

4. Climate Smart Agricultural Practices for Improving Soil Health and Enhancing Crop Productivity

Ritik Kumar Maurya¹, Nisha Pal¹, Paras Arya¹, Nitesh¹

¹ Ph.D. Research Scholar, Division: Department of Agronomy, University- Govind Ballabh Pant University of Agriculture and Technology, Pantnagar.

1. Introduction

Agriculture is simultaneously a major contributor to greenhouse gas emissions and highly vulnerable to the impacts of climate change. Rising temperatures, erratic precipitation, droughts, floods, and increased pest pressures jeopardise soil structure, nutrient availability, and crop yields. Soil degradation through erosion, nutrient depletion, organic matter loss, compaction, salinisation, and desertification undermines agricultural productivity and ecosystem resilience. The Food and Agriculture Organisation (FAO) estimates that up to one-third of the world's soils are degraded, threatening the food security of billions of people (FAO, 2015).

In response, Climate-Smart Agriculture (CSA) has emerged as a strategic approach that aims to increase agricultural productivity and farmer incomes, adapt to and build resilience against climate change, and reduce or eliminate greenhouse gas emissions where possible. CSA encompasses a suite

of practices, technologies, and enabling policies tailored to local contexts and integrated into broader development pathways.

1.2 Definition of Climate-Smart Agriculture

The Food and Agriculture Organisation defines climate-smart agriculture as *an approach that helps guide actions to transform and reorient agricultural systems to effectively support development and ensure food security in a changing climate* (FAO, 2013). CSA does not prescribe uniform solutions; instead, it emphasises context-specific practices that synergistically improve productivity, resilience, and mitigation.

1.3 Objectives of the Article

This article reviews climate-smart agricultural practices, focusing on improving soil health and enhancing crop productivity. It examines:

1. Core principles of soil health and climate-smart management

2. Specific CSA practices and mechanisms of action
3. Effects of CSA on soil physical, chemical, and biological properties
4. Crop productivity outcomes and food security impacts
5. Barriers to adoption and enabling conditions
6. Case studies and empirical evidence
7. Policy frameworks and future directions

2. Soil Health: Concepts and Indicators

2.1 What Is Soil Health?

Soil health (or soil quality) refers to the *continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans*. Healthy soils maintain essential biochemical processes, structural integrity, nutrient cycling, and resilience to stress.

2.2 Indicators of Soil Health

Soil health indicators can be physical, chemical, or biological:

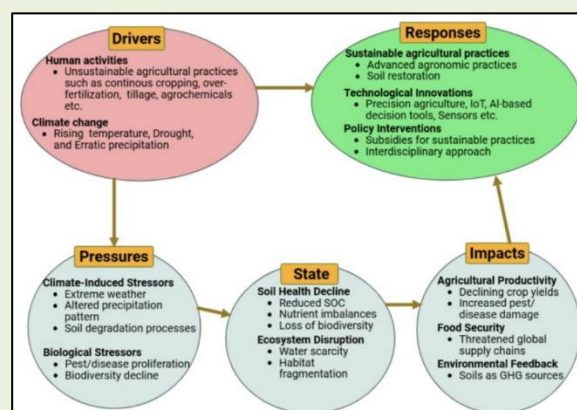
- **Physical:** soil texture, structure, bulk density, porosity, water infiltration, water-holding capacity
- **Chemical:** soil pH, cation exchange capacity (CEC), nutrient

availability (N, P, K, micronutrients), organic carbon

- **Biological:** microbial biomass and diversity, soil respiration, earthworms, enzymes (dehydrogenase, phosphatase)

2.3 Soil Degradation under Climate Change

Climate change accelerates soil degradation by intensifying erosion (via extreme rainfall), reducing soil organic matter (due to higher decomposition rates), increasing salinity in irrigated areas, and disrupting nutrient cycles. Degraded soils have lower water infiltration, reduced nutrient availability, and diminished biological activity, directly impacting crop productivity.



Soil health under climate change and anthropogenic pressures.

3. Core Principles of Climate-Smart Agriculture

Climate-smart agriculture integrates three main objectives:

1. **Productivity enhancement:** sustainable increases in crops and livestock outputs
2. **Adaptation and resilience:** strengthening capacity to anticipate, absorb, and recover from climate shocks
3. **Mitigation:** reducing greenhouse gas emissions and enhancing carbon sinks

These objectives overlap; for example, soil carbon sequestration can improve fertility (productivity), increase drought resilience (adaptation), and reduce atmospheric CO₂ (mitigation).

CSA promotes practices that improve soil structure, organic matter content, nutrient use efficiency, and water availability - all foundational to soil health and climate resilience.

4. Conservation Agriculture

4.1 Principles and Practices

Conservation Agriculture (CA) is a cornerstone of CSA. It is based on three principles:

1. **Minimal soil disturbance** (reduced or zero tillage)
2. **Permanent soil cover** (crop residues or cover crops)

3. **Diversified crop rotations**

4.2 Effects on Soil Health

4.2.1 Soil Organic Matter and Carbon Sequestration

Reduced tillage decreases soil organic carbon oxidation. Crop residues and cover crops add biomass, enhancing carbon inputs. Over time, CA increases soil organic matter (SOM), improving nutrient retention and soil structure.

4.2.2 Soil Structure and Water Dynamics

Minimal disturbance preserves soil aggregates, increasing porosity and infiltration. Residue cover reduces evaporation, enhances moisture retention, and buffers temperature extremes.

4.2.3 Biological Activity

Soil microorganisms thrive in undisturbed environments with continuous organic inputs, improving nutrient cycling and disease suppression.

4.3 Crop Productivity Outcomes

Studies show that CA often increases yields, especially under water-stress conditions. In semi-arid systems, CA has improved water use efficiency and yield stability.

4.4 Challenges and Limitations

- Initial yield penalties in some systems (especially during transition)
- Weed management in zero-till systems
- Need for specialised equipment

5. Cover Cropping and Green Manures

5.1 Definitions and Objectives

Cover crops are non-harvested crops planted to cover the soil between cash crops. **Green manures** are cover crops incorporated into the soil to enrich the soil with nutrients.

5.2 Benefits for Soil Health

5.2.1 Erosion Control

Cover crops protect soil from raindrop impact and runoff.

5.2.2 Nutrient Cycling and Soil Fertility

Leguminous cover crops (e.g., clovers, vetch) fix atmospheric nitrogen, increasing soil nitrogen. Deep-rooted species scavenge residual nutrients and deposit them near the surface upon decomposition.

5.2.3 Organic Matter and Biological Activity

Biomass inputs from cover crops boost SOM and microbial diversity.

5.3 Crop Productivity Enhancement

Cover cropping often increases subsequent cash crop yields by improving nutrient availability and soil structure.

5.4 Case Example: Midwest USA

In corn–soybean rotations, cover crops (rye, clover) reduced nitrate leaching, improved soil organic carbon, and increased yields in drought years.

6. Crop Diversification and Rotations

6.1 Concept and Rationale

Crop diversification broadens the range of species and functional traits in cropping systems. Crop rotations break pest and disease cycles, enhance soil nutrient dynamics, and improve resource use.

6.2 Soil Health Benefits

- **Disease and Pest Suppression:** rotation interrupts pathogen life cycles
- **Nutrient Balancing:** legumes add nitrogen; cereals scavenge phosphorus and potassium
- **Weed Control:** diverse crop traits reduce weed competitiveness

6.3 Productivity and Resilience

Rotations and intercropping often stabilise yields across variable climates by reducing dependencies on single crops.

7. Integrated Nutrient Management (INM)

7.1 Principles of INM

INM optimises nutrient use by integrating:

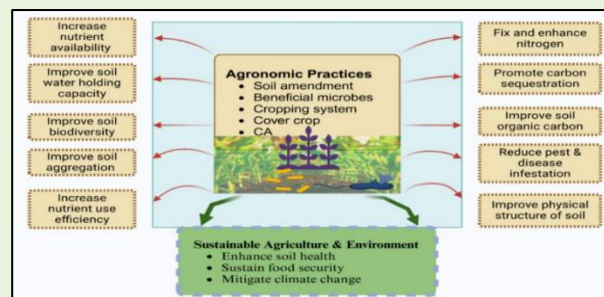
- Organic amendments (manure, compost)
- Inorganic fertilisers
- Biofertilizers (rhizobia, mycorrhizae)

7.2 Soil Fertility and Biological Function

Organic amendments increase SOM, buffer pH, and enhance microbial activity. Biofertilizers improve nutrient uptake efficiency.

7.3 Balanced Nutrition and Crop Productivity

INM reduces nutrient losses (leaching and volatilisation) and increases nutrient availability during critical crop growth stages, thereby positively affecting yields and fertiliser use efficiency.



Agronomic management practices for sustainable soil health, agricultural productivity and environmental protection

8. Agroforestry Systems

8.1 Definition and Types

Agroforestry integrates trees with crops and/or livestock. Types include:

- **Silvopasture:** trees + pasture + livestock
- **Alley cropping:** crops grown between tree rows
- **Windbreaks:** tree barriers reducing wind erosion

8.2 Soil Health Benefits

- **Litter and Root Inputs:** increase SOM
- **Microclimate Regulation:** tree shade reduces soil temperature extremes
- **Erosion Control:** roots stabilise soil

8.3 Productivity Trade-offs and Synergies

Trees may compete for light and water, but when properly managed, synergistic benefits (nutrient recycling and biodiversity) outweigh the costs.

9. Organic Farming and Biological Soil Amendments

9.1 Organic Fertility Sources

Organic farming emphasises compost, manure, crop residues, and amendments that build soil life and fertility.

9.2 Soil Biological Processes

Organic amendments enhance microbial diversity, earthworm populations, soil enzyme activities, and nutrient cycling.

9.3 Organic Yields and Market Value

While organic yields may initially lag conventional systems, premium market prices and improved resilience often offset yield gaps.

10. Precision Agriculture and Digital Technologies

10.1 Tools and Techniques

Precision agriculture uses GPS, sensors, drones, and data analytics to optimise inputs (water and nutrients) and reduce waste.

10.2 Soil Mapping and Variable-Rate Applications

Soil electrical conductivity, nutrient maps, and moisture sensors enable site-specific management that enhances soil health and crop performance.

10.3 Challenges and Adoption Barriers

- High initial investment
- Need for technical skills
- Data management complexity

11. Water-Efficient and Conservation Irrigation Practices

11.1 Deficit Irrigation and Soil Moisture Management

Practices that match water supply to crop demand improve water-use efficiency and prevent soil salinisation.

11.2 Mulching

Organic and plastic mulches reduce evaporation, protect soil structure, and suppress weeds.

11.3 Rainwater Harvesting and Storage

Improves water availability during dry spells and supports soil moisture stabilisation.

12. Reduced Tillage and Soil Disturbance

12.1 Mechanisms and Benefits

Reduced tillage preserves soil structure, reduces organic matter oxidation, and enhances microbial habitats.

12.2 Conservation Practices

- No-till
- Strip till
- Ridge till

These practices lower erosion, improve infiltration, and enhance soil carbon storage.

13. Enhancing Soil Biology and Ecosystem Services

13.1 Mycorrhizal Fungi and Plant Symbioses

Mycorrhizal associations increase phosphorus uptake, drought resilience, and soil aggregation.

13.2 Earthworms and Soil Fauna

Earthworms improve aeration, nutrient mixing, and the decomposition of organic matter.

13.3 Soil Microbial Diversity as a Resilience Indicator

Diverse microbial communities improve nutrient cycling, disease suppression, and system stability under stress.

14. Empirical Evidence: Effects of CSA on Soil Health and Productivity

14.1 Meta-Analyses and Global Synthesis

Multiple meta-analyses show CSA practices (CA, INM, cover cropping) increase soil organic carbon, water retention, nutrient use efficiency, and yield stability.

14.2 Regional Case Studies

- **Sub-Saharan Africa:** CA + INM increased maize yield by 25–40%
- **South Asia:** cover crops + balanced fertilisation improved rice–wheat systems
- **Latin America:** agroforestry enhanced soil carbon and coffee productivity

15. Barriers to CSA Adoption

15.1 Socioeconomic Constraints

- Land tenure insecurity
- Limited access to credit and inputs
- Knowledge gaps

15.2 Policy and Institutional Barriers

- Lack of tailored extension services
- Weak incentives for soil carbon sequestration

- Subsidies favouring conventional inputs

15.3 Technological and Knowledge Gaps

- Need for localised CSA practices
- Limited data and predictive tools

16. Policy and Institutional Frameworks

16.1 International Frameworks

- **Paris Agreement:** agriculture adaptation and mitigation
- **UN SDGs:** sustainable agriculture and land health

16.2 National Policy Instruments

National climate-smart strategies, soil health missions, subsidies for CSA practices, and carbon markets can incentivise adoption.

17. Future Research and Innovation Needs

17.1 Climate-Responsive Soil Health Indicators

Develop indicators that integrate soil biological and climate vulnerability metrics.

17.2 Digital and Decision-Support Tools

Climate and soil modelling, mobile advisories, and AI for precision CSA.

17.3 Scaling Inclusive CSA Pathways

Participatory approaches, gender integration, and youth engagement.

18. Conclusions

Climate-smart agriculture offers a pathway to reconcile productivity, resilience, and sustainability. Practices that build soil organic matter, optimise nutrient cycles, enhance biodiversity, and improve water retention strengthen the capacity of agricultural systems to withstand climate stress while enhancing crop productivity. Policy support, research investment, and targeted incentives are required to achieve large-scale CSA adoption. Integrating traditional knowledge with modern technologies can accelerate transitions to sustainable, climate-resilient food systems.

References

- FAO (2015). *Status of the World's Soil Resources*. Food and Agriculture Organisation of the United Nations.
- Lal, R. (2016). Soil health and carbon management. *Food and Energy Security*, 5(4), 212–222.
- Smith, P. (2019). How to measure, report and verify soil carbon change to realise the potential of soil carbon sequestration for atmospheric

- greenhouse gas removal. *Global Change Biology*, **26**(1), 219–241.
- Hobbs, P. R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B*, **363**(1491), 543–555.
- Thierfelder, C. (2017). Conservation agriculture and climate change resilience in smallholder systems of southern Africa. *Journal of Crop Improvement*, **31**(3), 1–29.
- Lal, R. (2020). Regenerative agriculture for food and climate. *Journal of Soil and Water Conservation*, **75**(5), 123A–124A.
- Pretty, J., & Bharucha, Z. P. (2014). Sustainable intensification in agricultural systems. *Annals of Botany*, **114**(8), 1571–1596.
- Burney, J. A. (2010). Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences*, **107**(26), 12052–12057.
- Powlson, D. S. (2011). Soil management in relation to sustainable agriculture and ecosystem services. *Food Policy*, **36**(S1), S72–S87.
- Pretty, J. (2008). Agricultural sustainability: Concepts, principles and evidence. *Philosophical Transactions of the Royal Society B*, **363**(1491), 447–465.
- Tittonell, P. (2014). Ecological intensification of agriculture. *Current Opinion in Environmental Sustainability*, **8**, 44–51.
- Giller, K. E. (2009). Conservation agriculture and soil carbon sequestration: What is realistic? *Field Crops Research*, **114**(1), 1–12.