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International Journal for Research Trends in Social Science & Humanities
ISSN: 2584-2455, Volume 4, Issue 4
Aug 2026, PP- 1-15

Climate-Smart Agriculture for Sustainable Food Security

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Abstract- Climate change is creating serious challenges for agriculture and food security, particularly for rural and smallholder farming communities. Rising temperatures, irregular rainfall, droughts, floods, water scarcity, soil degradation and biodiversity loss can reduce agricultural productivity and affect rural livelihoods. Climate-Smart Agriculture (CSA) provides an integrated approach to address these challenges by improving agricultural productivity, strengthening resilience to climate change and promoting sustainable management of natural resources. This study examines the role of CSA in achieving sustainable food security from a global perspective. The study adopts a descriptive and analytical research design based on secondary data collected from the Food and Agriculture Organization (FAO), World Bank, Intergovernmental Panel on Climate Change (IPCC), United Nations and other published sources. The study covers the period 2019–2025 and reviews major CSA practices, including conservation agriculture, water-smart agriculture, climate-resilient crop varieties, agroforestry, integrated crop-livestock systems and digital agriculture. The findings indicate that CSA can improve agricultural productivity, farmer income, climate resilience, nutritional security and resource conservation. However, limited climate finance, high technology costs, smallholder constraints, digital inequality, weak extension services and policy gaps continue to restrict adoption. The study recommends stronger financial support, affordable technologies, improved extension services and farmer-centred policies to promote inclusive CSA and strengthen sustainable food security.

Keywords- Climate-Smart Agriculture; Food Security; Climate Change; Sustainable Agriculture; Climate Resilience; Smallholder Farmers; Rural Development

I. Introduction

Agriculture is one of the most important sectors for rural communities because it provides food, employment and income. For many small and marginal farmers, agriculture is not simply an economic activity but a major source of livelihood and household food. However, agricultural production is highly dependent on natural conditions such as rainfall, temperature, soil quality and water availability. Climate change is increasingly disturbing these conditions and creating new risks for farmers across the world.

Global temperatures have increased, and climate-related events such as droughts, floods, heat waves and irregular rainfall are becoming major concerns for agricultural systems. The Intergovernmental Panel on Climate Change (IPCC, 2022) has highlighted that climate change is already affecting food and agricultural systems. Changes in temperature and rainfall can reduce crop yields, increase pest and disease risks and affect livestock production. Smallholder farmers are particularly vulnerable

International Journal for Research
Trends in Social Science & Humanities
ISSN: 2584-2455, Volume 4, Issue 4
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because they often depend on rain-fed agriculture and have limited access to irrigation, credit, insurance, technology and reliable markets.

Food security is another major challenge. Food security does not mean only producing enough food. It also requires that people have economic and physical access to sufficient, safe and nutritious food. The four major dimensions of food security are availability, access, utilization and stability. Climate change can affect all four dimensions. A drought may reduce food availability, a crop failure may reduce farmers' income and access to food, reduced dietary diversity may affect nutrition, and repeated climate shocks may reduce the stability of the food system.

In this context, Climate-Smart Agriculture (CSA) has gained increasing importance. The Food and Agriculture Organization (FAO) describes CSA as an approach that aims to sustainably increase agricultural productivity and incomes, strengthen resilience and, where possible, reduce or remove greenhouse gas emissions. CSA therefore connects agricultural development with climate adaptation and environmental sustainability.

CSA includes both traditional and modern practices. Conservation agriculture, crop diversification, rainwater harvesting, agroforestry and integrated farming can be useful for small farmers. At the same time, digital technologies such as artificial intelligence, remote sensing, geographic information systems, sensors and mobile advisory services can provide new opportunities for climate-risk management. The appropriate combination depends on local conditions, farmer needs and available resources.

The rationale for this study is that climate change, agricultural productivity and food security are closely connected. A decline in agricultural production can affect household income and food availability, while poor agricultural practices can further damage natural resources. Therefore, agriculture needs to become more productive while also becoming more resilient and environmentally sustainable.

Objectives of the study

The study has the following objectives:

1. To examine the concept and importance of Climate-Smart Agriculture.
2. To understand the relationship between CSA and sustainable food security.
3. To examine major climate-smart agricultural practices.
4. To review selected global experiences of CSA.
5. To identify the major challenges to CSA adoption.
6. To suggest policy measures for promoting inclusive and sustainable CSA.

Research Questions

The study addresses the following questions:

1. How does climate change affect agriculture and food security?
2. What are the major practices of Climate-Smart Agriculture?
3. How can CSA contribute to sustainable food security?
4. What lessons can be learned from international CSA experiences?
5. What are the major barriers to CSA adoption?
6. What policies can promote CSA among smallholder farmers?

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Scope of the Study

The study focuses on the relationship between CSA and sustainable food security. It covers selected global experiences, with particular attention to India, Kenya, Brazil, the Netherlands and Vietnam. The study period is 2019–2025. It focuses mainly on secondary evidence and discusses CSA from agricultural, economic, social and environmental perspectives.

II. Literature Review

Climate-Smart Agriculture

Definition

Climate-Smart Agriculture is an approach to agricultural development that seeks to address the combined challenges of food production and climate change. The FAO framework emphasizes three broad objectives: sustainable productivity and income improvement, adaptation and resilience, and mitigation of greenhouse gas emissions where possible (FAO, 2013).

CSA is not a single technology. It is a collection of practices and approaches that can be adapted to different agricultural and climatic conditions. Crop diversification, conservation agriculture, agroforestry, efficient irrigation, resilient crop varieties and digital agriculture can all contribute to CSA.

Evolution

The concept of CSA gained international attention around 2010 as policymakers increasingly recognized that conventional agricultural development approaches needed to respond to climate change. The idea developed from earlier work on sustainable agriculture, conservation agriculture, climate adaptation and low-carbon development. Over time, CSA has moved beyond increasing agricultural production and has increasingly emphasized resilience, resource conservation, farmer livelihoods and food security.

FAO Framework

The FAO framework is based on three interconnected pillars:

1. Productivity: Sustainably increase agricultural productivity and income.
2. Adaptation: Strengthen resilience and adaptation to climate change.
3. Mitigation: Reduce or remove greenhouse gas emissions where possible.

The framework is particularly relevant for developing countries because it recognizes that farmers need both increased productivity and greater protection from climate risks.

Food Security

Food security has four major dimensions.

Availability refers to the physical supply of food through agricultural production, stocks, trade and distribution.

Access refers to people's economic and physical ability to obtain food. Farmers who experience crop losses may face reduced income and therefore reduced access to food. Utilization refers to the nutritional and health benefits obtained from food. Food must be safe, nutritious and part of a diverse diet.

Stability refers to continuous access to food over time. Repeated droughts, floods and other climate shocks can threaten stability.
CSA can support all four dimensions through stable agricultural production, income diversification, improved nutrition and increased resilience.

Climate Change and Agriculture
Climate change affects agriculture through several interconnected pathways. Rising temperatures can create heat stress and reduce crop yields. Changes in rainfall can result in droughts or excessive rainfall. Floods can destroy crops and agricultural infrastructure.

Water resources are also under pressure. Increasing temperatures can raise evaporation, while changing rainfall patterns affect surface water and groundwater availability. Efficient irrigation, rainwater harvesting and soil-moisture conservation can reduce these risks.

Climate change can accelerate soil degradation through erosion, loss of organic matter and declining soil fertility. Conservation agriculture, crop rotation, mulching and agroforestry can improve soil health.

Biodiversity is another concern. Mono-cropping, land degradation and climate change can reduce agricultural biodiversity. Crop diversification and agroforestry can support biodiversity and increase the resilience of farming systems.

Climate-Smart Agriculture and Sustainable Development Goals
CSA has strong links with several Sustainable Development Goals.

- SDG 2 – Zero Hunger: CSA can improve agricultural productivity, food availability, nutrition and sustainable farming.
- SDG 13 – Climate Action: CSA strengthens climate adaptation and can contribute to mitigation through soil management, agroforestry and improved agricultural practices.
- SDG 12 – Responsible Consumption and Production: Efficient use of water, fertilizers, pesticides and energy can reduce resource waste.
- SDG 15 – Life on Land: Agroforestry, soil conservation and biodiversity-friendly agriculture can protect terrestrial ecosystems.

Thus, CSA provides a practical connection between agricultural development and the wider Sustainable Development Agenda.

Theoretical Framework
Sustainable Development Theory
Sustainable Development Theory emphasizes the balance between economic development, social well-being and environmental protection. The Brundtland Commission defined sustainable development as development that meets present needs without compromising the ability of future generations to meet their needs (WCED, 1987). CSA reflects this principle by seeking to improve agricultural productivity without destroying the natural resources required for future production.

Resilience Theory

Resilience Theory focuses on the capacity of individuals, communities and systems to withstand, adapt to and recover from shocks. In agriculture, resilience means the ability of farmers to manage droughts, floods, heat waves, pests and other disturbances. CSA practices such as crop diversification, water management and resilient varieties can strengthen agricultural resilience.

Agro ecological Theory

Agro ecological Theory views agriculture as an ecosystem in which crops, livestock, soil, water, biodiversity and people are interconnected. Crop rotation, mixed farming, agroforestry, biological pest management and recycling of organic materials reflect agro ecological principles.

Together, these three theories provide a useful framework for understanding CSA as a combination of economic sustainability, climate resilience and ecological management.

Research Gap

Existing literature provides substantial evidence on climate change and agriculture, but several gaps remain. Many studies focus on individual CSA practices rather than their combined contribution to food security. There is also a need to connect climate adaptation with food availability, access, utilization and stability.

Advanced technologies receive considerable attention, but smallholder farmers may not have the resources required to adopt them. There is therefore a need to emphasize affordable and locally appropriate CSA practices.
The present study addresses these gaps by examining CSA as an integrated approach linking productivity, resilience, farmer income, nutrition and environmental sustainability.

III. Research Methodology

The study adopts a descriptive and analytical research design. It is based primarily on secondary data and published literature. The descriptive approach is used to explain CSA concepts, practices and challenges, while the analytical approach is used to examine trends and relationships between climate change, agriculture and food security.

The study does not claim to measure the causal impact of individual CSA practices at the farm level. Instead, it provides an integrated assessment of available evidence.
The study uses secondary information from credible national and international sources, including: Food and Agriculture Organization (FAO) , FAOSTAT , World Bank , International Fund for Agricultural Development (IFAD) , IPCC , United Nations , Government reports Academic journals and books , Relevant research publications
Data were collected through a review of official databases, institutional reports and academic literature. Information was organized under the major themes of agricultural productivity, food security, climate risks, water resources, soil health, biodiversity and CSA practices.

The conceptual framework of the study is:
Climate Change → Agricultural Vulnerability → CSA Practices → Productivity + Resilience + Resource Conservation → Sustainable Food Security
The study also examines the contribution of CSA to SDGs 2, 13, 12 and 15.
Descriptive comparisons are used to identify broad trends and differences among countries and CSA practices.

The study has several limitations. First, it relies mainly on secondary data and therefore does not include primary information directly collected from farmers. Second, data availability differs across countries, making international comparisons difficult in some cases. Third, the definition and measurement of CSA practices vary across studies. Finally, some 2025 datasets may be incomplete.

Despite these limitations, the methodology provides a useful basis for understanding the global role of CSA in sustainable food security.

IV. Climate-Smart Agriculture Practices

Conservation Agriculture
Conservation agriculture is based on minimum soil disturbance, soil cover and crop diversification (FAO, 2013). Reduced tillage helps reduce soil erosion, while crop residues protect the soil from excessive heat and rainfall.
Crop rotation can improve soil fertility and reduce pest and disease problems. Conservation agriculture can also improve water retention and reduce dependence on irrigation.

For small farmers, these practices can be useful because they focus on improving natural soil processes. However, farmers may require training and suitable equipment to adopt conservation agriculture successfully.

Water-Smart Agriculture
Water availability is becoming increasingly uncertain due to climate change. Water-smart agriculture focuses on improving water-use efficiency.

Important practices include:
- Drip irrigation
- Sprinkler irrigation
- Rainwater harvesting
- Farm ponds
- Soil-moisture conservation
- Improved irrigation scheduling

Drip irrigation can deliver water directly to plant roots and reduce unnecessary water loss. Rainwater harvesting can provide additional water during dry periods.
Water-smart agriculture is particularly important for rural areas where agriculture depends heavily on rainfall or groundwater.

Climate-Resilient Crop Varieties
Climate-resilient crop varieties can tolerate drought, heat, flooding, salinity or certain pests and diseases. Such varieties can reduce the risk of crop failure.
Crop diversification is also important. Farmers who grow different crops are less dependent on the success of one crop. Traditional and locally adapted varieties may also contain valuable characteristics for climate resilience.
Access to affordable and quality seeds, however, remains essential.

Agroforestry
Agroforestry combines trees with crops and/or livestock. Trees can reduce wind speed, provide shade, control soil erosion and improve biodiversity.
Trees can also provide fruits, fuelwood, fodder and timber, creating additional income sources. Agroforestry therefore contributes to both environmental sustainability and rural livelihoods.

However, appropriate tree species must be selected because poorly planned tree planting may compete with crops for water and nutrients.

Integrated Crop-Livestock Systems
Integrated crop-livestock systems combine crop production and livestock activities. Crop residues can provide livestock feed, while livestock manure can improve soil fertility.

This creates a system of resource recycling. It also provides farmers with multiple sources of food and income.
Such diversification can strengthen resilience because farmers are not dependent on only one activity. However, successful integration requires adequate feed, veterinary services and technical knowledge.

Precision Agriculture
Precision agriculture uses data and technology to manage crops and inputs more accurately. GPS, sensors, satellite imagery and automated irrigation can help farmers apply water, fertilizers and pesticides according to crop requirements.

Precision agriculture can improve input efficiency and reduce environmental damage. However, high costs and limited digital skills can make these technologies difficult for small farmers to adopt.
Cooperative ownership and shared-service models can help reduce costs.

Digital Agriculture
Digital agriculture is increasingly important in climate-smart farming.

Artificial Intelligence
Artificial Intelligence can analyze agricultural data and support crop disease identification, yield prediction, weather-risk assessment and irrigation decisions.

Internet of Things
IoT connects agricultural sensors and equipment. Soil-moisture sensors can provide real-time information and support efficient irrigation.

Drones
Drones can capture high-resolution images to identify crop stress, pests, nutrient deficiencies and water problems.

Remote Sensing
Satellite and aerial imagery can monitor crop health, drought conditions, vegetation and soil moisture across large areas.

GIS
Geographic Information Systems can map soil conditions, water resources, drought-prone areas and agricultural land use.

Big Data
Big data combines information from weather stations, satellites, farms, markets and other sources. When combined with AI, it can improve agricultural planning and climate-risk management.

Table 1. Major Climate-Smart Agriculture Practices

Practice	Main Benefit	Climate Contribution
Conservation agriculture	Improves soil health	Adaptation
Water-smart agriculture	Saves water	Adaptation
Resilient crop varieties	Reduces crop losses	Adaptation
Agroforestry	Protects soil and biodiversity	Adaptation and mitigation
Integrated farming	Diversifies income	Resilience
Precision agriculture	Improves input efficiency	Resource conservation
Digital agriculture	Improves decision-making	Adaptation and efficiency

The important point is that CSA does not mean only advanced technology. Simple practices such as crop diversification, soil conservation and rainwater harvesting can be highly relevant to rural farmers. Modern digital tools can complement these practices where infrastructure and skills are available.

V. Climate-Smart Agriculture and Sustainable Food Security

Agricultural Productivity
CSA can improve agricultural productivity by helping farmers manage climate risks. Resilient varieties, improved irrigation, conservation agriculture and crop diversification can help maintain yields under changing climatic conditions.
Higher and more stable production contributes directly to food availability.

Climate Adaptation
Climate adaptation is central to CSA. Drought-resistant crops, rainwater harvesting, agroforestry, soil conservation and climate information can reduce farmers' vulnerability.
Farmers can also change planting dates and crop choices based on weather information.

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Climate Mitigation
Agriculture can contribute to greenhouse gas emissions through livestock, fertilizer use, rice production and land-use change. CSA can support mitigation through improved fertilizer management, agroforestry, conservation agriculture and better livestock management.

However, mitigation strategies should not compromise farmers' food security or income.

Farmer Income
Climate shocks can reduce farm income through crop losses. CSA can stabilize income through diversification and improved productivity.

Agroforestry can provide additional products, while integrated crop-livestock farming provides multiple sources of income. Digital market information can also improve farmers' marketing decisions.

Access to credit, insurance and markets remains essential.

Nutritional Security
Food security involves quality as well as quantity. Diversified farming can provide cereals, pulses, vegetables, fruits and livestock products.
Mixed farming can therefore improve household dietary diversity and nutritional security.

Resource Conservation
CSA encourages efficient use of land, water, soil and other resources. Drip irrigation can reduce water wastage, while conservation agriculture protects soil.
Resource conservation is important because agricultural production cannot remain sustainable if natural resources are continuously degraded.

Environmental Sustainability
Healthy ecosystems are essential for agriculture. Agroforestry, crop diversification, integrated pest management and conservation agriculture can protect biodiversity and reduce environmental damage.

The relationship can be summarized as:
CSA → Productivity + Resilience + Resource Conservation → Food Availability + Access + Nutrition + Stability → Sustainable Food Security
Therefore, CSA should be viewed as a broad rural development strategy rather than simply a collection of technologies.

VI. Global Best Practices and Case Studies

India
India has a large smallholder agricultural sector and faces droughts, floods, heat stress and irregular rainfall. Climate-smart practices include micro-irrigation, crop diversification, conservation agriculture, agroforestry, climate-resilient varieties and digital agricultural advisory services.

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The promotion of millets and other locally suitable crops is particularly relevant to climate resilience and nutritional security. India's experience shows that CSA does not always require expensive technology. Rainwater harvesting, soil conservation and crop diversification can provide important benefits.

Kenya

Kenya has promoted climate-smart agriculture among smallholder farmers through climate-resilient technologies, sustainable land management, market access and climate information.

The Kenya Climate-Smart Agriculture Project has supported agricultural productivity and resilience among smallholder farmers and pastoral communities. The experience demonstrates the importance of farmer training, climate information and community participation.

Brazil

Brazil provides an important example of low-carbon agriculture. Climate-smart initiatives have included recovery of degraded pasture, no-tillage farming, integrated crop-livestock-forestry systems and improved fertilizer management.

The Brazilian experience shows that agricultural productivity and environmental sustainability can be pursued together when farmers receive technical assistance and financial support.

Netherlands

The Netherlands represents a technology-intensive agricultural model. Greenhouse production, precision agriculture, automated systems and efficient use of water and nutrients are widely used.

The Dutch experience shows the potential of technology to increase resource efficiency. However, it also demonstrates that intensive agriculture can create environmental pressures. Therefore, technology must be accompanied by appropriate environmental regulation.

Vietnam

Vietnam's Mekong Delta provides an important example of climate-smart rice production. Farmers face drought, salinity and changing water conditions.
Water-saving methods such as alternate wetting and drying, improved fertilizer management and better residue management can reduce water use and emissions while maintaining rice production.

Table 2. Global CSA Experiences

Country	**Major Practice**	**Key Lesson**
India	Diversification and water management	Affordable practices are important
Kenya	Climate information and sustainable land management	Extension and community participation matter

Brazil	Low-carbon agriculture	Finance and technical assistance encourage adoption
Netherlands	Precision and greenhouse farming	Technology can improve efficiency
Vietnam	Water-saving rice	Adaptation and mitigation can work together

The main lesson is that there is no single model of CSA. Successful approaches depend on local climate, farm size, resources, institutions and farmer needs.

VII. Challenges to Climate-Smart Agriculture

Climate Finance
Many CSA practices require investment. Small farmers may not have sufficient savings or collateral to obtain loans. Climate finance therefore needs to reach farmers through affordable credit, insurance and targeted programmes.

High Technology Costs
Sensors, drones, automated irrigation and precision equipment can be expensive. Shared equipment services and cooperative models can make technology more accessible.

Smallholder Constraints
Small farms, limited capital, poor infrastructure and uncertain markets can discourage CSA adoption. Farmers need practical demonstrations, financial assistance and market support.

Digital Divide
Digital agriculture requires smartphones, electricity, internet access and digital skills. Rural communities may lack these resources. Local-language services and community-based digital training are therefore important.

Policy Gaps
Agricultural, climate, water and rural-development policies are sometimes poorly coordinated. CSA needs integrated policies and long-term government support.

Weak Extension Services
Farmers need practical information about climate-resilient crops, water management, soil conservation and digital tools. Strengthening agricultural extension is therefore essential.

Climate Uncertainty
Farmers cannot always predict rainfall, droughts and extreme weather events. Better forecasting, early-warning systems and insurance can reduce this uncertainty.

Table 3 CSA Challenges and Solutions

Challenge	Possible Solution
Climate finance	Affordable green credit and insurance
High technology costs	Subsidies and shared services
Smallholder constraints	Training and market support
Digital divide	Local-language digital services
Policy gaps	Integrated policies
Weak extension	More trained extension workers
Climate uncertainty	Forecasting and early-warning systems

These challenges are interconnected. Technology without finance or training may not be useful. Therefore, CSA needs an integrated institutional approach.

VIII. Policy Recommendations

Governments
Governments should integrate CSA into agricultural and climate policies. Investment should be increased in irrigation, rainwater harvesting, rural roads, storage, renewable energy and digital infrastructure.
Special support should be provided to small and marginal farmers through affordable credit, insurance and appropriate subsidies.

International Organizations
International organizations should provide climate finance, technical assistance and knowledge sharing. Greater attention should be given to ensuring that international climate finance reaches vulnerable farming communities.

Financial Institutions
Banks and other financial institutions should develop affordable green agricultural loans. Flexible repayment schedules are important because agricultural income is seasonal.
Crop and climate insurance should also be strengthened.

Research Institutions
Universities and research organizations should develop low-cost, locally suitable technologies. Research should focus on climate-resilient crops, soil health, efficient irrigation, agroecology and digital agriculture.
Scientific knowledge should be combined with farmers' traditional knowledge.

Private Sector
Private companies can provide affordable seeds, irrigation systems, digital platforms, machinery and renewable-energy solutions.
They can also improve market access by connecting farmers with buyers and processors.

Farmers
Farmers should be actively involved in selecting and adapting CSA practices. Farmer organizations and cooperatives can help with collective purchasing, knowledge sharing and market access.

Farmers can gradually adopt crop diversification, rainwater harvesting, agroforestry, conservation agriculture and integrated farming.

The most important principle is that small farmers should not be excluded from climate-smart development.

X. Conclusion

Climate-Smart Agriculture provides an important pathway for addressing the interconnected challenges of climate change, agricultural productivity and food security. Agriculture is highly vulnerable to climate-related risks, while millions of rural households depend on farming for their food and income. Therefore, strengthening the resilience and sustainability of agricultural systems is essential for achieving long-term food security.

The study examined major CSA practices including conservation agriculture, water-smart agriculture, climate-resilient crop varieties, agroforestry, integrated crop-livestock systems, precision agriculture and digital agriculture. The analysis indicates that these practices can contribute to agricultural productivity, climate adaptation, mitigation, farmer income, nutritional security, resource conservation and environmental sustainability.

The study also found that CSA has strong connections with the Sustainable Development Goals. It directly supports SDG 2 (Zero Hunger) and SDG 13 (Climate Action) while also contributing to SDG 12 (Responsible Consumption and Production) and SDG 15 (Life on Land).

The international experiences of India, Kenya, Brazil, the Netherlands and Vietnam demonstrate that CSA can take different forms. India highlights the importance of affordable and locally suitable practices, Kenya demonstrates the importance of extension and climate information, Brazil provides lessons in low-carbon agriculture, the Netherlands demonstrates the potential of advanced technology, and Vietnam shows how adaptation and mitigation can be integrated into rice production.

However, CSA adoption continues to face significant challenges. Limited finance, high technology costs, small landholdings, digital inequality, weak extension systems, policy gaps and climate uncertainty can prevent farmers from adopting suitable practices. These challenges are particularly serious for small and marginal farmers.

The main contribution of this study is its integrated approach to CSA and sustainable food security. It emphasizes that climate-smart agriculture should not be understood only as advanced technology. Simple practices such as crop diversification, soil conservation, rainwater harvesting and agroforestry can be highly valuable when adapted to local conditions.

The policy implication is that governments, financial institutions, international organizations, research institutions, private companies and farmers must work together. Future research should include primary field surveys, farmer-level data and econometric analysis to measure the actual economic, social and environmental impacts of CSA.

Overall, Climate-Smart Agriculture can help create agricultural systems that are productive, resilient, inclusive and environmentally sustainable. Its successful adoption can make an important contribution to sustainable food security and climate action, particularly when the needs and capacities of rural and smallholder farmers are placed at the centre of agricultural policy.

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