



## Advancing Climate-Smart Agriculture Integrated Strategies for Sustainable Production, Food Security, and Greenhouse Gas Mitigation

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Climate change is projected to significantly reduce global crop yields and intensify food insecurity, especially without transformative adaptation. Agriculture, a major contributor to greenhouse gas (GHG) emissions, also offers opportunities for mitigation through sustainable practices. This review highlights climate-smart agriculture (CSA) as a vital strategy to enhance productivity, resilience, and reduce emissions. While nitrogen use efficiency (NUE) has improved in developed regions, the global average remains low at 55.47%, emphasizing the need for precision nutrient management. With 40% of farmland degraded, regenerative agriculture is essential to restore soil health, boost biodiversity, and sequester carbon. CSA techniques—such as precision farming, agroforestry, biochar use, and regenerative methods—can enhance soil quality, food security, and climate resilience. However, regional variability necessitates site-specific strategies, and widespread adoption faces economic, technical, and social barriers. Strong policy support and investment are crucial to scaling CSA and securing sustainable, climate-resilient agriculture.

### Introduction

The impact of climate change on agriculture and food security is an escalating global concern. Human activities—including deforestation, excessive fertilizer use, and fossil fuel combustion—are driving greenhouse gas (GHG) emissions and increasing atmospheric carbon dioxide levels, intensifying global warming. Agri-food systems are major contributors, and immediate, decisive action is needed to reduce emissions and avoid severe climate consequences. Climate change, manifested through rising temperatures, altered rainfall patterns, and frequent droughts, continues to challenge global food production. Without transformative adaptation, crop yields are expected to decline significantly by mid-to late-century. Sustainable strategies must focus on reducing emissions, enhancing carbon capture, and adopting adaptive agricultural practices to safeguard food systems.

A fundamental transformation of agriculture is required to achieve sustainability, food security, and climate resilience. Climate-smart agriculture (CSA) offers a holistic solution by integrating precision farming, regenerative methods, biochar use, crop rotation, and agroforestry. These techniques improve soil health, nutrient efficiency, and carbon

sequestration while enhancing yields and reducing environmental impacts. Technologies such as sensors, AI, drones, and robotics enable precision agriculture to boost productivity and resource use efficiency. Regenerative CSA, though still emerging, shows strong potential in restoring ecosystems and reducing reliance on synthetic inputs. However, broader adoption faces challenges, including limited awareness, financial constraints, technical complexity, and gaps in empirical research.

## Climate-Smart Agriculture and Its Role in Mitigating GHG Emissions

Climate change—marked by rising temperatures, erratic rainfall, droughts, and increasing climate variability—poses a growing threat to global societies, particularly impacting smallholder farmers with declining yields and worsening food insecurity. Regions like Africa and small-scale farming communities are especially vulnerable due to limited adaptive capacity and resources. Agriculture plays a dual role in the climate crisis. While unsustainable practices contribute significantly to greenhouse gas (GHG) emissions, sustainable methods offer solutions through improved resource efficiency and carbon sequestration. The sector accounts for roughly one-third of global GHG emissions, a figure expected to grow as the global population nears 10 billion by 2050, increasing food demand and pressure on land and inputs.

To address these challenges, international agreements such as the Kyoto Protocol and Paris Agreement aim to curb emissions and limit global warming. However, current trends indicate that stronger, faster action is needed to meet these goals. In response, climate-smart agriculture (CSA) has emerged as a strategic approach to make agriculture more sustainable and resilient. Built on three pillars—increasing productivity, enhancing resilience, and reducing emissions—CSA integrates practices like precision farming, agroforestry, regenerative methods, and efficient water and nutrient management. Through innovation and sustainability, CSA supports food security while helping mitigate climate change.

## Strategies for Sustainable Agriculture and Greenhouse Gas Reduction

### 1. Precision Agriculture

Precision agriculture is a modern approach that uses detailed, location-specific data to guide smarter farming decisions. By analyzing factors like crop needs, soil conditions, and field variability, farmers can improve efficiency, boost yields, and reduce environmental impacts. This data-driven method enhances productivity and supports sustainable agriculture. Key technologies in precision agriculture include IoT devices, GPS-guided machinery, drones, sensors, and robotics. These tools enable real-time monitoring of field conditions, precise input application, and efficient resource use. Drones and remote sensing assess crop health and soil quality, while GPS equipment ensures accurate planting, fertilizing, and harvesting, minimizing waste and improving operational accuracy.

Beyond boosting productivity, precision agriculture also reduces greenhouse gas emissions by optimizing water, fertilizer, and energy use. Targeted nutrient and water management ensures inputs are applied only as needed, reducing excess and environmental harm. As a result, precision agriculture supports climate-resilient farming and contributes to long-term sustainability.

**Precision Nutrient Management:** Site-specific nutrient management (SSNM) is key to optimizing fertilizer use by aligning nutrient inputs with crop needs and existing soil nutrient levels. By improving nutrient use efficiency (NUE), SSNM boosts yields and profitability while reducing environmental harm—particularly from nitrogen overuse, which contributes to nitrous oxide emissions. Although some regions, like parts of Europe, have achieved NUE levels near 70%, the global average remains around 55%, highlighting the urgent need for more efficient, location-specific nitrogen management practices. Precision agriculture tools, such as variable rate technology (VRT), enable precise input application based on field variability. VRT, guided by GPS and real-time or map-based data, ensures accurate fertilizer placement—improving efficiency and reducing pollution. Studies show that VRT can reduce nitrogen use by over 24% in crops like groundnut and improve energy efficiency and

environmental performance in wheat farming. Tools like Nutrient Expert®, NDVI sensors, and the Leaf Color Chart have also proven effective in improving soil health, yields, and GHG reduction when combined with conservation tillage. Despite the proven benefits, adoption of precision nutrient management remains limited, especially in developing countries. Barriers include lack of awareness, financial constraints, insufficient technical skills, and infrastructure challenges. Even in developed countries, only about one-third of farms use automated spatial management tools. Encouraging broader adoption will require stronger research support, access to affordable technology, targeted education, and practical demonstrations to show the economic and environmental value of these technologies.

**Water Management:** The integration of technologies like artificial intelligence, remote sensing, the Internet of Things (IoT), and machine learning is revolutionizing smart irrigation systems. These advancements provide real-time data on soil moisture, weather, and crop health, helping farmers optimize water use, conserve resources, and maintain crop yields—especially crucial amid climate change and growing water scarcity. Soil moisture directly influences microbial activity and greenhouse gas emissions, making efficient water management vital for both productivity and climate mitigation. Sensor-based irrigation technologies, such as the bioristor biosensor in tomatoes and soil moisture threshold systems in soybeans, have demonstrated significant water savings (up to 50%) without compromising yields. Combining precision irrigation with nutrient management has further improved crop growth and water-use efficiency. Precision irrigation methods—including automated systems and sensor-guided scheduling—are becoming more popular due to their simplicity and effectiveness. The global smart irrigation market is projected to grow from USD 2.0 billion in 2024 to USD 5.8 billion by 2033, driven by technology advancements, water conservation awareness, and supportive policies. Despite these benefits, high initial costs and limited farmer training remain barriers to adoption. However, financial incentives and rising concerns about water scarcity are encouraging uptake. When integrated with precision agriculture, smart irrigation improves soil health, increases yields, and reduces greenhouse gas emissions. Widespread adoption will depend on strong policy support, financial aid, and farmer education to ensure sustainable and climate-resilient agriculture.

## 2. Regenerative Agriculture

Regenerative agriculture (RA) is a holistic farming approach that includes practices like cover cropping, crop rotation, livestock integration, and reduced or no tillage. While there's no single definition, RA broadly aims to restore soil health, enhance biodiversity, increase carbon sequestration, and reduce dependence on chemical inputs. These outcomes contribute to more resilient ecosystems and help mitigate climate change by storing carbon in the soil. RA is gaining attention as a solution to both environmental and social challenges. With nearly 40% of global farmland degraded, simply sustaining current practices is no longer enough. RA goes beyond sustainability by actively regenerating ecosystems—shifting the focus from maintenance to restoration. As the organization reNature puts it, “sustainability is the bridge, and regeneration is the destination.”

Unlike conventional agriculture, which often emphasizes seed inputs and yields, RA centers on soil health and ecosystem function. Its core pillars—soil, water, biodiversity, and carbon—form the foundation of its practices. While the principles are widely applicable, successful implementation depends on adopting site-specific strategies, which will be explored in the following section.

**No-Till or Minimum Tillage:** Soil degradation affects nearly 40% of global land and poses a serious threat to food security. Overuse of mechanical tillage is a major contributor, damaging soil structure, increasing erosion, and reducing fertility. No-till (NT) farming—planting crops without disturbing the soil—is a key solution, helping to preserve moisture, prevent erosion, and maintain organic matter. Particularly effective in sandy or sloped areas, NT also provides economic benefits, though it requires effective weed control through crop rotation, cover crops, mechanical tools, or selective herbicide use.



Minimum tillage (MT), which reduces but does not eliminate soil disturbance, offers a balanced approach that supports microbial activity, improves nitrogen fixation, and enhances soil structure. Conservation practices like retaining crop residues (at least 30% soil cover) instead of burning them can also improve soil moisture, increase carbon storage, and reduce erosion. Research shows NT and MT can significantly increase soil organic carbon (SOC)—by up to 30%—and reduce CO<sub>2</sub> emissions, particularly when combined with organic amendments like manure. However, results vary. In some cases, MT has led to yield losses (e.g., 67% in winter wheat) due to weed pressure and nutrient limitations. Still, long-term profitability under NT is often higher due to reduced input costs, even if yield gains are modest. Despite proven benefits, challenges remain—especially in weed control, nutrient distribution, and access to appropriate machinery. Soil compaction and reduced water infiltration can also limit success if not carefully managed. In developing regions, adoption is slow due to financial constraints and lack of technical infrastructure. While NT and MT offer long-term sustainability and resilience, overcoming practical barriers is essential for broader implementation.

**Cover Crop:** Cover crops are increasingly valued for their ability to improve soil health, reduce reliance on external inputs, and support sustainable agriculture. They enhance soil structure, water retention, microbial diversity, and nutrient cycling while minimizing erosion and nitrogen leaching. Typically planted after the main crop, cover crops can be annual, biennial, or perennial, and are either grazed or incorporated into the soil to boost organic nitrogen availability and support the following crop. Cover cropping contributes to climate resilience by increasing soil organic carbon (SOC), though results vary. While some studies show SOC gains of around 7.3%, others report mixed outcomes depending on factors such as biomass production, soil type, and management practices. A meta-analysis across 190 studies confirmed benefits like reduced compaction and improved infiltration, but emphasized the need for site-specific strategies to optimize results. In addition to enhancing SOC, cover crops reduce nitrate leaching and related nitrous oxide (N<sub>2</sub>O) emissions by limiting soil nitrate levels post-harvest. However, in some cases, they may also increase emissions depending on species, decomposition rates, and moisture conditions. For example, in corn–soybean rotations, cover crops cut nitrate losses by over 50% but raised N<sub>2</sub>O emissions during soybean years. Species like canola and mixed legumes offered more favorable outcomes than others like peas, which increased CO<sub>2</sub> emissions. Despite a slight average yield reduction (~4%) in main crops, combining legumes and non-legumes in cover cropping can boost yields by up to 13%. Integrated with practices like no-till farming, cover crops significantly enhance SOC levels, reduce greenhouse gas emissions, and support long-term food security—making them a cornerstone of climate-smart agriculture when properly managed and tailored to local conditions.

**Crop Rotation:** Crop rotation—the sequential planting of different crops on the same land—is a key practice in sustainable agriculture. It supports soil health by improving nutrient cycling, enhancing microbial diversity, balancing soil pH, and suppressing pests, diseases, and weeds. This method also improves water retention and resource use efficiency, contributing to long-term soil fertility. Integrating legumes into rotations is especially effective for boosting productivity and climate benefits. Studies show that replacing maize–wheat monocultures with legume and cash crop rotations can increase yields by 38%, reduce nitrous oxide (N<sub>2</sub>O) emissions by 39%, and raise soil organic carbon by 8%, while improving farmer income by 20%. Meta-analyses confirm that legume-based rotations are particularly beneficial in poor soils and favorable climates. Overall, crop rotation reduces reliance on chemical inputs, enhances soil carbon storage, and strengthens climate resilience. When combined with complementary practices like intercropping, canopy management, and the use of resistant crop varieties, it becomes a powerful strategy for improving food security and mitigating climate change.

### 3. Biochar Application

Biochar, produced through pyrolysis of organic materials like crop residues and manure, is increasingly recognized for its role in improving soil health, sequestering carbon, and reducing greenhouse gas (GHG) emissions. Its composition varies based on feedstock and production conditions, influencing its effectiveness across different soil types and climates. Biochar enhances soil structure, water retention, pH balance, and nutrient availability while promoting microbial activity. High-temperature, lignin-rich biochar is ideal for carbon sequestration and GHG reduction, particularly in acidic soils, whereas low-temperature, manure-based biochar benefits nutrient-poor soils. Studies report yield increases of 10–25%, and up to 179% when biochar is combined with fertilizers in acidic conditions.

Global analyses show biochar can raise soil organic carbon (SOC) by up to 34.8%, lower global warming potential by 27%, and reduce N<sub>2</sub>O and NO emissions. It also helps remediate contaminated soils and reduce the uptake of toxic metals by crops. However, results can vary depending on soil type, biochar characteristics, and management practices, underscoring the need for long-term research. When integrated with conservation practices like composting, biochar offers substantial gains in productivity and sustainability. Among climate-smart agriculture strategies, it ranks among the most effective for boosting SOC, especially in warm climates and low-input farming systems.

### 4. Agroforestry for Climate-Smart Agriculture

Agroforestry is widely promoted as a climate-smart farming approach that integrates trees, crops, and sometimes livestock within agricultural systems. This method supports biodiversity, improves ecosystem services, and strengthens food security while helping farmers adapt to and mitigate climate change. With agriculture under pressure from climate change, biodiversity loss, and soil degradation, agroforestry offers practical benefits like microclimate regulation, soil erosion control, and resource optimization. For example, systems with 50% tree shade can reduce heat stress and help maintain suitable conditions for crops like coffee.

Agroforestry is also effective in sequestering carbon—both aboveground and in soil—making it superior to monoculture systems in storing carbon and improving soil health. These systems can store 0.29–15.21 Mg C ha<sup>-1</sup> annually aboveground and 30–300 Mg C ha<sup>-1</sup> in soil, depending on tree species, density, and local conditions. Beyond environmental benefits, agroforestry provides additional income opportunities and enhances the resilience of rural livelihoods, making it a key strategy for sustainable, low-carbon agriculture.

## Enhancing Food Security and Nutrition Through the Adoption of CSA Practices

Climate-smart agriculture (CSA) is increasingly recognized as a vital approach to combat climate change's impacts on agriculture, improve resilience, and ensure food security. In developing regions—especially Sub-Saharan Africa—climate change, coupled with structural and institutional challenges, has worsened food insecurity. Issues like shrinking farmland, poor soil fertility, rising droughts, and reliance on rain-fed agriculture are reducing crop yields and threatening rural livelihoods. Climate change also affects food quality, lowering nutrient density in crops due to elevated CO<sub>2</sub> levels and shifting farming practices. This decline in food nutrition, combined with rising prices and disrupted supply chains, intensifies malnutrition, especially in vulnerable communities.

CSA offers a practical solution by linking climate adaptation with sustainable food production. Practices like regenerative agriculture, crop diversification, biochar use, and agroforestry improve soil health, enhance productivity, and reduce greenhouse gas emissions. These approaches not only boost food availability but also improve dietary diversity and household incomes. To effectively address food security under climate change, a collaborative and integrated approach is essential. Governments and stakeholders must support farmers through adaptive technologies, policy reforms, and targeted investments.

Strengthening local institutions and aligning climate and agricultural strategies are key steps toward building resilient, food-secure communities.

### **Bridging the Gap: Challenges, Opportunities, and Future Directions**

Climate change threatens sustainable agriculture through rising temperatures, erratic rainfall, and extreme weather, particularly impacting smallholder farmers in regions like sub-Saharan Africa. With agricultural productivity growing slowly and arable land shrinking due to urbanization, efficient farming practices are urgently needed. Precision agriculture (PA) offers promise for improving yields, resource use, and reducing emissions, but adoption in developing countries remains low due to high costs, limited infrastructure, and lack of training. While developed regions benefit from supportive policies, barriers such as small farm size, poor access to technology, and financial constraints hinder uptake elsewhere. Research shows that combining CSA practices—like crop rotation, intercropping, and soil fertility management—is more effective than using them individually, though success depends on local conditions. Expanding extension services, tailoring technologies to regional needs, and improving farmer access to training, finance, and institutions are essential for wider CSA adoption.

### **Conclusion**

Climate-smart agriculture (CSA) offers a promising path to boost productivity, resilience, and sustainability amid climate change. Precision agriculture enhances resource efficiency through targeted nutrient management, smart irrigation, and data-driven decisions, helping to reduce greenhouse gas (GHG) emissions. Regenerative agriculture further supports climate goals by restoring soil health, increasing carbon sequestration, and promoting biodiversity. However, adoption remains limited due to high costs, technical challenges, and the need for farmer training, especially in developing regions. A holistic strategy—combining policy support, investments, research, and capacity building—is essential to overcome these barriers. Expanding access to CSA technologies and fostering global cooperation can drive widespread adoption, contributing significantly to food security and climate mitigation.

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