based inputs significantly reduces indirect emissions. These principles converge with regenerative agriculture, agroecology, and traditional farming wisdom, forming a resilient backbone for climate-smart, carbon-negative production systems (Gliessman, 2016; [Rhodes, 2017](#)).

3. Components of Climate-Resilient Crop Systems

Building climate-resilient crop systems involves integrating multiple synergistic components that collectively enhance agricultural productivity,

ecosystem adaptability, and environmental sustainability. These systems are specifically designed to reduce vulnerability to climate-induced stresses such as drought, heatwaves, erratic rainfall, pest outbreaks, and soil degradation, which are becoming more frequent and intense due to climate change ([IPCC, 2022](#)). Simultaneously, they aim to maximize carbon sequestration, optimize water and nutrient use, and improve soil health, thereby contributing to both climate adaptation and mitigation efforts ([Lipper *et al.*, 2014](#); [Lal, 2020a&b](#)).

Central to this approach is the alignment of crop choices, management practices, and landscape-level strategies in ways that emulate natural ecosystems, promote diversity, and build resilience. The use of stress-tolerant crop varieties, diversified cropping systems, conservation agriculture, and agroforestry creates redundancy and stability in the face of environmental shocks while reducing dependence on external inputs ([Pretty *et al.*, 2018](#)). Moreover, integrating ecological elements such as beneficial insects, organic amendments, and soil microbial communities, enhances the regenerative capacity of farms over time.

These components do not function in isolation but are interconnected and mutually reinforcing, forming the backbone of carbon-smart and climate-resilient agriculture. As such, they offer a pathway toward transformative change in food systems that is both scientifically grounded and contextually adaptable across diverse agroecological zones. The following subheadings detail the essential components including stress-tolerant varieties, integrated cropping systems, conservation agriculture, and agroforestry that collectively form the backbone of climate-resilient and carbon-smart agriculture.

1. Stress-Tolerant and Carbon-Friendly Crop Varieties
2. Integrated Cropping Systems

3. Conservation Agriculture

4. Agroforestry Integration

3.1 Stress-Tolerant and Carbon-Friendly Crop Varieties

One of the fundamental building blocks of climate-resilient crop systems is the selection and cultivation of stress-tolerant crop varieties that can withstand a range of abiotic stressors such as drought, salinity, heat, and waterlogging. These climate-resilient cultivars not only ensure yield stability under fluctuating weather patterns but also frequently require fewer external inputs, such as irrigation or synthetic fertilizers, thereby reducing the carbon footprint and greenhouse gas (GHG) emissions associated with conventional crop production.

For instance, Sahbhagi Dhan, a drought-tolerant rice variety, and Swarna-Sub1, a submergence-tolerant variety, both developed by the International Rice Research Institute (IRRI), have shown remarkable resilience under water-scarce and flood-prone conditions, respectively. These varieties have also contributed significantly to mitigation by enabling alternate wetting and drying (AWD) irrigation practices, which reduce methane (CH₄) emissions by 30-50% compared to continuously flooded rice fields ([Ismail et al., 2008](#)). The reduction in CH₄, a potent greenhouse gas, makes these varieties an important tool for low-emission agriculture.

Additionally, deep-rooted crops like pigeon pea (*Cajanus cajan*), sorghum (*Sorghum bicolor*), and millets (e.g., finger millet, pearl millet) play a critical role in subsoil carbon sequestration. These crops deposit organic carbon into deeper soil layers where microbial activity is lower, thereby increasing the stability and longevity of sequestered carbon ([Lal, 2004b](#)). Their adaptability to semi-arid and marginal environments further enhances both resilience to climatic extremes and the mitigation potential of the

cropping system, making them ideal components of carbon-smart agriculture.

3.2 Integrated Cropping Systems

One of the foundational pillars of climate-resilient crop systems is the selection and promotion of stress-tolerant crop varieties that can endure a range of abiotic stressors such as drought, salinity, heat, and waterlogging. These resilient cultivars provide a dual advantage: ensuring yield stability under erratic and extreme weather conditions while also reducing dependency on high-input farming practices. By requiring less irrigation and synthetic fertilizers, they not only reduce production costs for farmers but also help to minimize the carbon footprint and associated greenhouse gas (GHG) emissions ([Wassmann *et al.*, 2009](#)).

For instance, Sahbhagi Dhan, a drought-tolerant rice variety, and Swarna-Sub1, tolerant to submergence, both developed by the International Rice Research Institute (IRRI), have demonstrated excellent performance in climate-vulnerable regions of South Asia. These varieties support the use of alternate wetting and drying (AWD) techniques, leading to 30-50% lower methane (CH₄) emissions compared to continuous flooding systems ([Bouman *et al.*, 2007](#); [Ismail *et al.*, 2008](#); [Bouman *et al.*, 2007](#)). This combination of genetic and water management innovation makes them critical tools in low-emission and climate-resilient agriculture.

Furthermore, deep-rooted crops such as pigeon pea (*Cajanus cajan*), sorghum (*Sorghum bicolor*), and various millets (*Eleusine coracana*, *Pennisetum glaucum*) play a crucial role in subsoil carbon sequestration. These species contribute to long-term soil organic carbon (SOC) stability by transporting carbon deeper into the soil profile, where it is less prone to microbial degradation ([Lal, 2004a](#); [Chivenge *et al.*, 2015](#)). Their natural

tolerance to low-input and dryland environments makes them ideal for cultivation in marginal areas, promoting both climate adaptation and mitigation.

Incorporating such resilient cultivars into farming systems not only strengthens food security but also supports national climate goals under initiatives like India's National Mission on Sustainable Agriculture (NMSA) and the Global Alliance for Climate-Smart Agriculture (GACSA) ([FAO, 2013](#)).

3.3 Conservation Agriculture

Conservation Agriculture (CA) is a sustainable farming approach based on three interrelated principles: minimal soil disturbance (no-till or reduced tillage), permanent soil cover (through crop residues or cover crops), and diversified crop rotations (including intercropping). Together, these practices aim to mimic natural soil-building processes, thereby improving soil health, enhancing input-use efficiency, and contributing significantly to climate change mitigation and adaptation ([Kassam *et al.*, 2009](#)).

One of the most notable benefits of CA is its potential for carbon sequestration. Studies indicate that CA practices can enhance soil organic carbon (SOC) by 0.2 to 1.0 tons per hectare per year, depending on the soil type, climate, and cropping system ([Palm *et al.*, 2014](#)). Reduced or zero tillage minimizes the exposure and oxidation of soil organic matter, thereby preserving carbon stocks ([Lal, 2004a](#)). Residue retention protects the soil from erosion, moderates temperature, and contributes organic material that feeds the soil microbiome. In addition, crop diversification supports functional biodiversity, improves nutrient cycling, and disrupts pest and disease cycles (Hobbs *et al.*, 2008).

Beyond carbon storage, CA has multiple co-benefits: it enhances water infiltration and retention, reduces evapotranspiration losses, improves soil

structure and porosity, and promotes biological pest control, all of which contribute to resilient agroecosystems. These multifunctional benefits make CA a cornerstone of climate-smart agriculture and a key strategy for sustainable intensification in both rainfed and irrigated systems ([Thierfelder & Wall, 2009](#)).

3.4 Agroforestry Integration

Agroforestry is a multifunctional land-use system that integrates woody perennials, trees or shrubs, with crops and/or livestock on the same land unit. It is widely recognized as a nature-based solution for climate resilience due to its capacity to enhance microclimatic buffering, reduce wind and water erosion, and provide continuous carbon inputs via litter fall, root turnover, and woody biomass accumulation ([Nair *et al.*, 2009](#)). The structural complexity and biological diversity of agroforestry systems mimic natural forest ecosystems, thus contributing to long-term ecological stability.

Quantitative studies indicate that well-managed agroforestry systems such as alley cropping, silvopasture, and home gardens can sequester between 1.5 to 3.5 tons of carbon per hectare per year, with contributions from both above-ground biomass and soil organic carbon pools ([Montagnini & Nair, 2004](#); [Jose, 2009](#)). These systems also foster functional biodiversity by providing habitat and food for pollinators, natural pest predators, and soil-enhancing microorganisms ([Schroth & Sinclair, 2003](#)).

Agroforestry is particularly effective in degraded and marginal lands, where it supports restoration of soil fertility, water retention, and ecosystem functionality. The canopy layer of trees in agroforestry systems moderates soil temperature, reduces evapotranspiration, and shields understory crops from climatic extremes such as heatwaves and heavy rains, thus enhancing

climate adaptation. Additionally, the diversified income streams from timber, fruits, fodder, and medicinal plants strengthen farm-level economic resilience against market or climate shocks ([Garritty, 2004](#)).

4. Enhancing Resilience and Sequestration through Soil and Water Management

Effective soil and water management lies at the heart of carbon-negative farming, providing critical foundations for ecosystem resilience, sustainable productivity, and long-term carbon sequestration. Healthy soils, rich in organic matter and microbial life, are not only more fertile but also better able to retain water, buffer temperature extremes, and resist erosion, features essential for adapting to climate variability and extreme weather events (Lal, 2004a&b). Simultaneously, improved water-use efficiency reduces the energy-intensive demands of irrigation, while well-managed soils act as powerful carbon sinks by stabilizing organic carbon in microbial and humic forms ([Paustian *et al.*, 2016](#)). These practices also mitigate nitrous oxide (N₂O) and methane (CH₄) emissions, which are major contributors to agricultural greenhouse gases. This section highlights three key strategies that synergistically enhance soil resilience and carbon storage:

1. Cover Cropping and Green Manuring
2. Organic Amendments and Compost Use
3. Efficient Water Management

4.1 Cover Cropping and Green Manuring

Cover cropping and green manuring are foundational agroecological strategies that significantly contribute to soil health improvement, carbon sequestration, and climate resilience. These practices involve growing specific plant species, often during fallow periods or between main crop

cycles not for harvest, but to protect, enrich, and regenerate the soil. By forming a living mulch, cover crops reduce soil erosion, suppress weeds, moderate soil temperature, and stimulate microbial activity, creating a more favorable environment for subsequent crops ([Snapp *et al.*, 2005](#)).

Both root biomass and aboveground residues from cover crops add to the soil organic carbon (SOC) pool, enhancing soil structure, nutrient availability, and moisture retention. Leguminous species such as clover (*Trifolium* spp.), vetch (*Vicia* spp.), and cowpea (*Vigna unguiculata*) are especially valuable as they fix atmospheric nitrogen through symbiosis with rhizobial bacteria, thereby reducing the need for synthetic nitrogen fertilizers and associated nitrous oxide (N₂O) emissions, a major greenhouse gas ([Drinkwater *et al.*, 1998](#); [Ladha *et al.*, 2011](#)).

Meta-analyses report that cover cropping can increase SOC by 0.3 to 1.1 t C ha⁻¹ yr⁻¹, depending on climate, soil type, and cropping history ([Poepplau & Don, 2015](#)). Moreover, cover crops increase biological resilience by boosting populations of beneficial soil organisms, improving nutrient cycling, and buffering against drought, disease, and other climate stressors ([Blanco-Canqui *et al.*, 2015](#)). When integrated effectively, these practices not only sequester carbon but also strengthen the adaptive capacity of agricultural systems.

4.2 Organic Amendments and Compost Use

The application of organic amendments such as compost, farmyard manure (FYM), green manure, and biochar plays a crucial role in improving soil fertility, restoring degraded soils, and enhancing carbon sequestration potential in agroecosystems. These inputs contribute to the formation of stable soil organic matter, promote microbial biodiversity, and improve soil structure, aeration, and water-holding capacity (Diacono & Montemurro,

2010). They serve as slow-release nutrient sources, enhancing the cation exchange capacity (CEC) and supporting long-term crop productivity while minimizing dependency on synthetic fertilizers.

Among these, biochar, a carbon-rich material produced through pyrolysis of biomass under limited oxygen, has emerged as a strategic amendment for carbon-negative farming. Due to its chemical recalcitrance, biochar can persist in soils for centuries to millennia, effectively locking atmospheric carbon into the terrestrial pool ([Lehmann & Joseph, 2009](#)). Its porous structure improves soil aeration, water retention, and provides a habitat for beneficial microbial colonization ([Glaser *et al.*, 2002](#)). Biochar's alkaline nature can also help neutralize soil acidity, making it especially valuable in tropical and degraded soils.

Recent studies estimate that biochar applications can sequester 1-3 tons of CO₂-equivalents per hectare per year, depending on feedstock type, pyrolysis conditions, and application rate ([Woolf *et al.*, 2010](#)). Furthermore, when combined with compost or FYM, biochar enhances nutrient retention and significantly reduces methane (CH₄) and nitrous oxide (N₂O) emissions during decomposition processes, creating a synergistic effect on soil health and GHG mitigation ([Schmidt *et al.*, 2015](#)). These combined benefits make organic amendments a cornerstone of regenerative and carbon-smart agriculture.

4.3 Efficient Water Management

Efficient water management is a critical pillar of climate-resilient and carbon-negative agriculture, especially in drought-prone, semi-arid, and water-stressed regions. Strategies such as drip and sprinkler irrigation, mulching, and alternate wetting and drying (AWD) in paddy systems optimize water-use efficiency, reduce evapotranspiration, and lower

greenhouse gas (GHG) emissions. These approaches not only conserve a vital resource but also mitigate the energy demand associated with water extraction and pumping, particularly where fossil fuels power irrigation systems ([Burney *et al.*, 2010](#)).

Drip irrigation, by delivering water directly to the root zone, can achieve up to 90-95% water-use efficiency compared to 30-50% in surface irrigation systems. When combined with organic or plastic mulching, this system also reduces soil temperature and minimizes evaporation, enhancing crop tolerance to heat and drought stress ([Kader *et al.*, 2017](#)).

In irrigated rice systems, the AWD technique involving intermittent drying and reflooding, has proven effective in cutting methane (CH₄) emissions by up to 50% without compromising yields ([Richards & Sander, 2014](#)). This method promotes aerobic soil conditions periodically, disrupting methanogenic activity while maintaining sufficient moisture for rice production ([Yagi *et al.*, 1997](#)).

Beyond direct water savings and emission reductions, water-efficient practices support carbon sequestration by fostering healthy root systems, enabling the integration of biochar and compost, and facilitating the use of stress-resilient, carbon-efficient crop varieties, thus linking adaptation and mitigation goals within climate-smart farming frameworks.

5. Socioeconomic and Institutional Dimensions

The widespread adoption and scaling of carbon-negative and climate-resilient farming systems rely as much on socioeconomic and institutional enablers as on technological or ecological interventions. While the biophysical benefits of such systems are well-documented, their real-world impact hinges on supportive governance structures, accessible knowledge systems, inclusive financial tools, and well-integrated markets. In particular, smallholder farmers, who are both the most vulnerable to climate impacts

and the stewards of large portions of arable land, require tailored support to overcome economic, informational, and infrastructural barriers (Thornton *et al.*, 2018). Institutional innovations such as climate-adaptive policies, decentralized extension networks, and financial incentives are essential to bridge the gap between scientific knowledge and on-ground application ([FAO, 2018](#)). This section outlines three critical components that shape the enabling environment for climate-smart and carbon-negative agriculture:

1. Extension Services
2. Input Subsidies and Incentives
3. Access to Climate Finance and Carbon Markets

5.1 Extension Services

Agricultural extension and advisory services are cornerstones for the diffusion of climate-resilient and carbon-negative farming practices, especially among smallholders and marginalized communities. These services serve as the bridge between scientific research and practical field-level application. In the context of climate change, extension systems must evolve beyond conventional technology transfer to embrace a holistic and participatory approach that empowers farmers with context-specific knowledge on regenerative practices such as conservation agriculture, agroforestry, integrated nutrient management, and climate-smart crop planning ([FAO, 2017](#)).

Farmer Field Schools (FFS), self-help groups, and community-based learning models have been particularly effective in building capacity through farmer-to-farmer learning and co-creation of knowledge ([Davis *et al.*, 2012](#)). Such participatory models enhance trust, encourage experimentation, and foster resilience. Evidence from sub-Saharan Africa and South Asia indicates that frequent contact with extension personnel

significantly increases adoption of climate-smart agricultural (CSA) practices, especially when training is adapted to agroecological realities and cultural preferences ([Anderson & Feder, 2007](#); World Bank, 2021).

The integration of digital tools, such as SMS alerts, mobile advisory apps (e.g., e-Sagu, Krishi Gyan), and interactive voice response systems has further expanded outreach, particularly for remote and underserved farmers. These platforms enable timely delivery of climate forecasts, pest alerts, market prices, and agronomic tips, improving decision-making and adaptive capacity ([Mittal & Mehar, 2016](#); [Klerkx *et al.*, 2019](#)).

5.2 Input Subsidies and Incentives

Public subsidies have historically played a pivotal role in influencing farmers' input choices and land management practices. However, in many developing countries, these subsidies remain disproportionately directed toward chemical fertilizers, synthetic pesticides, and irrigation infrastructure, remnants of Green Revolution-era policies focused primarily on maximizing short-term yields ([Jayne *et al.*, 2014](#)). Such input patterns often lead to soil degradation, water pollution, and increased greenhouse gas emissions from fertilizer overuse ([Tilman *et al.*, 2002](#)). To transition toward carbon-negative and regenerative agriculture, it is essential to redirect subsidies and incentives toward climate-friendly alternatives such as compost production units, biofertilizers, green manure seed banks, and stress-resilient crop varieties (Popp *et al.*, 2013; [Pretty *et al.*, 2011](#)).

Empirical evidence indicates that when economic incentives align with ecological sustainability, farmers are more willing to invest in long-term soil health and adopt diversified cropping systems that enhance carbon sequestration and ecosystem services (Pineiro *et al.*, 2022). For example, conditional cash transfers or “green subsidies” can incentivize the adoption of practices that contribute to biodiversity conservation, water regulation,

and carbon storage, effectively rewarding farmers for their environmental stewardship ([OECD, 2008](#)).

To maximize impact and equity, incentive programs must be context-specific, developed in close consultation with local stakeholders, and backed by robust monitoring, reporting, and verification (MRV) frameworks to ensure that subsidies lead to genuine and measurable climate mitigation outcomes ([FAO, 2017](#)).

5.3 Access to Climate Finance and Carbon Markets

Access to climate finance and carbon markets represents a transformative opportunity to align economic incentives with climate mitigation and adaptation goals, especially for resource-poor smallholder farmers. Mechanisms such as Payments for Ecosystem Services (PES) and voluntary carbon credit schemes provide financial rewards for the adoption of sustainable practices that increase carbon sequestration and enhance ecosystem health ([Wunder, 2005](#)). These programs help internalize the environmental benefits of climate-smart agriculture, making regenerative practices economically viable and scalable.

For example, farmers engaged in agroforestry, conservation tillage, biochar application, or cover cropping can generate quantifiable carbon offsets eligible for sale in carbon markets, contingent on the availability of robust Measurement, Reporting, and Verification (MRV) systems ([Peskest et al., 2011](#)). International certification platforms such as the Gold Standard, Plan Vivo, and the Verified Carbon Standard (VCS) play a critical role in validating and ensuring the credibility of these carbon credits by setting rigorous social and environmental safeguards ([Hamilton et al., 2016](#)).

However, smallholders often face challenges accessing these markets due to transaction costs, lack of technical capacity, and fragmentation. The [FAO \(2020\)](#) emphasizes the need for capacity building, aggregation mechanisms

like cooperatives or farmer producer organizations, and the use of digital tools for accurate data collection and monitoring. Furthermore, integrating carbon finance schemes with existing rural development programs and social safety nets can improve equity, ensuring that vulnerable and marginalized communities benefit from climate finance ([Grima *et al.*, 2016](#)). Such integrated approaches are crucial for building inclusive, resilient agricultural landscapes.

6. Case Studies

Real-world case studies serve as critical tools for understanding the practical implementation of carbon-negative and climate-resilient farming systems. These on-the-ground examples highlight how a combination of traditional knowledge, scientific innovation, policy alignment, and community participation can lead to substantial improvements in agricultural sustainability, carbon sequestration, and rural livelihoods. They demonstrate the importance of adapting strategies to local agroecological conditions while fostering social equity and environmental stewardship. According to [Altieri *et al.* \(2012\)](#), such knowledge-intensive, farmer-led systems are key to climate adaptation and long-term resilience in the Global South. The following case studies illustrate diverse approaches in different sociocultural and agro-climatic contexts, showcasing tangible outcomes from innovations in rice intensification, agroecology, and dryland farming:

1. System of Rice Intensification (SRI), India
2. Regenerative Agroecology, Latin America
3. Rainwater Harvesting and Dryland Horticulture, Rajasthan, India

6.1 System of Rice Intensification (SRI), India

The System of Rice Intensification (SRI) is a transformative agroecological methodology that enhances rice productivity while reducing the environmental footprint of cultivation. Originally developed in Madagascar in the 1980s, SRI has been successfully adapted in several Asian countries, including India. It is characterized by several key management principles: transplanting young seedlings (usually 8-12 days old), maintaining wider spacing (typically 25×25 cm in a square pattern), using organic soil amendments instead of synthetic fertilizers, and practicing alternate wetting and drying (AWD) irrigation rather than traditional continuous flooding ([Uphoff, 2007](#); [Thakur et al., 2010](#)). In India, SRI has gained prominence in states such as Tamil Nadu, Andhra Pradesh, Bihar, and West Bengal.

Empirical studies show that SRI can lead to 20-50% higher yields, 30-50% water savings, and up to 60-80% reductions in methane emissions, due to reduced anaerobic decomposition ([Sinha & Talati, 2007](#); [Richards & Sander, 2014](#); Rao et al., 2024). [Uphoff et al. \(2008\)](#) observed a 78% decrease in irrigation water use and a 40% increase in yield in Tamil Nadu, highlighting its efficiency and environmental benefits. SRI also enhances root vigor, improves soil structure, and fosters greater drought tolerance, making rice cultivation more resilient to climate variability ([Satyanarayana et al., 2007](#)). Its reduced seed requirement and minimal reliance on chemical inputs make it economically viable and particularly attractive for small and marginal farmers. The success of SRI in India underscores its potential as a climate-smart, resource-efficient, and scalable strategy for sustainable rice production.

6.2 Regenerative Agroecology, Latin America

In Latin America, regenerative agroecology has emerged as a powerful response to land degradation, rural poverty, and climate vulnerability. In areas like the Brazilian Cerrado and the Guatemalan highlands, smallholder

farmers are implementing agroecological systems focused on biodiversity, soil regeneration, and traditional ecological knowledge. According to [Altieri & Toledo \(2011\)](#), successful transformation hinges on community seed banks, participatory knowledge exchanges, and the integration of trees and legumes into cropping systems, supported by strong local food networks ([Altieri & Toledo, 2011](#); FAO, 2015). In Brazil's smallholder agroforestry initiatives, particularly in land reform settlements, farmers combine fruit trees with staple crops, enhancing carbon sequestration, dietary diversity, and income stability. These systems reduce reliance on agricultural chemicals and buffer against pests and drought via ecological resilience and biological pest control ([Rosset *et al.*, 2011](#)).

Moreover, these farmer-led systems are deeply community-rooted and supported by NGOs and local institutions, creating social capital that sustains innovation and resilience. Movements like “Campesino a Campesino” (farmer-to-farmer learning) have accelerated agroecological diffusion, empowering peasant organizations and fostering agroecological identity. These regenerative agroecological models also foster ecosystem services, including improved soil moisture, shadebenefits, and biodiversity conservation, shown to reduce local temperature, enhance pollinator habitats, and rebuild degraded landscapes.

6.3 Rainwater Harvesting and Dryland Horticulture, Rajasthan, India

In the semi-arid lands of Rajasthan, traditional and community-led rainwater harvesting (RWH) methods have been critically important for transforming drylands into productive agricultural landscapes. Indigenous systems such as Taankas, Johads, Chaukas, and check-dams capture monsoon runoff effectively, enabling farmers to cultivate high-value dryland horticulture even under minimal rainfall. A representative case is

Jagsa village in Barmer district, where annual rainfall is only about 280 mm. After the installation of rooftop Taanka systems and small on-farm storage tanks, farmers shifted to pomegranate cultivation using drip irrigation, boosting incomes from approximately ₹100,000 to ₹550,000 per hectare per year ([Down To Earth, 2023](#)).

Complementary farm pond models under the state's watershed scheme enabled them to irrigate during dry spells and add additional crops. A detailed evaluation in Tonk and Karauli districts showed that RWH adoption increased cropping intensity from 120% to nearly 190%, with benefit-cost ratios between 1.9 and 2.3, and significant enhancements in soil biodiversity and groundwater recharge ([Punera *et al.*, 2016](#)). Moreover, revived Johads and Chaukas built by community groups and NGOs, such as Tarun Bharat Sangh, have catalyzed landscape-level regeneration, recharging aquifers, reviving local springs, and enabling farmers to grow multiple crops annually ([Singh, 2015](#); [Yadav *et al.*, 2022](#)). These systems not only provide resilient water sources for horticulture and livestock, but also enhance soil carbon sequestration, plant biodiversity, and climate adaptation capacity. By combining traditional knowledge, institutional support, and modern practices like drip irrigation, these community-led interventions illustrate how low-cost, low-emission solutions can sustainably transform rural livelihoods in marginal dryland regions.

7. Conclusion and Way Forward

This chapter provides an in-depth examination of Climate-Resilient Crop Systems (CRCS) as a strategic response to the impacts of climate change on agriculture. The chapter underscores the urgency of transforming agricultural practices to ensure food security, ecological sustainability, and climate mitigation. Key principles emphasized include diversity, soil health management, water efficiency, ecosystem integration, and reduced external

inputs. The chapter highlights practical approaches such as conservation agriculture, agroforestry, stress-tolerant crop varieties, and integrated cropping systems, demonstrating how these synergize to build resilience and support carbon sequestration. Case studies from India and Latin America, including System of Rice Intensification (SRI), regenerative agroecology, and dryland horticulture with rainwater harvesting, illustrate successful on-ground applications. The chapter also explores enabling frameworks, including extension services, subsidy reforms, and climate finance mechanisms, crucial for mainstreaming CRCS. Emphasis is placed on the co-creation of knowledge, farmer participation, and institutional coordination to scale context-specific innovations.

Climate-resilient crop systems present a transformative solution to interlinked challenges of food insecurity, environmental degradation, and climate change. These systems support carbon-negative pathways through enhanced soil health, reduced greenhouse gas emissions, and ecosystem restoration. Success requires an integrated approach, blending ecological principles, scientific innovation, traditional knowledge, and inclusive policies. CRCS are not just technical solutions they represent a paradigm shift toward sustainable, adaptive, and regenerative food systems, vital for long-term planetary health and rural livelihoods.

To ensure the successful implementation and scaling of climate-resilient crop systems, a multifaceted set of recommendations is essential. First, extension and knowledge systems should be strengthened by developing participatory and localized training programs focused on regenerative and climate-smart agriculture, while leveraging digital platforms for timely advisories and decision-making tools. Second, agricultural subsidies must be redirected away from chemical-intensive inputs toward support for composting, biofertilizers, green manures, and climate-resilient seeds.

Promoting stress-tolerant and carbon-sequestering crop varieties such as millets, pulses, and deep-rooted perennials is critical for enhancing resilience and mitigating emissions. Additionally, smallholders should be integrated into voluntary carbon markets and Payments for Ecosystem Services (PES) through the establishment of aggregation platforms and robust MRV (Measurement, Reporting, and Verification) systems. Investments are also needed in soil and water management infrastructure, including biochar units, composting facilities, and efficient irrigation methods. Finally, multi-stakeholder collaboration and the integration of traditional knowledge and community institutions into formal agricultural policies are key to sustaining and scaling climate-resilient farming innovations.

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Chapter - 15

Education, Training and Capacity Building

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1. Introduction

The global imperative to mitigate climate change while ensuring food security has placed agriculture at the forefront of sustainable development efforts. Carbon-negative farming, agricultural systems designed to reduce greenhouse gas emissions and sequester carbon in soils and biomass, offers a promising pathway to achieve these dual goals ([Smith et al., 2008](#); [Lal, 2020](#)). However, the success of such transformative approaches depends heavily on the capacity of farmers, extension agents, policymakers, and other stakeholders to understand, adopt, and adapt innovative practices ([Pretty & Bharucha, 2014](#); [FAO, 2019a](#)). Education, training, and capacity building serve as foundational pillars that enable this transition. They provide the essential knowledge, skills, and attitudes required for effective implementation of carbon sequestration techniques, regenerative soil management, integrated pest management, water-efficient practices, and climate-smart cropping systems ([Altieri et al., 2015](#); [World Bank, 2021](#)). Moreover, these processes empower stakeholders to navigate complex challenges, including technological uncertainties, market mechanisms like carbon credits, and evolving policy landscapes ([Vermeulen et al., 2012](#); [Paustian et al., 2019](#)).

Historically, many smallholder farmers and indigenous communities have possessed deep ecological knowledge and sustainable farming

traditions that align closely with carbon-negative principles ([Berkes et al., 2000](#); [Altieri & Nicholls, 2020](#)). Modern education and training efforts now seek to build on these foundations by integrating scientific advancements, participatory learning methods, and digital innovations to enhance outreach and impact ([Pretty et al., 2011](#); [Klerkx & Rose, 2020](#)).

In this context, capacity building goes beyond one-time training; it is an ongoing, adaptive process that fosters resilience, innovation, and collaboration across scales from local communities to national agricultural systems ([UNDP, 2016](#); Scoones, 2016). Strengthening capacity is particularly critical in developing countries where resource limitations, literacy levels, and institutional gaps often constrain the diffusion of sustainable practices ([FAO, 2017](#); [Mirulla, 2018](#)).

This chapter explores the multifaceted role of education, training, and capacity building in accelerating the adoption of carbon-negative farming. It examines target groups, methodologies, challenges, and emerging best practices, highlighting how empowering people with knowledge and skills is key to transforming agriculture into a climate solution.

2. The Importance of Education and Training in Carbon Negative Farming

Carbon-negative farming is an advanced and transformative approach that aims not only to reduce greenhouse gas emissions but also to actively sequester carbon in soils and biomass, contributing to climate change mitigation. Achieving such outcomes requires farmers and agricultural stakeholders to acquire a comprehensive and interdisciplinary understanding that spans multiple domains.

Firstly, knowledge of soil science is essential because soil is the primary reservoir for carbon sequestration in agriculture. Farmers need to understand soil organic carbon dynamics, soil fertility management, and the

role of microbial communities in stabilizing carbon stocks ([Lal, 2004](#)). Without this understanding, adoption of regenerative practices like cover cropping, reduced tillage, and organic amendments may be suboptimal or even counterproductive.

Secondly, agroecology provides the systems-based framework for designing resilient farming landscapes that integrate biodiversity, nutrient cycling, and ecological pest management. Training in agroecological principles enables practitioners to manage farms holistically, balancing productivity with environmental health (Gliessman, 2016). This includes the integration of trees, livestock, and crops to enhance carbon pools and ecosystem services.

Thirdly, education on climate change mitigation specifically tailored to agriculture is critical. This includes understanding sources of emissions such as methane from rice paddies and livestock, nitrous oxide from fertilizers, and the potential of various practices to reduce or offset these emissions. Farmers and advisors need to grasp the concepts of carbon footprints, greenhouse gas accounting, and measurement techniques to make informed decisions and participate effectively in carbon markets or incentive programs ([Smith et al., 2014](#)).

Equally important are the socio-economic factors influencing the adoption of carbon-negative practices. Education and training must address issues such as cost-benefit analysis, market access, risk management, and policy environments. Understanding these dimensions empowers farmers to evaluate the economic viability of innovations and align them with their livelihood goals.

Traditional formal education systems, universities, agricultural colleges, and vocational schools, often lack curricula that fully integrate these interdisciplinary themes, focusing instead on conventional agricultural

production ([Pretty, 2008](#)). There is an urgent need for curriculum reforms to include climate-smart agriculture, regenerative principles, and carbon accounting to prepare the next generation of agricultural professionals. On the informal side, farmer-to-farmer learning, extension services, and community-based organizations play a pivotal role. As [Vermeulen et al. \(2018\)](#) highlight, education approaches that combine theoretical knowledge with experiential, hands-on learning are particularly effective in enabling farmers to innovate and adapt to rapidly changing climate and market conditions. Participatory learning models such as Farmer Field Schools allow farmers to experiment with and observe the effects of carbon-negative practices in real time, fostering confidence and local adaptation. Moreover, capacity building must be continuous and adaptive, as climate science and sustainable agriculture technologies evolve. This requires investment not only in initial training but also in ongoing refresher courses, knowledge exchange platforms, and access to real-time information via digital technologies.

Driving the shift toward sustainable food systems, education and training are the linchpins for scaling carbon-negative farming. They create the knowledge base, develop the technical skills, and foster the behavioral changes necessary for widespread adoption. By empowering farmers and stakeholders with a deep understanding of the complex interactions among soils, crops, climate, and socio-economic realities, education enables agriculture to become a robust solution to climate change.

3. Target Groups for Capacity Building

Building capacity among key stakeholders is essential to ensure the adoption, adaptation, and institutionalization of climate-resilient practices. Tailored training, knowledge exchange, and continuous support empower diverse actors from grassroots farmers to policymakers to drive

transformative change. The following sub-sections highlight the specific needs and roles of different target groups in advancing carbon-negative agriculture.

1. Farmers and Farm Workers
2. Extension Agents and Agricultural Advisors
3. Policy Makers and Institutional Stakeholders

3.1 Farmers and Farm Workers

Smallholder and commercial farmers are the primary agents of change in the transition toward carbon-negative farming. They are directly responsible for implementing on-the-ground practices such as regenerative soil management, agroforestry, organic amendments, and efficient water use that contribute to carbon sequestration and greenhouse gas mitigation. Given the diversity among farming communities in terms of culture, language, education, and resource access, training programs must be context-specific and culturally sensitive to be effective.

Many farmers, especially in developing regions, have varying literacy levels and limited access to formal education, which requires the use of participatory learning approaches that prioritize hands-on experience and peer learning. Farmer Field Schools (FFS) have been widely recognized as a successful model in this regard. These schools involve group-based experiential learning, where farmers engage in trial plots, observe outcomes, and collectively analyze results, thereby building practical skills related to soil health improvement, composting, agroforestry integration, and sustainable water management ([Davis et al., 2012](#)). Demonstration plots established in local contexts serve as visible examples of best practices, encouraging adoption by showing tangible benefits.

Such participatory methods not only enhance technical knowledge but also foster social capital and empower farmers to innovate and adapt technologies to local ecological and socio-economic conditions. Moreover, inclusion of women and marginalized groups in these programs is vital, as they play critical roles in agricultural labor and natural resource management but often face barriers to accessing training ([Doss, 2018](#)).

3.2 Extension Agents and Agricultural Advisors

Extension agents serve as critical intermediaries between research institutions and farming communities. They translate scientific knowledge into practical recommendations and provide ongoing support to farmers during the adoption and adaptation of carbon-negative practices. Therefore, capacity building for extension workers must be comprehensive and multi-dimensional.

Technically, extension agents require training in carbon accounting methods, understanding of ecosystem services, and knowledge of climate change mitigation strategies applicable at the farm level. This includes proficiency in measuring soil organic carbon, monitoring greenhouse gas fluxes, and advising on carbon-friendly crop varieties and management techniques ([Rivera & Qamar, 2003](#)).

In addition to technical skills, extension personnel must develop soft skills such as effective communication, facilitation of group learning, and conflict resolution. Given the gendered nature of agricultural roles in many societies, extension workers must be trained in gender-sensitive approaches to ensure inclusive outreach and equitable participation ([Meinzen-Dick et al., 2011](#)). Strengthening the capacity of extension systems not only improves the quality and credibility of advisory services but also enhances their reach, enabling more farmers to benefit from carbon-negative innovations.

3.3 Policy Makers and Institutional Stakeholders

The broader enabling environment for carbon-negative farming is shaped by policies, institutional frameworks, and financial mechanisms that require active engagement from governments, non-governmental organizations (NGOs), development agencies, and other institutional actors. These stakeholders play a pivotal role in designing, implementing, and monitoring policies and programs that incentivize carbon sequestration practices and integrate climate-smart agriculture into national development plans. Capacity building for policymakers and institutional actors involves equipping them with the skills to understand and manage complex mechanisms such as carbon markets, payment for ecosystem services (PES), and climate finance instruments. Training programs should focus on enhancing competencies in policy formulation, impact assessment, and program monitoring and evaluation, ensuring that agricultural interventions align with climate mitigation goals as well as broader socio-economic development targets ([FAO, 2017](#)).

Moreover, institutional capacity building promotes coordination across sectors (agriculture, environment, finance, and rural development) ensuring coherent policies that avoid conflicting incentives and maximize synergies. This includes understanding the nuances of carbon accounting standards, certification protocols, and legal frameworks that support transparent and credible carbon trading systems. Developing strong institutional capacity also fosters innovation by enabling stakeholders to design adaptive policies responsive to evolving scientific knowledge, market conditions, and farmer needs. Ultimately, empowered policymakers and institutional leaders can catalyze scaling of carbon-negative farming through supportive regulatory environments and resource mobilization.

4. Methods and Approaches in Education and Training

To build a knowledgeable and skilled workforce capable of advancing carbon-negative farming, diverse and inclusive educational strategies are needed. Effective capacity development must combine theoretical foundations with practical, context-specific learning tailored to different audiences. Blending formal, participatory, and digital approaches enhances reach, relevance, and impact. The sub-sections below detail key methodologies that support transformative learning and the widespread adoption of sustainable agricultural practices.

1. Formal Education and Curriculum Development
2. Participatory and Experiential Learning
3. Use of Digital and Remote Learning Technologies

4.1 Formal Education and Curriculum Development

Integrating carbon-negative farming concepts into formal education systems such as agricultural universities, vocational training centers, and agricultural colleges is crucial for cultivating a new generation of agronomists, farm managers, and rural development professionals equipped to address climate challenges. Traditional curricula often focus narrowly on maximizing production, neglecting environmental sustainability and climate resilience. Curriculum reforms should emphasize systems thinking, understanding agroecosystems as interconnected and dynamic, and incorporate principles of agroecology, soil health management, and climate-smart agriculture ([Pretty, 2008](#)). Courses need to provide foundational knowledge on carbon cycling, greenhouse gas emissions from agriculture, carbon accounting, and regenerative practices such as cover cropping, agroforestry, and organic amendments.

Moreover, curricula should integrate **interdisciplinary learning**, linking agronomy with environmental science, economics, and social sciences, to

equip students with holistic problem-solving skills. Hands-on laboratory and fieldwork components enable learners to apply theoretical concepts in real-world settings, enhancing comprehension and retention. Graduates from such programs are better prepared to lead research, extension, and policy formulation in support of carbon-negative farming.

4.2 Participatory and Experiential Learning

Participatory learning approaches empower farmers and rural communities by involving them directly in the learning process, fostering innovation and ownership of carbon-negative practices. Methods such as Farmer Field Schools (FFS), community workshops, and peer-to-peer knowledge exchanges are especially effective. These platforms encourage farmers to engage in experiential learning through observation, experimentation, and reflection ([Mezirow, 1991](#)). FFS, for instance, use season-long facilitated group sessions where farmers learn by doing, evaluating soil management techniques, testing organic inputs, and monitoring crop responses. This iterative process allows for adaptation to local ecological and socio-economic conditions, enhancing the relevance and sustainability of practices. Community workshops broaden participation by including marginalized groups such as women and indigenous peoples, integrating traditional knowledge with scientific insights.

Field demonstrations and farmer-led trials provide tangible evidence of benefits, building confidence and reducing perceived risks associated with adopting new technologies. Such bottom-up learning approaches foster social cohesion, collective problem solving, and the creation of farmer networks that can accelerate the diffusion of carbon-negative innovations.

4.3 Use of Digital and Remote Learning Technologies

The advent of Information and Communication Technologies (ICTs) has transformed the landscape of agricultural education and extension, breaking geographical and temporal barriers to knowledge dissemination. Digital platforms such as mobile applications, e-learning courses, and web-based advisory services have expanded access to training resources, particularly for remote and underserved farming communities ([Aker, 2011](#)). Mobile apps provide real-time weather forecasts, pest and disease alerts, market prices, and tailored crop management advice, enabling farmers to make informed decisions that enhance productivity and reduce emissions. Online courses and webinars allow learners to acquire theoretical and practical knowledge flexibly and at scale. E-extension platforms enable interactive communication between experts and farmers, facilitating timely problem-solving and feedback.

Emerging technologies like virtual reality (VR) and simulation modeling offer immersive training experiences that help learners visualize complex agroecosystems and practice decision-making in a risk-free environment. These tools can simulate soil carbon dynamics, crop growth under different management scenarios, and climate impacts, thereby deepening understanding and encouraging experimentation. Despite the promise of digital technologies, challenges such as limited internet connectivity, digital literacy gaps, and affordability must be addressed to ensure equitable access. Combining digital tools with traditional participatory methods creates hybrid models that maximize reach and impact.

5. Challenges in Capacity Building for Carbon Negative Farming

While capacity building is a cornerstone of transitioning to carbon-negative agriculture, its implementation is often hindered by a range of systemic, logistical, and socio-cultural barriers. These challenges can limit the

effectiveness, inclusivity, and sustainability of training efforts, especially among vulnerable populations. Addressing these constraints is essential for scaling climate-resilient practices and ensuring equitable access to knowledge and resources. The following sub-sections outline the key obstacles that must be overcome to strengthen capacity development initiatives.

1. Resource Constraints
2. Diverse Literacy and Cultural Barriers
3. Fragmented Institutional Coordination
4. Rapidly Evolving Knowledge Base

5.1 Resource Constraints

A critical barrier to effective capacity building for carbon-negative farming is the persistent scarcity of resources financial, infrastructural, and human which constrains both the reach and quality of training programs. In many regions, especially in the Global South, public sector agricultural extension systems are underfunded and overstretched, leaving them ill-equipped to deliver specialized training on regenerative and carbon-sequestering practices ([Pingali, 2007](#)). Limited funding often results in irregular or short-term capacity building initiatives that fail to provide sustained engagement or follow-up, undermining long-term adoption ([World Bank, 2021](#)).

Infrastructure deficits compound these challenges. Many rural areas lack accessible training centers, demonstration plots, or adequate digital connectivity, which restricts opportunities for farmers to access hands-on learning or virtual capacity building platforms ([FAO, 2019b](#)). This gap is particularly problematic for knowledge-intensive practices such as biochar application, agroforestry design, or precision nutrient management, which

require repeated exposure, practical demonstrations, and ongoing mentorship.

Human resource limitations further exacerbate the problem. In numerous contexts, the ratio of extension agents to farmers remains alarmingly low, and agents may themselves lack up-to-date technical knowledge on carbon-negative interventions ([Birner et al., 2009](#)). Additionally, without targeted investment in training trainers both in formal extension systems and community-based networks efforts to disseminate innovative practices risk becoming fragmented and inconsistent.

For marginalized and resource-poor farmers, these constraints are often more severe, as they face additional financial barriers to attending training (e.g., travel costs, opportunity costs of time away from farming) and may lack the necessary inputs to implement new techniques learned. Without mechanisms such as subsidized training, cost-sharing schemes, or provision of starter inputs, the benefits of capacity building risk being disproportionately captured by better-resourced farmers, widening equity gaps in the adoption of carbon-negative practices ([Pretty et al., 2020](#)).

Ultimately, overcoming resource constraints requires coordinated investment from governments, development agencies, and private sector actors, aimed not only at delivering training but also at ensuring that enabling resources financial, infrastructural, and human are in place to translate knowledge into action.

5.2 Diverse Literacy and Cultural Barriers

The effectiveness of capacity building for carbon-negative farming is often constrained by significant variations in literacy levels, language proficiency, and socio-cultural norms among farming communities. In many rural regions, especially in developing countries, a considerable proportion of farmers have limited formal education, which can hinder their ability to

interpret technical training materials, understand measurement-based carbon accounting methods, or navigate digital platforms used in knowledge dissemination ([FAO, 2014](#)). Low literacy not only restricts access to written resources but can also reduce confidence in engaging with formal training programs, thereby limiting participation (van den Ban & Hawkins, 2002).

Linguistic diversity further complicates outreach efforts. National or regional training programs are frequently delivered in official or dominant languages, which may not be the mother tongue of local farmers, leading to misinterpretation of technical terms or incomplete understanding of concepts such as soil organic carbon sequestration, agroforestry design, or biochar application ([Pretty et al., 2011](#)). Without translation into local languages and adaptation to culturally relevant analogies, the uptake of carbon-negative practices can be slow and uneven.

Cultural norms and traditional belief systems can also shape farmers' receptivity to new practices. In some contexts, agricultural decision-making is influenced by community elders, religious leaders, or established gender roles, meaning that training interventions which fail to engage these stakeholders risk being disregarded regardless of their technical merit ([Meijer et al., 2015](#)). For example, women who often play a central role in soil management and seed selection may be excluded from training sessions due to entrenched social norms, thereby reducing the dissemination and implementation of learned practices ([Colfer et al., 2015](#)).

Furthermore, certain climate-smart or carbon-negative techniques may conflict with traditional farming knowledge or local perceptions of risk, particularly when they involve altering long-standing crop rotations, land use patterns, or livestock management systems. In such cases, farmers may prefer to rely on intergenerational knowledge rather than external

recommendations, unless trust-building and participatory methods are used to co-design interventions (Chambers, 2014).

Addressing these literacy and cultural barriers requires a multi-pronged approach combining the use of visual, oral, and experiential learning methods; delivering content in local languages; engaging trusted community leaders; and ensuring inclusive participation across gender, age, and socio-economic groups. By embedding cultural sensitivity and literacy-appropriate communication into capacity building strategies, practitioners can significantly enhance the adoption and long-term sustainability of carbon-negative farming practices.

5.3 Fragmented Institutional Coordination

A major challenge to effective capacity building for carbon-negative farming is the lack of coherent coordination among the diverse institutions involved in agricultural development. These include government departments, research institutions, extension agencies, non-governmental organizations (NGOs), farmers' cooperatives, and private sector actors. In many contexts, these stakeholders operate in silos, pursuing parallel or overlapping initiatives without adequate alignment of objectives, methodologies, or timelines ([Hall et al., 2001](#)). This institutional fragmentation leads to duplication of efforts in some areas, while leaving critical gaps such as farmer access to carbon monitoring tools or market incentives for climate-smart produce unaddressed ([Klerkx & Proctor, 2013](#)).

In the context of carbon-negative agriculture, where integrated approaches are essential, poor coordination can undermine the synergy between research, extension, and policy. For example, research institutes may develop innovative soil carbon sequestration techniques, but without timely engagement with extension services, such innovations fail to reach farmers in usable formats ([Rivera & Qamar, 2003](#)). Similarly, policies

promoting regenerative practices may not be backed by sufficient field-level technical support or incentive mechanisms due to misalignment between ministries of agriculture, environment, and rural development ([Pretty et al., 2011](#)).

Competition for funding between institutions can exacerbate fragmentation, with organizations focusing on short-term, donor-driven projects rather than long-term, integrated strategies ([Hermans et al., 2013](#)). Additionally, the absence of standardized training curricula and knowledge-sharing platforms results in inconsistent messages being conveyed to farmers, leading to confusion and reduced trust in capacity building programs.

Addressing this challenge requires the establishment of multi-stakeholder coordination mechanisms that align institutional mandates and facilitate regular communication between actors at national, regional, and local levels. Successful models, such as agricultural innovation platforms and farmer-led innovation networks, demonstrate that when institutions share resources, harmonize training content, and jointly monitor progress, the effectiveness and reach of capacity building are significantly enhanced (Schut et al., 2016). For carbon-negative farming to scale effectively, institutional collaboration must be institutionalized, with clear roles, shared accountability, and integrated funding strategies that prioritize systemic transformation over isolated interventions.

5.4 Rapidly Evolving Knowledge Base

One of the more complex challenges in capacity building for carbon-negative farming lies in keeping pace with the rapidly evolving body of scientific, technical, and policy knowledge. The field is advancing quickly, driven by emerging research on soil carbon dynamics, innovative mitigation technologies, digital agriculture tools, and evolving carbon market

mechanisms ([Paustian et al., 2019](#)). While this dynamism presents opportunities for more effective and efficient farming practices, it also poses a barrier to consistent and up-to-date training delivery, particularly in regions where extension services and training curricula are updated infrequently ([Lal, 2020](#)).

Farmers and trainers alike may struggle to distinguish between well-validated practices and experimental techniques that are still under investigation. For example, methods such as enhanced rock weathering, microbial inoculants for carbon sequestration, or blockchain-based carbon credit tracking are promising but still subject to ongoing scientific assessment (Beerling et al., 2020). Without mechanisms to translate new research into farmer-friendly guidance, there is a risk that outdated or incomplete information will persist in the field, reducing effectiveness and possibly undermining trust in capacity building initiatives ([Klerkx et al., 2010](#)).

Furthermore, global climate policies, carbon accounting frameworks, and certification standards critical to the economic viability of carbon-negative farming are also in flux. Changes in international agreements, carbon credit verification methodologies, or national incentive schemes can quickly alter the feasibility or attractiveness of certain practices ([Smith et al., 2020](#)). For capacity building programs, this means that training materials, case studies, and demonstration models require frequent revision, a process that demands resources, technical expertise, and institutional agility.

The challenge is compounded in contexts where knowledge dissemination is still predominantly top-down, with weak feedback loops between researchers, policymakers, and practitioners. Without dynamic knowledge exchange platforms such as digital farmer networks, living labs, or continuous professional development systems for trainers there is a lag in

incorporating cutting-edge findings into field-level action ([Hall et al., 2005](#)).

To address this, capacity building for carbon-negative farming must adopt adaptive learning frameworks that are iterative, participatory, and responsive to new evidence. This includes fostering partnerships between research institutions, farmer-led innovation networks, and policy bodies to co-create and update training resources in near real time. By institutionalizing mechanisms for rapid knowledge integration, training programs can remain both scientifically relevant and practically applicable in an era of accelerated agricultural innovation.

6. Innovations and Best Practices in Capacity Building

To overcome traditional barriers and enhance the effectiveness of training programs in carbon-negative farming, innovative and inclusive approaches are essential. Emerging best practices emphasize collaboration, equity, and grassroots innovation, helping to tailor capacity building to diverse agroecological and socio-cultural contexts. The following sub-sections explore proven strategies that foster effective knowledge transfer, strengthen community resilience, and accelerate the transition to sustainable agricultural systems.

1. Multi-Stakeholder Partnerships
2. Gender-Responsive Training
3. Farmer-Led Innovation Networks

6.1 Multi-Stakeholder Partnerships

Multi-stakeholder partnerships have emerged as a cornerstone in scaling carbon-negative farming by fostering collaboration among diverse actors, including farmers, researchers, policymakers, private sector entities, civil

society organizations, and international development agencies. These partnerships help bridge the gap between scientific knowledge and practical application, ensuring that training programs are context-specific, participatory, and adaptable to local agroecological conditions ([Pretty et al., 2020](#)). By combining the complementary strengths of different stakeholders such as the technical expertise of research institutions, the policy leverage of government bodies, the innovation capacity of agribusiness, and the experiential knowledge of farming communities partnerships can design and deliver more holistic and effective capacity-building interventions (World Bank, 2019).

In carbon-negative farming, multi-stakeholder platforms facilitate co-creation of solutions, where end-users (farmers) are not passive recipients of information but active collaborators in developing and validating practices such as conservation tillage, agroforestry integration, and biochar application ([Lal, 2020](#)). This inclusive approach increases adoption rates because farmers are more likely to embrace practices they have helped design and test. Partnerships also enable pooling of financial and logistical resources, making it possible to reach marginalized groups such as smallholders, women, and indigenous communities who are often excluded from conventional agricultural training ([FAO, 2021](#)).

Additionally, multi-stakeholder collaboration supports long-term sustainability by embedding training programs into broader policy frameworks and market mechanisms. For instance, partnerships can link farmers trained in carbon-negative techniques to voluntary carbon markets, providing both environmental benefits and additional income streams ([Wang et al., 2021](#)). Digital platforms have further strengthened these collaborations, enabling real-time exchange of knowledge, monitoring of practice adoption, and scaling of innovations across regions ([Klerkx &](#)

[Rose, 2020](#)). When carefully structured with transparent governance and equitable decision-making, multi-stakeholder partnerships act as both the catalyst and the backbone for transformative change towards climate-resilient and low-carbon agricultural systems.

6.2 Gender-Responsive Training

Gender-responsive training is essential for ensuring equitable participation in carbon-negative farming, recognizing that women and men often have different roles, responsibilities, access to resources, and decision-making power in agricultural systems ([Meinzen-Dick et al., 2019](#)). In many rural contexts, women are heavily involved in farm labor, seed selection, composting, and crop diversification activities directly linked to soil health and carbon sequestration yet they frequently face systemic barriers such as limited access to land, credit, extension services, and technical training (FAO, 2011). Addressing these disparities through targeted, inclusive capacity-building programs not only enhances gender equity but also strengthens the overall effectiveness of climate-smart agricultural interventions.

Gender-responsive training incorporates methodologies and content that are tailored to meet the specific needs, constraints, and aspirations of women farmers. This includes flexible training schedules that accommodate women's household responsibilities, use of locally appropriate languages and communication channels, and ensuring safe, accessible training venues ([Quisumbing et al., 2014](#)). Moreover, women trainers and facilitators can play a crucial role in fostering trust, confidence, and peer learning among female participants ([Beuchelt & Badstue, 2013](#)).

Integrating gender considerations into carbon-negative farming training also helps to leverage women's unique knowledge of biodiversity, indigenous crop varieties, and sustainable soil and water management

practices, which can enhance resilience and adaptation strategies ([Carr & Thompson, 2014](#)). For example, involving women in decision-making around agroforestry species selection, composting systems, or cover cropping can improve adoption rates and long-term sustainability of carbon-sequestering practices.

Beyond content delivery, gender-responsive approaches must be embedded in institutional frameworks and policies, ensuring that women's participation is not tokenistic but transformative. This includes establishing gender quotas in training cohorts, integrating gender-disaggregated monitoring indicators, and linking women farmers to market opportunities such as carbon credit schemes or value-added processing enterprises ([Huyer, 2016](#)). Ultimately, gender-responsive training is not merely about inclusion it is about empowering women as leaders, innovators, and equal partners in the transition toward climate-resilient, low-carbon agricultural systems.

6.3 Farmer-Led Innovation Networks

Farmer-led innovation networks (FLINs) are increasingly recognized as powerful drivers of knowledge exchange, adaptation, and technology dissemination in sustainable and carbon-negative farming systems. These networks are built on the principle that farmers are not merely recipients of external knowledge but active experimenters, innovators, and disseminators of contextually relevant practices ([Scoones & Thompson, 2009](#)). By centering farmers in the innovation process, FLINs leverage local ecological knowledge, experiential learning, and peer-to-peer exchange to co-develop solutions that are technically sound, economically viable, and socially acceptable.

In the context of carbon-negative farming, FLINs play a crucial role in testing, adapting, and scaling practices such as agroforestry integration,

biochar application, organic amendments, conservation tillage, and diversified cropping systems ([Hellin et al., 2020](#)). These networks often employ participatory research methods, where farmers design and implement on-farm trials in collaboration with researchers, extension agents, and sometimes private sector partners (Chambers, 2014). This approach enhances the credibility and adoption of innovations because they are grounded in real-world farm conditions rather than solely in controlled research settings.

FLINs also foster collective problem-solving and resource sharing, enabling smallholder farmers often marginalized in formal agricultural systems to access knowledge, planting materials, and technical support that might otherwise be unavailable ([Spielman et al., 2011](#)). They help bridge gaps between traditional agricultural knowledge and modern climate-smart techniques, creating hybrid solutions that enhance resilience and productivity while sequestering carbon. Moreover, farmer-led networks can act as advocacy platforms, influencing local and national agricultural policies to better support regenerative and carbon-negative practices ([Kroma, 2006](#)).

Digital tools and social media platforms have further expanded the reach and impact of FLINs, allowing farmers to connect across geographic boundaries, share best practices, and crowdsource solutions to emerging climate and market challenges (Klerkx et al., 2012). When supported by enabling policies, fair market linkages, and inclusive governance structures, farmer-led innovation networks become not only conduits for technical knowledge but also catalysts for systemic transformation toward sustainable, low-carbon agriculture.

7. Conclusion and Way Forward

Education, training, and capacity building are key to enabling carbon-negative farming by equipping farmers, extension agents, policymakers, and other stakeholders with the essential knowledge, technical skills, and adaptive capacities needed to implement sustainable and climate-resilient agricultural practices. This involves integrating carbon-negative and climate-smart agriculture into both formal education systems such as universities and vocational institutes and informal learning pathways like community workshops and farmer field schools. Participatory learning approaches, which emphasize experiential, peer-to-peer, and locally contextualized training, further enhance engagement and long-term adoption. Additionally, the use of digital tools and platforms including mobile apps, e-learning modules, and virtual advisory services has significantly broadened access to real-time, tailored information, especially in remote and underserved areas. Despite this progress, significant challenges remain. Limited financial and human resources, socio-cultural barriers, gender and literacy gaps, and weak institutional coordination continue to hinder the wide-scale adoption of carbon-negative practices. These constraints are especially pronounced in developing regions, where systemic inequalities and fragmented support systems restrict farmers' ability to benefit from emerging innovations and policy incentives.

Effective capacity building is therefore not a one-time intervention but a continuous, dynamic process that must be sustained over time. A holistic and inclusive approach one that blends formal instruction with hands-on learning, supports digital innovation, and fosters collaboration among diverse stakeholders is essential for scaling carbon-negative farming. By empowering individuals and institutions with updated knowledge, practical tools, and social support networks, capacity-building efforts can drive a meaningful shift toward more resilient, productive, and low-carbon food

systems. Empowered farmers are not only better positioned to enhance on-farm carbon sequestration but also to improve their livelihoods, strengthen food security, and contribute to broader ecosystem health and climate goals.

To advance carbon-negative farming, several key actions are recommended. First, curricula in agricultural universities and vocational institutions should be updated to include carbon-negative and climate-smart topics, ensuring future professionals are well-equipped for sustainability challenges. Second, inclusive training approaches must be promoted, utilizing participatory methods and local languages to effectively reach marginalized groups, including women and indigenous communities. Third, the use of digital tools such as ICTs, mobile platforms, and e-learning resources should be expanded to improve access to timely and context-specific information, particularly in remote areas. Fourth, institutional collaboration across research bodies, extension services, government agencies, NGOs, and the private sector should be strengthened to ensure coherent and scalable capacity-building efforts. Fifth, farmer innovation should be supported through the creation of learning hubs and peer networks that enable experimentation and knowledge exchange. Sixth, mechanisms for lifelong learning should be established, including refresher programs and ongoing knowledge-sharing platforms to keep pace with evolving climate science and technologies. Lastly, securing sustainable funding through public investment, development assistance, and carbon finance mechanisms will be essential for the long-term success and scalability of these capacity-building initiatives.

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Chapter - 16

Urban and Peri-Urban Carbon-Negative Farming

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1. Introduction

The global food system is a major contributor to greenhouse gas (GHG) emissions, accounting for approximately 31% of total anthropogenic emissions, largely due to land use change, fertilizer use, transportation, and energy-intensive production ([Crippa *et al.*, 2021](#)). Urbanization, meanwhile, is expanding rapidly, with nearly 70% of the global population projected to live in urban areas by 2050 (UN [DESA, 2019](#)). This demographic shift has not only strained peri-urban ecological systems but also increased the carbon intensity of food supply chains, owing to long-distance transportation, energy use in cold chains, and packaging. In this context, urban and peri-urban agriculture (UPA) has emerged as a strategic opportunity to localize food production, minimize carbon footprints, and contribute to carbon-negative farming systems that both reduce and sequester atmospheric carbon.

Carbon-negative farming refers to agricultural systems that result in a net removal of CO₂ from the atmosphere, either through carbon sequestration in biomass and soil or by reducing emissions beyond the system's own footprint ([Smith *et al.*, 2019](#)). When applied to cities and their peripheries, this approach emphasizes compact, decentralized production using resource-efficient, climate-smart technologies such as hydroponics, aquaponics, rooftop farming, vertical agriculture, and circular waste

management ([Despommier, 2011](#); [Pennisi et al., 2025](#)). These innovations, combined with practices like composting of urban organic waste, biochar application, and renewable energy integration, can transform cities from carbon emitters into carbon sinks, contributing directly to climate mitigation and food system resilience ([Weidner & Yang, 2020](#)).

Moreover, urban farming enhances local food security, reduces dependence on high-emission imports, and creates green employment opportunities, especially for youth and women in cities ([Orsini et al., 2013](#)). The peri-urban fringe, often characterized by transitional land and underutilized space, can serve as a buffer zone for agroforestry, regenerative agriculture, and community-supported bio-intensive models that are both economically viable and carbon-sequestering ([Wiskerke & Viljoen, 2012](#)).

Importantly, policy environments are beginning to recognize the carbon mitigation potential of UPA. Initiatives like Green Infrastructure Planning, Smart Cities Missions, and local carbon credit schemes are increasingly aligning with urban farming goals, though integration remains limited in many regions. There is a growing need for systematic carbon accounting, incentive frameworks, and community-level innovation hubs to scale such carbon-negative practices across urban landscapes ([FAO, 2022a&b](#)).

As cities grapple with the twin crises of climate change and food insecurity, the role of urban and peri-urban agriculture is gaining renewed attention, not just as a food production strategy, but as a transformative climate action tool. This chapter delves into the practices, policies, and innovations driving this movement, showcasing how cities can be reimaged as resilient, carbon-negative agri-ecosystems.

2. Urban and Peri-Urban Farming Systems: An Overview

Urban and peri-urban farming systems are increasingly recognized as vital components of sustainable city planning and climate-smart agriculture. By

bringing food production closer to consumption centers, these systems reduce transportation emissions, recycle urban organic waste, and utilize underused spaces for green infrastructure. In the face of growing urban populations, food insecurity, and climate challenges, these innovative farming models offer integrated solutions that enhance resilience, circularity, and carbon mitigation. The following sub-sections explore the typology of urban farming systems, assess their comparative carbon footprint against conventional agricultural models, and highlight their role in land use optimization within densely populated urban landscapes.

- 1. Typologies of Urban and Peri-Urban Farming
- 2. Comparative Carbon Footprint: Traditional vs Urban Farming
- 3. Land Use Optimization in Densely Populated Areas

2.1 Typologies of Urban and Peri-Urban Farming

Urban and peri-urban agriculture (UPA) encompasses a diverse array of farming systems adapted to the spatial, infrastructural, and socioeconomic constraints of cities and their outskirts. The typology of these systems reflects varying levels of technological input, land availability, and integration into urban food systems ([Table 16.1](#)).

Table 16.1 Visual Representation of Urban and Peri-Urban Farming Typologies

Label	Typology	Description
A (Top left)	Rooftop Hydroponics	Leafy greens cultivated in NFT channels on urban rooftops
B (Top center)	Vertical Farming	Indoor vertical stacks under LED lighting for controlled-environment growing
C (Bottom left)	Hydroponic NFT System	Horizontal channel-based hydroponics inside a greenhouse

Label	Typology	Description
D (Bottom center)	Vertical Towers	Tower-based hydroponic systems optimizing vertical space
E (Right)	Community Garden	Open-space urban garden plots with mixed vegetables in raised beds

Rooftop farms are among the most widely adopted forms of urban agriculture, utilizing the unused space on building tops for cultivating vegetables, herbs, and microgreens. These systems, often integrated with lightweight soil or soilless media, can significantly reduce food miles and provide thermal insulation to buildings, thus indirectly reducing energy consumption ([Specht *et al.*, 2014](#)).

Vertical farms represent a more technologically advanced typology, where crops are grown in stacked layers under controlled environmental conditions, often using LED lighting and automated nutrient delivery systems. These farms are particularly suited to high-density urban cores where horizontal land is scarce. Their year-round production capacity and isolation from external contaminants make them ideal for high-value crops and sensitive greens ([Benke & Tomkins, 2017](#)).

Community gardens offer a more participatory and socially embedded model of UPA. These shared plots, often located in public parks, school grounds, or vacant lots are managed by neighborhood groups or local institutions. They contribute not only to food production but also to urban greening, community cohesion, and educational outreach ([Armstrong, 2000](#)).

Hydroponic systems, which grow plants in nutrient-enriched water without soil, are gaining prominence in both commercial and domestic settings. Hydroponics allows for precise control over nutrient inputs, water

use efficiency, and space optimization attributes critical for urban environments with limited resources ([Resh, 2022](#)).

Aquaponics, a hybrid of hydroponics and aquaculture, integrates fish farming with plant cultivation in a closed-loop system. The fish waste provides organic nutrients for the plants, while the plants filter and clean the water for the fish. This symbiotic relationship exemplifies circular resource use, aligning closely with the principles of carbon-negative farming ([Goddek *et al.*, 2015](#)).

2.2 Comparative Carbon Footprint: Traditional vs Urban Farming

Urban and peri-urban farming systems generally demonstrate a lower carbon footprint per unit of production when properly designed, primarily due to the elimination of long-distance transportation, minimized packaging needs, and reduced postharvest losses. Studies show that urban farms can reduce emissions related to food transport by up to 90% compared to rural farms supplying the same urban markets ([Goldstein *et al.*, 2016](#)). Additionally, urban farms often repurpose organic waste and greywater, further lowering net emissions ([Van de Walle, 2023](#)).

Conversely, high-tech systems like vertical farms or climate-controlled hydroponics may initially exhibit higher operational energy inputs, particularly from artificial lighting and HVAC systems. A lifecycle analysis by [Al-Kodmany \(2018\)](#) showed that vertical farms may consume between 16 to 38 kWh of electricity per kg of leafy greens, depending on design and energy source. In comparison, greenhouses average about 97 kWh/m² per year, and conventional field farming requires just 20 kWh/m² ([Dorr *et al.*, 2023](#)).

Despite the high initial energy demand, vertical farms powered by renewable energy and equipped with heat recovery, solar integration, and

LED optimization can significantly reduce their lifecycle emissions. Under optimized conditions, vertical farms have been shown to emit as little as 0.48 kg CO₂e per kg of lettuce, making them competitive with traditional systems ([Dorr *et al.*, 2023](#); [Benke & Tomkins, 2017](#)).

Peri-urban farming systems offer a hybrid advantage, combining larger land availability with proximity to markets. This supports the adoption of regenerative and agro-ecological practices such as no-till farming, agroforestry, composting, and cover cropping. These practices not only enhance soil organic carbon sequestration but also reduce direct and indirect emissions ([Tittonell & Giller, 2013](#)).

2.3 Land Use Optimization in Densely Populated Areas

Land scarcity is a defining constraint in urban environments. Therefore, land use optimization is key to maximizing the benefits of urban farming. By utilizing marginal, abandoned, or underused spaces such as rooftops, building facades, balconies, parking lots, and peri-urban fringes, urban and peri-urban agriculture (UPA) systems contribute to productive urban landscapes without competing with conventional land uses ([Orsini *et al.*, 2013](#)).

Innovative spatial planning approaches, including multi-functional land use, agri-tecture (integration of agriculture and architecture), and green infrastructure zoning, are enabling cities to integrate food production with environmental services, such as stormwater control, biodiversity enhancement, and urban greening. These approaches help optimize land resources by accommodating multiple ecosystem functions in the same spatial footprint. Moreover, densification strategies such as vertical farming and modular micro-farms dramatically enhance productivity per square meter, often surpassing traditional open-field agriculture in terms of yield

intensity ([Graamans et al., 2018](#)). These systems allow cultivation in places previously unsuitable for agriculture and reduce the land-use pressure from urban expansion.

To implement such optimization strategies, spatial planning models are employed to guide land allocation. These models typically include demand forecasting, land suitability analysis, scenario simulation, and multi-objective spatial allocation. In peri-urban areas, where transitional land is more accessible, mixed-use zoning can support a mosaic of market gardens, agroforestry buffers, solar-integrated farms, and community-supported agriculture (CSA) units. These models not only optimize land productivity but also act as carbon sinks, urban buffers, and biodiversity corridors ([Dubbeling et al., 2010](#)).

3. Carbon Footprint of Urban Agriculture

Understanding the carbon footprint of urban agriculture is essential for evaluating its contribution to climate change mitigation. While urban farming can offer substantial environmental benefits, it also involves emissions from inputs, energy use, and infrastructure. A comprehensive assessment must consider both direct and indirect sources of greenhouse gas (GHG) emissions associated with different urban farming models. At the same time, local food production plays a critical role in reducing emissions by minimizing transportation, storage, and packaging needs. Tools such as the Cool Farm Tool and COMET-Farm have been developed to quantify GHG emissions and carbon sequestration in agricultural systems, and are increasingly being adapted for urban contexts.

The sub-sections below explore key emission sources, highlight how urban agriculture contributes to emission reductions, and introduce practical tools for urban carbon accounting.

3.1 Emission Sources in Urban Agriculture

Although urban agriculture (UA) is often promoted as a sustainable practice, it still involves several direct and indirect GHG emission sources. These emissions vary widely depending on the type, scale, technology, and inputs used in a given system. Input-related emissions arise from the production and transportation of seeds, growing media (e.g., peat, cocopeat, rockwool), fertilizers, and pesticides. Commercial soil mixes, synthetic nutrients, and non-renewable substrates can carry significant embodied carbon, particularly when imported from distant locations ([Goldstein *et al.*, 2016](#)). Organic urban farms using composted local waste tend to have much lower input-related emissions compared to input-intensive, soilless setups that rely on industrial nutrient solutions ([McDougall *et al.*, 2019](#)).

Energy use is another major contributor, especially in controlled-environment agriculture (CEA) systems such as vertical farms and hydroponic units. Lighting (particularly when LED lights replace natural sunlight), climate control (heating, cooling, humidity management), and water pumping systems all require energy. If this energy is derived from fossil fuels, it can result in substantial CO₂ emissions. For example, vertical farms relying entirely on grid electricity can have life-cycle emissions equivalent to or exceeding rural open-field farms, unless powered by renewable energy ([Graamans *et al.*, 2018](#); [O'Sullivan *et al.*, 2019](#)). Transportation-related emissions are often lower in urban agriculture due to proximity to consumers. Conventional food systems typically involve “food miles” from rural production zones to urban centers, transporting food over long distances in cold chains, which contributes significantly to GHG emissions. UA reduces these emissions by shortening the supply chain and avoiding postharvest losses during transit and storage ([Weber & Matthews, 2008](#)).

3.2 Role of Local Food Production in Reducing GHG Emissions

Urban agriculture has the potential to play a meaningful role in climate mitigation, particularly when designed with sustainability and circularity in mind. One of the most immediate benefits is the reduction in food transportation and packaging emissions, which account for up to 11% of total food-related GHG emissions globally ([Vermeulen *et al.*, 2012](#)). In addition to transport-related benefits, on-site composting of food and green waste can significantly reduce methane emissions associated with landfills. Composting also enriches soil carbon and reduces the need for synthetic fertilizers, both of which are major sources of nitrous oxide (N₂O), a potent greenhouse gas. Urban farms that integrate bio-waste recycling, water reuse, and plant residue incorporation can demonstrate net-zero or even carbon-negative balances over the long term (Sanye-Mengual *et al.*, 2015).

Furthermore, local food systems contribute to urban resilience by decreasing dependency on energy- and carbon-intensive global supply chains. During crises such as pandemics or climate shocks, locally sourced food with a lower carbon footprint can act as a buffer, offering both environmental and social co-benefits ([FAO, 2022a&b](#)).

3.3 Tools and Models for Urban Carbon Accounting

Accurately quantifying the carbon footprint of urban agriculture requires standardized carbon accounting tools, several of which have been adapted from traditional agricultural models. The Cool Farm Tool (CFT) is one of the most widely used life cycle assessment (LCA)-based models, offering estimates of emissions from agricultural practices, including fertilizers, energy, transportation, and land use. Although originally designed for rural farms, it has been successfully applied to urban rooftop and community farms to assess GHG savings from reduced transport and packaging ([Hillier](#)

[et al., 2011](#)). COMET-Farm, developed by the USDA, provides detailed estimates of soil carbon sequestration, GHG emissions, and mitigation potential. While it is primarily tailored for conventional field agriculture, it can be adapted for peri-urban and community farming systems with modifications to land use data and management inputs ([Miller, 2013](#); [Van de Walle, 2023](#)).

Other tools such as GHG Protocol Agricultural Guidance, SimaPro, and OpenLCA have also been employed to assess the life cycle emissions of different urban agricultural systems, particularly in research studies comparing conventional, rooftop, hydroponic, and aquaponic setups (Sanye-Mengual *et al.*, 20). Emerging innovations in sensor-based carbon monitoring, remote sensing, and blockchain-integrated carbon registries are expanding the possibilities for real-time carbon footprint tracking in urban agri-systems, which could support inclusion in local carbon credit schemes and ESG frameworks.

4. Pathways to Carbon-Negative Urban and Peri-Urban Agriculture (UPA)

Achieving carbon-negative outcomes in urban and peri-urban agriculture requires deliberate integration of climate-smart techniques, resource-efficient technologies, and circular systems. These pathways not only reduce greenhouse gas (GHG) emissions but also enhance urban resilience, food security, and ecological regeneration. Urban farming systems can act as carbon sinks through practices that improve soil health, reduce energy and input use, and repurpose organic waste.

The sub-sections that follow detail three key approaches: climate-smart agronomic practices, soilless and controlled environment agriculture, and organic waste recycling and composting, each offering scalable solutions to transform UPA into a climate-positive force within urban ecosystems.

- Climate-Smart Practices
- Soilless and Controlled Environment Agriculture
- Organic Waste Recycling and Composting

4.1 Climate-Smart Practices

Urban and peri-urban agriculture (UPA) must adopt climate-smart practices that enhance resource efficiency, improve soil health, and sequester carbon to build resilience against climate change. These practices aim to reduce greenhouse gas emissions, enhance adaptation capacity, and ensure sustainable food production in limited spaces. In community plots, rooftop gardens, and container-based systems, the following climate-smart approaches can significantly improve environmental performance:

- Zero tillage, mulching, and cover cropping in community plots
- Biochar application and carbon sequestration in containers and raised beds

Zero Tillage, Mulching, and Cover Cropping in Community Plots

In community garden plots and peri-urban farms, the adoption of zero or minimal tillage reduces soil disturbance, thereby decreasing carbon loss through oxidation of organic matter and conserving microbial habitats ([Lal, 2004](#)). Tillage-based systems can emit up to 40-60% more CO₂ from soil respiration compared to no-till systems ([Six et al., 2002](#)). Mulching with crop residues, green waste, or biodegradable materials not only suppresses weeds and conserves moisture but also contributes to carbon input to soils, particularly when organic mulches are used. This method is highly applicable in urban farms where green waste is readily available ([Kader et al., 2017](#)). Cover cropping, using species like legumes, mustards, and ryegrass, serves as a multifunctional strategy by sequestering carbon, fixing

nitrogen, improving soil health, and suppressing pests. These crops can be rotated or intercropped in small urban plots to maintain continuous vegetative cover, enhance carbon inputs, and reduce bare soil exposure ([Blanco-Canqui *et al.*, 2015](#)).

Biochar Application and Carbon Sequestration in Containers and Raised Beds

Biochar, a stable form of carbon produced via pyrolysis of organic material, is increasingly recognized for its dual benefit in carbon sequestration and soil enhancement. When incorporated into urban growing beds, containers, or rooftop farms, biochar improves soil aeration, water retention, and microbial activity, while locking carbon in the soil for decades to centuries ([Lehmann & Joseph, 2015](#)). Urban applications of biochar, particularly using locally produced biomass waste (e.g., pruning residues, kitchen scraps), offer a decentralized, scalable solution for carbon-negative nutrient cycling (Schmidt *et al.*, 2021). Even small quantities in raised beds and containers can meaningfully enhance carbon stocks and reduce nitrous oxide (N₂O) emissions.

4.2 Soilless and Controlled Environment Agriculture

To meet the challenges of climate change, urban space constraints, and resource scarcity, soilless cultivation and controlled environment agriculture (CEA) offer promising solutions for sustainable food production. These systems decouple crop production from soil and seasonality, enabling precise control over growing conditions, optimizing resource use, and minimizing environmental impact. Integrating soilless technologies with climate-smart innovations can significantly improve productivity and resilience in urban and peri-urban settings. Key components of this approach include:

- Hydroponics, Aeroponics, Aquaponics: High-Efficiency Systems
- Energy and Water-Saving Technologies
- CO₂ Enrichment with Carbon Capture Potential

Hydroponics, Aeroponics, Aquaponics: High-Efficiency Systems

Soilless cultivation systems like hydroponics, aeroponics, and aquaponics offer remarkable resource use efficiency, particularly in water-scarce and space-constrained urban environments. Hydroponics can reduce water usage by up to 90% compared to conventional soil-based agriculture, while delivering higher yields in less time and space ([Resh, 2022](#)). According to [Resh \(2022\)](#), “hydroponic systems allow for precise control over nutrient delivery, virtually eliminating nutrient leaching into the environment”. Additionally, they remove the need for tillage, thereby lowering soil-related emissions and preserving soil biodiversity. Aeroponics, which involves growing plants in a misted nutrient-rich environment without a substrate, is even more efficient in terms of water and nutrient use. It enhances oxygen availability to roots, promoting faster growth and greater nutrient uptake. Aeroponic systems have been reported to use “up to 98% less water than conventional agriculture and 60% less than hydroponics” ([Resh, 2022](#)), making them highly suitable for arid urban regions and controlled environments.

Vertical stacking of hydroponic and aeroponic units further multiplies land productivity and enhances carbon efficiency per kilogram of produce, a crucial factor in sustainable urban food systems. By producing more biomass per square meter, these systems reduce the land-use change emissions typically associated with agriculture. Aquaponics, an integrated system combining hydroponics with recirculating aquaculture, creates a symbiotic relationship between plants and fish. As [Goddek et al. \(2015\)](#) explain, “nutrient-rich effluent from fish tanks is used to fertilize the plants,

while the plants help purify the water for the fish". This closed-loop design minimizes waste, eliminates the need for synthetic fertilizers, and reduces both water and greenhouse gas (GHG) footprints. Moreover, aquaponics enables the co-production of plant and animal protein, boosting nutritional output per unit area and enhancing food security in urban landscapes.

In summary, these soilless systems offer a synergistic blend of efficiency, scalability, and environmental stewardship, aligning closely with the goals of carbon-smart urban and peri-urban agriculture.

Energy and Water-Saving Technologies

While controlled environment agriculture (CEA) systems often have high energy demands due to artificial lighting, climate control, and continuous system operation, these impacts can be significantly reduced or even neutralized through the integration of renewable and resource-efficient technologies. The use of solar panels, wind energy, and energy storage systems allows growers to transition toward net-zero or carbon-neutral operations. Rainwater harvesting systems combined with advanced filtration can supply clean irrigation water, reducing dependency on municipal supplies ([Sabeh et al., 2020](#)). Innovations such as low-energy LED lighting tailored to crop-specific spectra reduce electricity use while optimizing photosynthetic efficiency ([Pinho et al., 2012](#)). Closed-loop water recirculation systems help minimize water wastage by capturing and reusing nutrient-rich runoff, thereby reducing both water and fertilizer inputs ([Sabeh et al., 2020](#)). In addition, heat recovery ventilation systems and automated climate control using smart sensors and AI-driven algorithms enable real-time adjustments that enhance thermal efficiency and reduce overall energy consumption ([Barbosa et al., 2015](#); [Graamans et al., 2018](#)). Collectively, these technologies enhance the environmental

sustainability of CEA systems, making them more viable for urban and peri-urban agriculture.

CO₂ Enrichment with Carbon Capture Potential

In controlled environment agriculture (CEA), CO₂ enrichment has emerged as a powerful tool to enhance photosynthetic efficiency, improve crop yields, and accelerate biomass accumulation. Most crops, especially C3 plants like lettuce, basil, and tomato, respond positively to elevated CO₂ levels, with productivity gains of 20-40% under optimal light and nutrient conditions. According to [Al-Kodmany_\(2018\)](#), *“CO₂ concentrations in indoor farming environments are often maintained at 800-1,200 ppm, nearly three times atmospheric levels, to stimulate growth and reduce production cycles.”* What makes this strategy even more climate-resilient is its integration with carbon capture technologies. Recent innovations now enable the coupling of direct air capture (DAC) systems devices that filter CO₂ directly from ambient air, with CEA setups, turning atmospheric carbon into a growth input for plants. Some models also utilize biogenic CO₂ derived from composting, anaerobic digestion, or fermentation processes, thereby recycling organic waste streams into usable carbon.

This closed-loop carbon approach significantly enhances the sustainability profile of indoor agriculture. As [Al-Kodmany_\(2018\)](#) notes, *“when paired with renewable energy sources and circular nutrient flows, CO₂ enrichment via captured or recycled sources can create carbon-negative urban farms.”* In such cases, the captured CO₂ is temporarily sequestered in plant biomass and may be long-term stored through biochar conversion or food waste recycling representing a potential net-negative emission scenario. Moreover, integrating CO₂ reuse from industrial or fermentation exhausts with urban farming can contribute to localized

decarbonization while reducing the need for industrially produced CO₂ tanks, lowering both costs and lifecycle emissions.

4.3 Organic Waste Recycling and Composting

Urban and peri-urban areas generate substantial volumes of organic waste, including food scraps, yard trimmings, and agricultural residues. Without proper management, this waste often ends up in landfills, where it decomposes anaerobically and emits methane a greenhouse gas with over 25 times the global warming potential of CO₂. Recycling organic waste into nutrient-rich compost or biofertilizers offers a sustainable solution that supports circular nutrient flows, improves soil health, and significantly reduces greenhouse gas emissions. In the context of climate-smart urban agriculture, the following approaches play a crucial role:

- Vermicomposting, Bokashi, and Black Soldier Fly Integration
- Urban Organic Waste-to-Fertilizer Systems
- Emissions Reduction from Waste Diversion

Vermicomposting, Bokashi, and Black Soldier Fly Integration

Urban areas generate vast amounts of biodegradable waste, which can be transformed into valuable inputs for carbon-negative farming. Vermicomposting using earthworms converts kitchen waste into high-quality compost with minimal methane release. The microbial activity in worm castings enhances soil carbon stabilization ([Domínguez & Edwards, 2011](#)). Bokashi fermentation, an anaerobic composting technique using effective microorganisms (EM), rapidly transforms food scraps into nutrient-rich material suitable for soil amendment, while producing negligible GHGs ([Zhang *et al.*, 2020](#)). Black Soldier Fly Larvae (BSFL) systems are gaining traction in urban contexts for processing organic waste.

The larvae consume large volumes of biodegradable material, producing larval biomass for animal feed and frass that can be used as a low-emission biofertilizer, effectively diverting waste from landfills and reducing methane emissions ([Gold *et al.*, 2018](#)).

Urban Organic Waste-to-Fertilizer Systems

Decentralized composting units, biogas digesters, and community-scale waste-to-resource hubs are increasingly being implemented in cities to transform urban bio-waste into valuable agricultural inputs such as compost, digestate, and liquid biofertilizers. These systems help reduce landfill burden, lower methane emissions, and close the nutrient loop within urban food systems. As Cerón-Palma *et al.* (2012) note, “*urban waste can be effectively integrated into food production cycles, reducing dependence on external fertilizers while enhancing urban resilience.*” Such models support circular economies by creating local jobs, lowering input costs for urban farmers, and minimizing the environmental footprint of both waste disposal and fertilizer use. Compact, low-tech community composting units and anaerobic digesters can be scaled to neighborhood or ward levels, making them highly adaptable for diverse urban contexts.

Emissions Reduction from Waste Diversion

Landfilling organic waste produces significant amounts of methane (CH₄), a greenhouse gas more than 25 times stronger than CO₂ over a 100-year timescale. In urban areas, food and green waste often dominate the municipal waste stream, and improper disposal in landfills contributes heavily to greenhouse gas emissions. Diverting organic waste toward composting, biochar production, or anaerobic digestion helps urban farms mitigate emissions while producing useful by-products like compost, biofertilizers, or renewable biogas. Biochar sequesters carbon in a stable form, and anaerobic digesters capture methane for energy rather than

releasing it into the atmosphere. As [Papargyropoulou et al. \(2014\)](#) state, *“diverting just 50% of food waste in urban areas toward composting can lead to GHG reductions equivalent to removing thousands of cars off the road annually.”* The [IPCC \(2019\)](#) also emphasizes composting and waste diversion as high-priority climate mitigation strategies for urban systems. In addition, [Brown et al. \(2008\)](#) highlight that *“integrating organic waste into local nutrient cycles reduces dependency on synthetic fertilizers,”* further lowering emissions embedded in their production and use. Thus, waste diversion is not only a sustainable waste management strategy but also a vital component of **carbon-smart urban agriculture**.

5. Renewable Energy Integration in Urban Farming

Integrating renewable energy into urban and peri-urban farming systems is a critical step toward achieving carbon-negative agriculture. Urban farms often rely on artificial lighting, water pumps, and climate control systems that consume electricity, frequently sourced from fossil fuels. Replacing these with clean energy technologies significantly reduces the carbon footprint while enhancing energy self-sufficiency and operational sustainability. The following sub-sections explore practical applications of solar-powered systems, the role of microgrids and biogas units in decentralized energy generation, and the bioenergy potential of urban green waste and wastewater. Together, these innovations support climate-smart urban food production and contribute to broader city-wide decarbonization goals.

1. Solar-powered irrigation and grow lights
2. Integration of microgrids, rooftop solar panels, biogas units
3. Urban bioenergy potential from green waste and wastewater

5.1 Solar-Powered Irrigation and Grow Lights

Solar energy is the most readily accessible renewable resource in urban areas and plays a vital role in powering off-grid farming operations. Solar-powered irrigation systems, which use photovoltaic (PV) panels to pump water from storage tanks or underground sources, have shown high viability for small-scale urban farms and community gardens. These systems reduce dependence on fossil fuel-based grid electricity and enhance operational sustainability, especially in informal settlements and peri-urban areas ([Burney *et al.*, 2010](#)).

In controlled environment agriculture (CEA) systems, including vertical farms and greenhouses, solar-powered LED grow lights can dramatically lower the carbon footprint associated with artificial lighting. With the declining cost of high-efficiency LEDs and improved solar storage technologies, urban farms can achieve near off-grid autonomy during peak sunlight periods. Studies show that solar-powered CEA setups can reduce energy-related emissions by over 60% compared to conventionally powered vertical farms ([Graamans *et al.*, 2018](#)). Furthermore, the modularity of solar units allows easy integration into container farms, rooftops, balconies, and mobile micro-farms, making them highly adaptable to various urban contexts.

5.2 Integration of Microgrids, Rooftop Solar Panels, and Biogas Units

Urban farms can enhance their resilience and emission savings by participating in local energy microgrids. These microgrids, which interconnect renewable energy sources like rooftop solar panels, small wind turbines, and energy storage units, allow urban farms to both draw and supply electricity within the local network, improving efficiency and reducing reliance on carbon-intensive grids ([Soshinskaya *et al.*, 2014](#)).

Rooftop solar panels are particularly well-suited for urban farms co-located on top of residential, institutional, or commercial buildings. The dual use of rooftops, for energy and food, maximizes the utility of limited space and promotes energy-food-water nexus sustainability ([Orsini *et al.*, 2013](#)). Some initiatives have even explored “agrivoltaic” systems, where semi-transparent PV panels allow partial sunlight penetration for plant growth underneath, effectively combining solar generation and cultivation in the same footprint ([Barron-Gafford *et al.*, 2019](#)).

Biogas units integrated into urban farms offer a complementary solution for managing organic waste while generating clean energy. Anaerobic digesters convert kitchen waste, animal manure, or crop residues into biogas (a mix of methane and CO₂) and digestate (a nutrient-rich fertilizer). Biogas can be used for cooking, heating greenhouses, or even electricity generation, while the digestate returns nutrients to the soil, closing resource loops and reducing emissions from synthetic fertilizer use and waste decomposition ([Pastorelli *et al.*, 2021](#); Lamolinara *et al.*, 2022).

5.3 Urban Bioenergy Potential from Green Waste and Wastewater

Urban areas generate large quantities of green waste, including food scraps, yard trimmings, and market waste which can serve as feedstock for bioenergy production. Techniques such as anaerobic digestion, pyrolysis, and gasification can convert these wastes into biogas, biochar, syngas, or bio-oil, all of which have agricultural applications. When linked to urban farming, such bioenergy systems provide a decentralized renewable energy source while diverting waste from landfills, significantly lowering methane emissions ([Zhang *et al.*, 2021](#)). In addition to solid waste, urban wastewater presents an underutilized resource. Algal bioreactors, for instance, can be employed in wastewater treatment facilities to capture nutrients and

produce biomass, which can be converted into biofuels or biogas. Treated wastewater can also be reused in irrigation systems, further conserving freshwater and reducing the energy intensity of water pumping and purification in urban farms ([Craggs *et al.*, 2011](#)). The potential of integrated bioenergy-urban farming systems is especially high in megacities, where large waste streams, high energy demand, and limited space converge. When properly managed, such systems contribute to a circular urban metabolism, enhancing energy security, reducing emissions, and promoting sustainable urban livelihoods.

6. Policy, Planning, and Urban Design for Carbon-Negative Agriculture

The transformation of urban and peri-urban agriculture (UPA) into a carbon-negative system requires supportive policies, integrated urban planning, and enabling institutional frameworks. Strategic governance interventions can align food production with climate, land use, and sustainability goals. By embedding agriculture into the fabric of urban design and land management, cities can promote green infrastructure, enhance ecosystem services, and reduce emissions. The sub-sections below examine the critical elements that drive this transformation, including zoning regulations for green infrastructure, municipal incentives and carbon credit integration, and innovative land tenure models that enable access to public spaces for climate-resilient farming.

1. Green infrastructure and urban agriculture zoning
2. Role of municipal support, incentives, and carbon credits
3. Land tenure and lease models to promote farming on public land

6.1 Green Infrastructure and Urban Agriculture Zoning

Green infrastructure planning refers to the strategic use of natural and semi-natural spaces green roofs, community gardens, wetlands, and parks, to deliver ecosystem services. Urban agriculture fits well into this concept by providing food while sequestering carbon, enhancing biodiversity, reducing urban heat island effects, and improving stormwater management ([Lovell, 2010](#)). Cities such as Chicago, Singapore, and Toronto have pioneered green roof bylaws and incentives that include provisions for productive rooftop gardens. Integrating urban agriculture into municipal zoning regulations, often termed urban agriculture zoning, ensures that food production is recognized as a legitimate land use in residential, institutional, and even commercial areas ([Grewal & Grewal, 2012](#)). Overlay zones, special agricultural use designations, and urban farming districts are tools used by progressive cities to facilitate land allocation for agriculture within dense urban cores. For example, Detroit's zoning code explicitly permits farming in all residential zones, including indoor and vertical farms ([Colasanti et al., 2012](#); [Meenar et al., 2017](#)).

6.2 Role of Municipal Support, Incentives, and Carbon Credits

Municipal governments are uniquely positioned to provide institutional support for UPA through financial incentives, technical assistance, and inclusion in climate action plans. Examples include:

- Tax abatements or credits for properties practicing rooftop or community agriculture
- Start-up grants and micro-finance for youth and women-led urban farms
- Technical training and extension services in composting, hydroponics, and biochar application

- Integration of UPA into city climate resilience plans and food security strategies

One emerging approach is linking urban agriculture with carbon credit markets. While current carbon credit systems largely favor large-scale rural projects, pilot programs have started quantifying urban farming contributions to GHG mitigation through composting, soil carbon sequestration, and waste diversion. In cities like Paris and New York, urban farms are being considered for local offset programs ([Wolch *et al.*, 2014](#)). Further, some municipalities are working to integrate UPA into climate budgeting tools, assessing their role in meeting net-zero city targets. This requires better carbon accounting protocols for small-scale systems, but the potential for local carbon offsetting is growing with improved MRV (monitoring, reporting, and verification) methodologies (Sanyé-Mengual *et al.*, 2015b).

6.3 Land Tenure and Lease Models to Promote Farming on Public Land

Access to land remains one of the most significant barriers to scaling up urban agriculture. Many promising initiatives are stalled due to insecure land tenure, bureaucratic hurdles, or short-term leases. Progressive cities are now experimenting with innovative lease models that allow access to idle public or institutional land for agricultural use.

These include:

- License-to-operate agreements for school yards, government buildings, or parks
- Land trusts or community land banks that allocate land specifically for agriculture

- Incentive-based leasing, where reduced or zero-rent public land is offered in return for ecosystem services (e.g., composting, stormwater control, biodiversity enhancement)

For instance, in San Francisco, the Public Utilities Commission offers unused lands to local nonprofits for farming under long-term leases. Similarly, Seoul's Urban Agriculture Ordinance encourages land sharing between public institutions and citizen groups, while Delhi's DDA Master Plan (2041) recommends using community land for kitchen gardens and terrace farms (Tiboris & Milgrom-[DDA, 2021](#); [GNCTD, 2022](#)). By formalizing tenure and providing long-term access, such models enable investment in carbon-sequestering practices like raised beds, tree planting, and composting infrastructure, which are otherwise neglected in temporary or informal setups.

7. Socioeconomic and Ecological Benefits

Urban and peri-urban carbon-negative agriculture (UPA) offers multiple co-benefits beyond emission reduction. It supports employment generation, especially for women, youth, and marginalized groups, through urban farms, composting enterprises, and green jobs. Women-led initiatives enhance economic empowerment and household nutrition. By enabling local food production, UPA strengthens food sovereignty, reduces dependency on external supply chains, and increases resilience to disruptions caused by climate events or market shocks. Ecologically, UPA promotes urban biodiversity by creating green spaces, pollinator habitats, and supporting native species. It also helps regulate microclimates by reducing the urban heat island effect, improving air quality, and contributing to thermal comfort and energy savings. Together, these benefits make UPA a powerful tool for building inclusive, climate-resilient cities.

1. Employment generation, women empowerment, and youth engagement
2. Food sovereignty and reduced dependence on external supply chains
3. Urban biodiversity conservation and microclimate regulation

7.1 Employment Generation, Women Empowerment, and Youth Engagement

UPA is a significant source of green employment opportunities in cities, especially for marginalized populations including women and youth. The labor-intensive nature of urban farming, ranging from soil preparation and planting to harvesting and marketing, can generate meaningful livelihoods, particularly in low-income urban communities ([Bryld, 2003](#)). Women's participation in UPA often enhances household food security and nutrition, given their traditional roles in food preparation and child care. Empowering women through access to land, training, and microfinance promotes gender equity and community resilience ([FAO, 2011](#)). Additionally, engaging urban youth in agriculture creates pathways for skill development, entrepreneurship, and reconnection with nature, which is crucial for their social well-being and employment prospects (Despommier, 2010). Programs integrating urban agriculture into education curricula and youth development initiatives have demonstrated positive outcomes in reducing urban poverty and promoting sustainable livelihoods ([Russ & Gaus, 2021](#)).

7.2 Food Sovereignty and Reduced Dependence on External Supply Chains

By producing food close to consumers, UPA enhances food sovereignty, the right of people to define their own food systems, prioritizing local production, cultural preferences, and sustainable methods ([Patel, 2009](#)).

This localized production reduces the vulnerability associated with globalized food supply chains, which are often prone to disruptions from climate events, pandemics, or geopolitical tensions ([HLPE, 2020](#)). Shorter supply chains lead to reduced food loss and waste, less packaging, and fresher produce availability, contributing to improved urban nutrition and health outcomes ([Morgan & Sonnino, 2010](#)). UPA also diversifies urban diets by enabling the cultivation of culturally significant and nutrient-dense crops that are often unavailable through conventional markets ([Taylor & Lovell, 2014](#)).

7.3 Urban Biodiversity Conservation and Microclimate Regulation

UPA contributes to urban biodiversity conservation by creating habitats for pollinators, birds, and beneficial insects in otherwise highly modified cityscapes. Diverse crop plantings, agroforestry practices, and green infrastructure associated with UPA foster ecological networks that support urban wildlife and enhance ecosystem services ([Lin *et al.*, 2015](#)). Moreover, vegetation cover from urban farms plays a critical role in microclimate regulation by reducing the urban heat island effect. Evapotranspiration, shade provision, and carbon sequestration collectively help moderate local temperatures, improve air quality, and mitigate flood risks through enhanced stormwater infiltration ([Yazdi *et al.*, 2021](#)). These ecological benefits synergize with carbon-negative farming goals, making UPA a multifunctional urban land use that promotes resilient, healthy, and sustainable cities.

8. Case Studies

Urban and peri-urban agriculture is emerging as a powerful contributor to carbon-negative food systems, particularly in densely populated areas

where land, water, and emissions constraints demand innovative solutions. These localized models enhance food security, reduce food miles, recycle urban waste, and sequester carbon through green infrastructure and regenerative practices. Case studies from India and across the globe illustrate how cities are transforming food production systems through climate-smart urban farming initiatives. These examples, ranging from rooftop hydroponics and organic waste conversion to peri-urban agroforestry, demonstrate context-specific strategies that align productivity with environmental stewardship and offer scalable models for sustainable urban development.

8.1 India

1 Delhi: Rooftop Hydroponic Farming Networks

In India's capital, rooftop hydroponics are gaining popularity among households, schools, and residential complexes seeking healthier, home-grown produce. With space limitations and growing concerns over food safety, these decentralized systems allow for soilless cultivation using nutrient film techniques (NFT), deep-water culture (DWC), and vertical growing structures. These systems use 90-95% less water than traditional farming and produce no soil-related emissions, making them inherently low-carbon. Importantly, hydroponic setups reduce food miles, since produce is grown and consumed locally. This minimizes emissions from transportation and refrigeration. In some networks, such as those supported by citizen-led initiatives in South Delhi, solar-powered hydroponics have been piloted, further lowering the carbon footprint. The National Institute of Urban Affairs (NIUA, 2021) identified rooftop hydroponics as a key innovation in Delhi's transition toward sustainable urban food systems, supporting environmental goals, dietary diversity, and climate adaptation.

2 Bengaluru: Waste-to-Food Urban Farming Models

Bengaluru, a tech-savvy city grappling with solid waste challenges, has embraced circular economy solutions by converting organic waste into high-quality compost for urban agriculture. Initiatives like Daily Dump, SWMRT, and Hasiru Dala have created decentralized composting models where households, schools, and businesses compost kitchen waste on-site. The compost is then used in rooftop gardens and peri-urban organic farms on the city's outskirts. These models achieve dual goals:

- **Carbon sequestration in soil** through organic matter addition,
- **Methane reduction** by diverting biodegradable waste from anaerobic landfills.

Peri-urban farms around Bengaluru, supported by such compost, adopt natural farming practices, integrating native tree species and agroforestry, contributing to soil regeneration and carbon drawdown. The model also generates green jobs, particularly for women and waste workers transitioning into urban farmers. [UN-Habitat \(2020\)](#) and [FAO \(2015\)](#) highlight Bengaluru's waste-to-food ecosystem as a replicable model for low-emission, resource-efficient urban development. Both Delhi and Bengaluru showcase how Indian cities are leveraging innovation and community participation to implement carbon-negative farming practices. These efforts whether through high-tech rooftop systems or low-tech waste-to-farm solutions, demonstrate the power of localized, circular approaches to transform urban environments into climate-resilient food production zones.

8.2 Global

- Paris' "Fermes Urbaines" (Urban Farms)

- New York's Gotham Greens
- Havana's organopónicos
- Nairobi's peri-urban agroforestry belt

Paris' "Fermes Urbaines" (Urban Farms)

Paris is home to Europe's largest rooftop farm, Nature Urbaine, located atop the Paris Expo Porte de Versailles. Spanning over 14,000 square meters, this vertical farm grows more than 30 different crops using aeroponic and organic techniques, reducing pesticide use and conserving water. Integrated with rainwater harvesting and solar energy, these farms contribute to urban greening, biodiversity, and carbon sequestration. According to [Despommier \(2011\)](#), such farms can cut urban food transport emissions drastically and create local green jobs. Paris' ambitious "Plan Alimentaire Durable" (Sustainable Food Plan) aims to produce 25% of the city's food locally by 2030.

New York: Gotham Greens

Founded in 2009, Gotham Greens operates commercial-scale greenhouses on rooftops across New York and other U.S. cities, producing leafy greens with 95% less water than conventional farming. Using controlled-environment agriculture (CEA), the farms run on renewable energy and employ closed-loop hydroponics, drastically reducing fertilizer runoff and GHG emissions. According to [Specht et al. \(2014\)](#), Gotham Greens exemplifies the synergy between innovation, sustainability, and urban productivity in modern food systems.

Havana: Organopónicos

In the wake of the 1990s economic crisis, Havana's organopónicos emerged as a community-based urban farming response. These biointensive, organic plots repurpose abandoned lots and urban land for vegetable cultivation

without synthetic inputs. Farmers use compost, vermiculture, and intercropping techniques to enhance soil health and sequester carbon. According to [Altieri *et al.* \(1999\)](#), these systems feed a significant portion of Havana's population, reduce food insecurity, and regenerate urban ecosystems.

Nairobi: Peri-Urban Agroforestry Belt

In Nairobi, Kenya, the development of peri-urban agroforestry systems has played a crucial role in enhancing urban resilience and food access. NGOs and local government support smallholders in planting fast-growing multipurpose trees like *Grevillea*, *Leucaena*, and *Moringa*, integrated with food crops and livestock. These systems sequester carbon, stabilize soil, and provide timber, fodder, and food for urban markets. [FAO \(2015\)](#) highlights Nairobi's peri-urban belt as a leading example of nature-based solutions that bridge ecological and economic goals.

9. Metrics and Monitoring for Urban Carbon-Negative Farming

Accurate measurement and monitoring are essential for evaluating the performance and credibility of urban carbon-negative farming systems. Quantifying environmental benefits, particularly carbon sequestration and emission reductions, not only guides management decisions but also enables participation in carbon markets and policy frameworks. Robust metrics help validate claims, attract investment, and promote transparency in climate-smart urban agriculture. To capture the diverse impacts of urban farming, a range of indicators are used, including greenhouse gas (GHG) savings, soil organic carbon (SOC) levels, and avoided emissions from reduced transportation, fertilizer use, and waste diversion. These metrics provide a comprehensive understanding of how urban agriculture contributes to climate mitigation.

The integration of digital agriculture tools, such as IoT sensors, AI-powered monitoring systems, and Life Cycle Assessment (LCA) software, enables real-time tracking of inputs, outputs, and carbon flows in both open and controlled environments. These technologies enhance precision, efficiency, and scalability in data collection. Equally important is the role of citizen science and community-based monitoring, which democratizes data generation and fosters local ownership. By involving farmers, residents, and local institutions in tracking environmental indicators, urban agriculture initiatives can build inclusive, transparent, and adaptive monitoring frameworks. The sub-sections that follow elaborate on these key dimensions, indicators, digital tools, and participatory monitoring, which together form the foundation for credible and effective carbon accounting in urban farming systems.

9.1 Indicators: GHG Savings, Soil Organic Carbon (SOC), Avoided Emissions

Quantifying greenhouse gas (GHG) savings from urban farming involves accounting for both direct and indirect emission reductions. Key indicators include:

- **Net GHG savings:** The balance of emissions from farm inputs, energy use, transportation, and activities versus carbon sequestered through soil and biomass.
- **Soil Organic Carbon (SOC):** SOC is a primary long-term carbon sink and a reliable proxy for soil health and carbon storage. Regular monitoring of SOC in urban gardens, raised beds, and container media allows assessment of carbon accumulation rates ([Paustian *et al.*, 2016](#)).

- **Avoided emissions:** Emissions avoided through shorter supply chains, reduced food waste, organic waste diversion, and renewable energy use. These indirect effects often represent a significant proportion of UPA's climate benefit ([Sanye-Mengual *et al.*, 2015b](#)).

Comprehensive carbon accounting frameworks must capture these elements to assess urban agriculture's true climate impact and identify best practices for scaling carbon-negative approaches.

9.2 Role of Digital Agriculture: IoT, AI-Based Monitoring, LCA Tools

The advent of digital agriculture technologies is revolutionizing data collection, analysis, and decision-making in UPA. Key technological enablers include:

- **Internet of Things (IoT) sensors:** Soil moisture, temperature, CO₂ concentration, and nutrient sensors provide real-time data to optimize inputs and enhance carbon sequestration ([Wolfert *et al.*, 2017](#)).
- **Artificial Intelligence (AI):** Machine learning models analyze multi-dimensional datasets from sensors, weather stations, and satellite imagery to predict crop performance, carbon fluxes, and resource use efficiency. AI can identify inefficiencies and suggest climate-smart interventions dynamically ([Kamilaris *et al.*, 2018](#)).
- **Life Cycle Assessment (LCA) tools:** Tools like the Cool Farm Tool, COMET-Farm, and SimaPro enable comprehensive environmental footprint analysis of urban farming systems, incorporating cradle-to-farm-gate emissions and sequestration processes ([Hillier *et al.*, 2011](#)). These allow comparison of

production systems, energy sources, and waste management practices on a common carbon metric.

Integration of these tools helps urban farmers, planners, and policymakers make data-driven decisions that maximize climate benefits while maintaining productivity and social goals.

9.3 Citizen Science and Community-Based Monitoring

Involving urban communities in citizen science and participatory monitoring fosters transparency, education, and local ownership of carbon-negative agriculture efforts. Community members can contribute data on soil quality, biodiversity indicators, composting effectiveness, and crop yields using mobile apps and simplified protocols ([Conrad & Hilchey, 2011](#)). Such approaches democratize science, expand monitoring coverage beyond institutional capacity, and generate locally relevant knowledge. Examples include urban soil carbon mapping projects in cities like New York and London, where residents' contributions supplement scientific assessments and inform municipal climate actions ([McPhearson *et al.*, 2014](#)). Community monitoring also builds social capital and strengthens networks that support sustainable urban food systems, ensuring that carbon-negative initiatives are equitable and culturally resonant.

10. Challenges and Barriers

Despite the growing potential of urban and peri-urban carbon-negative farming, several significant challenges limit its widespread adoption and effectiveness. Space constraints in densely populated cities restrict the scale of farming activities, while water scarcity poses additional hurdles for sustainable cultivation, especially in regions facing frequent droughts. Moreover, the high costs of controlled-environment agriculture (CEA)

setups, such as hydroponics and vertical farms, can be prohibitive for many urban growers, limiting access to advanced, resource-efficient technologies. Beyond physical and financial barriers, lack of integrated urban policies often leads to fragmented support for urban agriculture, hindering coordination among planning, waste management, and food systems sectors. This policy gap reduces incentives and institutional backing necessary for scaling carbon-negative practices. Furthermore, technical knowledge gaps among city dwellers, who may lack agricultural experience, pose challenges for effective implementation and maintenance of urban farms. Training and capacity-building programs are critical to overcoming this barrier. The sub-sections below delve into these key obstacles, space and resource limitations, policy integration issues, and knowledge deficits, that need addressing to unlock the full potential of carbon-negative urban agriculture.

4. Space Constraints, Water Scarcity, and Cost of Controlled-Environment Setups
5. 10.2 Lack of Urban Policy Integration
6. Technical Knowledge Gaps among City Dwellers

10.1 Space Constraints, Water Scarcity, and Cost of Controlled-Environment Setups

One of the primary challenges in urban agriculture is the limited availability of land and growing space. Urban areas are characterized by dense populations and competing land uses, often leaving only fragmented plots or rooftops for cultivation. This spatial scarcity necessitates innovative solutions such as vertical farming, container gardening, and hydroponics; however, these controlled-environment agriculture (CEA) systems involve high capital investment and operational costs ([Despommier, 2011](#)). The cost

of infrastructure, including lighting, climate control, and nutrient delivery systems, can be prohibitive, especially for small-scale and community-based initiatives ([Al-Kodmany, 2018](#)). Moreover, water scarcity presents a significant constraint, particularly in cities experiencing seasonal droughts or with stressed municipal supplies. Although technologies like drip irrigation and rainwater harvesting improve efficiency, the demand for clean, reliable water for irrigation and cooling remains a limiting factor (Fernández, 2018). Water reuse from greywater or treated wastewater is an option but requires robust safety protocols and infrastructure investments.

10.2 Lack of Urban Policy Integration

Urban agriculture often suffers from a lack of integration in city planning and policy frameworks. Many municipal governments have yet to formally recognize UPA as a critical component of urban land use, leading to inconsistent zoning laws, regulatory uncertainty, and limited institutional support ([Grewal & Grewal, 2012](#)). This fragmented policy environment creates barriers for farmers who face difficulties securing land tenure, obtaining permits, and accessing incentives. Furthermore, the absence of coherent climate and food policies that explicitly include urban agriculture limits the flow of public resources and impedes the scaling of carbon-negative practices. Cross-sectoral coordination between urban planners, agricultural departments, and environmental agencies remains weak, constraining opportunities for integrated climate-smart urban development ([Sanye-Mengual *et al.*, 2018](#)).

10.3 Technical Knowledge Gaps among City Dwellers

A significant social barrier to UPA is the lack of technical knowledge and skills among urban residents, many of whom may have limited agricultural experience. Practices like soil management, pest control, nutrient cycling,

and carbon sequestration require specialized understanding that is often absent in city populations ([Taylor & Lovell, 2014](#)). Additionally, operating advanced CEA technologies such as hydroponics and aquaponics necessitates training in system maintenance, water quality management, and energy optimization. Without accessible extension services, training programs, and community support networks, the adoption of climate-smart techniques remains slow ([Specht *et al.*, 2014](#)). Efforts to bridge this knowledge gap through urban agriculture education, workshops, and demonstration projects are critical for empowering diverse urban stakeholders and ensuring the longevity and success of carbon-negative farming initiatives.

11. Future Perspectives and Recommendations

As urbanization accelerates globally, embedding carbon-negative agriculture within city planning and development frameworks offers a pathway to sustainable, resilient urban futures. Integrating urban farming into initiatives like India's Smart Cities Mission and AMRUT (Atal Mission for Rejuvenation and Urban Transformation) can mainstream climate-smart food production, improve resource efficiency, and enhance livability. These national programs provide platforms to pilot and scale innovative urban agriculture models aligned with sustainability goals. Emerging innovations such as micro-farming units, modular vertical gardens, and portable carbon sinks present scalable solutions for maximizing green space in constrained urban settings. These technologies optimize resource use and enhance carbon sequestration potential while catering to diverse user groups, from households to commercial growers.

Looking ahead, the vision of carbon-negative eco-districts integrates food, energy, and water systems (the FEW nexus) to create closed-loop urban ecosystems. Such districts prioritize multifunctional land use,

renewable energy integration, and circular resource management to minimize environmental footprints and maximize resilience. To realize these ambitions, targeted research is needed to develop context-specific technologies, socio-economic models, and monitoring frameworks. Strengthening public-private partnerships will accelerate innovation, finance, and knowledge exchange, fostering collaborative governance and investment in urban carbon-negative agriculture. The following subsections expand on these strategic areas, policy integration, technological innovation, systems vision, and collaborative frameworks that will shape the future of sustainable urban food systems.

1. Integration into Smart Cities Mission and AMRUT (India)
2. Innovations in Micro-Farming Units and Portable Carbon Sinks
3. Vision for Carbon-Negative Eco-Districts and Food-Energy-Water (FEW) Nexus
4. Research Needs and Public-Private Partnerships

11.1 Integration into Smart Cities Mission and AMRUT (India)

In India, flagship urban development programs such as the Smart Cities Mission and Atal Mission for Rejuvenation and Urban Transformation (AMRUT) provide unique platforms to embed carbon-negative agriculture within city planning. The Smart Cities Mission's emphasis on sustainable infrastructure, green spaces, and efficient resource management aligns well with urban farming initiatives ([MoHUA, 2018](#)). By incorporating urban agriculture into Smart Cities' policies ranging from rooftop farming to community gardens powered by renewable energy, municipalities can simultaneously address urban heat islands, food security, and carbon emissions. Likewise, AMRUT's focus on improving urban ecosystems through water and waste management offers synergies for nutrient recycling

and waste-to-energy solutions that underpin carbon-negative practices ([MoHUA, 2020](#)). Coordinated inclusion of urban farming indicators into these missions' monitoring frameworks would incentivize local governments to adopt and scale climate-smart agriculture as part of urban resilience strategies.

11.2 Innovations in Micro-Farming Units and Portable Carbon Sinks

Technological advances are catalyzing the development of micro-farming units, compact, modular farming systems designed for small urban spaces. These include container farms, vertical farming modules, and hydroponic/aquaponic kits that maximize productivity with minimal resource inputs ([Al-Kodmany, 2018](#)). Portable carbon sinks represent an emerging innovation, such as biochar-enriched planter boxes and soil amendment kits that can be deployed in urban gardens and balconies to enhance carbon sequestration in soils and growing media ([Lehmann *et al.*, 2011](#)). Coupled with smart monitoring sensors and automated irrigation, these technologies empower city dwellers to contribute actively to carbon-negative goals. Further innovation is expected in integrating renewable energy, waste recycling, and IoT-enabled climate control into micro-farming units, facilitating their replication and scaling across diverse urban contexts.

11.3 Vision for Carbon-Negative Eco-Districts and Food-Energy-Water (FEW) Nexus

Looking ahead, the concept of carbon-negative eco-districts offers a holistic approach that integrates urban farming with energy production, water recycling, and sustainable transportation within self-sufficient neighborhoods ([Kennedy *et al.*, 2015](#)). Such districts leverage the Food-Energy-Water (FEW) nexus to optimize resource use, where urban farms

utilize renewable energy, recycle wastewater, and valorize organic waste while supplying fresh produce locally. This synergy reduces urban footprints, enhances resilience, and improves quality of life. Policy frameworks and design guidelines promoting mixed-use zoning, green infrastructure, and community participation are vital to realizing these eco-districts. Pilot projects worldwide are already demonstrating the feasibility of such integrated models, setting blueprints for future urban development ([Sanyé-Mengual *et al.*, 2020](#)).

11.4 Research Needs and Public-Private Partnerships

To accelerate urban carbon-negative farming, targeted research is needed in areas such as carbon accounting protocols for small-scale farms, lifecycle analyses of urban production systems, optimization of energy-water use efficiencies, and socio-economic impact assessments. Public-private partnerships (PPPs) play a pivotal role in translating research into practice. Collaborations between municipal bodies, academic institutions, technology providers, NGOs, and financial institutions can facilitate innovation diffusion, capacity building, and resource mobilization ([Pretty, 2008](#)). Establishing urban agriculture innovation hubs and funding mechanisms will support entrepreneurship, foster social inclusion, and catalyze climate-positive investments. Policies encouraging PPPs for infrastructure development, training, and market access are crucial to mainstreaming carbon-negative UPA.

12. Conclusion and Way Forward

Urban and peri-urban agriculture (UPA) has emerged as a transformative pathway toward developing carbon-negative and climate-resilient food systems within cities. By localizing food production through innovative systems such as rooftop hydroponics, vertical farms, aquaponics, and

community gardens, UPA substantially reduces greenhouse gas (GHG) emissions linked to long-distance transportation, packaging, and conventional agriculture. These approaches optimize the use of underutilized urban spaces and integrate renewable energy technologies—such as solar panels, biogas units, and decentralized microgrids—to further reduce the carbon footprint of urban food systems. Climate-smart agronomic practices like zero tillage, mulching, and biochar application, combined with soilless cultivation systems and circular waste management through composting, vermiculture, and anaerobic digestion, contribute to resource efficiency, carbon sequestration, and emission mitigation. Beyond environmental benefits, UPA delivers multiple socioeconomic and ecological co-benefits, including green employment generation, food sovereignty, biodiversity enhancement, and improved urban microclimates. The integration of digital tools such as IoT-based sensors, AI-driven monitoring, and participatory carbon accounting strengthens transparency and eligibility for carbon credits, as demonstrated in successful examples from Indian cities like Delhi and Bengaluru, and globally from Paris, New York, Havana, and Nairobi.

Realizing the full potential of carbon-negative urban farming requires strategic integration into city planning, zoning, and climate action frameworks, supported by enabling land-use policies and fiscal incentives. Strengthening the technical and entrepreneurial capacities of urban farmers, particularly women and youth, through targeted training and incubation programs will enhance adoption and innovation. Promotion of affordable micro-farming technologies powered by renewable energy, along with IoT and AI-based decision systems, can further improve efficiency and scalability. Establishing waste-to-resource systems through composting, biochar, and biogas production will help close nutrient loops and enhance

soil carbon stocks. Continued research on carbon accounting, soil health, and social impacts—supported by innovation hubs, public–private partnerships, and citizen science—will strengthen evidence-based policymaking. Aligning these initiatives with national urban development programs such as Smart Cities and AMRUT will embed carbon-negative agriculture within India’s sustainable urban agenda, transforming cities into resilient, self-reliant, and regenerative food-producing ecosystems.

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Chapter - 17

Carbon-Negative Livestock Systems

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1. Introduction

Livestock production contributes significantly to global greenhouse gas (GHG) emissions. The FAO estimated that livestock contributed 14.5% of global greenhouse gas emissions ([Gerber *et al.*, 2013](#)), a figure based on data from 2004-2005 that is still widely cited today. However, newer analyses suggest a broader range, with recent FAO estimates lowering the figure to 12%, while some peer-reviewed studies place it as high as 19.6%. This variation highlights the uncertainty and evolving nature of emissions data. Regardless of the precise percentage, reducing livestock-related emissions is increasingly recognized as critical for achieving meaningful climate action. Emerging research suggests that mitigation in this sector could yield even greater climate benefits than previously understood. The primary sources of emissions in livestock systems are enteric methane (CH₄) generated by microbial fermentation in the digestive tracts of ruminants, nitrous oxide (N₂O) released from manure management, and carbon dioxide (CO₂) associated with feed production, land use change, and energy consumption ([Herrero *et al.*, 2016](#)). This environmental footprint has raised concerns about the sustainability of conventional animal agriculture in the context of climate change mitigation.

However, recent research has highlighted the potential of carbon-negative livestock systems, where emissions are offset and net carbon sequestration is achieved through integrated management approaches. These systems

leverage regenerative practices such as silvopastoral agroforestry, adaptive grazing management, improved feed formulations, and advanced manure treatment technologies to reduce emissions intensity and enhance soil carbon stocks ([Nair *et al.*, 2010](#); [Herrero *et al.*, 2011](#); [Teague *et al.*, 2016](#)). Moreover, innovations in feed additives, such as seaweed-based supplements, show promise in significantly lowering enteric methane emissions (Kinley *et al.*, 2016).

The conceptual shift towards carbon negativity in livestock aligns with the broader framework of climate-smart agriculture, which integrates productivity, resilience, and mitigation objectives ([Lipper *et al.*, 2014](#)). By transforming livestock systems into net carbon sinks, it is possible not only to curb emissions but also to restore ecosystem services, improve animal welfare, and sustain rural livelihoods. This chapter explores these emerging pathways, synthesizes evidence on mitigation potentials, and examines the socio-technical and policy dimensions necessary for scaling carbon-negative livestock systems globally.

2. Greenhouse Gas Emissions in Livestock Systems

A combination of biological mechanisms and on-farm management activities within livestock systems contribute to greenhouse gas emissions. A key source is enteric fermentation, a natural digestive process in ruminants like cattle, sheep, and goats, which produces methane as a by-product. Additionally, manure management contributes significantly to emissions, as the storage and application of manure lead to the release of both methane and nitrous oxide, potent greenhouse gases. The production of animal feed, involving crop cultivation, fertilizer application, and land-use change, adds further emissions, particularly through nitrous oxide and carbon dioxide. Moreover, energy use in livestock systems such as electricity, fuel for machinery, and transportation, also plays a role in the

sector's carbon footprint. The emission intensity, or the amount of GHGs emitted per unit of livestock product, varies significantly depending on the production system, animal breed, feed composition, and regional practices. The sections below delve into the key emission sources and critical hotspots within livestock systems that drive their overall greenhouse gas footprint.

1. Sources of Emissions
2. Emission Intensity and Hotspots

2.1 Sources of Emissions

Livestock systems contribute significantly to greenhouse gas (GHG) emissions through a combination of biological processes and management practices. Key sources include enteric fermentation, manure management, feed production, and on-farm energy use, each varying in intensity based on species, production systems, and regional factors.

Manure management also contributes substantial emissions of both methane and nitrous oxide (N_2O), depending on storage methods, environmental conditions, and treatment practices. Methane is released under anaerobic conditions in storage systems, while N_2O arises from nitrogen transformations when manure is applied to soils ([Baral *et al.*, 2018](#)). Additionally, feed production indirectly drives emissions through fertilizer use, fossil fuel consumption, and land-use change. Synthetic fertilizers release N_2O during application, and deforestation or land conversion for feed crops results in CO_2 emissions from lost biomass and soil carbon ([Liu *et al.*, 2010](#)).

Although relatively smaller in share, energy-related CO_2 emissions from farm operations such as machinery use, feed transport, and housing systems, contribute to the overall carbon footprint. These emissions represent an important mitigation target through strategies like renewable

energy adoption and energy-efficient technologies ([Mottet *et al.*, 2017](#)). Collectively, these sources define the emission profile of livestock systems and highlight multiple intervention points for climate-smart livestock management.

2.2 Emission Intensity and Hotspots

The emission intensity of livestock production, measured as greenhouse gas emissions per unit of product such as milk, meat, or eggs, varies widely across different production systems, breeds, diets, and geographical contexts. Intensive, high-input systems often have lower emission intensities due to higher productivity per animal, while extensive grazing systems may have higher per-unit emissions but offer greater potential for soil carbon sequestration ([Gerber *et al.*, 2013](#); Herrero *et al.*, 2016). Geographic variation influences emission profiles because of differences in climate, feed availability, and husbandry practices. For instance, tropical regions generally have higher methane emissions due to poorer feed quality and animal genetics compared to temperate zones ([Mottet *et al.*, 2017](#)).

Identifying emission hotspots (specific practices, processes, or regions responsible for disproportionate emissions) is essential for targeting mitigation strategies effectively. Hotspots include enteric fermentation in ruminants, manure storage under anaerobic conditions, and feed production systems linked to deforestation ([Gerber *et al.*, 2013](#)). Focused interventions in these areas can achieve significant emission reductions and improve the overall sustainability of livestock production.

3. Pathways to Carbon-Negative Livestock Systems

Achieving carbon-negative outcomes in livestock production requires a multifaceted approach that targets both emission reduction and carbon sequestration opportunities across the system. Emerging scientific advances

and regenerative practices offer viable strategies to minimize greenhouse gas emissions while enhancing environmental resilience and productivity. One of the most promising avenues is improving feed efficiency and reducing enteric methane emissions through dietary interventions, precision nutrition, and selective breeding for low-emission traits ([Kinley *et al.*, 2016](#)). Simultaneously, manure management innovations such as anaerobic digestion for biogas, composting, and biochar application can substantially reduce methane and nitrous oxide emissions while generating value-added co-products (Baral *et al.*, 2018).

Beyond emission reduction, livestock systems can serve as carbon sinks through pasture-based strategies such as silvopastoral systems, rotational grazing, and the restoration of degraded rangelands. These practices enhance soil organic carbon, biodiversity, and ecosystem functioning (Nair *et al.*, 2010; Teague *et al.*, 2016). Furthermore, integrated crop-livestock systems offer synergistic benefits by closing nutrient cycles, enhancing land-use efficiency, and reducing dependence on synthetic inputs. Such systems promote long-term soil health and carbon storage while diversifying farm productivity (Delandmeter *et al.*, 2024). Together, these pathways provide scalable, regionally adaptable solutions for transforming livestock into an agent of climate mitigation and agricultural sustainability. The following subsections explore these key strategies in detail, from enteric methane reduction and manure innovations to pasture carbon capture and integrated farming systems.

1. Improving Feed Efficiency and Enteric Methane Reduction
2. Manure Management Innovations
3. Pasture-Based Carbon Sequestration
4. Integrated Crop-Livestock Systems

3.1 Improving Feed Efficiency and Enteric Methane Reduction

Enteric methane produced by ruminants during fermentation is a major source of livestock-related GHG emissions. Dietary interventions have shown great promise in mitigating this emission pathway. Notably, supplementation with certain seaweed species such as *Asparagopsis taxiformis* has been demonstrated to inhibit methanogenic archaea in the rumen, reducing methane emissions by up to 80% *in vitro* and significant reductions *in vivo* ([Kinley et al., 2020](#)). Additionally, natural compounds like tannins and essential oils act as methanogenesis inhibitors, contributing to lower methane output while potentially improving animal health and feed efficiency. Beyond additives, precision feeding *i.e.*, tailoring nutrient supply to the animals' physiological needs, minimizes excess nitrogen excretion and optimizes fermentation processes, thereby decreasing methane intensity per unit of product (Pinares-Patiño *et al.*, 2013). Furthermore, selective breeding programs aiming for low-methane-emitting animals and better feed conversion efficiency are emerging, harnessing genetic variability to reduce the carbon footprint of herds over generations (Wall *et al.*, 2014).

3.2 Manure Management Innovations

Manure emits methane and nitrous oxide during storage and field application, yet it also represents a resource for renewable energy and soil amendments. Anaerobic digestion technologies capture methane from manure in controlled biogas plants, converting it into renewable energy for heating, electricity, or transportation fuel, thereby reducing net emissions ([Baral et al., 2018](#)). Digestate, a nutrient-rich solid or semi-liquid residue produced through anaerobic digestion, can be used as a fertilizer, thereby helping to close nutrient loops. Composting manure stabilizes organic matter and, when combined with biochar amendments, enhances carbon

retention in soils and lowers nitrous oxide emissions ([Wang *et al.*, 2012](#)). An innovative approach involves integrating black soldier fly larvae (BSFL) into manure management systems. BSFL consume organic waste, converting it into high-protein feed ingredients while reducing waste volume and associated emissions ([Makkar *et al.*, 2014](#)).

3.3 Pasture-Based Carbon Sequestration

Pasture lands offer significant potential for carbon sequestration, particularly through silvopastoral systems, which integrated land-use practice that combines trees or shrubs, forage plants, and livestock on the same land unit in a mutually beneficial way. Trees in these systems increase carbon stocks both above ground (wood biomass) and below ground (root biomass and soil organic carbon), improving biodiversity and providing shade and forage for animals ([Nair *et al.*, 2010](#)). These systems promote a multifunctional landscape that supports productivity and ecosystem services. Rotational and adaptive grazing management practices improve soil structure, increase plant root biomass, and enhance microbial activity, leading to increased soil organic carbon stocks (Teague *et al.*, 2016). Carefully managed grazing also prevents overgrazing and land degradation, facilitating restoration of degraded rangelands. Additionally, wetlands connected to grazing lands can act as carbon sinks and biodiversity hotspots, emphasizing the importance of landscape-scale approaches to livestock carbon management.

3.4 Integrated Crop-Livestock Systems

Combining crop and livestock production maximizes nutrient cycling and land use efficiency. Application of manure to croplands returns essential nutrients, increasing soil organic matter and fertility, which in turn promotes crop productivity and carbon sequestration ([Delandmeter *et al.*, 2024](#)). Such

nutrient recycling reduces dependence on synthetic fertilizers, decreasing associated emissions from their manufacture and application. Mixed farming systems, where crops and livestock coexist, optimize resource use by utilizing crop residues for feed and manure for soil amendment. This integration reduces external inputs, lowers the overall carbon footprint, and enhances resilience to climate variability. In these systems, circular flows of nutrients and energy contribute to sustainable, carbon-negative outcomes.

4. Technological Innovations and Digital Tools

The integration of technological innovations and digital tools into livestock systems marks a transformative shift toward climate-smart and carbon-resilient animal agriculture. These advancements enable producers to monitor, analyze, and optimize livestock performance and environmental impacts in real time. From precision livestock farming and sensor-based monitoring to advanced data analytics and life cycle assessment, these tools are central to improving resource efficiency, animal welfare, and greenhouse gas (GHG) mitigation across livestock value chains. As climate change pressures intensify, such innovations offer critical support for both sustainable productivity and carbon footprint reduction in the livestock sector. These technological innovations can be broadly categorized into following four key areas that are revolutionizing climate-smart livestock systems:

1. Use of sensor technology and precision livestock farming
2. Methane sensors and gas analyzers for real-time emission tracking
3. AI and big data analytics for decision support
4. Life cycle assessment (LCA) tools for carbon accounting

4.1 Use of Sensor Technology and Precision Livestock Farming

Precision Livestock Farming (PLF) employs sensor-based technologies to collect real-time data on individual animals, monitoring health, behavior, reproduction, and productivity. These systems enhance farm management by providing timely insights into the animal's condition, thereby enabling early disease detection, optimizing feed efficiency, and reducing the environmental impact of overfeeding or underperformance. For example, accelerometers, temperature sensors, RFID tags, and automated weighing platforms help farmers track animal movement, feed intake, and growth patterns. This data-driven approach supports informed decisions that align animal welfare with climate-smart outcomes. As [Berckmans \(2017\)](#) noted, “PLF enables the continuous, automated monitoring of individual animals, making livestock farming more sustainable and economically efficient by reducing resource waste and improving animal well-being.”

4.2 Methane Sensors and Gas Analyzers for Real-Time Emission Tracking

Methane emissions, primarily from enteric fermentation in ruminants, are a significant source of agricultural GHGs. Methane sensors and gas analyzers provide real-time quantification of these emissions, enabling accurate measurement, benchmarking, and mitigation planning. Technologies such as photoacoustic spectroscopy, Fourier-transform infrared (FTIR) spectroscopy, and laser-based gas detection allow continuous, non-invasive monitoring of emissions either directly from animals or in barn environments. These systems help in validating mitigation strategies, such as dietary interventions or breeding low-emission animals. According to [Chagunda *et al.* \(2013\)](#), “real-time methane quantification tools are essential for understanding emission variability and guiding both policy and farm-level interventions.”

4.3 AI and Big Data Analytics for Decision Support

The use of Artificial Intelligence (AI) and big data analytics in livestock systems enables smart decision-making across the value chain, from feed optimization and animal health management to reproductive planning and environmental performance. AI models can process vast volumes of sensor and environmental data to identify patterns, predict disease outbreaks, and suggest optimal interventions. In the context of climate-smart farming, AI also supports feed formulation strategies to reduce enteric methane emissions and optimize manure output. As [Wolfert *et al.* \(2017\)](#) explain, “Big data analytics transforms raw information from sensors and IoT devices into actionable knowledge, supporting precise, efficient, and environmentally sustainable livestock management.”

4.4 Life Cycle Assessment (LCA) Tools for Carbon Accounting

Life Cycle Assessment (LCA) is a scientific method used to assess the total environmental impact of a product or process across its entire lifecycle, from feed production and animal rearing to waste disposal and product transport. In livestock systems, LCA tools help identify carbon hotspots, evaluate different mitigation options (e.g., improved feed, better manure management, agroforestry integration), and quantify both GHG emissions and carbon sequestration potential. This enables farmers, policymakers, and companies to make data-driven decisions that align with climate targets. [Gerber *et al.* \(2013\)](#) emphasized that “LCA is vital in evaluating the environmental footprint of livestock production and in designing interventions that lead to lower emissions per unit of product.”

Together, these technological innovations enable data-driven management that improves efficiency, reduces emissions, and supports the scaling of carbon-negative livestock systems worldwide.

5. Policy, Economic Incentives, and Market Mechanisms

Achieving carbon-negative outcomes in livestock systems requires not only technological innovations but also a supportive policy environment, economic incentives, and market-based mechanisms. Governments, financial institutions, and international bodies play a crucial role in shaping the landscape through subsidies, regulations, and climate finance initiatives that promote low-emission livestock practices. By aligning economic drivers with environmental goals, such mechanisms encourage farmers to adopt sustainable strategies that enhance productivity while reducing greenhouse gas (GHG) emissions. In this context, the following key areas highlight the most influential policies and mechanisms shaping climate-resilient livestock development:

1. Carbon Markets, Subsidies & Ecosystem Payments
2. Policy Frameworks for Methane & Carbon Management
3. Certification for Climate-Friendly Livestock Products
4. Barriers: Access, Measurement & Policy Coherence

5.1 Carbon Markets, Subsidies & Ecosystem Payments

Policy frameworks and economic incentives play a critical role in promoting the adoption of carbon-negative livestock systems by encouraging low-emission practices and supporting sustainable agricultural transformation. One of the most effective tools to incentivize emission reductions is the establishment of carbon markets, where farmers and producers can earn carbon credits for implementing practices that lower greenhouse gas emissions or enhance carbon sequestration. These credits can be traded or sold, providing financial returns that motivate the adoption of climate-smart technologies such as improved manure management, feed additives, and silvopastoral systems ([Lipper *et al.*, 2014](#)). Additionally,

subsidies and payments for ecosystem services (PES) programs offer direct support to livestock farmers who maintain or enhance ecosystem functions, including soil carbon storage and biodiversity conservation. These programs help reduce economic barriers to sustainable practices and encourage wider adoption ([Wunder, 2015](#)).

5.2 Policy Frameworks for Methane & Carbon Management

At the global level, policy frameworks such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC) guidelines establish methodologies for methane reduction and soil carbon accounting in agricultural sectors. These guidelines support countries in developing national inventories, setting emission reduction targets, and implementing mitigation strategies aligned with the Paris Agreement ([IPCC, 2019](#)). National policies often translate these international commitments into localized regulations, standards, and incentives tailored specifically to livestock systems, thereby fostering mitigation efforts at the grassroots level.

5.3 Certification for Climate-Friendly Livestock Products

To enhance market-based incentives, certification schemes for climate-friendly animal products have emerged. Labels such as “carbon-neutral,” “regeneratively raised,” or “climate-smart” enable consumers to identify and support products produced with reduced environmental footprints. These certifications help producers command **premium prices** and create market differentiation, thus encouraging wider adoption of sustainable practices ([Tziva et al., 2018](#)).

5.4 Barriers: Access, Measurement & Policy Coherence

Despite these advances, several barriers hinder widespread implementation. Smallholder farmers, who represent a large proportion of global livestock producers, often face limited access to finance, technology, and knowledge. This restricts their ability to participate in carbon markets or adopt new climate-smart practices ([Makkar *et al.*, 2015](#)). Moreover, measurement and verification challenges related to accurately quantifying emissions reductions and soil carbon sequestration pose difficulties for credible carbon accounting and market participation (Paustian *et al.*, 2016). Finally, policy coherence remains an issue, as conflicting regulations or lack of integration between agricultural, environmental, and economic policies can impede holistic approaches to carbon-negative livestock farming ([IPCC, 2023](#)).

Addressing these barriers through capacity building, transparent monitoring systems, and inclusive policy design is crucial to unlocking the full potential of policy and market mechanisms in driving the transition toward sustainable, carbon-negative livestock systems.

6. Socioeconomic and Environmental Co-Benefits

The transition toward carbon-negative livestock systems not only contributes to climate change mitigation but also delivers a range of socioeconomic and environmental co-benefits. By adopting sustainable and integrated approaches such as silvopastoral systems, improved animal management, and circular resource use, livestock farming can become a driver of rural development, ecosystem restoration, and climate resilience. Beyond reducing greenhouse gas emissions, these systems offer tangible improvements in livelihoods, natural resource management, and animal welfare, especially when designed to support smallholders and marginalized communities. The following key areas highlight the broader co-benefits associated with sustainable livestock practices:

1. Livelihoods, Employment & Poverty Reduction
2. Biodiversity & Habitat Restoration in Silvopastoral Systems
3. Animal Welfare, Soil Health & Climate Resilience

6.1 Livelihoods, Employment & Poverty Reduction

Sustainable livestock practices contribute significantly to livelihood improvement and rural employment. They create jobs across the value chain including animal husbandry, feed production, manure management, and marketing which supports income diversification for smallholders and marginalized groups such as women and youth. This fosters inclusive economic growth and contributes to poverty alleviation ([Herrero *et al.*, 2013](#)). Integrated systems such as silvopastoralism and crop-livestock integration enhance resource use efficiency and productivity, improving household food security and providing a buffer against income shocks ([Thornton & Herrero, 2010](#)).

6.2 Biodiversity & Habitat Restoration in Silvopastoral Systems

From an environmental perspective, carbon-negative livestock systems foster biodiversity conservation and habitat restoration, particularly when implemented as silvopastoral or agroforestry systems. Integrating trees with pastures and croplands enhances habitat complexity, supporting a wider range of wildlife species by offering food and shelter ([Jose, 2009](#)). These systems also improve landscape connectivity, help restore degraded ecosystems, and promote ecological resilience, especially in regions facing deforestation or land degradation ([Jose & Dollinger, 2019](#)).

6.3 Animal Welfare, Soil Health & Climate Resilience

Sustainable livestock systems also advance animal welfare, acknowledging both its ethical significance and its role in improving farm productivity. Practices that reduce animal stress, provide proper nutrition, and enable natural behaviors lead to healthier animals with higher feed efficiency and lower GHG emissions ([Whiting, 2011](#)). Additionally, improved grazing management such as rotational or managed intensive grazing, enhances soil structure and organic matter content, leading to better water retention and fertility ([Teague *et al.*, 2016](#)). These benefits collectively increase resilience to climate variability, helping farms adapt to droughts, floods, and other extreme events while maintaining productivity.

7. Case Studies

Real-world case studies provide valuable insights into effective carbon-negative farming practices across diverse agroecosystems and regions. They illustrate how tailored approaches can simultaneously enhance productivity, increase carbon sequestration, and reduce greenhouse gas emissions. By analyzing successful models, stakeholders can better understand practical implementation challenges, benefits, and scalability potential in different socio-economic and environmental contexts. The following sub-sections examine three notable examples: smallholder silvopastoral systems in Latin America, biogas manure management in European dairy farms, and seaweed feed additives trials in Australia and the U.S. Each case highlights innovative strategies that contribute to carbon mitigation while supporting farmer livelihoods.

1. Smallholder silvopastoral systems in Latin America demonstrating increased carbon stocks and productivity
2. Biogas manure management in European dairy farms reducing emissions and generating renewable energy

3. Seaweed feed additive trials in Australia and the U.S. cutting enteric methane by up to 80%

7.1 Smallholder Silvopastoral Systems in Latin America

Smallholder farmers across Latin America are increasingly turning to silvopastoral systems, a land use practices that combine trees, pasture, and livestock, to boost productivity while enhancing environmental resilience. These integrated systems promote ecological balance and improve livelihoods by diversifying income streams. According to Montagnini and Nair (2012), silvopastoral practices substantially enhance carbon sequestration both above and below ground, with tree biomass acting as a major carbon sink and improved soil organic matter enhancing long-term soil health. Moreover, trees offer shade and wind protection, contributing to better animal welfare, particularly under heat stress conditions. These systems also help reduce soil erosion, regulate microclimates, and increase biodiversity ([Jose & Dollinger, 2019](#)).

7.2 Biogas Manure Management in European Dairy Farms

Across Europe, particularly in countries like Germany, the Netherlands, and Denmark, dairy farms are adopting biogas digesters as a core part of sustainable manure management. These anaerobic digestion systems capture methane, a potent greenhouse gas produced from decomposing manure, and convert it into biogas, a renewable energy source that can be used on-site or fed into national energy grids ([Holm-Nielsen *et al.*, 2009](#)). This not only reduces greenhouse gas emissions from manure storage but also contributes to farm energy self-sufficiency. The remaining digestate, rich in nutrients such as nitrogen and phosphorus, is recycled as fertilizer, closing nutrient cycles and reducing the reliance on synthetic inputs (Moller and Müller, 2012). The integration of biogas technology into dairy farming

supports the circular bioeconomy, enhances farm profitability, and aligns with EU climate mitigation targets.

7.3 Seaweed Feed Additive Trials in Australia and the U.S.

Innovative feed strategies involving marine resources are gaining traction in Australia and the United States, where recent trials have shown that supplementing cattle diets with specific seaweed species can drastically reduce methane emissions from enteric fermentation. Notably, research led by [Kinley *et al.* \(2020\)](#) found that adding *Asparagopsis taxiformis* to cattle feed at small concentrations (less than 1%) can reduce methane emissions by up to 80%. The seaweed contains bromoform, a compound that inhibits the activity of methanogenic archaea in the rumen, thereby curbing methane production without negatively affecting animal health or productivity. These trials, supported by both public research institutions and private sector partners, point to a scalable solution for lowering the climate footprint of ruminant livestock globally, particularly in coastal regions with access to marine bioresources ([Roque *et al.*, 2019](#)).

Together, these case studies illustrate diverse pathways to carbon-negative agriculture, emphasizing the importance of innovation, adaptation, and integrated management across farming systems.

8. Challenges and Future Directions

The transition toward carbon-negative livestock and farming systems holds considerable promise for mitigating climate change. However, realizing this potential involves overcoming multiple scientific, technical, and social challenges. Addressing these obstacles is critical to ensure the scalability, accuracy, and sustainability of mitigation strategies while fostering inclusive stakeholder engagement. This section outlines key challenges and future directions essential for advancing carbon-negative agriculture.

1. Technical challenges in methane mitigation scalability and feed additive cost
2. Measuring and verifying carbon sequestration at farm level
3. Integrating livestock systems into broader landscape-level carbon accounting
4. Research gaps in soil carbon dynamics and emission trade-offs
5. Need for multi-stakeholder collaboration and participatory approaches

8.1 Technical Challenges in Methane Mitigation Scalability and Feed Additive Cost

Innovative approaches such as seaweed-based feed additives have demonstrated significant potential to reduce enteric methane emissions from ruminants ([Kinley *et al.*, 2020](#)). Nonetheless, scaling these solutions from experimental trials to commercial livestock operations remains a significant challenge. Production of additives like *Asparagopsis taxiformis* involves complex cultivation and processing, which currently results in high costs and supply limitations ([Beauchemin *et al.*, 2022](#)). Ensuring consistent quality, regulatory approval, and acceptance by farmers are further hurdles to widespread adoption. Overcoming these constraints is essential to unlock methane mitigation at scale.

8.2 Measuring and Verifying Carbon Sequestration at Farm Level

Robust measurement, reporting, and verification (MRV) frameworks are fundamental to quantify carbon sequestration benefits and validate climate outcomes at the farm level. Yet, variability in soil types, climate, and management practices complicate accurate quantification ([Smith *et al.*, 2019](#)). Advanced tools such as remote sensing, soil sampling, and modeling

can improve accuracy but are often costly and inaccessible to smallholders. Developing affordable, scalable MRV approaches remains a priority to support carbon markets and incentive programs.

8.3 Integrating Livestock Systems into Broader Landscape-Level Carbon Accounting

Livestock production interacts with multiple components of the agricultural landscape, including croplands, forests, and water bodies. Integrating emissions and sequestration from livestock systems into comprehensive landscape-level carbon accounting avoids double counting and captures ecosystem synergies ([Herrero *et al.*, 2016](#)). This holistic approach supports more effective climate policies and land-use planning but requires interoperable data systems and coordinated governance across sectors.

8.4 Research Gaps in Soil Carbon Dynamics and Emission Trade-Offs

Despite advances, significant knowledge gaps remain concerning soil carbon processes under diverse management regimes. Understanding how carbon is stabilized, mineralized, or lost is essential for predicting long-term sequestration potential ([Paustian *et al.*, 2016](#)). Furthermore, some mitigation practices may unintentionally increase other greenhouse gases, such as nitrous oxide from fertilizer use, leading to emission trade-offs ([Tian *et al.*, 2020](#)). Filling these research gaps is crucial for developing balanced, climate-positive farming strategies.

8.5 Need for Multi-Stakeholder Collaboration and Participatory Approaches

Complex challenges in carbon-negative agriculture cannot be addressed by scientists or policymakers alone. Multi-stakeholder collaboration involving

farmers, researchers, industry, and civil society ensures that solutions are contextually appropriate, socially equitable, and environmentally sound ([Reed *et al.*, 2010](#)). Participatory approaches empower local actors, promote knowledge sharing, and facilitate co-creation of innovations, thereby increasing adoption and sustainability of mitigation measures.

9. Conclusion and Way Forward

Carbon-negative livestock systems represent a transformative shift in agricultural sustainability, aiming to reduce greenhouse gas emissions while enhancing carbon sequestration within the broader food system. Case studies from Latin America, Europe, Australia, and the U.S. demonstrate how practices such as silvopastoral farming, biogas manure management, and methane-reducing feed additives offer viable pathways to mitigate climate impacts. These innovations not only contribute to environmental sustainability but also improve farm productivity, animal welfare, and economic resilience. Despite their promise, the widespread adoption of such practices is hindered by technical, economic, and policy-related challenges that require coordinated action. The transition to carbon-negative livestock systems is not only feasible but increasingly necessary in the face of accelerating climate change and pressure on agricultural resources. Integrating mitigation strategies such as improved feed efficiency, circular waste management, agroforestry, and digital monitoring into livestock operations can result in measurable reductions in emissions while supporting livelihoods and ecosystem health. However, the complexity of livestock systems, regional variability, and socio-economic constraints demand a holistic approach rooted in science, innovation, and inclusive governance.

To support the transition to carbon-negative livestock systems, key actions are needed across technology, policy, and stakeholder engagement.

Proven mitigation strategies such as feed additives, precision feeding, and biogas systems should be scaled through subsidies, extension services, and public-private partnerships. Robust, low-cost tools for monitoring soil carbon and methane are essential for accurate carbon accounting and access to carbon markets. Integrating livestock with broader landscape-level carbon strategies can enhance synergies and minimize emissions. Multi-stakeholder collaboration, including farmers, researchers, policymakers, and industry, should be prioritized to co-develop practical, location-specific solutions. Smallholders must be supported through tailored financing and technical assistance to ensure equitable participation. Aligning climate, agricultural, and environmental policies will provide clearer guidance, while digital tools like AI and sensors can boost efficiency and transparency. Ongoing research on soil carbon dynamics and emission trade-offs will further refine effective mitigation strategies.

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Chapter - 18

Digital and AI-Based Tools for Carbon Farming

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1. Introduction

Agriculture is both a significant contributor to greenhouse gas (GHG) emissions and a vital sector for climate change mitigation through carbon sequestration. Carbon farming encompasses a suite of agricultural practices aimed at reducing net emissions by increasing soil organic carbon stocks and reducing emissions from inputs and operations (Lal, 2016). The complexity and variability of carbon fluxes in agricultural landscapes present challenges for monitoring, reporting, and verifying carbon outcomes, which is crucial for the credibility of climate mitigation efforts and incentive mechanisms such as carbon markets ([Paustian *et al.*, 2016](#)). Recent advances in digital technologies and artificial intelligence (AI) have introduced powerful tools to address these challenges by enabling precise, scalable, and data-driven management of carbon farming practices ([Kamilaris *et al.*, 2018](#)). Remote sensing platforms, Internet of Things (IoT) devices, sensor networks, and machine learning algorithms generate and analyze large datasets that improve our understanding of carbon dynamics and support real-time decision-making (Gebbers & Adamchuk, 2010; [Wolfert *et al.*, 2017](#)). AI-driven models and digital decision support systems help optimize inputs such as water, fertilizers, and crop selection, minimizing emissions and maximizing carbon sequestration (Liakos *et al.*, 2018).

Moreover, integrated digital platforms facilitate carbon accounting, monitoring of greenhouse gas emissions, and transparent reporting as these are critical elements for participation in carbon markets and payments for ecosystem services (Rejeb *et al.*, 2020). These innovations empower farmers, policymakers, and researchers with actionable insights to implement climate-smart agriculture at scale. However, despite their potential, digital and AI tools face challenges including data accessibility, infrastructure gaps in rural areas, high costs, and the need for capacity building among end-users (Kamilaris *et al.*, 2018). Addressing these barriers is essential to liberalize access and ensure equitable benefits across farming communities, particularly in developing regions. This chapter explores the landscape of digital and AI-based technologies that underpin carbon farming, highlighting their applications, benefits, limitations, and future prospects in enabling a sustainable, carbon-negative agricultural transition.

2. Digital Technologies in Carbon Farming

Digital technologies are becoming foundational to the transformation of agriculture into a climatesmart and carbon-conscious sector. By enabling real-time data collection, precise intervention, and continuous monitoring, these tools significantly improve the efficiency and environmental sustainability of farming systems. Their integration allows farmers to enhance carbon sequestration, reduce greenhouse gas emissions, and make informed decisions based on accurate and site-specific information. The convergence of technologies such as remote sensing, IoT, and precision agriculture represents a major shift in how carbon farming is practiced, moving from manual, reactive methods to proactive, datadriven systems. These innovations are particularly crucial as agriculture faces growing pressure to reduce its carbon footprint while ensuring food security.

According to [Gebbers and Adamchuk \(2010\)](#), the precision offered by digital farming tools not only improves input efficiency but also contributes directly to climate change mitigation. Remote sensing technologies, IoT-enabled sensor networks, and GPS-guided machinery are now central to implementing precision carbon management strategies that were previously unattainable at scale ([Frampton *et al.*, 2013](#); Wolfert *et al.*, 2017). Together, these technologies form the backbone of a digitally enhanced carbon farming framework.

The following sub-sections explore the key categories of digital technologies driving carbon farming, highlighting their specific roles, mechanisms, and potential impacts on emission reduction and carbon sequestration.

1. Remote Sensing and Geospatial Technologies
2. Internet of Things (IoT) and Sensor Networks
3. Precision Agriculture Tools

2.1 Remote Sensing and Geospatial Technologies

Remote sensing technologies, including satellite imagery, drones (unmanned aerial vehicles), and ground-based sensors, offer powerful capabilities to monitor agricultural landscapes at various spatial and temporal scales. High-resolution data derived from these platforms provide valuable insights into soil health, vegetation cover, biomass accumulation, and land use changes, parameters essential for estimating soil organic carbon (SOC) and vegetation carbon stocks. Advanced sensing techniques such as Light Detection and Ranging (LiDAR), multispectral, and hyperspectral imaging capture detailed spectral signatures of vegetation and soil properties, enabling accurate differentiation of crop types, biomass estimation, and soil characteristics ([Frampton *et al.*, 2013](#)). For instance,

hyperspectral data can identify specific biochemical constituents related to carbon content, improving soil carbon mapping accuracy. Geographic Information Systems (GIS) integrate diverse spatial datasets, facilitating the creation of carbon hotspot maps, identifying areas of high sequestration potential, and monitoring temporal changes in carbon stocks. GIS-based spatial analysis supports decision-making at field, farm, and landscape levels, helping farmers and policymakers prioritize interventions and evaluate the impacts of carbon farming practices (Gebbers & Adamchuk, 2010).

2.2 Internet of Things (IoT) and Sensor Networks

The proliferation of IoT technologies has revolutionized real-time monitoring of key environmental parameters crucial for carbon farming. IoT-enabled sensors deployed in the field continuously record variables such as soil moisture, temperature, pH, nutrient concentrations, and greenhouse gas emissions like carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) at fine temporal resolutions. These data streams enable precision management by informing site-specific practices such as variable fertilizer application, irrigation scheduling, and soil amendments to optimize carbon sequestration while minimizing losses through runoff or volatilization ([Wolfert *et al.*, 2017](#)). For example, soil moisture sensors guide irrigation to prevent overwatering, which can lead to denitrification and increased N₂O emissions. Gas sensors detect sudden rises in greenhouse gas levels (called emission spikes), allowing timely action to reduce pollution. Additionally, IoT systems support scalable monitoring and allow farmers to access actionable insights through dashboards and mobile applications by facilitating remote data transmission and cloud computing integration. ([Kamilaris *et al.*, 2018](#)).

2.3 Precision Agriculture Tools

Precision agriculture employs advanced machinery and technologies to enhance input use efficiency and reduce environmental footprints. Variable Rate Technology (VRT) enables differential application of water, fertilizers, and pesticides based on spatial variability within fields, thereby reducing overapplication, lowering emissions associated with manufacturing and application, and minimizing nutrient runoff that can cause indirect emissions (Gebbers & Adamchuk, 2010). GPS-guided tractors and automated farm equipment improve the accuracy of field operations such as planting, fertilizing, and tillage, decreasing overlap and soil disturbance. Precision tillage practices minimize soil disruption, which helps maintain soil organic carbon levels by reducing oxidation of organic matter. Cover cropping and crop rotation decisions, when supported by digital tools analyzing soil and climate data, further promote soil carbon sequestration by enhancing biomass input and improving soil structure (Lal, 2016). Overall, precision agriculture integrates seamlessly with digital monitoring platforms to enable carbon farming that is economically viable and environmentally sustainable.

3. Artificial Intelligence Applications

Artificial Intelligence (AI) technologies offer vast potential to transform carbon farming by automating data collection, pattern recognition, and decision-making across multiple agricultural functions. AI tools can monitor and optimize a wide range of farming operations, from irrigation management and soil health analysis to harvesting schedules, pest and weed protection, and even supply chain logistics ([Wolfert *et al.*, 2017](#); [Liakos *et al.*, 2018](#)). These AI-driven systems use machine learning algorithms to analyze sensor data, satellite imagery, and weather models, enabling farmers to implement precision interventions that minimize greenhouse gas

(GHG) emissions and maximize carbon sequestration. For instance, AI-enabled irrigation systems reduce water and energy use by delivering precise amounts of water based on soil and weather conditions ([Gaitan *et al.*, 2025](#)). Similarly, intelligent spraying systems apply fertilizers or pesticides only where needed, reducing chemical runoff and nitrous oxide emissions ([Kamilaris *et al.*, 2017](#); [Shamshiri *et al.*, 2018](#)). By automating complex tasks and enabling predictive insights, AI contributes significantly to the efficiency, sustainability, and climate resilience of agricultural systems, making it a cornerstone technology in the shift toward carbon-negative farming ([Wolfert *et al.*, 2017](#); [Rose *et al.*, 2021](#)).

The sub-sections below explore the core AI applications in carbon farming, illustrating how machine learning, decision support systems, and automated emission monitoring contribute to carbon accounting and sustainable land management.

1. Machine Learning for Carbon Stock Prediction
2. AI-Driven Decision Support Systems (DSS)
3. Automated Monitoring of Greenhouse Gas Emissions

3.1 Machine Learning for Carbon Stock Prediction

Large, complicated datasets can be processed by machine learning (ML) algorithms to find patterns and create predictive models. In carbon farming, ML techniques integrate diverse data sources such as soil sample analyses, remote sensing imagery, climatic variables, and land management histories to accurately estimate soil organic carbon (SOC) stocks and their sequestration potential ([Minasny *et al.*, 2019](#)). By training on high-quality field data, models such as random forests, support vector machines, and neural networks can generalize predictions across different soils and agroecosystems, overcoming limitations of traditional empirical models.

These predictive models support mapping of carbon-rich soils and identification of areas with high sequestration potential, facilitating targeted interventions. Furthermore, ML algorithms can monitor temporal changes in SOC in response to management practices, enabling adaptive carbon farming strategies that maximize sequestration while considering environmental variability.

3.2 AI-Driven Decision Support Systems (DSS)

AI-powered Decision Support Systems (DSS) synthesize diverse data streams such as weather forecasts, soil nutrient levels, crop phenology, and carbon flux measurements, to deliver targeted recommendations for carbon farming interventions ([Liakos et al., 2018](#)). These systems support optimized decisions related to crop rotations, cover cropping, agroforestry design, and tillage methods to enhance soil carbon sequestration while maintaining productivity ([Kamilaris et al., 2017](#)). An AI-driven DSS integrates wireless sensors, remote sensing technologies, and real-time data processing to facilitate climate-smart agricultural decisions. Wireless sensors deployed in the field monitor soil moisture, nutrient content, temperature, crop health, and carbon fluxes, capturing both greenhouse gas emissions and sequestration patterns ([Feng et al., 2015](#)). These data streams are merged with weather forecasts, satellite imagery, and management records, and transmitted to a centralized platform for processing. Using machine learning algorithms, the DSS analyzes this data to identify patterns, detect anomalies, and generate predictive insights based on historical and real-time information ([Minasny et al., 2019](#)). For example, the system can forecast pest outbreaks or disease risks based on microclimatic conditions and vegetation indices. It provides actionable recommendations for irrigation scheduling, fertilization timing, and planting windows, thereby enhancing input efficiency and reducing carbon

footprints ([Yang *et al.*, 2025](#)). Real-time monitoring further enables adaptive management. Crop monitoring tools provide insights into growth stages and stress responses, while soil monitoring ensures optimal pH, nutrient balance, and moisture levels for productivity and carbon stability. The system supports early detection of pests, weeds, and diseases, promoting precise, low-emission interventions ([Bilal *et al.*, 2025](#)). This integration of AI and sensing technologies helps transition conventional farming into a carbon-negative model that aligns with broader climate resilience goals ([Tey & Brindal, 2012](#)). By simulating outcomes under various management scenarios, DSS tools allow farmers to evaluate trade-offs and adopt strategies best suited to their conditions. User-friendly dashboards and mobile applications make these insights accessible, enabling real-time decisions and improved responsiveness of carbon farming operations (Khanal *et al.*, 2020).

3.3 Automated Monitoring of Greenhouse Gas Emissions

Monitoring greenhouse gas emissions such as methane (CH₄) and nitrous oxide (N₂O) at farm scales is challenging due to spatial and temporal variability. AI algorithms enhance the processing and interpretation of sensor data collected from emission monitoring devices, including chamber systems, flux towers, and portable analyzers ([Ma, 2024](#)).

Machine learning models can identify emission patterns, detect hotspots of high flux, and evaluate the effectiveness of mitigation measures in near real-time. This capability enables timely management interventions, for example, adjusting manure management or fertilizer application, to reduce emissions dynamically. Furthermore, AI facilitates integration of emission data into carbon accounting frameworks, improving transparency and accuracy for certification and incentive programs. Overall, AI applications

transform carbon farming from a static, knowledge-intensive practice into a dynamic, data-driven system capable of maximizing environmental and economic outcomes.

4. Data Analytics and Carbon Accounting

Data analytics plays a pivotal role in carbon farming by enabling the quantification, verification, and communication of greenhouse gas (GHG) emissions and carbon sequestration at the farm level. With agriculture contributing significantly to global emissions, transparent and standardized methods for measuring carbon flows are essential for integrating farms into climate action frameworks and carbon markets. Digital tools powered by big data, artificial intelligence, and decentralized systems now allow for detailed tracking of carbon performance across agricultural value chains. These tools not only inform decision-making at the farm level but also support compliance with environmental regulations and participation in carbon credit schemes.

Life Cycle Assessment (LCA) and carbon footprinting tools, when embedded in digital platforms, offer structured frameworks to analyze emissions from inputs to outputs, including soil, water, machinery, and energy use ([de Vries & de Boer, 2010](#)). Meanwhile, blockchain technology has emerged as a promising solution for ensuring traceability, data integrity, and accountability in carbon transactions, making it easier for smallholder farmers and cooperatives to access incentive-based programs such as payments for ecosystem services (Rejeb *et al.*, 2020). These innovations collectively advance the credibility and scalability of carbon accounting in agriculture. The sub-sections below highlight how Life Cycle Assessment tools and blockchain technology are being utilized to support rigorous, transparent, and inclusive carbon accounting systems in agriculture.

1. Life Cycle Assessment (LCA) and Carbon Footprinting Tools
2. Blockchain for Traceability and Carbon Credit Verification

4.1 Life Cycle Assessment (LCA) and Carbon Footprinting Tools

To comprehensively assess the environmental impact of a product or process, Life Cycle Assessment (LCA) is employed as a standardized methodology that quantifies resource use and emissions across all stages of a product's life. This includes raw material extraction, production, distribution, use, and end-of-life disposal, and aligns with internationally accepted protocols such as ISO 14040 and ISO 14044 ([ISO, 2006](#)).

In the context of carbon farming, LCA-based digital tools enable comprehensive analysis of emissions from all farm-related activities, including fertilizer manufacture, fuel consumption, soil management, and residue handling. By incorporating soil carbon sequestration into the LCA framework, these tools generate a net carbon footprint of farming systems and allow comparative evaluation of different management practices (de Vries & de Boer, 2010). Advanced carbon footprinting platforms further enhance precision by integrating site-specific parameters such as geographic, climatic, and operational data, which are critical for credible carbon certification schemes and reporting obligations.

Such tools are fundamental to carbon accounting and data analytics, offering transparency in the identification of GHG emission hotspots (e.g., CO₂, CH₄, N₂O), and informing targeted interventions for emission reduction. Moreover, modern LCA platforms support scenario modeling, enabling the assessment of potential outcomes from various low-carbon farming strategies. The transparency and scientific rigor of LCA methodologies underpin both voluntary and compliance carbon markets,

ensuring that emission factors and reporting are standardized, traceable, and verifiable ([Finkbeiner *et al.*, 2006](#); [Weidema *et al.*, 2008](#)).

Furthermore, LCA tools facilitate scenario modeling, allowing stakeholders to evaluate potential outcomes of adopting different carbon farming practices and technologies. The transparency and rigor of LCA underpin voluntary and regulatory carbon markets by providing scientifically robust emission factors and methodologies that satisfy stakeholder and verifier requirements.

4.2 Blockchain for Traceability and Carbon Credit Verification

Blockchain technology, a decentralized and immutable digital ledger, is increasingly applied to enhance trust, transparency, and traceability in carbon farming carbon markets (Rejeb *et al.*, 2020). By securely recording carbon sequestration data, farming activities, and associated transactions, blockchain ensures the integrity of carbon credit issuance and trading processes. The process involves emission data recording, credit tokenization, third-party verification, and final retirement, all of which are securely documented on the blockchain. This technology addresses common challenges in carbon markets such as data manipulation, double counting, and verification delays by providing a tamperproof record accessible to all stakeholders including farmers, verifiers, buyers, and regulators. Smart contracts automate verification and payment processes based on predefined carbon sequestration criteria, reducing administrative burdens and transaction costs.

Blockchain platforms also facilitate the participation of smallholder and marginalized farmers in Payment for Ecosystem Services (PES) schemes by simplifying carbon credit certification and enabling direct peer-to-peer trading opportunities. The transparency offered by blockchain builds consumer confidence in climate-friendly agricultural products, enhancing

market incentives for carbonnegative farming. Integrating blockchain with IoT sensor data and AI analytics further strengthens the accuracy and real-time monitoring capabilities of carbon accounting systems, creating a robust digital infrastructure to support scalable, transparent, and trustworthy carbon farming markets.

5. Integration of Digital Technologies for Scalable Carbon Farming

The integration of digital technologies is critical for scaling carbon farming practices beyond isolated pilot projects into mainstream agricultural systems. When artificial intelligence (AI) is combined with other digital innovations such as remote sensing, IoT-based sensors, precision agriculture tools, and blockchain, it creates a synergistic ecosystem that enhances the efficiency, accuracy, and reach of carbon monitoring and mitigation strategies (Kamilaris & Prenafeta-Boldú, 2018). Such integration allows for real-time data collection, automated analytics, and predictive modelling, enabling farmers and institutions to adopt adaptive, site-specific carbon practices at scale. This convergence of technologies also helps overcome key limitations in traditional carbon accounting, such as inconsistent measurements, fragmented data systems, and high verification costs. As emphasized by [Wolfert *et al.* \(2017\)](#), the interoperability of digital systems is essential to building robust, data-driven agricultural frameworks that support climate-smart decision-making. Moreover, integrated platforms facilitate the linkage between farm-level practices and global carbon markets, providing farmers with incentives and policy-aligned tools to participate in climate action (Rose *et al.*, 2021). The following section explores how the strategic integration of digital technologies including AI, IoT, remote sensing, and blockchain, enables scalable, efficient, and verifiable carbon farming across diverse agroecosystems.

1. Interoperability of Digital Systems in Agriculture
2. Integrated Monitoring and Verification Systems (MRV)
3. Digital Infrastructure for Smallholder Inclusion
4. AI-Enabled Decision Support Across Platforms
5. End-to-End Carbon Credit Ecosystems

5.1 Interoperability of Digital Systems in Agriculture

Interoperability, the ability of different digital systems and platforms to seamlessly exchange and use data, is essential for the effective implementation of scalable carbon farming. Linking AI algorithms with IoT-based field sensors, satellite data, and geospatial analysis tools (GIS) enables comprehensive, real-time insights into soil health, crop conditions, and emissions dynamics. Without interoperability, data remains fragmented, leading to inefficiencies and incomplete decision-making frameworks. [Wolfert et al. \(2017\)](#) emphasize that integrated data infrastructures are foundational to the success of smart farming initiatives, as they allow stakeholders across the agricultural value chain to collaborate and act on consistent datasets.

5.2 Integrated Monitoring and Verification Systems (MRV)

Robust Monitoring, Reporting, and Verification (MRV) systems are critical for ensuring the credibility of carbon sequestration claims. Integrated MRV combines remote sensing, sensor networks, AI-based analytics, and blockchain to monitor changes in soil organic carbon, vegetation biomass, and GHG emissions. These systems help reduce reliance on manual field measurements and lower the cost of verification, which is often a barrier to carbon market entry for smallholders. According to [World Bank. \(2022\)](#), digital MRV systems improve transparency and accountability in climate

finance mechanisms, enabling the scaling of nature-based solutions across agricultural landscapes.

5.3 Digital Infrastructure for Smallholder Inclusion

To ensure equity and scale, carbon farming technologies must be accessible to smallholder farmers who form the backbone of global food systems. Mobile-based applications, low-power sensors, and offline-compatible tools are increasingly being designed for use in remote and resource-constrained regions. Rejeb *et al.* (2021) argue that building inclusive digital infrastructure involves not only developing appropriate technologies but also investing in digital literacy, local language content, and support systems. Inclusion-focused design ensures that smallholders can benefit from carbon credits, advisory services, and adaptive climate tools.

5.4 AI-Enabled Decision Support Across Platforms

AI-powered decision support systems (DSS) are revolutionizing carbon farming by synthesizing data from multiple sources into actionable insights. These platforms combine weather forecasts, satellite imagery, sensor data, and historical field records to guide practices such as cover cropping, fertilizer application, and tillage. [Kamilaris and Prenafeta-Boldú \(2018\)](#) highlight how cross-platform AI models enhance predictive capabilities and improve farmers' response to dynamic climate and soil conditions. When deployed at scale, these tools contribute to optimized resource use and enhanced carbon sequestration potential.

5.5 End-to-End Carbon Credit Ecosystems

An integrated digital ecosystem is essential to support the full lifecycle of carbon credit generation, from data collection and MRV to tokenization, market listing, and payout. Blockchain technology offers a secure,

transparent ledger for carbon credit transactions, minimizing fraud and ensuring traceability. Combined with satellite data and AI-based verification, this approach enables scalable and trustworthy participation in voluntary and compliance carbon markets. According to [Bocknor & Samuels \(2024\)](#), end-to-end digital platforms are instrumental in linking climate-smart practices to economic incentives, especially for smallholders and cooperatives in developing regions.

Thus, integrated digital systems are no longer just a technological possibility, they are becoming a necessary infrastructure for scalable, verifiable, and economically viable carbon farming, especially in the era of climate accountability, regenerative agriculture, and sustainability-driven markets.

6. Case Studies and Innovations

Digital and AI-based technologies are revolutionizing carbon farming by enabling more accurate measurement, verification, and enhancement of carbon sequestration practices. These innovations not only improve productivity and resource-use efficiency but also help farmers actively participate in carbon markets through reliable and transparent data systems. From AI-driven decision-making to blockchain-enabled credit trading, real-world applications are emerging across diverse agroecological contexts. The following case studies highlight innovative applications of digital and AI-based tools in diverse agricultural settings, showcasing how these technologies are driving measurable outcomes in soil carbon enhancement, methane monitoring, and smallholder access to carbon markets.

1. AI-enabled precision agriculture systems in Australia enhancing soil carbon
2. Drone and sensor integration for methane monitoring in dairy farms

3. Blockchain-based carbon credit platforms linking smallholder farmers in Africa

6.1 AI-Enabled Precision Agriculture Enhancing Soil Carbon in Australia

Australia has been at the forefront of applying artificial intelligence (AI) to optimize carbon sequestration through precision agriculture. In a notable study, [Gaitan *et al.* \(2025\)](#) demonstrated how AI algorithms integrated with remote sensing, weather data, and soil information helped farmers make site-specific decisions to enhance soil organic carbon. The system analyzed historical land use, crop rotations, and fertilization patterns to recommend practices such as cover cropping and minimal tillage. These data-driven strategies led to measurable increases in soil carbon content over two growing seasons, especially in semi-arid zones of Queensland and New South Wales. AI-powered platforms also reduced the need for blanket fertilizer applications, further contributing to emissions reduction. [Zouizza *et al.* \(2023\)](#) stressed that such tools are crucial in transitioning Australian agriculture toward a low-emissions future.

6.2 Drone and Sensor Integration for Methane Monitoring in Dairy Farms

Methane emissions from ruminant livestock remain a major challenge for achieving carbon neutrality in agriculture. In response, researchers in New Zealand have pioneered the use of drone-mounted gas sensors and ground-based infrared cameras to map methane fluxes from dairy farms in real time. [Fosco *et al.* \(2025\)](#) reported a case where autonomous drones equipped with Tunable Diode Laser Absorption Spectroscopy (TDLAS) technology were deployed over pasturelands to identify high-emission zones and optimize grazing rotation. The system significantly improved the

accuracy of methane quantification, allowing for targeted feed interventions and reduced emissions per unit of milk produced. Moreover, these tools facilitated continuous, non-invasive monitoring, a significant improvement over traditional chamber-based methods. This innovation illustrates how combining sensor technologies with AI-based analytics can help reduce livestock emissions at scale.

6.3 Blockchain-Based Carbon Credit Platforms for African Smallholders

In Africa, smallholder farmers often lack access to carbon markets due to high verification costs and inadequate digital infrastructure. However, blockchain technology is emerging as a game-changer. [Mantey *et al.* \(2025\)](#) described a pilot initiative in Kenya where small-scale farmers using agroforestry and conservation agriculture could register their carbon gains on a blockchain-based platform. Smart contracts automatically verified practices based on satellite imagery, mobile data, and on-ground sensors, drastically reducing transaction costs. Once validated, carbon credits were tokenized and sold to international buyers, with revenues directly transferred to farmers via mobile money systems. This transparent and decentralized system empowered rural communities to benefit financially from carbon sequestration while encouraging sustainable land use. The platform also provided training modules and geospatial feedback to farmers, creating a holistic digital ecosystem for carbon farming.

These case studies demonstrate that digital and AI-enabled tools are not futuristic concepts but active contributors to real-world carbon farming. Their ability to support data-driven decision-making, improve transparency, and create financial incentives makes them central to the future of sustainable agriculture. As adoption scales up, integrating these

technologies with participatory governance and equitable access will be key to ensuring their long-term impact across regions and farming systems.

7. Challenges and Limitations

While digital and AI-based tools are transforming carbon farming by enabling more precise, scalable, and market-linked climate solutions, their deployment is not without significant challenges. High initial investment costs, technical complexity, and limited digital literacy can exclude smallholder and marginalized farmers from adopting these innovations (World Bank, 2021; [Sustainability, 2023](#); [Agriculture, 2024](#)). The lack of robust digital infrastructure such as internet connectivity, interoperable data platforms, and secure cloud services, further constrains the reach and effectiveness of these tools, particularly in rural and under-resourced regions ([Birner *et al.*, 2021](#)). Another critical limitation lies in the transparency, fairness, and ownership of farm-level data. Data privacy and control are emerging concerns, as AI systems often rely on large-scale data aggregation from farmers, raising ethical and legal questions about consent and usage rights ([Carbonell, 2016](#)). Moreover, the predictive accuracy of AI models in agriculture can be influenced by environmental variability, incomplete datasets, and algorithmic biases, which may lead to inconsistent carbon measurements and recommendations (Kamilaris & Prenafeta-Boldú, 2018). Addressing these challenges requires inclusive policy frameworks, targeted capacity-building initiatives, and the co-design of digital tools with farmers and local institutions to ensure equitable adoption and sustained impact. The key challenges and limitations outlined below reflect these broader concerns, highlighting the barriers that must be addressed to ensure the inclusive and effective deployment of digital and AI-based carbon farming technologies.

1. High Initial Costs and Technological Barriers for Smallholders
2. Data Privacy, Interoperability, and Infrastructure Issues
3. Need for Capacity Building and Farmer Training
4. Uncertainties in AI Model Predictions and Carbon Measurement Variability

7.1 High Initial Costs and Technological Barriers for Smallholders

The adoption of precision agriculture tools, remote sensing services, and AI-powered platforms often entails significant upfront investment in hardware, software, connectivity, and technical support ([Kamilaris *et al.*, 2017](#)). Many smallholders cannot afford IoT sensors, GPS-guided machinery, or commercial AI platforms without external support. Moreover, the cost-benefit ratio may not be immediately visible to farmers lacking long-term financial security or access to carbon credit markets. This creates a digital divide, where larger or commercial farms benefit disproportionately from technology while smallholders are left behind (Wolfert *et al.*, 2017).

7.2 Data Privacy, Interoperability, and Infrastructure Issues

The increasing reliance on digital data in agriculture raises important questions about data ownership, privacy, and security. Farmers are often hesitant to share sensitive data such as farm yields, soil health, or management practices, without guarantees on how this data will be used or monetized ([Wolfert *et al.*, 2017](#)). Interoperability is another concern, as many digital tools and platforms use proprietary formats or operate in isolation, preventing seamless integration and data sharing across systems. Furthermore, limited internet access, erratic power supply, and inadequate

digital infrastructure in rural regions pose significant implementation barriers, particularly in the Global South (Kamilaris *et al.*, 2017).

7.3 Need for Capacity Building and Farmer Training

Effective use of digital technologies requires a level of digital literacy, data interpretation skills, and understanding of carbon farming principles. Many farmers, especially older and marginalized ones, face difficulties in navigating digital dashboards, interpreting AI recommendations, or troubleshooting sensor systems. Without targeted capacity building, extension services, and user-centered tool design, the adoption and sustained use of digital carbon farming tools will remain limited ([Klerkx *et al.*, 2019](#)). Bridging the knowledge gap is critical to ensure equitable access and widespread participation in carbon farming innovations.

7.4 Uncertainties in AI Model Predictions and Carbon Measurement Variability

While machine learning models and AI tools provide advanced predictive capabilities, their outputs are inherently subject to uncertainties due to variability in input data, model assumptions, and environmental heterogeneity. Factors like soil type, management history, and microclimatic conditions can significantly affect carbon flux dynamics, complicating the generalizability of AI predictions ([Minasny *et al.*, 2019](#)). Similarly, accurate quantification of soil organic carbon and GHG emissions is constrained by spatial and temporal variability, sensor limitations, and a lack of standardized measurement protocols (Paustian *et al.*, 2016).

These limitations affect the credibility of digital carbon accounting for use in carbon markets and regulatory frameworks.

8. Future Directions

As the global urgency to mitigate climate change intensifies, digital and AI-based solutions for carbon farming are poised for rapid advancement. Emerging trends suggest a shift toward the democratization of technology, with increasing efforts to develop low-cost, accessible tools for smallholder and resource-constrained farmers (Rose *et al.*, 2021b). Open-source AI models, affordable remote sensors, and mobile-based platforms are being designed to lower entry barriers and expand the reach of carbon-smart practices. These innovations promise to bridge the digital divide while enhancing data availability and real-time decision-making at the farm level. Future directions also emphasize the deeper integration of digital carbon farming tools with climate-smart agriculture (CSA) frameworks and digital extension services. This includes combining carbon monitoring systems with adaptive irrigation, precision fertilization, and agroecological practices to build holistic, resilient food systems (Gebbers & Adamchuk, 2010; [Aggarwal *et al.*, 2018](#)). Advances in synthetic data generation and AI model training are expected to overcome the limitations of sparse field data, allowing for more robust and context-specific carbon predictions ([Rose *et al.*, 2021](#)). Additionally, supportive policy environments including investment in digital infrastructure, regulatory clarity on data use, and incentives for innovation, will be critical to scaling these technologies in an inclusive and equitable manner ([World Bank, 2021](#)). The following future directions highlight key technological, institutional, and policy innovations needed to overcome current limitations and scale digital carbon farming solutions across diverse agricultural landscapes.

These broader concerns, highlighting the barriers that must be addressed to ensure the inclusive and effective deployment of digital and AI-based carbon farming technologies.

1. Development of Low-Cost Sensors and Open-Source AI Tools
2. Enhanced Integration with Climate-Smart Agriculture and Digital Extension Services
3. Use of Synthetic Data and Advanced AI Models for Improved Predictions
4. Policy Frameworks Supporting Digital Innovation in Carbon Farming

8.1 Development of Low-Cost Sensors and Open-Source AI Tools

A major limitation in digital carbon farming is the cost of advanced sensors and proprietary software. Future research and innovation must focus on developing low-cost, rugged, and modular sensors for real-time measurement of key parameters such as soil organic carbon, methane flux, and nitrate leaching ([Gholizadeh *et al.*, 2018](#)). Coupled with mobile compatibility and energy efficiency (e.g., solar-powered sensors), such tools can democratize access to carbon monitoring technologies. Simultaneously, opensource AI platforms and libraries (e.g., TensorFlow, PyTorch) can be customized for agricultural applications, enabling academic institutions, start-ups and public-sector bodies to co-develop tailored solutions without high licensing costs (Kamilaris & Prenafeta-Boldú, 2018). These developments can help bridge the digital divide and promote wider adoption among smallholders and cooperatives.

8.2 Enhanced Integration with Climate-Smart Agriculture and Digital Extension Services

Future systems should aim to integrate carbon farming with the broader paradigm of climatesmart agriculture (CSA), which encompasses productivity, adaptation, and mitigation. AI tools will increasingly be

embedded into digital extension services that provide holistic farm advice - ranging from crop selection and pest management to soil health and carbon credit participation ([World Bank, 2017](#)). Chatbots, SMS alerts, and voice-enabled apps in local languages can deliver personalized, low-bandwidth recommendations to farmers in real time, improving both accessibility and impact. Integration with national agricultural advisory systems and agri-tech incubators will be key to scaling these services ([Klerkx et al., 2019](#)).

8.3 Use of Synthetic Data and Advanced AI Models for Improved Predictions

A major bottleneck in AI applications for carbon farming is the lack of high-quality, labeled datasets. Synthetic data generation using simulations and AI techniques like generative adversarial networks (GANs) can augment limited field data, enhancing the robustness of models in data-scarce regions ([Lee, 2023](#)). Additionally, advanced AI models such as deep learning, ensemble learning, and spatialtemporal forecasting will enable better modeling of nonlinear, context-dependent carbon fluxes under varying climate and management scenarios ([Liakos et al., 2018](#)). These models can also support predictive analytics for climate risk, guiding proactive adaptation and mitigation strategies.

8.4 Policy Frameworks Supporting Digital Innovation in Carbon Farming

Creating an enabling environment for digital carbon farming requires forward-looking policies that support research, innovation, and ethical deployment of technology. Public investments in rural connectivity, open data platforms, and agri-tech innovation hubs will be essential. Moreover, regulatory frameworks must address data privacy, interoperability, and digital inclusion while promoting standards for digital carbon measurement

and reporting that align with international carbon markets ([Bronson & Knezevic, 2016](#)). Subsidies, tax incentives, and green public procurement can further incentivize the development and uptake of climate-smart digital tools.

Aligning these efforts with national climate action plans, digital agriculture roadmaps, and international commitments (e.g., the FAO's 1000 Digital Villages Initiative) will ensure coherence and long-term impact.

9. Conclusion and Way Forward

This chapter underscored the transformative role of digital and artificial intelligence (AI) technologies in enabling carbon-negative farming. Tools such as remote sensing, IoT sensors, machine learning, and blockchain are reshaping how greenhouse gas (GHG) emissions and soil carbon sequestration are measured, verified, and optimized. Life Cycle Assessment (LCA) frameworks and AI-powered decision support systems (DSS) provide granular insights and site-specific recommendations, enhancing carbon outcomes and resource efficiency. The integration of these innovations into mobile platforms has democratized access, enabling participatory approaches and inclusion in carbon markets and payment for ecosystem services (PES).

Despite this potential, significant challenges persist, particularly for smallholder farmers. These include high upfront costs, inadequate rural digital infrastructure, limited access to data, and a lack of technical training. Moreover, the effectiveness of AI depends heavily on the quality and representativeness of input data, while uncertainties in soil carbon measurement and emission estimation remain a concern. Bridging these gaps will require an inclusive, systems-oriented approach to ensure the equitable adoption of digital carbon farming technologies.

To achieve this, targeted policy and programmatic interventions are essential. These include promoting affordable, open-source tools for smallholders, improving rural connectivity and sensor networks, and developing standardized, transparent carbon accounting protocols aligned with global frameworks. Capacity building through farmer training and digital literacy must be prioritized, along with institutional support to align carbon farming with national climate goals. Additionally, ongoing research into AI and synthetic data models should be encouraged to improve predictive capabilities. Safeguarding data rights, privacy, and benefit-sharing is also vital to ensure a just and sustainable digital transition in agriculture.

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GLOSSARY

Adaptive Grazing

A livestock management practice involving flexible rotation of animals across pastures to optimize forage use, prevent overgrazing, and enhance soil organic carbon sequestration.

Adaptive Management

Dynamic and flexible farming practices adjusted based on monitoring, evaluation, and changing environmental conditions.

Additionality

A principle in carbon markets requiring that emission reductions or carbon sequestration achieved by a project would not have occurred under a “business-as-usual” scenario.

Adult Learning (Andragogy)

A discipline focused on methods and principles of teaching adults, emphasizing experiential, problem-based, and self-directed learning approaches.

Aeroponics

A soilless cultivation method where plant roots are suspended in air and supplied with a fine mist of nutrient solution, enabling high water- and nutrient-use efficiency.

Afforestation

Planting of trees in areas that were not previously forested to increase biomass and carbon sequestration.

Aggregation

The arrangement of soil particles into clusters, enhancing water infiltration, root growth, and reducing erosion.

Agriculture 4.0

The application of advanced digital technologies (AI, IoT, robotics, big data, blockchain) to agriculture for efficiency, sustainability, and climate-smart practices.

Argo-biodiversity

The variety and variability of animals, plants, and microorganisms used directly or indirectly for food and agriculture. It includes crop species, livestock, fisheries, forestry, and microbes that contribute to ecosystem services such as pollination and nutrient cycling.

Agroecology

Farming system based on ecological processes, traditional practices, and sustainable management, often adapted in developing regions for climate resilience.

Agroforestry/ Silvopasture

Integrating trees with crops or livestock to enhance biodiversity, carbon sequestration, and resilience.

Albedo

The measure of the reflectivity of a surface. In agriculture, increasing albedo (e.g., through certain crops or soil covers) can reflect more solar radiation and have a cooling effect.

Alley Cropping

Planting rows of trees or shrubs alongside crops, providing wind protection, soil conservation, and additional carbon sequestration.

Allometry

The study of the relationship between the size of an organism and the size of any of its parts; often used for estimating tree biomass and carbon stocks from easily measured parameters like trunk diameter or height.

Anaerobic Digestion

A biological process in which microorganisms break down organic matter (e.g., manure, crop residues) in the absence of oxygen, producing biogas and nutrient-rich digestate.

Animal Welfare

The ethical and scientific consideration of animals' physical and psychological wellbeing, including nutrition, housing, and freedom from stress, often linked with reduced emission intensity.

Aquaforestry

Integrating trees with aquatic systems (e.g., mangroves with aquaculture), enhancing carbon sequestration, biodiversity, and water quality.

Arbuscular Mycorrhizal Fungi (AMF)

Symbiotic fungi that colonize plant roots, enhancing nutrient uptake (especially phosphorus) and contributing to soil aggregation and carbon sequestration.

Artificial Intelligence (AI) in Agriculture

The use of AI technologies to analyze farm data, predict conditions, and support decision-making for more efficient, sustainable farming.

Artificial Intelligence (AI)

Computer systems that mimic human intelligence by learning from data, recognizing patterns, and making decisions. In agriculture, AI supports tasks like irrigation scheduling, pest detection, yield forecasting, and carbon accounting.

Asparagopsis taxiformis

A red seaweed species rich in bromoform, used as a ruminant feed additive to inhibit methanogenic archaea and reduce enteric methane emissions.

Atmospheric Lifetime

Duration a greenhouse gas remains in the atmosphere before removal by natural processes, influencing its climate impact.

AWD (Alternate Wetting and Drying)

A water-saving practice in paddy rice systems where fields are allowed to dry intermittently rather than being kept continuously flooded, reducing water use and methane emissions.

Benefit-Sharing

A framework ensuring that communities and Indigenous peoples equitably receive economic, social, or environmental benefits from natural resource use, climate finance, or carbon markets.

Big Data

Extremely large datasets from multiple sources (e.g., satellites, sensors, farm records) that can be analyzed computationally to reveal trends and inform decisions in carbon farming.

Biochar

A carbon-rich, stable material produced by pyrolysis (thermal decomposition under limited oxygen) of biomass, used as a soil amendment for long-term carbon sequestration and soil improvement.

Biodiversity Conservation

The protection, management, and restoration of diverse biological species and ecosystems to maintain ecological balance and resilience.

Biodiversity Credits

Market instruments rewarding conservation and enhancement of species and habitats alongside carbon credits.

Biodiversity Loss

Decline in variety and abundance of living organisms caused by habitat degradation, pollution, and climate change.

Bioenergy

Energy produced from organic matter such as crop residues and animal manure, used to generate biogas or bioethanol, reducing reliance on fossil fuels.

Biofertilizers

Products containing beneficial microorganisms that promote plant growth by increasing nutrient availability in the soil.

Biogas

A renewable energy source consisting mainly of methane and CO₂, produced via anaerobic digestion of organic waste, used for cooking, heating, and electricity generation.

Biogeochemical Cycles

The pathways by which chemical substances, such as carbon, nitrogen, and phosphorus, move through the biotic (living) and abiotic (non-living) components of Earth. Carbonnegative farming aims to optimize these cycles.

Biological Innovations

Advancements in breeding, crop improvement, soil biology, and biotechnologies that enhance agricultural productivity with lower environmental impact.

Biological Pump

The process by which oceans transport carbon from the surface to the deep ocean via phytoplankton and the marine food web.

Biopesticides

Pest control agents derived from natural materials such as plants (e.g., neem), bacteria (e.g., *Bacillus subtilis*), fungi, or minerals, used as alternatives to synthetic chemical pesticides.

Biostimulants

Natural or synthetic substances that enhance plant growth, soil health, and microbial activity, supporting carbon sequestration and resilience.

Black Soldier Fly Larvae (BSFL)

Insects that can convert organic waste such as manure into highprotein feed and organic fertilizer, reducing waste volumes and greenhouse gas emissions.

Blockchain in Carbon Markets

Use of distributed ledger technology to enhance transparency, traceability, and trust in carbon trading.

Blockchain

A decentralized, immutable digital ledger that records transactions securely. In carbon farming, it ensures transparency and trust in carbon credit generation, verification, and trading.

Capacity Building

The process of developing skills, knowledge, tools, and institutions that enable individuals, communities, and organizations to adapt and implement carbon-negative farming practices effectively.

Cap-and-Trade System

A compliance market mechanism setting a cap on total emissions and allowing trading of emission allowances.

Carbon Accounting

The process of measuring, reporting, and verifying greenhouse gas (GHG) emissions and removals (sequestration) from farming systems, often aligned with global standards (e.g., ISO, GHG Protocol).

Carbon Budget

The maximum amount of carbon dioxide that can be emitted to the atmosphere while still limiting global warming to a specific target (e.g., 1.5°C).

Carbon Credit Certification

The process of validating and verifying carbon sequestration projects to ensure credibility for trading in carbon markets.

Carbon Credit Market

Trading system where entities buy and sell credits representing quantified reductions or removals of carbon emissions.

Carbon Credit

A tradable certificate representing one metric tonne of CO₂ (or its equivalent) removed from the atmosphere or prevented from being emitted.

Carbon Cycle

The regular movement of carbon through the Earth's atmosphere, oceans, soil, plants, and fossil fuels.

Carbon Dashboard

A digital or online platform that tracks and reports carbon emissions, sequestration, and related farm metrics.

Carbon Dioxide (CO₂)

A major greenhouse gas produced by fossil fuel combustion, deforestation, and agricultural practices; central to climate change.

Carbon Dioxide Equivalent (CO₂e)

A metric measure expressing emissions of various greenhouse gases in terms of the amount of CO₂ that would cause the same amount of warming, based on their global warming potential.

Carbon Dioxide Removal (CDR)

Technologies and practices that actively remove CO₂ from the atmosphere and store it in long-term reservoirs.

Carbon Drawdown

The process of actively removing carbon dioxide (CO₂) from the atmosphere. This is the core objective of carbon-negative farming.

Carbon Emissions

The release of carbon, usually in the form of CO₂, into the atmosphere from human or natural sources (e.g., fossil fuel combustion, respiration).

Carbon Farming

Agricultural practices designed to enhance carbon sequestration and reduce emissions.

Carbon Flux

The rate of transfer of carbon between different pools (e.g., atmosphere, vegetation, soil, oceans), often measured in tonnes of carbon per hectare per year (t C ha⁻¹ yr⁻¹).

Carbon Footprint

The total amount of GHG emissions (CO₂, CH₄, N₂O) caused directly or indirectly by farming operations, expressed as CO₂-equivalents.

Carbon Market

A system that allows trading of carbon credits to incentivize emission reductions and sequestration activities.

Carbon Negative Agriculture

Farming systems that remove more CO₂ from the atmosphere than they emit, creating net-negative emissions.

Carbon Negativity

A condition where a system removes more carbon from the atmosphere than it emits, resulting in a net-negative carbon balance.

Carbon Neutrality (Net-Zero)

Achieving a balance between carbon emitted and carbon removed from the atmosphere; emissions are fully offset by removals or credits.

Carbon Pool (Stock)

Components of the Earth's system where carbon is stored, such as soil, vegetation, dead organic matter, sediments, and fossil reserves.

Carbon Pricing

Economic tools (taxes or trading systems) assigning a cost to carbon emissions to incentivize reductions.

Carbon Sequestration Rate (CSR)

The amount of carbon captured and stored in soil per unit area per year, typically expressed in $\text{Mg C ha}^{-1} \text{ year}^{-1}$.

Carbon Sequestration

Long-term storage of atmospheric CO_2 in plants, soils, oceans, or geological formations.

Carbon Sink

Natural or managed systems (forests, soils, wetlands, oceans) that absorb and store more carbon than they release.

Carbon Tax

A direct levy on fossil fuel emissions, encouraging emission reduction through higher costs.

Carbon-Negative Agriculture

Farming practices that remove more carbon dioxide from the atmosphere than they emit, achieving net-negative greenhouse gas emissions.

Carbon-Neutral Agriculture

Managing agriculture so that greenhouse gas emissions and removals are balanced, resulting in net-zero emissions.

Case Study

An in-depth examination of real-world examples or interventions to understand their implementation, outcomes, and lessons.

Cation Exchange Capacity (CEC)

A measure of how well soil can retain and supply cations (positively charged ions) to plant roots. It is key for soil fertility.

Circular Bioeconomy

A resource-efficient economic system where biological resources are sustainably managed and recycled, for example, using manure for biogas or crop residues as livestock feed.

Circular Economy

An approach that minimizes waste and maximizes reuse, recycling, and regeneration of resources, often linked with sustainable farming systems.

Circular Farming Systems

Farming approaches where outputs (waste, residues) are reintegrated into the farm to maximize resource efficiency and minimize environmental impact.

Circular Resource Use

A system of managing resources where outputs, including wastes, are reused or recycled, minimizing loss and maximizing ecological efficiency.

Climate Change Adaptation Training

Structured educational programs that strengthen the ability of farmers and communities to adjust practices and systems in response to climate variability and long-term change.

Climate Finance

Financial mechanisms such as subsidies, grants, or carbon credits that support the adoption of climate-smart and carbon-negative technologies in agriculture.

Climate Literacy

The ability to understand, communicate, and make informed decisions about climate science, impacts, and solutions, essential for effective adoption of carbon-negative farming.

Climate-Positive Branding

Marketing of products that achieve a net reduction in greenhouse gas emissions during their life cycle, exceeding mere “carbon neutrality.”

Climate-Resilient Crop Systems (CRCS)

Integrated agricultural systems designed to maintain productivity and sustainability under changing climate conditions by enhancing diversity, soil health, water efficiency, and ecosystem functions.

Climate-Resilient Land Management

Approaches to managing land and farming practices that increase the ability to withstand adverse climate impacts, such as droughts and

floods.

Climate-Smart Agriculture (CSA)

A farming approach that sustainably increases productivity, strengthens resilience, and reduces greenhouse gas emissions.

Climatic Variability

Unpredictable changes in weather patterns, including droughts, floods, and heatwaves, impacting agricultural productivity and carbon sequestration.

Co-benefits

Positive side effects of carbon-negative practices, including soil health, biodiversity conservation, and rural livelihoods.

Commons

Natural resources such as forests, grazing lands, and water bodies that are collectively managed and used by communities.

Community-Based Learning

Education and training approaches conducted within local communities that emphasize participatory problem-solving and integration of indigenous knowledge.

Community-Based Natural Resource Management (CBNRM)

A participatory approach in which local communities hold authority and responsibility for managing forests, pastures, water bodies, and other natural resources.

Compliance Carbon Markets

Regulated markets established by law (e.g., EU ETS, California Cap-and-Trade).

Composting and Organic Amendments

Recycling organic residues into humus-rich material that enhances soil fertility and sequesters carbon.

Composting

A controlled biological decomposition process that converts organic waste (such as crop residues, manure, or kitchen waste) into nutrient-rich soil amendment.

Conservation Agriculture

A set of soil management practices including minimal soil disturbance (no-till), permanent soil cover (mulching/cover crops), and diversified crop rotation to enhance soil structure, water use, and biodiversity.

Conservation Tillage / No-Till

A soil management practice that reduces soil disturbance, improves aggregation, and lowers erosion, resulting in improved soil structure and reduced GHG emissions.

Controlled Environment Agriculture (CEA)

Crop production systems (e.g., vertical farming, hydroponics, aeroponics) in controlled indoor environments with optimized conditions for growth, resource efficiency, and low emissions.

Cooperatives

Organizations of farmers or producers who collaborate to improve market access, reduce costs, and increase bargaining power.

Cost-Benefit Analysis (CBA)

An evaluation comparing the costs of carbon-negative practices with economic, social, and environmental benefits.

Cover Cropping

Growing crops such as legumes or grasses between main crop cycles to fix nitrogen, add organic matter, and increase soil carbon.

Cradle-to-Grave

A product assessment approach considering all stages from raw material extraction through production, use, and disposal.

Crop Rotation and Diversification

Sequential cultivation of different crops on the same land to enhance soil biodiversity, nutrient cycling, and break pest and disease cycles.

Customary Law

Locally developed, unwritten rules and traditions guiding land use, natural resource governance, and social relations in Indigenous and rural communities.

Decarbonization

The reduction of carbon intensity in energy, agriculture, and other sectors to mitigate climate change.

Decentralized Governance

Distribution of decision-making authority from central governments to local or community institutions for more context-specific management.

Decentralized Waste Management

Community- or household-level systems for managing organic and inorganic waste streams, reducing transport emissions and supporting circular farming.

Decision Support System (DSS)

Digital platforms that combine data (weather, soil, crop, GHG) with AI/ML analytics to provide farmers with actionable recommendations for carbon-smart practices.

Deep-Rooted Perennials

Long-lived plant species with extensive root systems that deposit carbon deep into soil layers, promoting long-term soil organic carbon stabilization.

Deficit Irrigation

A water management strategy where crops are intentionally irrigated below their full water requirements during less sensitive growth stages, improving water productivity without significantly reducing yields.

Deforestation

Permanent removal or conversion of forests for non-forested use, contributing significantly to CO₂ emissions.

Denitrification

Microbial process in soils where nitrate is converted to gaseous nitrogen forms (including N₂O), especially under anaerobic conditions.

Digital Agriculture

The integration of digital technologies (AI, IoT, drones, remote sensing, big data, blockchain) into farming systems to enhance productivity and sustainability.

Digital Extension

The use of mobile apps, online platforms, artificial intelligence, and other digital tools for knowledge dissemination, farmer advisory services, and climate-smart training.

Digital Twin

A virtual replica of a farm or field created using real-time sensor and satellite data to simulate and optimize agricultural decisions.

Direct Emissions

Emissions released from sources that are owned or controlled by an entity (e.g., onsite fuel combustion).

Diversification (in agriculture)

Integrating multiple crops, livestock, or income streams to reduce risks and increase resilience.

Diversity (Genetic/Species/System)

The presence of multiple crop varieties (genetic diversity), different species (species diversity), and farm system components (system

diversity) to build resilience against pests, diseases, and climate stressors.

Drip Irrigation

An efficient irrigation method that delivers water directly to the root zone of plants through a system of tubes and emitters, reducing water loss and improving water use efficiency.

Eco-Labeling

The use of special labels on products to indicate environmentally friendly or sustainable production practices.

Ecosystem Functionality

The natural processes and interactions within ecosystems that sustain environmental health and productivity

Ecosystem Integration

The practice of connecting various elements (e.g., trees, crops, livestock, beneficial insects) within a farming system to enhance ecosystem services, resilience, and sustainability.

Ecosystem Service Markets

Markets that provide financial rewards for maintaining or enhancing ecological functions like carbon storage, biodiversity, or water quality.

Ecosystem Services

Benefits derived from ecosystems, including carbon storage, water regulation, biodiversity support, and soil fertility.

E-Learning

Electronic and online methods of delivering educational content, often including interactive modules, webinars, and digital resources tailored to climate-smart and carbon-negative farming.

Emission Factors

Numerical values representing the average emission rate of a given GHG for an activity (e.g., kg CO₂ emitted per liter of diesel burned).

Emission Hotspots

Specific stages or processes within a system that account for the majority of greenhouse gas emissions, such as enteric fermentation in livestock or waste transport in urban farming.

Emission Intensity

The quantity of greenhouse gases emitted per unit of agricultural output (e.g., CO₂e per liter of milk or kilogram of vegetables).

Emission Inventory

A comprehensive listing and quantification of GHG emissions and removals from specified sources and sinks within a defined boundary and time period.

Emission Reduction Units (ERUs)

Certified credits under mechanisms such as the Kyoto Protocol.

Enhanced Rock Weathering (ERW)

A carbon dioxide removal strategy that involves applying finely ground silicate rocks (e.g., basalt) to croplands to accelerate natural weathering processes, enhancing soil fertility and sequestering CO₂.

Enteric Fermentation

A digestive process in ruminants where microbes in the rumen break down fibrous feeds, producing methane as a by-product.

Enteric Methanogenesis

The microbial pathway in the rumen that produces methane during fermentation, largely carried out by methanogenic archaea.

Environmental Governance

The institutions, policies, and processes through which decisions about natural resources and climate are made and implemented.

Environmental, Social, and Governance (ESG) Investing

Investment approach integrating sustainability criteria, including carbon performance.

Experiential Learning

A hands-on, practice-oriented approach to training that allows learners to gain knowledge through direct experience, reflection, and application in farming contexts.

Extension Education

A branch of education that transfers agricultural innovations and knowledge to farmers through demonstrations, advisory services, and participatory approaches.

Farmer Field Schools (FFS)

Community-based learning groups where farmers experiment, observe, and learn sustainable practices together under guided facilitation.

Farmer Profitability

The economic viability and income sustainability for farmers engaging in carbon-negative farming, influenced by market access, price premiums, and infrastructure.

Farmyard Manure (FYM)

A mixture of animal dung, urine, bedding material, and leftover feed used as an organic soil amendment.

Feed Additives (Methane Inhibitors)

Compounds such as seaweed, tannins, or essential oils added to livestock diets to suppress methane-producing microbes in the rumen.

Financial Barriers

Constraints such as high upfront costs and limited access to credit that hinder adoption of sustainable practices.

Flux

See Carbon Flux.

Food Miles

The distance food travels from production to consumption, with associated transport-related emissions.

Food Security

Availability, accessibility, and affordability of safe and nutritious food; linked to climate-smart agriculture.

Food-Climate Policies

Legislation and strategies aimed at aligning food systems with climate action goals.

Fossil Fuels

Natural fuels (coal, oil, natural gas) formed from ancient organic matter, whose combustion releases significant CO₂.

Free, Prior, and Informed Consent (FPIC)

A principle ensuring Indigenous peoples' right to give or withhold consent to projects affecting their land, resources, or knowledge systems.

Gender Mainstreaming

The process of ensuring equal participation of men and women in education, training, and capacity-building initiatives for climate-resilient and carbon-negative farming.

Generative Adversarial Networks (GANs)

AI models that generate synthetic datasets to supplement limited real-world agricultural data for carbon modeling.

Geographic Information Systems (GIS)

Tools for capturing, analyzing, and mapping spatial data to support land-use planning and carbon hotspot identification.

GHG (Greenhouse Gas)

Atmospheric gases that trap heat; includes CO₂, CH₄ (methane), N₂O (nitrous oxide), etc.

Global Warming Potential (GWP)

A relative measure of how much heat a greenhouse gas traps in the atmosphere compared to CO₂ over a specified time, usually 100 years.

Glomalin

A soil protein secreted by arbuscular mycorrhizal fungi, important for soil aggregation and long-term carbon stabilization.

Governance Frameworks

Policy, regulatory, and institutional arrangements guiding carbon markets and sustainable agriculture.

Green Bonds

Debt instruments financing environmentally friendly projects, including carbonnegative farming.

Green Finance

Financial flows directed toward sustainable and climate-resilient activities.

Green Subsidies

Financial incentives provided by governments or organizations to support environmentally beneficial farming practices.

Greenhouse Gas (GHG) Emissions

Gases that trap heat in the atmosphere, leading to the greenhouse effect and climate change. Key agricultural GHGs include carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O).

Human Capital Development

Investments in education, health, and training that enhance the productivity, resilience, and innovation capacity of individuals and farming communities.

Hydroponics

A soilless farming system where plants are grown in nutrient-rich water solutions, often used in vertical farming and urban agriculture.

Hyperspectral Imaging

Remote sensing technique capturing narrow bands of the electromagnetic spectrum to detect detailed soil and crop characteristics.

Indigenous and Traditional Farming Systems

Agricultural methods developed by local communities over generations, often emphasizing ecological balance, biodiversity, and low-intensity input use.

Indigenous Knowledge (IK)

Local, place-based knowledge developed by Indigenous peoples through generations of interaction with ecosystems, often transmitted orally and through practice.

Indirect Emissions

Emissions that are a consequence of an entity's activities but occur from sources not owned or controlled by the entity (see Scope 2 and Scope 3).

Infrastructure Gaps

Deficiencies in facilities such as cold storage, processing units, and transport logistics that limit farmers' ability to add value and access markets.

Integrated Crop-Livestock Systems (ICLS)

Agricultural systems combining crops and livestock to recycle nutrients, improve soil fertility, and enhance carbon sequestration.

Integrated Nutrient Management (INM)

Combining organic, inorganic, and biofertilizer sources to optimize nutrient use efficiency and reduce emissions.

Intergenerational Transmission

The process by which knowledge, values, and practices are passed from elders to younger generations.

Internet of Things (IoT)

A network of interconnected devices (e.g., soil sensors, drones, weather stations) that collect and share real-time agricultural data.

IPCC (Intergovernmental Panel on Climate Change)

UN body assessing climate science and informing policy.

Knowledge and Awareness Gaps

Insufficient understanding, information, or training among farmers and stakeholders about carbon-negative farming techniques and benefits.

Knowledge Co-Creation

A participatory process where scientists, farmers, policymakers, and other stakeholders collaborate to generate context-specific solutions.

Landscape Stewardship

The collective, long-term management of land and ecosystems by communities to sustain biodiversity, soil health, and ecological balance.

Leaching

The loss of water-soluble nutrients from soil, often due to excessive rainfall or irrigation.

Leakage

The unintended increase in greenhouse gas emissions in one area because of a carbon reduction project in another.

Life Cycle Assessment (LCA)

A method to evaluate the environmental impacts of a product or process from production to disposal, including carbon footprint and energy use.

Lifecycle Emissions

All GHG emissions over the entire lifecycle of a product or process, from raw materials to disposal, also called “cradle-to-grave.”

Light Detection and Ranging (LiDAR)

Remote sensing technology using lasers to map surface features, useful for biomass estimation and carbon modeling.

Livelihood Resilience

Capacity of rural communities to withstand shocks such as climate change impacts.

Low External Inputs

Farming systems designed to minimize dependence on synthetic fertilizers, pesticides, and other externally sourced chemicals, relying instead on on-farm and ecological inputs.

Low/Zero Tillage

Agricultural practice minimizing or eliminating soil disturbance to enhance soil structure, reduce erosion, and build soil organic carbon.

Low-Carbon Agriculture

Farming systems that reduce the emissions intensity per unit output but may not achieve net-zero or carbon-negative status.

Machine Learning (ML)

A branch of AI where algorithms learn patterns from data to make predictions (e.g., estimating soil organic carbon stocks).

Manure Management

The collection, storage, treatment, and utilization of animal manure to reduce methane and nitrous oxide emissions while recycling nutrients.

Market Recognition and Rewards

Economic incentives or premiums provided to farmers who adopt sustainable practices, reflecting the environmental value of their production.

Measurement, Reporting, and Verification (MRV)

Processes ensuring transparency and credibility of emission reductions or sequestration.

Methane (CH₄)

A potent greenhouse gas with high warming potential, mainly emitted by livestock digestion, manure, and rice paddies.

Methane Sensors

Devices (e.g., infrared or laser-based) that measure methane emissions from livestock or manure systems in real time.

Methanogenic Bacteria

Microbes that produce methane in anaerobic environments (e.g., rice paddies, manure storage).

Microbial Biomass

The total mass of the living component of soil microorganisms, important for nutrient cycling and soil fertility.

Microbial Necromass

The remains of dead microbial cells in soils, which form one of the most stable pools of soil organic carbon.

Micro-Irrigation

An umbrella term for various forms of low-volume irrigation (such as drip or sprinkler) that apply water directly to the plant root zone, increasing efficiency.

Milpa System

A traditional Mesoamerican rotational polyculture system, usually involving maize, beans, and squash (“Three Sisters”), which enhances soil fertility, food security, and carbon sequestration.

Minimal or No-Tillage

An agricultural practice that reduces or eliminates soil disturbance during planting and cultivation. This helps to prevent the release of soil organic carbon into the atmosphere and improves soil structure.

Mitigation Potential

Maximum capacity of a system to reduce GHG emissions or increase removals.

Mitigation Strategies (Livestock)

Practices designed to reduce greenhouse gas emissions in animal agriculture, including dietary interventions, manure treatment, agroforestry, and renewable energy adoption.

Mitigation

Measures undertaken to reduce GHG emissions or enhance carbon sinks.

Monitoring, Reporting, and Verification (MRV)

A structured framework for tracking, documenting, and validating carbon sequestration and emissions reductions to ensure credibility in carbon markets.

Monoculture

Cultivation of a single crop species over a wide area, often associated with higher vulnerability and emissions.

MRV (Measurement, Reporting, and Verification)

A framework to ensure transparency and accuracy in reporting emission reductions and carbon sequestration.

Mulching

The practice of covering the soil surface with organic (e.g., straw, leaves) or inorganic materials to conserve moisture, suppress weeds, and improve soil health.

N₂O (Nitrous Oxide)

A potent greenhouse gas with a global warming potential 298 times higher than CO₂ over 100 years.

Nationally Determined Contributions (NDCs)

Climate action commitments submitted by countries under the Paris Agreement.

Nature-Based Solutions (NbS)

Ecosystem-based strategies addressing climate change while supporting biodiversity and human well-being.

Net Zero Agriculture

Farming systems where greenhouse gas emissions are balanced with sequestration or offsets to achieve no net contribution to climate change.

Net-Zero

Achieving a balance between GHG emissions produced and removals, resulting in no net increase in atmospheric GHG concentrations.

Nitrogen Cascade

Movement of excess nitrogen through ecosystems, causing emissions and ecological impacts beyond the application site.

Nomadic Pastoralism

A livestock-rearing system where herders move seasonally with animals across landscapes, maintaining grassland health and carbon storage.

No-Till/Reduced Tillage

Agricultural practice minimizing soil disturbance, improving soil carbon retention and reducing erosion.

Nutrient Cycling

Processes by which nutrients move within the soil-plant system, including uptake by roots, transformation by microbes, and return through organic matter decomposition.

Ocean Acidification

Decrease in ocean pH caused by CO₂ absorption, threatening marine life and reducing ocean carbon sequestration capacity.

Ocean Sequestration

Uptake and storage of carbon by the world's oceans.

Organic Amendments (Compost/Manure)

The use of decomposed organic materials to improve soil organic matter, fertility, and microbial life.

Paludiculture

Cultivation of crops in wet or rewetted peatlands to maintain carbon storage while producing biomass.

Participatory Rural Appraisal (PRA)

A set of participatory tools and methods that enable local communities to analyze their conditions, identify priorities, and plan solutions collectively.

Pastoralism

A livelihood system based on livestock herding, often using rotational or transhumant grazing to sustain grassland ecosystems.

Payment for Ecosystem Services (PES)

Financial compensation to farmers or landowners for providing ecological services, such as carbon sequestration.

Peer-to-Peer Learning

A knowledge exchange model where farmers and practitioners share experiences and best practices directly with one another.

Perennial Cropping

Cultivation of long-lived crops that regrow year after year, maintaining permanent soil cover and storing carbon in deep roots.

Perennial Crops

Plants that live for multiple years, reducing soil disturbance, enhancing carbon storage, and providing continuous cover compared to annual crops.

Peri-Urban Agriculture

Farming systems located on the outskirts of cities, supplying fresh food to urban centers while integrating waste recycling and carbon-negative practices.

Permanence

Ensuring that sequestered carbon remains stored over the long term without reversal.

Photosynthesis

The process by which plants capture sunlight, CO₂, and water to produce biomass, the foundation of carbon sequestration.

Photosynthetic Uptake

Absorption of atmospheric CO₂ by plants through photosynthesis, resulting in carbon storage in plant biomass.

Policy Disconnect

The gap between traditional or community knowledge systems and formal scientific or policy frameworks that often marginalizes Indigenous contributions.

Policy Incentives

Government-led financial or institutional measures encouraging sustainable agriculture (e.g., subsidies, tax breaks).

Polluter Pays Principle

Environmental policy principle requiring emitters to bear costs of pollution control.

Post-Harvest Losses

Loss of agricultural produce quality or quantity after harvest, often due to inadequate storage and processing.

Precision Agriculture Tools

Technologies such as sensors, GPS equipment, and remote sensing systems used to optimize inputs and tailor management to local conditions.

Precision Agriculture

A farming management approach that uses GPS, sensors, drones, and data analytics to optimize input application (water, fertilizer, pesticides), enhancing efficiency and reducing emissions.

Precision Feeding

Nutritional management that aligns feed inputs with the precise requirements of animals, reducing waste and lowering emissions.

Precision Livestock Farming (PLF)

The application of digital technologies, sensors, and automation to monitor animal health, productivity, and emissions in real-time.

Pyrolysis

A thermochemical process of heating biomass in limited or no oxygen to produce biochar, syngas, and bio-oil.

Rebound Effect

The tendency for a reduction in carbon emissions from one source to be offset by an increase in emissions from another source, often due to behavioural or economic changes.

Regenerative Agriculture

A system of farming practices that restore soil health, biodiversity, and ecosystem services while enhancing carbon storage.

Remote Sensing

The use of satellite, drone, or airborne sensors to gather data about land, crops, and ecosystems over large areas.

Renewable Energy in Agriculture

Use of solar, wind, or bioenergy to reduce fossil fuel dependence and emissions from farms.

Resilience (Agricultural)

The ability of farming systems to adapt to and recover from climate shocks while maintaining productivity.

Resource-Conserving Agriculture

Farming practices that maximize agricultural productivity with minimal use of external inputs, leveraging natural ecological processes.

Respiration

The process by which living organisms release CO₂ back to the atmosphere through metabolism.

Result-Based Finance

Funding mechanisms that reward outcomes (such as verified carbon sequestration) rather than inputs or activities, encouraging effective climate action.

Result-Based Financing (RBF)

Payments tied to measurable climate or ecosystem outcomes (closely related to PES).

Rhizodeposition

The release of organic compounds (e.g., sugars, amino acids) from plant roots into the surrounding soil, supporting microbial activity and carbon stabilization.

Rights and Resources Initiative (RRI)

A global coalition advocating for secure land and resource rights for Indigenous peoples and local communities.

Risk Management

Strategies to mitigate the adverse effects of environmental, market, or operational risks on farming livelihoods.

Rotational Grazing

A method of grazing management where animals are moved between pastures to allow vegetation recovery, improving forage quality and soil carbon sequestration.

Ruminant Livestock

Animals (cattle, sheep, goats) with digestive systems that produce significant methane emissions via enteric fermentation.

Sacred Groves

Forest patches preserved due to cultural or spiritual beliefs, functioning as biodiversity hotspots and carbon sinks.

Scalability

The potential to expand and replicate farming practices or interventions across larger geographic areas or different contexts.

Scope 1 Emissions

Direct emissions from sources owned or controlled by an organization.

Scope 2 Emissions

Indirect emissions from the generation of purchased electricity, steam, heat, or cooling consumed by the reporting entity.

Scope 3 Emissions

All other indirect emissions, upstream and downstream, including supply chain and product end-of-life stages.

Sequestration

See Carbon Sequestration.

Shifting Cultivation (Jhum)

A rotational agricultural system where land is cultivated temporarily and then left fallow to regenerate, often integrated with agroforestry practices.

Silvopastoral Systems

Integrated production systems where trees, forages, and livestock coexist, delivering benefits such as shade, biodiversity, and carbon sequestration.

Silvopasture

A form of agroforestry that integrates trees, forage, and livestock, enhancing carbon storage and providing co-benefits for productivity.

Skill Development

Targeted training activities aimed at enhancing specific technical or managerial competencies necessary for implementing carbon-negative farming systems.

Smart Farming

Technology-driven agricultural practice that enhances productivity and sustainability through real-time data monitoring and management.

Smart Irrigation

Advanced irrigation systems using soil moisture sensors, weather data, and automation to optimize water use and reduce energy and emissions.

Social Equity in Climate Policy

Ensuring that marginalized and vulnerable groups benefit equitably from carbon-negative initiatives.

Social Inclusion

Ensuring equitable participation and benefit-sharing of all community members, including marginalized groups, in agricultural development.

Socioeconomic Co-Benefits

Additional positive outcomes of carbon-negative livestock practices, including livelihood diversification, poverty reduction, improved animal welfare, and rural employment.

Soil Carbon Dynamics

The processes of carbon input, storage, and release in soils, influenced by farming practices and environmental conditions.

Soil Health

The capacity of soil to function as a living system, supporting plant growth, maintaining environmental quality, and promoting plant, animal, and human health.

Soil Moisture Sensors

Devices used to measure the amount of water present in the soil, enabling more efficient irrigation scheduling.

Soil Organic Carbon (SOC)

Carbon stored in soil organic matter, a key indicator of soil health and sequestration.

Soil Organic Matter (SOM)

Composed of decomposing plant and animal residues, microbial biomass, and humic substances. SOM drives soil fertility, nutrient supply, pH buffering, and soil structure.

Soil Variability

Differences in soil physical, chemical, and biological properties across regions or fields affecting management outcomes.

Soil-Carbon Dynamics

The processes and interactions governing the storage, release, and transformation of carbon within soils.

Stakeholder Engagement

The process of involving communities, policymakers, scientists, and private actors in decision-making to ensure inclusive governance.

Stress-Tolerant Varieties

Crop varieties bred or selected for their ability to withstand biotic (e.g., pests, diseases) and abiotic (e.g., drought, heat, salinity) stresses.

Sustainability Education

Teaching and learning approaches that integrate environmental, social, and economic dimensions of sustainability, preparing communities for long-term resilience.

Sustainability Standards

Certification frameworks ensuring agricultural and carbon projects meet environmental and social benchmarks.

Sustainable Agriculture

Practices that meet current food needs without compromising the ability of future generations to do the same.

Sustainable Development Goals (SDGs)

A set of 17 global goals adopted by the UN in 2015, addressing poverty, inequality, climate change, and sustainability.

Sustainable Intensification

Increasing agricultural productivity from existing farmland while minimizing environmental impact and conserving resources.

Synthetic Biology

An interdisciplinary field that designs and engineers biological systems, including plants and microbes, to enhance traits such as carbon fixation, nitrogen-use efficiency, or stress tolerance.

Synthetic Data

Artificially generated datasets used to train AI models when real-world field data is scarce.

Synthetic Inputs

Chemical substances such as synthetic fertilizers and pesticides, used to boost crop yields but often leading to environmental degradation when excessively applied.

System Stability

The capacity of a farming system to maintain consistent output and function in the face of environmental, economic, or social disturbances.

Systems Thinking

An integrated perspective recognizing ecological, social, and economic interactions as interdependent parts of a whole, guiding holistic land-use decisions.

Technological Innovations (in Agriculture)

New tools, machinery, data analytics, or practices-such as sensors, remote sensing, drones, and AI-that improve farming efficiency and sustainability.

Technology Transfer

Sharing of tools, methods, and innovations for climate-smart and carbonnegative agriculture.

Tillage

Physical agitation of the soil for cultivation; conventional tillage releases carbon, while reduced/minimum tillage enhances SOC.

Tilth

The physical condition of soil in relation to its suitability for planting and root development.

Traceability

The ability to track agricultural products and carbon credits across the supply chain, often enabled by blockchain.

Tradable Permits

Allowances under cap-and-trade systems enabling market-based emission reductions.

Trade-Offs (Emission)

Situations where reducing one greenhouse gas (e.g., methane) may unintentionally increase another (e.g., nitrous oxide), requiring holistic mitigation planning.

Traditional Ecological Knowledge (TEK)

A subset of Indigenous knowledge focused on understanding ecological processes, resource management, and human–nature relationships, accumulated through generations of observation.

Train-the-Trainer (ToT) Programs

Educational initiatives that prepare a group of trainers or extension workers who can then disseminate knowledge and practices widely.

Transhumance

Seasonal movement of pastoralist communities and their livestock between lowland and highland pastures to optimize grazing, ecosystem health, and carbon retention.

Transpiration

Loss of water vapor from plant leaves, which influences carbon and water cycles.

UN Framework Convention on Climate Change (UNFCCC)

An international treaty adopted in 1992 to address climate change by stabilizing greenhouse gas concentrations.

United Nations Sustainable Development Goals (SDGs)

Global goals promoting sustainable development, several of which (e.g., Climate Action, Zero Hunger, Life on Land) link directly to carbon-negative farming.

Unmanned Aerial Vehicle (UAV) / Drone

Aircraft without human pilots, equipped with cameras or sensors for crop monitoring, methane detection, and carbon mapping.

Urban Agriculture

The cultivation, processing, and distribution of food in urban areas, often using innovative methods such as hydroponics, aquaponics, and rooftop farming.

Value Chain Development

Building efficient systems from production to consumption that maximize benefits for producers and consumers.

Variable Rate Technology (VRT)

A precision agriculture tool that applies inputs (fertilizer, seeds, pesticides) at varying rates across a field according to site-specific conditions, minimizing waste and emissions.

Verification (MRV)

Critical evaluation and documentation of climate benefits or carbon removals, necessary for incentives, credits, and scientific integrity.

Verified Carbon Standard (VCS)

One of the most widely recognized certification standards for carbon credits.

Vermicompost

A nutrient-rich organic fertilizer produced through the breakdown of organic matter by earthworms.

Vertical Farming

A form of controlled environment agriculture where crops are grown in vertically stacked layers, often in urban settings, to maximize space and resource efficiency.

Vocational Training

Practical, career-oriented training that equips individuals with technical skills for employment in agriculture, renewable energy, and sustainable farming systems.

Voluntary Carbon Markets

Non-regulated markets where entities purchase carbon credits to offset emissions beyond compliance.

Waste-to-Energy Systems

Technologies that convert organic waste streams into usable energy forms such as biogas, electricity, or bio-oil, reducing landfill methane emissions.

Water Efficiency/Water Use Efficiency (WUE)

Measures of how effectively water is used in crop production, often defined as crop yield per unit of water used.

Wetland Restoration & Peatland Conservation

Protecting and rehabilitating carbon-rich wetlands and peatlands to avoid emissions and restore carbon sink functions.

Windbreaks / Shelterbelts

Rows of trees or shrubs planted to reduce wind erosion, protect soils, and contribute to carbon storage.

Zabo Farming System

An Indigenous system from Nagaland, India, integrating water harvesting, livestock, agroforestry, and paddy cultivation in a cyclical, carbon-sequestering model.