Annamalai University & MANAGE, Hyderabad

CLIMATE SMART
AGRICULTURAL TECHNOLOGIES

Edited by

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N. Balasubramani

National Institute of Agricultural Extension Management (MANAGE)
(An Autonomous Organization of Ministry of Agriculture and Farmers' Welfare Government of India)
Rajendranagar, Hyderabad

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This e-book is a compilation of resource materials obtained from various subject experts in the collaborative online training programme on "Climate Smart Agriculture Technologies" which was conducted from 16-18 September, 2025 by MANAGE, Hyderabad and Centre for Natural Farming and Sustainable Agriculture, Faculty of Agriculture, Annamalai University, Tamil Nadu. This e-book is designed for researchers, academicians, extension workers, research scholars and students in the field of agriculture and allied sectors. The information published in this e-book is useful for educational and knowledge sharing purpose only. Neither the publisher nor the contributors, authors and editors assume any liability for any damage or injury to persons or property from any use of methods, instructions, or ideas contained in the e-book.

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Foreword

Climate change presents unprecedented challenges to agriculture, necessitating innovative, adaptive, and sustainable solutions to ensure food security and environmental resilience. In this context, *Climate Smart Agriculture Technologies* is a timely and relevant publication that addresses the urgent need to align scientific advancements with practical, climate-resilient agricultural strategies.

This edited volume is an outcome of the Collaborative Online Training Programme on "Climate Smart Agriculture Technologies", jointly organized by the Centre for Natural Farming and Sustainable Agriculture (CNFSA), Faculty of Agriculture, Annamalai University, and the National Institute of Agricultural Extension Management (MANAGE), Hyderabad, during 16–18 September 2025. Such collaborations between academic and extension institutions play a crucial role in strengthening capacity building and translating research into field-level impact.

The book brings together contributions from eminent experts, offering integrated insights into climate-resilient practices, technological innovations, and extension approaches essential for adapting agriculture to changing climatic conditions, and its availability as an e-book through MANAGE ensures wide access for diverse stakeholders.

This publication will be highly beneficial to students, researchers, academicians, extension personnel, policymakers, and farming communities, serving as both a reference and a practical guide for promoting sustainable and climate-smart agriculture.

I congratulate the editors for their vision, dedication, and coordinated efforts, and commend all the authors for their valuable scholarly contributions. These are indeed commendable efforts. I wish the team all the best and am confident that this book will be immensely helpful to stakeholders engaged in agricultural development and climate resilience.

(A.Velmurugan)

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Preface

Agriculture in the twenty-first century faces the challenge of sustaining productivity under the increasing pressures of climate change, natural resource degradation and increasing food demand. Erratic rainfall patterns, rising mean temperatures, shifting pest-disease dynamics, declining soil health and ecosystem instability have collectively intensified the vulnerability of farming systems across diverse agro-ecologies. Ensuring food and nutritional security for a growing population, while safeguarding environmental quality, necessitates a paradigm shift toward climate-resilient and resource-efficient agricultural practices.

Climate Smart Agriculture (CSA) has emerged as a holistic and adaptive strategy designed to address the productivity enhancement, resilience building and mitigation of greenhouse gas emissions. By integrating smart agricultural practices with ecological sustainability and policy support, CSA offers viable solutions to minimize climate risks.

The edited volume, Climate Smart Agricultural Practices, comprises fourteen comprehensive chapters that offer a multidimensional perspective on climate-resilient agricultural development. This compilation of chapters is an outcome of the Collaborative Online Training Programme on "Climate Smart Agriculture Technologies", conducted by the Centre for Natural Farming and Sustainable Agriculture, Annamalai University, Tamil Nadu, with the support of MANAGE, Hyderabad. These chapters are thoughtfully curated by the researchers and academicians working at the forefront of climate-resilient agriculture

This compilation is intended to serve as a valuable resource material for researchers, academicians, students, policymakers, extension personnel and progressive farmers engaged in advancing climate-resilient agricultural systems. We hope that the insights presented herein will facilitate informed decision-making and contribute to building sustainable and adaptive farming systems capable of withstanding the challenges of a changing climate.

We gratefully acknowledge the contributions of all chapter authors whose expertise and commitment have made this volume possible. We wish to express our sincere gratitude to the authorities of Annamalai University for their encouragement and institutional support extended throughout the preparation of this volume and during the online training programme. We are also thankful to the authorities of MANAGE for their recognition of the importance of climate-smart agriculture and their valuable support in offering training to scientists, students, stakeholders, extension officials and farmers across the country to enrich their knowledge on climate-smart agriculture, thus facilitating the publication of this book successfully.

R. RAMAN

N. BALASUBRAMANI

CONTENT

CLIMATE SMART AGRICULTURAL PRACTICES TO ENHANCE THE PRODUCTIVITY OF CROPS AND ENSURE FOOD SECURITY

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ABSTRACT

Climate change presents an unprecedented, multifactorial threat to global agriculture, jeopardizing the very foundation of food security. For a nation like India, a recognized global agricultural powerhouse, the challenge is particularly severe. Transitioning towards a resilient and sustainable agricultural paradigm is a national imperative. Climate-Smart Agriculture (CSA) emerges as a powerful, integrated approach to address this challenge. This chapter provides a comprehensive overview of CSA, articulating its core principles of sustainably increasing productivity, enhancing adaptive capacity and reducing or removing greenhouse gas emissions. We delve into a suite of field-tested, scientifically-validated agronomic interventions, organized by key management pillars: climate-smart soil, water, nutrient, pest and weed management. The chapter also explores the critical role of next-generation agronomic and genetic innovations, including holistic models like Organic and Natural Farming and the transformative power of the Digital Revolution for Climate-Smart Agriculture. Drawing upon recent scientific evidence and case studies, this chapter illustrates the tangible benefits of CSA in boosting crop yields, optimizing resource use and securing farmer livelihoods in the face of a changing climate.

Keywords: *Climate change, Climate-Smart Agriculture, Food security, Resilience and Sustainability.*

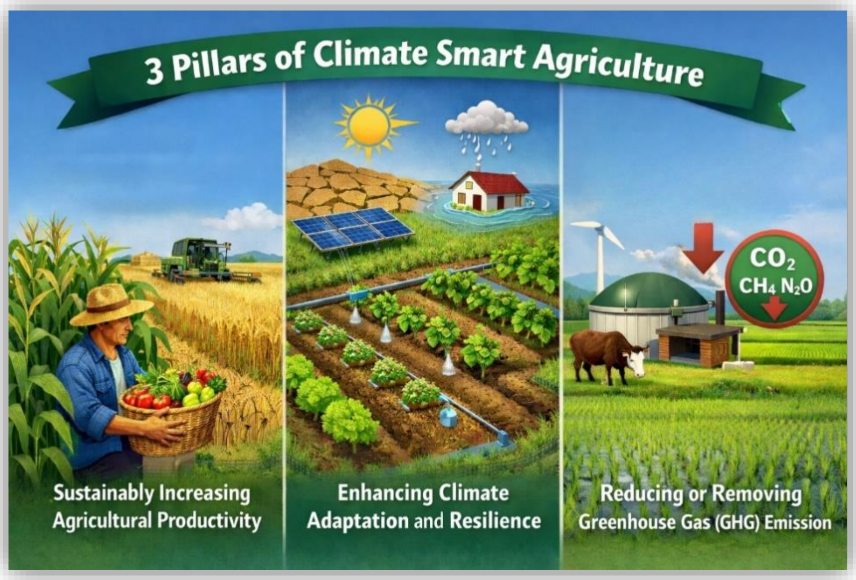
1. INTRODUCTION

The Unfolding Climate Crisis and the Agricultural Imperative

The 21st century is defined by the dual challenge of feeding a growing global population while coping with the escalating impacts of climate change. Agriculture, the bedrock of human civilization, sits at the epicentre of this challenge, being both a victim and a contributor to the climate crisis. India, despite its status as a global agricultural leader, being the world's largest producer of milk and pulses and holding the largest area under rice and wheat, faces profound vulnerability. Our agricultural sector is highly sensitive to climate variability, including rising temperatures, erratic rainfall and the increasing frequency of extreme weather events like droughts and floods. The consequences are already visible. Studies confirm that a mere 1°C rise in temperature can reduce the yield of some major crops by 5-10% in India, threatening our national food basket. These climate impacts directly affect crop yields and indirectly influence farming practices, creating a cascade of negative effects on food security, nutrition and rural livelihoods (Shukla *et al*., 2023).

This precarious situation demands a transformation from conventional, resource-intensive practices toward systems that are resilient, efficient and environmentally sound. **Climate-Smart Agriculture (CSA)** provides a holistic and effective pathway forward. The Food and Agriculture Organization (FAO) defines CSA as an approach for transforming and reorienting agricultural production systems and food value chains to support sustainable development and to ensure food security under a changing climate (FAO, 2017). It is built upon three interconnected pillars:

1) **Sustainably Increasing Productivity** to enhance agricultural output and incomes without degrading the natural resource base.
2) **Enhancing Adaptation and Resilience** to reduce the vulnerability of farmers to climate shocks by strengthening their adaptive capacity and
3) **Reducing or Removing Greenhouse Gas (GHG) Emissions** by lowering emissions for each unit of food produced and sequestering atmospheric carbon wherever possible.



This chapter synthesizes the scientific evidence behind key CSA practices and agronomic interventions, with a special focus on their applicability in the Indian context.

2. THE PILLARS OF CLIMATE-SMART AGRICULTURE

At its core, CSA is a practical, on-the-ground approach. Its success is built upon a foundation of integrated, evidence-based agronomic practices. We explore these practices through five key management pillars.

2.1. Climate-Smart Soil Management

Climate-smart soil management focuses on building soil health as the primary buffer against climate shocks, enhancing fertility and sequestering atmospheric carbon.

2.1.1. Conservation Agriculture (CA)

Conservation Agriculture is a foundational system for climate resilience. It is defined by the synergistic combination of three principles: minimal soil disturbance (zero or minimum tillage), permanent soil cover with crop residues or cover crops, and diversified crop rotations.

This system breaks the cycle of soil degradation by reducing erosion, enhancing water infiltration and building soil organic carbon. The residue mulch layer is particularly critical, as it conserves soil moisture, moderates soil temperature and suppresses weeds, creating a stable and favourable environment for crop roots (Ahmad and Wang, 2023).

2.1.2. Carbon Farming and Soil Organic Carbon (SOC) Sequestration

This practice focuses on turning agricultural soils into a net carbon sink. SOC is the cornerstone of soil health, improving its structure, water-holding capacity and nutrient supply. Climate-smart practices like conservation agriculture, agroforestry, biochar application, crop rotation, use of cover crops and improved nutrient management practices directly contribute to SOC sequestration. Some of these practices add more biomass to the soil and reduce the rate of its decomposition, which is often accelerated by intensive tillage and high temperatures (Paustian *et al*., 2016).

2.1.3. Cover Cropping and Green Manuring

These practices involve growing specific crops, such as legumes (e.g., Sesbania, Crotalaria, Cowpea) or non-legumes (e.g., mustard), primarily to benefit the soil rather than for harvest. As cover crops, they protect bare soil from wind and water erosion between main cropping seasons. As green manures, they are incorporated into the soil to add a large amount of organic matter and, in the case of legumes, significant amounts of biologically fixed nitrogen, thereby reducing the need for synthetic fertilizers (Blanco-Canqui *et al*., 2015).

2.1.4. Biochar Application

Biochar is a carbon-rich, charcoal-like substance produced *via* the pyrolysis (low-oxygen heating) of organic residues. Its application to agricultural soils is a powerful mitigation and adaptation strategy. Due to its stable structure, it sequesters carbon for hundreds to thousands of years. Its porous nature dramatically improves soil water retention, increases cation exchange capacity and can help neutralize soil acidity, making crops more resilient to both drought and nutrient stress (Lehmann & Joseph, 2015; Purakayastha *et al*., 2019).

2.1.5. Amelioration of Problem Soils

Climate change is exacerbating soil problems like salinity, particularly in coastal and improperly irrigated areas. Climate-smart amelioration involves using salt-tolerant crops and varieties, improving drainage and applying amendments like gypsum. For acidic soils, which are common in high-rainfall regions, the application of lime or biochar can correct pH, unlocking nutrient availability and improving root growth, which is essential for resilience.

2.1.6. Probiotic Soil Management (PGPR & AMF)

This "living soil" approach involves inoculating soils with beneficial microbes. Plant Growth-Promoting Rhizobacteria (PGPR) can enhance nutrient mineralization, produce phytohormones that boost root growth and induce systemic resistance against diseases. Arbuscular Mycorrhizal Fungi (AMF) form a symbiotic network with plant roots, effectively extending the root system to forage for water and immobile nutrients like phosphorus, significantly enhancing drought tolerance (Mahanty *et al*., 2017).

2.2. Climate-Smart Water Management

Given that climate change primarily manifests through water (droughts and floods), "more crop per drop" is a non-negotiable goal.

2.2.1. Micro-Irrigation Technologies (Drip & Sprinkler)

Micro-irrigation systems represent a paradigm shift from inefficient flood irrigation. Drip systems deliver water and nutrients directly to the root zone, minimizing evaporation and deep percolation losses, achieving application efficiencies of over 90%. Sprinkler systems are well-suited to crops with close spacing and to undulating or sloping lands where surface irrigation is difficult, and it ensures fairly uniform distribution of water under controlled pressure conditions. Both are critical for adapting to water scarcity and can be powered by solar energy for a low-carbon footprint (Kumar *et al*., 2015).

2.2.2. AI, IoT and Sensor-Based Irrigation Scheduling

This is the frontier of smart irrigation. Instead of fixed irrigation schedules, this approach uses data from soil moisture sensors, tensiometers and on-site mini-weather stations, enabling real-time adjustments in irrigation, based on the soil water status measurements and climatic conditions (Nsoh *et al*., 2024). This real-time data is fed into an Internet of Things (IoT) network. Artificial Intelligence (AI) and Machine Learning (ML) algorithms then process this data, along with weather forecasts and crop-growth models, to create probabilistic models that predict the exact water needs (factoring soil, climate & crop parameters) and automate irrigation valves (Srivastava *et al*., 2024; Sekar *et al*., 2024). This transitions from reactive to predictive water management by enabling dynamic variable rate irrigation depending on soil moisture levels and by optimizing every drop of water (Vellidis *et al*., 2016).

2.2.3. Water-Saving Agronomic Systems (AWD, SRI & DSR)

Several agronomic techniques are specifically designed for rice, Asia's thirstiest crop. Alternate Wetting and Drying (AWD) involves periodically drying the paddy, which saves 20-38% of water and drastically cuts methane emissions (Lampayan *et al*., 2015). The System of Rice Intensification (SRI) is a management package that includes transplanting younger seedlings, wider spacing and intermittent wetting, which promotes robust root growth and high yields with less water. Direct-Seeded Rice (DSR) eliminates the need for puddling and transplanting, offering massive labour and water savings.

Alternate Wetting and Drying (AWD)

Direct-Seeded Rice (DSR)

Courtesy: IRRI

2.2.4. Rainwater Harvesting and Watershed Management

This landscape-level approach involves capturing monsoon runoff that would otherwise be lost. On-farm, this includes farm ponds and check dams. At the community level, a watershed management approach integrates soil and water conservation measures (like contour bunding) across the entire catchment to slow water, increase infiltration, recharge groundwater and ensure water availability for dry-season supplemental irrigation.

2.2.5. Soil Moisture Conservation (Mulching & Hydrogels)

These moisture conservation measures link water and soil management. Applying organic or plastic mulch to the soil surface is a highly effective way to reduce direct evaporation, a major source of water loss. Hydrogels, or super-absorbent polymers, can be added to the soil in the root zone. They absorb hundreds of times water of their dry weight and release it slowly to the plant, providing a buffer against short-term drought spells (Muhammad *et al*., 2025).

2.2.6. Physiological Approaches (Antitranspirants)

This is a specialized approach that targets water loss from the plant itself (transpiration). Antitranspirants are compounds (e.g., wax emulsions) sprayed onto the leaves to partially block stomata. More commonly, kaolin clay, a white, reflective mineral, is sprayed on crops. It forms a “particle film” that reflects incoming solar radiation, reducing leaf temperature and transpiration, thereby mitigating both heat and water stress.

2.3. Climate-Smart Nutrient Management

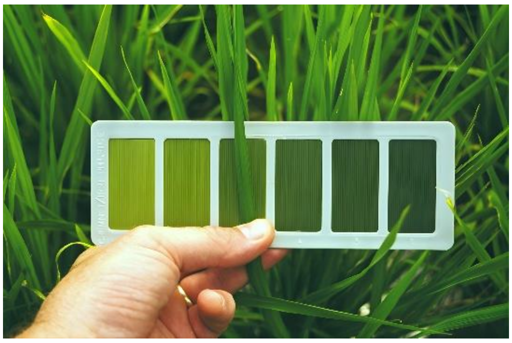
This pillar aims to synchronize nutrient application with crop demand, enhancing efficiency while minimizing environmental losses that contribute to air and water pollution.

2.3.1. The 4R Nutrient Stewardship Framework

This is the guiding philosophy: applying the Right nutrient source, at the Right rate, at the Right time and in the Right place. This data-driven framework moves beyond blanket recommendations to optimize crop uptake, maximize profitability and minimize environmental impact, especially the emission of nitrous oxide (N_2O) (Fertilizer Canada, 2015).

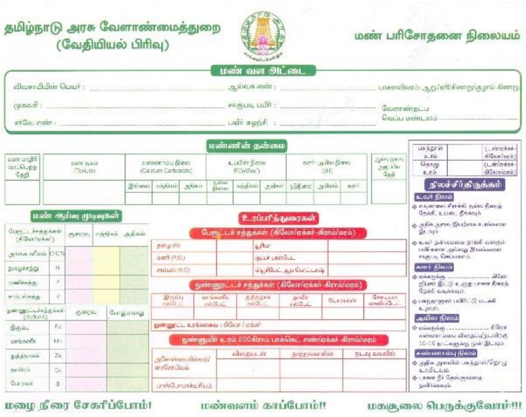
2.3.2. Site-Specific Nutrient Management (SSNM) and Decision Support Systems (DSS)

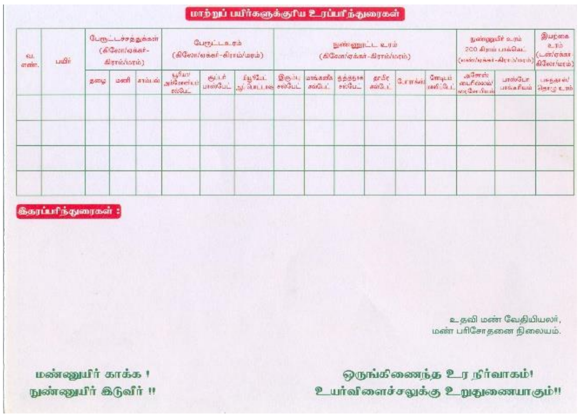
SSNM operationalizes the 4R framework. It uses diagnostic tools like soil health cards, optical sensors (e.g., Green Seeker) and Leaf Colour Charts (LCC) to assess the nutrient needs of a specific field. This data is then fed into Decision Support Systems (like Nutrient Expert®), which are software or mobile apps that provide a field-specific fertilizer recommendation, integrating current conditions with crop models.



Leaf Colour Chart

Green Seeker





Tamil Nadu Government State Department of Agriculture - Soil Health Card

Courtesy: TNAU

2.3.3. Enhanced-Efficiency and Nano-Fertilizers

This is the cutting-edge of fertilizer technology. Enhanced-Efficiency Fertilizers (EEFs) include slow-release, controlled-release and stabilized fertilizers (like neem-coated urea) that protect nutrients from losses. Furthermore, Nano-fertilizers (e.g., IFFCO's nanourea, DAP) are a revolutionary development (Yadav and Mandaliya, 2025). By delivering nutrients encapsulated in nanoparticles, they offer unprecedented nutrient use efficiency, controlled release and targeted delivery (Yadav *et al*., 2023), allowing farmers to reduce fertilizer application rates while maintaining or even increasing yields, all with a minimal environmental footprint (Biswas *et al*., 2025; Yadav *et al*., 2023).

2.3.4. Integrated Nutrient Management (INM) and Bio-formulations

INM is an ecological approach that combines the use of organic manures, composts and green manures with synthetic fertilizers. This synergy builds long-term soil fertility. A key component is the use of biofertilizers, microbial inoculants like Rhizobium, Azotobacter and phosphate-solubilizing bacteria (PSB). Modern liquid bio-formulations and microbial consortia (e.g., Jeevamrutha in natural farming) deliver a diverse community of beneficial microbes that work synergistically to fix nitrogen, solubilize minerals and promote plant health (Mahanty *et al*., 2017).

2.3.5. Fertigation

This practice directly links smart water and smart nutrient management. Fertigation is the application of water-soluble fertilizers through a micro-irrigation (drip) system. This is the ultimate in precision, as it delivers nutrients in small, frequent doses directly to the active root zone, leading to improved nutrient uptake, minimal waste and significantly higher water and nutrient use efficiency.

2.4. Climate-Smart Pest Management

Climate change is altering pest ranges and life cycles, demanding more resilient pest control strategies.

2.4.1. Integrated Pest Management (IPM) as a Core Philosophy

IPM is the foundational strategy, moving away from reactive, calendar-based spraying to a proactive, ecosystem-based approach. It uses monitoring (scouting) and economic thresholds to determine when action is needed, and then prioritizes non-chemical methods first, using pesticides only as a last resort.

2.4.2. Biological Control (Conservation and Augmentation)

Biological control is the use of natural enemies to regulate insect pest populations. Conservation biological control involves modifying the agro-ecosystem through habitat management practices, such as the establishment of flower strips or banker plants, to conserve and support existing populations of beneficial insects like predators (like ladybugs) and parasitoids. Augmentative biological control involves the mass rearing and periodic release of natural enemies or microbial agents to increase their population density and achieve effective pest suppression (Sanda and Sunusi, 2014).

2.4.3. Biopesticides and Natural Plant Products

This is a fast-growing category of “green” pesticides. Microbial pesticides use insect-killing bacteria (*Bacillus thuringiensis*), fungi (*Metarhizium anisopliae*) or viruses (NPV). Botanical pesticides, such as those derived from neem (*Azadirachta indica*), have antifeedant and insect-growth-regulating properties. These products are highly specific, biodegradable and safe for beneficial insects (Jhala *et al*., 2020).

2.4.4. Semiochemicals and Behavioural Manipulation

This high-tech approach uses insect chemical communication. Pheromones (insect sex attractants) are used in traps to monitor pest populations or in mass trapping to "mop up" adult males. In a more advanced technique called mating disruption, the air in an orchard or field is saturated with pheromones, confusing the males and preventing them from finding females, thereby disrupting the next generation.

2.4.5. Next-Generation Biologics (RNAi)

This is a revolutionary, non-GM approach. RNA interference (RNAi) uses topically applied, double-stranded RNA (dsRNA) molecules that are highly specific to a target pest. When the pest ingests the dsRNA (e.g., by spraying it on a leaf), it silences a critical gene, leading to mortality (Darrington *et al*., 2017). This technology is hyper-specific, non-toxic to all other organisms (including humans and bees) and leaves no environmental residue.

2.4.6. Sterile Insect Technique (SIT)

SIT is an environmental friendly, species-specific form of "birth control". It involves mass-rearing a target pest, sterilizing the males (usually with radiation) and releasing them in vast numbers into the wild. These sterile males mate with wild females, who then produce no offspring, causing the pest population to collapse over time (International Atomic Energy Agency - IAEA).

2.5. Climate-Smart Weed Management

Weeds are formidable competitors for light, space, water and nutrients, and climate change may enhance their competitiveness. Integrated Weed Management (IWM) provides a multi-tactic, sustainable solution.

2.5.1. Integrated Weed Management (IWM) Framework

Similar to IPM, IWM is a holistic strategy that combines multiple tactics to manage weeds below their economic threshold, with the goal of reducing reliance on synthetic herbicides. It emphasizes a "many little hammers" approach rather than a single "silver bullet".

2.5.2. Preventive and Cultural Weed Control

This is the first and most important line of defense. It includes preventive measures like using certified clean seed, clean implements, well decomposed FYM, weed free irrigation channels, restricting livestock movement from infested areas, maintaining clean right-of-ways, cutting reproductive weed parts before seed dispersal and enforcing strict weed quarantine laws to block invasive species. Cultural methods are highly effective: crop rotation disrupts the life cycles of specific weeds, while planting cover crops or competitive crop varieties can smother and outcompete weeds for light, space, water and nutrients (Choudhary *et al*., 2024).

2.5.3. Allelopathy for Natural Weed Suppression

Allelopathy is the natural phenomenon where one plant releases biochemicals (allelochemicals) that inhibit the growth and development of another (Sathishkumar *et al*., 2021). This can be harnessed for weed control in several ways: 1) Using allelopathic cover crops (e.g., sorghum, sunflower, brassicas) which residues act as a natural herbicide (Rithiga *et al*., 2024); 2) Intercropping with allelopathic companion plants; and 3) Developing bioherbicides based on these natural allelochemicals, providing an eco-friendly alternative to synthetic chemicals (Scavo and Mauromicale, 2021).

Table 1. Allelochemicals identified from certain important crops

Source Crop	Allelochemicals Present
Arachis hypogaea L.	Phenolic acids (*p*-coumaric and benzoic) and fatty acids (tetradecanoic, hexadecanoic, octadecanoic)
Avena sativa L.	Flavonoids (2-*O*-glucoside, isovitexin 2"-*O*-arabinoside), phenolic acids (caffeic, ferulic, coumaric, salicylic, cynnamic & derivatives) and saponins (avenacoside, 26-desglucoavenacoside, 26-desglucoavenacoside)
Brassica spp.	Glucosinolates [isothiocyanates (allyl-ITC, 2-phenylethyl, 3-butenyl, 4-pentenyl, 4-methylthiobutyl, 5-methylthiopentyl), nitriles (5-methylthiopentanenitrile, 6-methylthiohexanenitrile), oxazolidinethione (goitrin)] and brassinosteroids (brassinolide, 24-epibrassinolide, 28-homobrassinolide)
Carthamus tinctorius L.	Sesquiterpene lactones (dehydrocostuslactone, costunolide) and strigolactones (solanacol, GR24 and abacyl acetate)
Helianthus annuus L.	Sesquiterpene lactones (helivypolide, leptocarpin, annuolide, helieudesmanolide, β-angeloiloxicumambranolide), heliannuoles (heliannuol), bisnorsesquiterpenes (annuionone, dehydrovomifoliol), flavonoids (heliannone, kukulkanine, heliannone, tambuline) and loliolide
Oryza sativa L.	Diterpenes (momilactones & oryzalexins), phenolic acids (caffeic, ferulic, coumaric, salicylic, syringic, p-hydroxybenzoic, cynnamic & derivatives), flavones (5,7,4'-trihydroxy-3',5'-dimethoxyflavone) and cyclohexenones (3-isopropyl-5-acetoxycyclohexene-2-one-1)
Sorghum bicolor L. & *Sorghum halepense*	Benzoxazinoids, benzoquinones (sorgoleone), cyanogenic glycosides (dhurrin), phenolic acids (*p*-hydroxybenzoic, *p*-hydroxybenzaldehyde, coumaric, ferulic)
Triticum aestivum L. & *Triticum durum*	Benzoxazinoids, phenolic acids (trans-ρ-coumaric, cis-ρ-coumaric ferulic, vanillic, syringic, ρ-hydroxybenzoic), fatty acids (acetic, propionic and butyric), triterpenoids and steroids (cholesterol, ergosterol, campesterol, stigmasterol, sitosterol, spinasterol and stigmastanol)

Source: Scavo and Mauromicale (2021)

2.5.4. Physical Methods

This category involves non-chemical, physical interventions. Mulching (with crop residues or plastic) is a important practice that blocks sunlight and prevents weed germination. Soil solarization (covering moist soil with clear plastic in summer) uses solar heat to kill weed seeds and pathogens in the topsoil. The stale seedbed technique involves preparing a seedbed, allowing the first flush of weeds to germinate, and then killing them with a light cultivation or contact herbicide before planting the crop.

2.5.5. Sustainable Weed Control through Bio-agents

Biological weed control offers a sophisticated, nature-based alternative to chemical intervention by utilizing the intricate relationships between plants and their natural enemies. By deploying specialized insects, such as the *Zygogramma* beetle or the *Dactylopius* cochineal, and integrating macro-fauna like grass carp, farmers can build a self-sustaining ecosystem that keeps weed populations below the economic threshold level. These living bio-agents act as targeted tools - consuming weed seeds, boring into stems, or defoliating invasive leaves, thereby reducing the weed's competitive advantage without leaving synthetic residues in the soil or harming the primary crop.

Table 2. Some examples of Bioagents used for targeted weed control

Bioagent	Target Weed	References
a. Insects		
Dactylopius opuntiae, *Dactylopius tomentosus*	Prickly pear (*Opuntia spp.*)	Bankar *et al*. (2023)
Procecidochares utilis	Crofton weed (*Ageratina adenophora*)	
Zygogramma bicolorata	*Parthenium hysterophorus*	
Neochetina bruchi, *Neochetina eichhorniae*	Water hyacinth (*Eichhornia crassipes*)	
Epinotia lantana	*Lantana camara*	
Phytomyza orobanchia	Broomrape (*Orobanche spp.*)	
Agasicles hygrophila, *Amynothrips andersoni*	Alligator weed (*Alternanthera philoxeroides*)	Tanveer *et al*. (2018)
b. Animals		
i. Fish Common carp & Chinese carp	Aquatic weeds	Meena and Sharma (2024)
ii. Mammals Manatee or sea-cow	Aquatic weeds & Water hyacinth	
iii. Snails *Marisa sp.* & other freshwater snails	Submerged weeds like coontail and algae	
iv. Geese and Pigs	*Cyperus rotundus* L.	Cheema (2015)

2.5.6. Weed Control through Bioherbicides - Mycoherbicides

This is an emerging field that uses the natural enemies of weeds. The term "mycoherbicide" refers to the use of plant pathogenic fungi (spores or mycelia) to control weeds. Mycoherbicides are formulations containing specific, host-pathogenic fungi (e.g., *Colletotrichum gloeosporioides*) that are sprayed onto a target weed, causing a disease that kills it without harming the main crop. This is a highly targeted and environmentally safe method.

Table 3. Examples of registered Mycoherbicides and their targeted weeds

Product	Pathogen	Target Weed
DeVine	*Phytophthora palmivora*	Strangle vine in Citrus
Collego	*Colletotrichum gloeosporoides f. sp. aeschynomene*	Joint vetch in Rice & Soybean
Bipolaris	*Bipolaris sorghicola*	Jhonson grass
Biolophos	*Steptomyces hygroscopicus*	Non-specific, general vegetation
Lubao	*Colletotrichum gloeosporioides f. sp. cuscutae*	Dodder in soybean
BioMal	*Colletotrichum gloeosporioides f. sp. malvae*	Round leaved mallow in Wheat, Lentil and Flax
Stumpout	*Cylindrobasidium leave*	Acacia species in native vegetation and water supplies
CASST	*Alternaria cassiae*	Sickle pod and coffee senna in Soybean and Groundnut

Source: Meena and Sharma (2024)

2.5.7. Precision and "See and Spray" Technology

This technology drastically reduces herbicide use. Advanced systems use drones or tractor-mounted cameras with machine vision (AI) to "see" and identify weeds in real-time. This activates "spot-spray" nozzles that apply a microdose of herbicide only to the weed, leaving the crop and soil untouched. This "see and spray" approach can reduce herbicide consumption, saving money and protecting the environment (Shaner and Beckie, 2014).

3. AGRONOMIC AND GENETIC INNOVATIONS: THE BLUEPRINT FOR RESILIENCE

While the previous sections focus on managing inputs, this section addresses the fundamental design of the farming system itself, the genetics we use and the spatial and temporal arrangement of those genetics on the landscape.

3.1. Genetic and Breeding Innovations

Creating crops that are inherently resilient to climate shocks from the cellular level is most critical in CSA.

3.1.1. Molecular Breeding (MAS and Genomic Selection)

This represents a significant leap beyond conventional selection. Marker-Assisted Selection (MAS) allows breeders to see the genes responsible for a desired trait (like drought tolerance) using molecular markers. This accelerates the breeding of climate-resilient varieties by allowing for the selection of superior plants at the seedling stage, most famously used to pyramid the SUB1 gene for flood tolerance in rice. Genomic Selection (GS) is even more advanced, using genome-wide marker data to predict the performance of complex, polygenic traits (like yield under heat stress), further enhancing the speed and precision of breeding programs.

3.1.2. Genome Editing (CRISPR-Cas9)

This is the revolutionary tool of modern genetics. CRISPR-Cas9 and related technologies allow for the precise, targeted editing of a plant's existing DNA to enhance specific traits (Erdogan *et al*., 2023). Unlike traditional GMOs, this can be used to simply knock out a gene related to stress susceptibility or finely tune the expression of a resilience gene. This technology is being used to rapidly develop crops with stacked tolerance to multiple abiotic stresses like heat, drought and salinity, which often occur simultaneously in a changing climate (Kanth *et al*., 2025; Kaur *et al*., 2025).

3.1.3. Breeding for Root System Architecture (RSA)

A hidden but critical climate-smart trait is what happens below ground. Breeders are now actively selecting for superior Root System Architecture. This includes traits like a deeper, more vigorous root system to "mine" water from lower soil profiles during drought or a steeper root angle to improve nutrient foraging efficiency. This is a key frontier in developing "drought-avoidant" cultivars.

3.1.4. Biofortification for Nutritional Resilience

Climate change, particularly elevated atmospheric CO_2, has been shown to reduce the concentration of essential micronutrients like zinc and iron in staple crops. Biofortification is a climate adaptation strategy that uses breeding (both conventional and molecular) to develop crop varieties (e.g., high-zinc wheat, iron-rich pearl millet) that are inherently more nutritious, ensuring food security also means nutritional security.

3.2. Climate-Smart Cropping and Farming Systems

This involves redesigning the farm as an integrated, resilient ecosystem, moving away from vulnerable monocultures.

3.2.1. Crop Diversification (Intercropping, Relay and Strip Cropping)

This system is the opposite of a monoculture. Growing a wide range of crops helps reduce the risks associated with climate variability, total crop loss and soil degradation, and provides multiple source of food and income (Raman *et al*., 2025). Intercropping involves growing two or more crops together in the same field at the same period of time (e.g., a cereal-legume mix), creating biodiversity that can confuse pests, improve soil fertility (*via* the legume) and provide a buffer if one crop fails. Relay cropping (planting a second crop into the first before harvest) and strip cropping (planting crops in alternating, narrow strips) are other methods to maximize resource use efficiency (light, water, nutrients) and build system resilience.

3.2.2. Adoption of Climate-Resilient Crops (e.g., Millets)

A key agronomic shift is replacing water-intensive, climate-vulnerable crops (like rice and sugarcane) with crops that are naturally resilient. Millets (e.g., sorghum, pearl millet, finger millet) are a prime example. These "smart crops" are deeply rooted, highly water-use efficient, tolerant of high temperatures and nutritionally dense, making them an ideal choice for adapting to arid and semi-arid regions. Millets exhibit lower carbon footprint compared to major staple crops (Zhang *et al*., 2017) and the carbon sequestration potential of millets is exponentially higher than that of other crops (Meena *et al*., 2022).

3.2.3. Agroforestry and Silvopastoral Systems

Agroforestry is a quintessential CSA practice that integrates trees and shrubs with crop and/or livestock systems. This multi-stratum system creates a buffered microclimate, reduces wind and water erosion, enhances biodiversity (including pollinators) and provides diversified income (timber, fruit, fodder, fuelwood). Silvopastoral systems (trees + pasture + livestock) are particularly resilient, as the trees provide shade and fodder for animals, reducing heat stress and improving animal welfare (Jose, 2019).

3.2.4. Integrated Farming Systems (IFS)

IFS represents the pinnacle of on-farm synergy and resilience. It is a holistic model that combines multiple enterprises such as crops, livestock, aquaculture, poultry, duckery, apiculture and agroforestry in a way that the waste from one component becomes a resource (input) for another. For example: crop residues feed livestock; livestock manure feeds a biogas digester (providing cooking fuel); the digested slurry fertilizes crops and feeds a fish pond. This "closed-loop" system minimizes external inputs, recycles nutrients, provides multiple income streams (spreading risk) and ensures year-round food and energy security for the farm family (Biswas *et al*., 2024).

Integrated Rice + Fish + Poultry System established in the Experimental Farm, Department of Agronomy, Annamalai University, Tamil Nadu

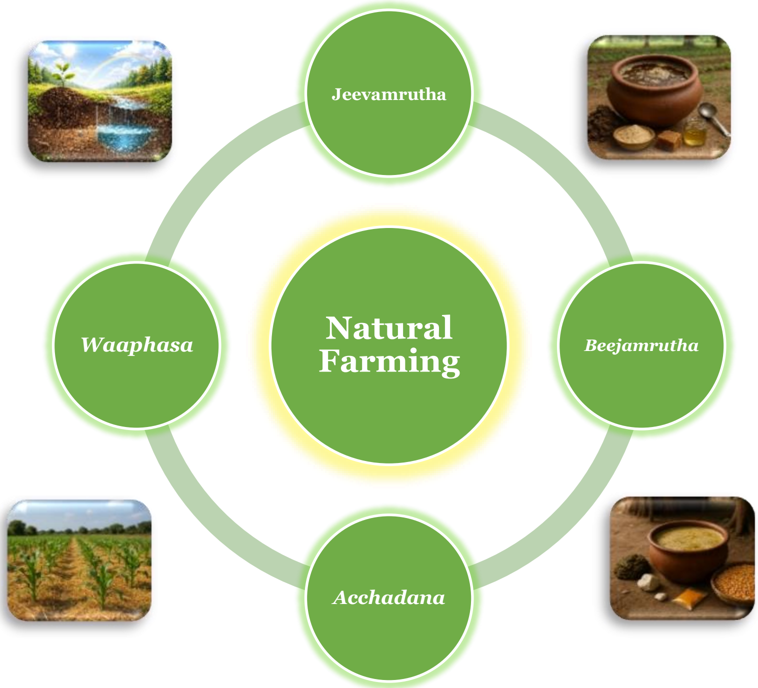
3.2.5. Organic Farming Systems

Organic Farming is a certified system that builds resilience by making high soil organic matter as its central pillar. By prohibiting synthetic fertilizers and pesticides, it relies on compost, green manures and crop rotation. This methodology results in soils with demonstrably higher organic carbon and superior water-holding capacity, making them more resilient to drought and extreme rainfall. The primary mitigation benefit is the complete avoidance of synthetic nitrogen fertilizer, which eliminates the associated N_2O emissions from its production and application (Reganold and Wachter, 2016). The Organic and Natural Farming systems are holistic systems and by their very design, are climate-smart.

3.2.6. Natural Farming Systems

Natural Farming system, such as India's Zero Budget Natural Farming (ZBNF), is a low-cost, climate-resilient model focused on enhancing soil microbiology using *in-situ* resources (Saxena *et al*., 2022). Its core principles are *Jeevamrutha* (a fermented microbial inoculant), *Beejamrutha* (a seed treatment), *Acchadana* (mulching) and *Waaphasa* (soil air & water balance), which are direct climate-adaptation strategies (Prem et al., 2023). Acchadana (mulching) conserves soil moisture and buffers soil temperature, while *Waaphasa* reduces water needs (Deb and Bhowmick, 2023).

By fostering a "living soil" through microbial formulations derived from local cow dung and urine, this system aims to restore ecosystem function and nutrient cycling (Kumar *et al*., 2020). Its emphasis on eliminating external inputs provides profound economic resilience, protecting farmers from debt and volatile input markets, which is a critical adaptive capacity in itself (Das *et al*., 2024).



3.2.7. Carbon Farming

Carbon farming refers to a range of land use and land management practices designed to reduce emissions from farming activities or sequester carbon in natural sinks such as soil and vegetation (Smith *et al*., 2005). Carbon farming is a whole-farm approach with a set of agronomic practices aimed at capturing and storing carbon in soils, reducing greenhouse gas emissions and preserving already stored carbon (Petropoulos *et al*., 2025).

Carbon capture and storage, emission avoidance, and emission reduction are the primary goals of Carbon farming. Carbon farming practices include minimal tillage, crop residue management, cover cropping, mulching, biochar application, manure management, agroforestry, wetland restoration, etc. These regenerative practices hold immense potential to mitigate greenhouse gas emissions, enhance soil health, foster biodiversity and strengthen farm resilience to climate variability by sequestering carbon in the soil and vegetation.

4. MITIGATING AGRICULTURAL GREENHOUSE GAS EMISSIONS

The third principle of CSA is mitigation and it is not merely a supplementary but is deeply integrated into the management practices discussed. It involves targeted strategies to reduce the three primary gases: methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2).

4.1. Methane (CH_4) Mitigation

Methane, a potent GHG with a high short-term warming potential, originates primarily from anaerobic decomposition in rice field and livestock.

4.1.1. Methane mitigation from Rice field: The goal is to interrupt anaerobic methanogenesis.

- **Water Management (AWD & DSR):** Alternate Wetting and Drying (AWD) is one of the most effective strategy for methane emission reduction in rice fields. By introducing aerobic periods and intermittent irrigation, it breaks the methane production cycle (Sarma and Boruah, 2024). IRRI states that AWD has proven to effectively mitigate methane from rice production by 30-70%, without causing a yield reduction. Direct-Seeded Rice (DSR) is another strategy that avoids the initial, methane-intensive puddling and flooding phase altogether.
- **Organic Matter Management:** While organic matter is good for soil, incorporating large amounts of fresh crop residue just before flooding provides a massive food source for methanogens. Climate-smart mitigation involves composting residues aerobically before incorporation or applying them well before flooding.
- **Nutrient Amendments:** The use of sulfate-containing fertilizers (e.g., ammonium sulfate) can suppress methanogens, as sulfate-reducing bacteria outcompete them for substrate.

4.1.2. Methane mitigation from Livestock (Enteric Fermentation): This is a major challenge, focused on rumen microbiology.

- **Advanced Feed Supplements:** This is a rapidly advancing field. Specific compounds are added to the feed to inhibit methanogenesis. Leading examples include the red seaweed *Asparagopsis taxiformis*, which has shown >80% reduction in methane, and synthetic inhibitors like 3-Nitrooxypropanol (3-NOP), which is now commercially available in many regions (Duin *et al*., 2016).

- **Improved Forage and Diet Quality:** Higher-quality, more digestible forages pass through the rumen faster and leave less substrate for fermentation, lowering methane emissions per unit of milk or meat produced.
- **Genetic Selection:** Breeding programs are now beginning to identify and select for cattle that are naturally low-methane emitters, a trait that appears to be heritable.

4.1.3. Methane mitigation from Manure Management: Storing manure in anaerobic lagoons is a major source of methane.

- **Anaerobic Digesters:** This is a "win-win" technology. Instead of letting manure decompose in an open lagoon or pit, it is placed in a sealed digester. The anaerobic microbes still produce methane, but it is captured. This "biogas" is then burned for electricity or heat, converting the potent CH_4 into CO_2 (which is ~28 times less potent).
- **Aerobic Composting & Solid Separation:** By separating solids from liquid manure and aerobically composting them, the entire methanogenic pathway is prevented.

4.2. Nitrous Oxide (N_2O) Mitigation

N_2O, a long-lived and extremely potent GHG (nearly 300 times the warming potential of CO_2), is primarily released from agricultural soils through the microbial processes of nitrification and denitrification, which are supercharged by excess nitrogen fertilizers.

4.2.1. The 4R Framework as the Foundation

As discussed earlier, applying the Right Source, Rate, Time and Place is the most important mitigation strategy (Johnston and Bruulsema, 2014). This philosophy, when operationalized, ensures that nitrogen (N) is taken up by the crop, not lost to the environment.

4.2.2. Precision Technologies (SSNM & VRT):

Site-Specific Nutrient Management and Variable Rate Technology (VRT) are the key players in mitigating N_2O. By using sensors and data to apply only the amount of N the crop needs in a specific zone, we prevent the surplus N from becoming the substrate for N_2O production.

4.2.3. Enhanced-Efficiency Fertilizers (EEFs): These are technologically advanced products designed to outsmart the microbial processes that lead to N_2O loss.

- **Nitrification Inhibitors:** Compounds like DCD (dicyandiamide), Nitrapyrin and neem-coating on urea specifically inhibit the enzymatic action of *Nitrosomonas* bacteria. This slows the conversion of stable ammonium (NH_4^+) to mobile nitrate (NO_3^-), reducing the amount of N available for both nitrate leaching and denitrification (which produces N_2O) (Ruser and Schulz, 2015).
- **Urease Inhibitors (e.g., NBPT):** These compounds slow the initial breakdown of urea, reducing gaseous losses as ammonia (NH_3). This keeps more N in the soil in a stable

form, improving efficiency and indirectly reducing the total amount of N fertilizer needed, thus lowering the N_2O potential.

- **Slow/Controlled-Release Fertilizers:** Products like polymer-coated urea release N gradually, synchronizing availability with the crop's uptake curve. This "spoon-feeding" approach prevents the large pool of excess N in the soil that drives N_2O emissions.

4.2.4. Integrated Nutrient Management (INM): By integrating legumes (which fix atmospheric N) into rotations and using composted manure, the total reliance on synthetic N fertilizer is significantly reduced. Less synthetic N applied means a smaller substrate pool for N_2O production.

4.3. Carbon Dioxide (CO_2) Mitigation and Sequestration

CO_2 emissions in agriculture come from energy use and soil degradation, but uniquely, agriculture offers the single largest potential to remove CO_2 from the atmosphere and sequester it in the carbon sink.

4.3.1. Reducing CO_2 Emissions (Energy Use):

- **On-Farm Renewable Energy:** This involves replacing fossil fuels. The most common examples are solar-powered irrigation pumps and biogas digesters for cooking and electricity.
- **Fuel Efficiency:** Conservation tillage/No-till is a major CO_2 mitigation tool, as it drastically reduces the number of tractor passes, reducing diesel consumption (Shakoor *et al.*, 2024). **Precision agriculture** using GPS guidance also optimizes tractor paths and reduces fuel use.
- **Avoiding Land-Use Change:** By increasing yields on existing land (sustainable intensification), CSA prevents the single largest source of agricultural emissions: the deforestation and clearing of new land for farming.

4.3.2. Enhancing CO_2 Sequestration (Carbon Farming):

- **Conservation Agriculture:** By reducing tillage, conservation agriculture prevents the rapid oxidation (release as CO_2) of soil organic matter that has been built up over time (Hussain *et al.*, 2021).
- **Agroforestry and Silvopasture:** This is one of the most powerful sequestration strategies. Trees are, in effect, carbon-capture-and-storage units. They pull CO_2 from the atmosphere and store it in their woody biomass (trunks, branches, roots) for decades or centuries (Jose, 2009).
- **Cover Cropping and Perennials:** Keeping the soil covered with a living plant (either a cover crop or by integrating perennial crops) ensures year-round photosynthesis and addition of biomass, leading to improved soil organic carbon concentration (Blanco-Canqui *et al.*, 2015). This perennialization continuously pumps atmospheric CO_2 into the soil *via* roots and root exudates.

- **Biochar:** When biomass decomposes, its carbon returns to the atmosphere as CO_2. By pyrolyzing it into biochar, that carbon is transformed into a stable, recalcitrant form that resists decomposition, effectively locking it in the soil for centuries (Lehmann & Joseph, 2015).

5. THE DIGITAL REVOLUTION FOR CLIMATE-SMART AGRICULTURE

Nowadays, the “smart” in Climate-Smart Agriculture is increasingly powered by the digital revolution. These technologies are not just additions; they are essential enablers that provide the central system for precision management, allowing farmers to implement the complex strategies discussed above, with accuracy and efficiency.

5.1. Precision Geomatics (GPS, GIS and Remote Sensing)

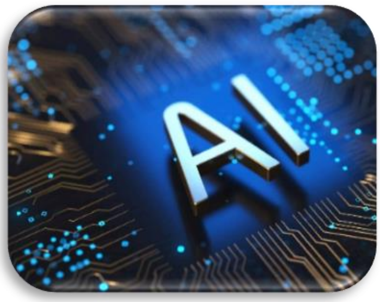
This is the foundation for “seeing” the farm in a new way. Global Positioning System (GPS) receivers on tractors enable precise guidance, auto-steering and the creation of farm maps. Geographic Information Systems (GIS) act as the digital database, layering information (e.g., soil type, yield data, nutrient levels) onto these maps. Remote Sensing, *via* satellites (e.g., Sentinel, Landsat) and Unmanned Aerial Vehicles (UAVs or drones), provides real-time, high-resolution data on crop health (NDVI), water stress and soil conditions, allowing for targeted interventions.

5.2. IoT, Sensors and Actuators for Real-Time Management

If geomatics is the “eyes”, the Internet of Things (IoT) are the “nerves”. This refers to a network of physical devices on the farm that collect and share data. On-site sensors (e.g., soil moisture probes, in-field mini-weather stations, leaf wetness sensors) gather granular, real-time data. This data is transmitted wirelessly to a central platform. The system is completed by actuators, which are the “muscles”; these are the devices that receive commands to automatically turn on irrigation valves, start fertigation pumps or open greenhouse vents based on the sensor data (Nsoh *et al*., 2024).

5.3. Artificial Intelligence (AI) and Machine Learning (ML) in Decision Support

This is the "brain" that turns data into wisdom. AI and ML algorithms analyze the massive, continuous data streams from IoT sensors and drones (Sekar *et al*., 2024). They identify patterns and build predictive models that are impossible for a human to see. This powers the advanced Decision Support Systems (DSS), for example, provide a highly accurate probabilistic irrigation schedule (Srivastava *et al*., 2024; Vaidya *et al*., 2025), forecast pest and disease outbreaks using AI-powered predictive analysis (Palani *et al*., 2023) or recommend a precise, variable rate of nitrogen fertilizer, all delivered through a simple mobile app.



5.4. Big Data, Cloud Computing and Mobile Platforms

The billions of data points generated on a smart farm require a robust infrastructure. Cloud computing provides the scalable, on-demand power to store and process this "Big Data" without requiring expensive on-farm servers (Nsoh *et al*., 2024). The final and most critical, link is the mobile platform. Complex AI-driven insights are translated into simple, actionable recommendations (e.g., "Irrigate Zone B for 45 minutes" or "Pest risk high in north field") and delivered to the farmer's smartphone, democratizing access to powerful technology (Farmonaut Blog, 2025).

5.5. Blockchain for Traceability and Climate-Smart Value Chains

This technology provides the "proof" of climate-smart practices. Blockchain creates a secure, decentralised and immutable (permanent) digital ledger. In agriculture, this can be used to trace a product from the farm to the consumer. This traceability allows a farmer to prove that a product was grown using specific CSA methods. This builds consumer trust, opens access to premium markets and crucially, provides the transparent, verifiable mechanism needed to manage and monetise carbon credits earned from sequestration practices like no-till and agroforestry (Farmonaut Blog, 2025).

6. POLICY, INSTITUTIONS AND THE PATH FORWARD

The most advanced agronomic and digital tools are useless if they are not adopted. Technology is only one part of the solution; the path to a climate-smart future must be built on a foundation of supportive policy, innovative finance and empowered people. The primary barriers for millions of farmers, particularly smallholders, are high upfront costs, perceived financial risk and a lack of technical knowledge. A successful national strategy must therefore break these barriers systematically. This begins with a clear policy signal from governments, moving CSA from a niche concept to the mainstream by integrating it into national agricultural strategies (Aggarwal *et al*., 2018).

A critical step in this policy shift is the strategic realignment of financial support. Public funds must evolve from rewarding resource consumption, such as blanket subsidies for power and fertilizer to actively incentivizing resource conservation. This means increasing financial support toward the adoption of specific CSA technologies like drip irrigation, no-till seeders and solar pumps. This public investment also serves to "de-risk" the transition for farmers and attract private capital. Furthermore, new markets must be established that create a direct economic incentive for stewardship. The development of robust, verifiable agricultural carbon credit markets, for example, can provide a new, tangible income stream for farmers who adopt practices like agroforestry and conservation agriculture that sequester carbon in their soil and biomass.

Finally, a climate-smart transformation is impossible without investing in human capital. The knowledge-intensive nature of CSA, from digital tools to ecological pest management, requires a complete re-imagining of our agricultural extension systems. We must invest in re-training and empowering extension agents to become facilitators of these new technologies. The most effective path forward will combine high-tech digital advisories (delivered *via* mobile phones) with high-touch, participatory learning. Farmer-to-farmer networks and community-based models, such as the Climate-Smart Village approach, are essential for empowering farmers to test, adapt and scale the innovations that are best suited for their unique local conditions (Aggarwal *et al*., 2018).

7. CONCLUSION: CULTIVATING A CLIMATE-RESILIENT FUTURE

The challenge of climate change is not a distant forecast; it is the immediate reality for farmers in India and across the world. The task of ensuring food security in the face of this volatility is the defining agricultural mission of our time. This chapter has demonstrated that Climate-Smart Agriculture is not a singular technology but a holistic, scientifically-grounded approach for this mission. It offers a practical framework to build a food system that is simultaneously productive, resilient and sustainable.

We have moved beyond the era of isolated practices. The true power of CSA lies in the synergies it creates, the way healthy soils built through conservation tillage enhance water infiltration, making crops more resilient to drought; the way precision nano-fertilizers reduce N_2O emissions while boosting profitability; and the way diversified agroforestry systems sequester carbon while providing new income. The digital revolution, as detailed, acts as the catalyst, providing the data to make this complex integration possible at a national scale.

The path forward is clear. It requires a committed, collaborative effort from scientists to innovate, policymakers to enable, institutions to support and farmers to implement. This is not just about adapting to a new climate; it is about designing a new, more intelligent and more resilient future for agriculture. By embracing the principles outlined in this chapter, we can and will build a food-secure nation capable of weathering the challenges to come.

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CONSERVATION TECHNOLOGIES FOR CLIMATE SMART AGRICULTURE

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Introduction

The status of global soil resources published by FAO, 2015 highlights that '...the majority of the world's soil resources are in only fair, poor, or very poor condition'. The report stresses that, soil erosion is still a major threat to ecosystem stability and agricultural productivity, worldwide. Anthropogenic factors such as unsuitable land use practices in modern agriculture, deforestation and overgrazing are some of the causes that trigger the soil erosion thus lead to cascading effects such as nutrient loss, loss of carbon stock and declining biodiversity. More intense hydrological cycles and extreme rainfall events induced by the changing climate are potentially accelerating the erosion rates. Climate change most likely to increase the soil erosion and sediment yield rate by changing the rainfall–runoff erosivity. The extreme rainfall events and continuously changing precipitation patterns are accelerating the rainfall-runoff erosivity and thereby impacts the soil erosion process (Talchabhadel *et al.*, 2020). The significant impact of climate change on soil erosion by changing the precipitation intensity is also demonstrated by Routschek *et al.* (2014); Wen *et al.* (2015); Teng *et al.* (2018) and Borrelli *et al.* (2020).

Soil carbon stock is an important soil fertility component needed to sustain the agricultural production and also regulates the global carbon cycle by controlling the atmospheric CO_2. Soil erosion is a major hazard which is directly affected by the rainfall change caused by the climate change. Accelerated soil erosion as a result of change in the rainfall pattern also depletes the soil organic carbon. Kannan *et al.* (2019) reported that clay loss and organic carbon loss were 4.9 t/ha and 185 kg/ha at 28% slope in Nilgiri hills and these losses resulted in severe productivity loss in cabbage crop. Mondal *et al.* (2016) made an attempt to quantify the impact of climate change on future soil erosion and soil organic carbon under different slope and land use categories in Narmada river basin in India. Least square support vector machine method using Hadley Center coupled model version 3 was used to estimate the future rainfall and reported that, sediment load has changed by 5.33, 17.97 and 58.37% in the 2020s, 2050s and 2080s respectively from the current erosion rate. Similarly, future rainfall data was generated by Khare *et al.* (2016) with the downscaling of global circulation model data to study the climate change impact on soil erosion in the Mandakini river basin, India. The results have clearly showed that, future soil erosion will be increased due to the increasing rainfall intensity due to the extreme weather events.

Many studies have clearly indicated that, significant loss in crop productivity due to the soil erosion. Moreover, loss of the fertile top soil can have considerable impact on nutrient availability; soil water availability and plant growth properties. In a predominantly agricultural system, the objective of improving the productivity, profitability and prosperity of the farmers and achieving agricultural development on an ecologically sustainable basis can be attained only when conservation of the natural resources are assured. Soil erosion control is a pre requisite to achieve the agricultural sustainability in a climate change scenario. Soil erosion can be mitigated using sustainable land management techniques based on the engineering, agronomic, biological and scientific land management practices. This review paper addresses the various soil management strategies to achieve the agricultural sustainability under climate change scenario.

Soil and Water Conservation Strategies

The losses caused by extreme climatic events like high intensity rainfall, drought degradation of soil quality can be minimized by if appropriate soil and water conservation measures are adopted. In rainfed farming, information on rainfall pattern and moisture deficits over time is very helpful in crop planning, rainwater management and other hydrological studies related to agriculture.

A. Agronomical Measures for Arable land

Biological or vegetative measures are preferred in soil and water conservation programmes as they are eco-friendly, sustainable and cost effective (Sharda *et al.,* 2006) These area measures are normally adopted on land having mild slope, less runoff and sediment flow. These can be adopted singly or in combination with mechanical measures depending upon the intensity of soil erosion.

1.0 Tillage

Land and water are closely interconnected and consequently they influence land productivity, therefore, land management techniques that encourage more rainfall to enter the soil are key strategies for improving productivity of rain-fed systems. Climate change scenarios predict an increase in the intensity and frequency of droughts in many cropping regions of the world (Olesen *et al.,* 2011). Deep tillage might be a tool to make crops more resilient to climate change and mitigate yield losses caused by droughts. The soil moisture content in the root zone during the crop growing period in these regions appreciably affects crop growth, development and the overall land productivity especially in semi arid regions. Tillage roughens the soil surface and breaks any soil crust. This leads to increased water storage by increased infiltration. However, response to tillage varies with rainfall, soil type and kind of crops. The crops like maize, pigeon pea, cotton, castor, soybean and sunflower respond very favorably to deep tillage. Mohanty *et al.* (2007) found that sub soiling every year resulted in faster water infiltration rates, greater water storage, and maintained a smaller soil penetration resistance than sub soiling in alternate years or conventional tillage. The yield and water use efficiency after sub soiling was greater than under conventional tillage. Regar *et al.* (2007) found that deep tillage during monsoon season increased seed yield of mustard in loamy soil in semi arid region of Rajasthan. Patil *et al.* (2016) reported that conventional tillage conserved greater rainfall and improved soil physical properties, grain yield and Water Use Efficiency (WUE) compared to reduced tillage in Vertisols of Karnataka (Table 1)

Table 1 Soil moisture, infiltration, sorghum yield and WUE influenced by tillage

Tillage practices	Soil moisture (mm /60 cm depth) at the time of sowing	Infiltration (cm/hr)	Sorghum grain yield (kg/ha)	WUE (kg/ha/mm)
Conventional tillage	278	9.0	433	2.21
Reduced tillage	210	8.2	388	2.0
Less tillage	195	7.4	343	1.87

Source: Patil *et al.* (2016)

Sharda *et al.* (2006) reported that deep tillage has a definite edge over shallow tillage in improving the yields of different dry land crops in the red soils also in southern India, irrespective of type of season (Table 2). Deep tillage with plough followed by chiseling/ cultivator (Channappa, 1994) opens the hard layers and increases the infiltration rate and water-storage capacity and greater availability of soil moisture to plants during drought or drought-like situation caused by climatic variability in the red soils at Bengaluru, Karnataka and Coimbatore, Tamil Nadu, India (Table 3).

Table 2 Effects of shallow and deep tillage on the yield of different crops in Southern India

Type of season	Crop	Grain yield (q/ha)		Rainfall during the crop growth period (mm)
		Shallow tillage	Deep tillage	
Sub normal	Sorghum	17.4	18.1	264
	Finger millet	1.0	1.5	124
	Castor	3.8	4.3	264
	Castor	2.8	2.8	269
	sunflower	8.1	8.1	149
Normal	Pigeon pea	2.5	2.9	149
	Sorghum	26.6	29.5	259
	Pearl millet	19.4	22.3	399
	Castor	7.8	12.7	621
Above normal	Sorghum	26.1	26.5	609
	Pearl millet	16.0	16.3	529
	Castor	9.6	12.7	883

Table 3. Water storage in the profile as influenced by deep tillage in red soil

Depth (cm)	Soil moisture content (%) after 81 mm rainfall	
	Ploughed area	Non-ploughed area
0-15	10.74	3.59
15-30	13.22	7.13
30-45	12.27	8.59
45-60	13.33	dry

Source: Channappa, 1994

2.0 Land Configuration

Management of rainwater, especially *in situ* conservation, is an important component of resource conservation practices for augmenting crop productivity in slopy dry land conditions. Few of the land on figurations *viz.*, contour farming, land smoothening, dead furrows, compartmental bund broad bed furrow and raised and sunken bed system that are very effective in-situ rainwater-conservation measures, particularly in low-rainfall areas are discussed below.

2.1 Contour cultivation or cultivation across slope

Contour farming is any effective and low-cost method of controlling erosion, conserving moisture and improving crop yields. The purpose of contour farming is to reduce runoff and soil erosion on mild slopes. This practice can also increase crop yield through the soil moisture retention in arid and semiarid regions. Generally, the common method of cultivation on sloping land is along the slope and it cause spoor rainfall infiltration and accelerates soil erosion. Carrying out all the field operations including owing of crops across the slope and along contour (contour cultivation) provides a series of miniature barriers to running rainwater and reduces runoff, soil loss and increases soil water and nutrient storage in soil profile. Contour cultivation is recommended for all types of soils, rainfall up to 1,000 mm and slope varying from 0.5 to 4%. It helps in reduction of runoff by impounding rain water in small depressions and reduces the development of rills. In practice it is often difficult to establish all crop rows on the true contour because of non-uniform slopes in most of the fields under Indian situations. In some situations, it is desirable to provide a small slope along the row (cultivation across the slope), to prevent runoff from a large storm breaking over the small ridges formed during the contour cultivation. The effectiveness of this practice varies with rainfall, soil type and topography. Maximum effectiveness of this practice is on medium slopes and on permeable soil. The relative effectiveness decreases as the land grade becomes very flat or very steep. On long slopes, where bunding is done to decrease the slope length, the bunds can act as guidelines for contour cultivation. On the mild slopes where bunding is not necessary, contour guidelines may be marked in the field. On undulating fields having number of depressions and ridges, contour cultivation is likely to be difficult. Land smoothing is needed to fill up such depressions.

Contour cultivation on steep slopes or under conditions of high-rainfall intensity may cause formation of gullies because row breaks may release the stored runoff water to next downstream row. The simple contour cultivation in the farmers' fields in red soils of Kabbalanala watershed near Bengaluru reduced runoff and soil loss conserved rainwater in-situ and increased soil moisture in the profile, thus increasing the yields of sesame (*Sesamum indicum* L.), fingermillet [*Eleusine coracana* (L.) Gaertn] and groundnut (*Arachis hypogaea* L.) over farmers' practice of up and down cultivation. The moisture-conservation effect of contour cultivation was more felt when crops were supplemented with NPK fertilizers (Krishnappa *et al.,* 1994, 1999). Contour cultivation resulted in 35% and 22% higher grain yields in sorghum and setaria (*Setaria* sp.), respectively, in black soils and 66% more grain yield in sorghum in red soils over up and down cultivation (Rammohan Rao *et al.,* 1985). This simple technology of contour cultivation at Bellary, India, was more beneficial (92% increase in yield) over farmers' practice of up and down cultivation during a drought year (Ramamohan Rao *et al.,* 2000). Ramajaneyulu *et al.* (2020) reported that contour farming gave higher corn equivalent yield and conserved more moisture than up down farming in a rainfed alfisols. Contour cultivation of maize reduced runoff by 23.7% and soil loss by 31.6% compared to up and down cultivation, and contour cultivation increased maize yield by 24% in Chandigarh (Sharda *et al.* 2006).

2.2 Compartmental bunding

Compartmental bunds convert the area square/rectangular compartment to impound rainwater. These are practices in medium and black soil area to store rainwater in the soil profile during mansoon for the use of rabi crop. Compartmental bunds provide greater opportunity time for rainwater to infiltrate into the soil and wet the soil profile completely for early sowing of winter crops thus giving greater crop yields. The size of the compartmental bunding varies with slope and slope of the field. Compartments of 6m x 6 m upto 1% slope; 4.5 m x 4.5 m for 1-2% slope, and 3m x 3m for 2% slopes are recommended (Sharda *et al.,* 2006). In Vertisols of Bijapur, compartmental bunding conserved more rainwater and resulted in 23% higher winter sorghum yield over flat sowing (Patil and Sheelavantar, 2004). In Vertisols at Bellary, compartmental bunding increased sorghum yields by 17% and water-use efficiency by 13% over flat bed (Patil, 2003). Effect of compartmental bunding on crop productivity was more during a drought year compared to normal rainfall situation. Increased soil moisture content and 36.7% higher chickpea yield due to compartmental bunding was also reported by Patil *et al.* (2026) in Vertisol of Ballary area.

2.3 Ridges and furrows

Formation of fridges and furrows has been found most suitable for soil moisture conservation and to reduced runoff and soil loss, particularly in light soils. Open the furrows at 50 to 60 cm apart across the slope in medium to deep black soils, after completion of primary tillage, during the second fortnight of June to lay out the field into ridges and furrows. This can be done through a ridger/plough attached to either tractor or bullocks. Cultivation of crops under ridge- and furrow-system across the major land slope with a gradient of 0.2 to 0.4% in land having 1 to 3% slope will conserve more rainwater in situ. This is suitable for widely spaced crops with 60 cm or more row spacing. A field length of 60 to 90 m is optimum for cultivation of crops with ridges and furrows. Gupta (1995) reported that the bare ridge and furrow method of rainwater harvesting can significantly improve the tree growth of *Azadirachta indica*, *Tecomella undulata* and *Prosopis cineraria* in the Indian desert with an annual rainfall of about 30 cm which is characterized by a few showers of high intensity. In Vertisols of Bellary, ridges and furrows were more effective in conservation of rainwater and increased more winter sorghum grain yield during a drought year (36%) compared to normal year (16%). In sunflower, seed yield increased by 21 and 24% and WUE by 11 and 21% at research farm and farmers' fields, respectively (Patil *et al.*, 2013). Even ridges and furrows increased the WUE of winter sorghum by 16% over flat sowing. Similarly, at Bijapur, India, formation of ridges and furrows in Vertisols conserved more rainwater in situ and resulted in 26% higher winter sorghum grain yields and 25% greater WUE over flat sowing (Patil and Sheelvantar, 2004). Studies conducted on moisture conservation for cowpea [*Vigna unguiculata* (L.) Walp.]– ragi double cropping system in the red soils at Bengaluru revealed that ridging up after flat on a grade sowing is more advantageous. An evaluation of furrows for managing soil and water

2.4 Broad-bed furrow system

The ridges and BBF developed by the International Crops Research Institute for semi-arid tropics (ICRISAT, India) for increasing the productivity of semi-arid poorly drained Vertisols, provide more opportunity for infiltration of rainwater and at the same time prevent water logging of the crop growing on the bed. The BBF system consists of a relatively raised flat bed or ridge approximately 95 cm wide and shallow furrow about 55 cm wide and 15 cm deep across the slope on a grade of 0.2 to 0.6% for optimum performance. The bed width also depends on the crops, soil type, and rainfall. The furrow act as drainage for removing excess water and broad bed stores rainwater. In block soil crops are sown in pre-formed beds made before the season and maintained year after year. This will save considerable cost as well as improve the soil health. This is suitable for narrow-spaced row crops. Even if a few rows are lost due to the furrow, the yields are made up owing to better in-situ rainwater conservation. Wani *et al.* (2005) also observed the performance of the broad bed and furrow system was consistently superior to the traditional system in reducing annual run-off, soil loss, and peak run-off rate. Mishra *et al.* (2003) observed during normal rainfall years, BBF landform treatment alleviated water logging and increased productivity of soybean. In an experiment conducted at Gujarat, India to compare various sixes of broad-bed furrow system for its efficiency against conventional flat bed system revealed that significantly highest groundnut pod (932 kg ha^{-1}) yield with the minimum runoff (22.73%) and soil loss (483.40 kg ha^{-1}) was observed under the broad bed (90 cm width) and furrow (45 cm). Vekaria et al. (2015) found that adoption of broad bed (90 cm width) and furrow (45 cm) with 3 row was found superior for groundnut yield, net returns along with B:C ratio for maintaining higher soil moisture in root zone as well as for minimizing run off and soil loss in medium black soils under rainfed condition of North Saurashtra Agro-climatic Zone of Gujarat (Table 4).

Table 4 Effect of broad and furrow on groundnut yield and erosion

Treatments	Runoff (%)	Soil loss (kg/ha)	Soil moisture %	Groundnut yield (kg/ha)	BC ratio
Flat bed 45 cm row spacing	25.6	582	24.24	832	2.5
Broad bed (90) cm and furrow (30 cm) with 3 crop row	22.7	483	25.87	932	2.7

The relative performance of different bedding systems, i.e. flat bed (FB), BBF, narrow bed and furrow (NBF) and raised- sunken bed (RSB), was studied in black soils at Indore, India. The results indicated that the maximum maize yields (2.01 tonnes/ha and water-use efficiency of 8.81 kg/ha-mm) were observed in BBF system followed, by RSB and FB systems. This bedding system is getting more adoption in the farmers' fields in the Indore region of Madhya Pradesh, for soybean [*Glycine max* (L.) Merr.] cultivation in the Vertisols, as it is useful in draining excess rainwater during high-rainfall years and conserving and mitigating drought during cropping season or in drought years. In Vertisols of Bellary, bedding system proved effective in conserving the rainwater, increasing the soil water in the profile and resulted 24% higher winter sorghum grain yield and safflower (*Carthamus tinctorius* L.) yield was 8% higher than flat sowing (Average of 8 years).

2.5 Conservation furrow system

The conservation furrow is a simple and low cost in-situ soil- and rainwater-conservation practice adopted in Alfisols and associated soils with problems of crusting and sealing for rainfed areas (400–900 mm rainfall) with moderate slope varying from 1 to 4%. Due to crusting early runoff is quite common in these soils. Furrows at 3–5 m apart on contour or across slope are opened either during planting or during intercultural operation using country plough in this system. These furrows harvest the local runoff water and improve the soil moisture in the adjoining crop rows, particularly during the period of water stress. The practice has been found to increase the crop yields by 10–25%. Tewodros Gebreegziabher (2009) reported that conservation furrow decreased runoff by 42% and soil loss by 62% in Ethiopia at moderate slopes.

2.6 Zingg terracing

Zingg terracing is adopted in low- to medium-rainfall areas in Vertisols with contour/ graded bunds. In Zing terrace nearly 30% of the area in the upstream side of the bund is levelled, so that in this levelled area assured crop yields are realized even during drought years. This is done by cutting 15 cm soil and putting it all near the bund to make flat land for 30% of the area in the upstream side of the bunds. Lower one-third portion of inter-bunded area is levelled to spread the runoff water in a large area. Usually water-intensive crops are cultivated in the levelled portion (receiving area), while dry crops are cultivated in the unlevelled (donor) area. In the levelled one-third portions, normal crop can be harvested even during severe drought year and it is possible to cultivate two crops during a normal year. This will increase both cropping intensity and crop yields in the region. In Vertisols of Bijapur, layout of field with Zingg terrace increased the winter sorghum and safflower yields by 4 and 30%, respectively over the control (AICRDA, 1989; 1990). The effect of Zingg terrace was more felt in the levelled portion than the unlevelled portion. In the levelled portion the yields of winter sorghum and safflower increased by 25 and 44%, respectively, over the control.

3.0 Mulching and residue management

3.1 Organic mulch

Mulching is the process of covering the soil between crops rows with the layer of crop residues, manures and other litter to reduce evaporation, increase infiltration, reduce runoff and control weeds. Mulches dissipate the kinetic energy of the rain drops, prevent soil erosion (splash erosion), facilitate infiltration, soil temperature regulation, improve the water-holding capacity of the soil. As a result, supplemental water demand of the crops is reduced. Mulching is a useful practice for controlling erosion, weed growth and conserve moisture as well as nutrient in the soil in rainfed hilly region (Sharma *et al.*, 2010). Application of mulch found to influence the soil physical characters positively. Kukman Nagaya Mulumba and Ratan Lal (2008) found that mulch rates significantly increased available water capacity by 18–35%, total porosity by 35–46% and soil moisture retention at low suctions from 29 to 70%. Chakraborty *et al.* (2010) reported that organic mulching using rice husk increased moisture (3%), produced more roots (25 and 40% higher root weight and root length densities compared to no-mulch) , increased wheat grain yield (13-21%) and water use efficiency by 25% in semi-arid environment. Further through organic mulching and residue incorporation the biomass is returned to the soil which help in organic carbon build up in the soil. More importantly, mulching improves the burrowing activities of earthworms and improves air-moisture balance in the soil. Besides improving soil physical properties, like better drainage in clayey soil, mulches improves soil micro-nutrients and microbial population. Further, the effect of mulch on soil prosperities and yield is enhanced when it is combined with conservation tillage.

3.2 Vertical mulch and live mulch

Vertical mulching involves opening trenches of 30 cm depth and 15 cm width across the slope at vertical intervals of 30 cm and stuffing sorghum stubbles vertically in these trenches, so that they protrude 10 cm above the ground. Vertical mulches of sorghum act as intake points and guide runoff water into subsoil layers thus, increases profile soil moisture and increased winter sorghum yields to a greater extent in a dry/drought year compared to wet/normal or above normal rainfall years. This technique in medium to deep stiff and clayey soils increased sorghum yield varying from 26 to 78% respectively. (Ramamohan Rao *et al.*, 1978).

Live mulch is a cover crop, preferably leguminous crop inter planted or under sown with a main crop, to serve the purposes of a mulch, such as weed suppression and regulation of soil temperature and other environmental benefits. The concept of live mulching is based on mixed cropping whereby fast growing legume is established before or simultaneously along with widely spaced season grain crops and returned to the soil at an appropriate stage. In an experiment conducted at Dehradun, sunhemp (*Crotalaria juncea* L.), dhaincha (*Sesbania aculeata* Pers.) and cowpea (*Vigna unguiculata* L.) as a live mulch in maize-wheat cropping system. Results revealed that legume mulch accumulated 1.09 – 1.17 t/ha dry biomass and added 27.9-31 kg N/ha at 30 days after sowing and increased wheat yield by 13.3-14.0% (Sharma *et al.,* 2010a). Dupe *et al.* (2015) reported that sun hemp live mulch significantly increased soil moisture growth attributes, yield attributes, and quality of Anola and reduced the runoff and soil loss. Sharma et al.(2010b) reported beneficial effect of live mulch of sunhemp on maize and wheat yield at Dehradun condition (Table 5)

Table 5 Effect of legume mulching soil properties and yield of maize and wheat

Treatment	Bulk density (g/cc)	Infiltration rate (mm/hr)	Organic C (%)	Maize yield (t/ha)	Wheat yield (t/ha)
Control	1.44	6.33	0.57	2.05	1.86
Sunhemp	1.41	7.36	0.64	2.23	2.04
Leucaena	1.36	7.67	0.66	2.19	2.06
Sunhemp+ leucaena	1.36	8.34	0.69	2.36	2.38

Source: Sharma et al(2010b)

3.3 Plastic mulch

Plastic mulching is the process or practice of covering the soil/ground with plastic sheets of varying colours and thickness, with an objective to provide more favourable conditions for plant growth, development and efficient crop production. Plastic film mulching plays an important role in agriculture owing to its ability to improve grain crop yields and water use efficiency (WUE) by maintaining soil moisture, suppressing weeds and increasing soil temperature. Plastic mulches directly affect the microclimate around the plant by modifying the radiation budget of the surface and decreasing the soil water loss. The colour of plastic-film mulch largely determines its energy-radiating behavior and its influence on the microclimate around a plan. Black plastic mulch, the predominant colour used in crop production, is an opaque black body absorber and radiator. The efficiency with which black mulch increases soil temperature can be improved by optimizing the condition for transferring heat from the mulch to the soil. Earlier harvest, reduced evaporation, fewer weed problems, reduced fertilizer leaching, soil compaction, elimination of root pruning, increased crop growth, and reduced drowning of crops were the advantages of the use of plastic mulches for vegetable production which is reported by the several authors.

Subramaniyan *et al.* (2019) found that transparent plastic mulch reduced moisture loss and increased black gram and groundnut yield under rainfed condition in Tamil Nadu, India. Even though plastic mulch role is well known, many environmentalists expressed concern about plastic pollution. To overcome negative environmental problems caused by persistent plastic waste from Plastic mulch, biodegradable plastic mulches (BDM) have been developed as a promising alternative to Plastic films, providing a sustainable and environmentally friendly solution for agricultural activities. Biodegradable plastic mulch use is on the rise as it provides many of the benefits of PE mulch with the advantage of being tilled in or composted at the end of the season, avoiding the disposal problems of plastic mulch. In his review, In their review, Liu *et al.* (2021) reported that BDMs treatments increased maize, wheat, cotton and potato yields by 26%, 24%, 26% and 18%,and water Use Efficiency by 24%, 23%, 15% and 20%, respectively. Beneficial effect of plastic mulch in increasing vegetable yield is given in Table 6.

Table 6 Increase in yield of Vegetable crops through plastic mulching

Crop	**Yield (t/ha)**		**Increase in yield (%)**
	Un mulched	**Mulched**	
Broccoli	15.6	25.1	60.7
Cauliflower	18.6	25.0	34.7
Brinjal	36.7	47.0	28.1
Tomato	69.1	94.8	37.3
Okra	6.9	8.6	23.9
Bitter gourd	20.12	25.6	27.4
Chilli	16.8	19.7	17.4
cabbage	14.3	19.9	39.1

Source: NCPH, New Delhi

4.0 Conservation agriculture

Conservation Agriculture (CA), comprising minimum mechanical soil disturbance and direct seeding, organic mulch cover from residues and cover crops, and crop species diversification through rotations and associations, is now practiced globally on about 125 M ha and worldwide. The technologies of CA provide opportunities to reduce the cost of production, save water and nutrients, increase yields, increase crop diversification, improve efficient use of resources, reduce runoff and soil loss and benefit the environment. In India, CA adoption is still in the initial phases. Over the past few years, adoption of zero tillage and CA has expanded to cover about 1.5 million hectares (Jat *et al.*, 2012). The major CA based technologies being adopted is zero-till (ZT) wheat in the rice-wheat (RW) system of the Indo-Gangetic plains (IGP). In other crops and cropping systems, the conventional agriculture-based crop management systems are gradually undergoing a paradigm shift from intensive tillage to reduced/zero-tillage operations (Suraj Bhan and Behera, 2014). Positive influence of CA on soil physical characters and soil organic build up were reported by several authors. Sapkota *et al.* (2017) reported that CT which involves zero tillage direct seeded rice + zero tillage direct seeded wheat and residue incorporation increased soil organic carbon by six fold in rice-wheat cropping sequence in Indo- Gangetic Plains.

5.0 Cover crops

Cover crops have been defined as crops grown to protect the soil from erosion losses and losses of nutrients via leaching and runoff. This definition was expanded in the *Encyclopedia of Soil Sciences* to those crops that are grown for improving soil, air, and water conservation and quality; nutrient scavenging, cycling and management; increasing populations of beneficial insects in integrated pest management; and/or for short-term (e.g., over-winter) animal-cropping grazing systems. Cover crops provide multiple benefits for erosion and runoff control, soil quality enhancement, nutrient scavenging, and pest suppression. Cover crops reduce sediment production from cropland by intercepting the kinetic energy of rainfall and by reducing the amount and velocity of runoff. Cover crops increase soil quality by improving biological, chemical and physical properties including: OC content, CEC, aggregate stability, and water infiltrability.

Several researchers have reported the benefits of cover crops to *reduce sediment off-site transport* (Dabney, 1998; Delgado *et al.*, 1999). McFarlane *et al.*, (1991) reported that the cover crops of oats greatly reduced both sheet and rill erosion on post-harvest plots of potato. Additionally, several studies have reported the impacts of cover crops on *increasing nutrient use efficiencies and C sequestration* (Little *et al.*, 2004; Edgar *et al.*, 2009). In an experiment conducted at Nilgri hills to assess the benefit of winter cover crops viz., buckwheat, lupin, mustard and fodder oats on potato based cropping system, Kannan *et al.* (2020) reported that cover crops added N (71.28 kg), P (19 kg) and K (28.5 kg) d under reduced tillage. There was a positive change in soil organic carbon (18.5 to 38.8 Mg ha^{-1}) when cover crop was introduced during winter compared to fallow and increased the sustainable yield index ranged from 0.61 to 0.79 (Table 7)

Table 7 Biomass, nutrition addition and system productivity by different cover crops in potato-carrot sequence

Cover crop	**Biomass (t ha^{-1}) Average of Five years)**		**Nutrient addition (kg ha^{-1}) from cover crop (Average over tillage methods)**				**System productivity (PEY* t ha^{-1})**		**SYI**	
	CT	RT	C	N	P	K	CT	RT	CT	RT
Fodder oat	4.3	4.5	1980	52.8	17.6	22	59.7	64.1	0.66	0.79
Lupin	2.8	2.2	1064	50	12.5	15	57.7	58.1	0.73	0.66
Buckwheat	3.2	3.8	1155	56	17.5	10.5	62.7	61.3	0.70	0.73
Mustard	4.6	4.9	1615	71.2	19	28.5	63.9	69.0	0.72	0.75
No cover crop							55.6	54.4	0.61	0.63
Average	3.72	3.85					59.9	61.4	0.68	0.74

Source: Kannan et al.(2020)

8.0 Vegetative barrier

Vegetative barrier, also known as live bunds are closely spaced plantations usually of a few rows of grasses or shrubs grown along the contour for erosion control in agricultural fields. These vegetative barriers not only help in resource conservation, but also provide much needed biomass to meet the needs of rural communities. In higher slopes it can be combined small bunds for improving its effectives. Vegetative barriers technology is highly beneficial for marginal and small farmers since it is cost effective and easier to establish. In India, Different vegetative barriers have been identified for various agro-ecological regions and different soil (Sharda *et al.,* 2006). *Saccharum* spp. for alfisol of Orissa and Shivwaliks, *Cenchrus ciliaris* in dry vertisols, *Pennisetum hohenackeri* in dry Alfisols, *Pennisetum maximum* in the sub-humid lower wester Himalayas, *Panicum antidotale* and *Pennisetum polystachyon* for North Eastern Region were identified as effective or vegetative barrier. In an experiment conducted at Dehradun under rainfed condition, planting two rows of grass (*Cymbopogon martini*) at one meter vertical interval in 2% slope reduced runoff, soil loss and increased soil moisture availability and yields of maize-wheat cropping system (Gosh *et al.,* 2015). In another experiments conducted in the field having 25% slope at Nilgiri hills revealed that plating geranium across the slope at 10 meter interval produced lesser soil loss higher potato equivalent yield. It was observed that within 3 years the original slope of 25.11% was reduced to 20.55% between the barriers resulting in a Land Improvement Index of 18.35 (Muralidharan *et al.,* 2008, Table 8).

Table 8 Change in slope (%) due to the vegetative barrier of Geranium on sloping land (S_6) and land improvement index

Original slope	Average slope after		LII after	
	3 years	4 years	3 years	4 years
21.54	17.21	16.77	20.10	22.14
25.59	20.75	20.27	18.91	20.79
28.21	23.69	22.73	16.02	19.43
(Mean) 25.11	20.55	19.92	18.35	20.79

Source: Muralidharan et al. (2008)

9.0 Geo-textiles

Geo-textiles are woven nets of fibre made from jute, coir or any other natural fibre used in soil conservation or any other soil related constrains in crop production. Several studies reported the benefits of geo-textiles in river bank protection and slope stabilization. The benefit of geo-textiles in field crop production and soil conservation also reported by few writers. Adhikari and Shankar (2018) reported that application of jute geo textiles increased rainfed groundnut yield by 64.2% and soil organic matter by 53% under rainfed condition n West Bengal, India. Field experiment conducted at Dehradun, on a 4% land slope in the Indian Himalayan Region (IHR) revealed that Agro Geo Textiles (AGT) prepared from giant-cane (*Arundo donax*) placed at 1 m vertical intervals recorded the highest ($p<0.05$) maize grain yield (2.8 Mg ha-1), which was 36% higher than maize crops raised without AGT (conservation agriculture only). This treatment also reduced runoff (24%) and conserved soil losses (8.22 t ha-1 year -1. Productivities of succeeding pea (*Pisum sativum var. hortense*) and wheat (*Triticum aestivum* L. emend Fiori & Paol.) crops were enhanced by 122 and 36%, respectively (Raman Jeet Singh *et al.,* 2019). Manivann et al.(2018) reported that that 700 GSM open weave

JGT proved to be more effective in reducing runoff, soil and nutrient loss and increased soil moisture retention capacity of the soil(Table 9)

Table 9 Effect of different open weave jute geo textiles on runoff

Year	**Rainfall (mm)**	**Runoff (mm)**				**Percentage of runoff to rainfall**			
		500 GSM JGT	600 GSM JGT	700 GSM JGT	Control	500 GSM JGT	600 GSM JGT	700 GSM JGT	Control
2012	798.3	86.5	58.3	66.6	140.0	10.8	7.3	8.3	17.5
2013	1142.5	85.0	69.5	57.1	174.3	7.4	6.1	5.0	15.3
2014	1098.4	79.4	49.8	30.4	169.0	7.2	4.5	2.8	15.3
Mean	1013.1	83.6	59.2	51.4	161.1	8.5	6.0	5.4	16.0

Source: Manivannan et al.(2018)

B. Soil and Water Conservation Measures at Terrace level

1.0 Contour bund and Graded bunds

Field bunding across the slope retains run-off in the cultivated field and facilitates its infiltration. Contour bunds are laid across the major land slope along the contour lines in the areas having 1.5 to 6% land slope and having less than 600 mm annual rainfall. The minimum height of contour bund is 50 cm with a cross section of 1.61 m2 having a vertical interval of 0.9 m and the horizontal interval between the bunds may vary from 50 to 70 m depending on the land slope. Bunds are stabilized in 2 to 3 years by growing local grasses on them and are particularly recommended for red soils. The surplus runoff is safely disposed through waste weirs. The graded bunds are constructed with a longitudinal grade of 0.2 to 0.4%, having a vertical interval of 0.75 m to divert the runoff from the fields. The cross-section area of the bund is 0.83 m2 and the horizontal distance is 60 to 70 m. These bunds are more suitable for black soils with greater water logging in the periods of intense rainfall. With adequate vegetation the height of the bunds can be reduced to 50 cm. These bunds are recommended for the soils having less than 6% land slope. The graded bunds are connected to the water ways or water-harvesting structures with waste weirs. In an experiment conducted at loamy soil of semi-arid region of Rajasthan, field bunding significantly increased mean mustard seed yield by 14.4% and biological yield by 15.3% over no bunding because of increased availability of soil moisture. Water-use efficiency also increased by 9.7 kg/ha-mm (Regar *et al.*, 2007).

2.0 Bench terracing

Bench terracing is widely practiced soil conservation measures in hilly areas having high degree of slopes. It comprises of transforming original steep land into series of level strips supported by risers. It breaks the length of slopes and reduces the degree of slopes as well thereby conserving moisture and soil for better crop production (Sharda *et al.*, 2006). Though it is recommended for 16 to 33% slope, bench terracing is being practiced up to 50% slope in Nilgiri and Himalayan hills owing to socio economic condition. Bench terraces may be outward sloping, levelled or inward slopping based on crops grown, rainfall and soil. Levelled or table top bench terrace is recommended for medium rainfall region with highly permeable deep soil. Inward sloping bench terracing is more effective in high rainfall are for vegetable crops which require good drainage and susceptible to water stagnation. High rainfall region like Nilgiri hills inward bench terracing with 2.5% and 1% longitudinal gradient is recommended for sae disposal of water.

3.0 Puertorican terraces

Formation of bench terrace by conventional half cut and half fill method is expensive and if proper soil depth surveys are not conducted will result in exposure of sub-soil leading to reduced crop yields, in addition to the per cent area lost under risers which is equal to the per cent slope of land for 1.1 batter. To overcome these undesirable effects, studies on different types of terraces were conducted at ICAR-Indian Institute of Soil and Water Conservation, Research Centre, Udhagamandalam to evolve a cheaper and effective method of developing bench terraces. It was found that Puertorican terrace with vegetative barriers using Guatemala grass (*Tripsacum laxum*) and Hybrid Napier reduced the cost of construction to one sixth and one third of the cost involved in the traditional method (Padmanabhan *et al*., 1988). Mixed vegetative barrier of two rows of pineapple and one row of Guatemala grass downstream at 1.0 and 1.5 m vertical interval also was successful in the formation of terraces at Gudalur. This technology is cheaper, easy to adopt, economical and eco-friendly.

In the Western Ghats region, where majority of the cultivated area is highly sloping and the cultivation of annual crops and vegetable is underway in large areas, this technology is most appropriate in terms of both sustainable production and natural resource management. Vegetative barrier can be established with locally and economically suitable plants and additional income can be obtained from this also. Thus, this technology can create revolution in the area of Natural Resource Management. Puertorican terraces can be developed by first establishing a mechanical (earthen bunds or stone walls) or vegetative (a quick growing stiff stemmed vegetation that can stand the pressure of oncoming soil) barrier at the desired vertical along contour or graded line and then moving the soil against the barriers year after year at the time of preparation of cultivation, without incurring any extra expenditure. Studies have indicated that regular bench terraces can be developed by this method over a period of 3 to 5 years (Steeper the slope, shorter is the duration). The recommended soil moisture measures based on rainfall is given in Table 10.

Table 10 Recommended soil and moisture-conservation measures for different rainfall zones in India

Seasonal rainfall (mm)			
<500	**500-750**	**750-1000**	**>1000**
Contour cultivation	Contour cultivation	BBF (vertisols)	BBF (vertisols)
Conservation/ dead furrows	Conservation furrows	Conservation furrows	Field bunds
Ridges and furrows	Ridging	Sowing across slope	Vegetative barriers

Sowing across slope	Sowing across slope	Tillage	Graded bunds
Mulching	Vegetative barriers	Vegetative barriers	Vegetative bunds
Scoops	Scoops	Small basins	Chos
Compartmental bunding	Tied ridges	Vegetative bunds	Level terrace
Graded border strips	Mulching	Field bunds	
Tied ridges	Zing terrace	Graded bunds	
Off-season tillage	Off-season tillage	Nadi	
Inter-row water harvesting system	BBF	Zingg terrace	
Small basins	Inter-row water harvesting system		
Contour bunds	Small basins		
Field bunds	Modified contour bunds		
Khadin	Field bunds		
Graded bunds	Graded bunds		

C. Water harvesting and recycling for climate resilient agriculture

Rainwater management is one of the critical components in rainfed farming and the successful crop production depends on *insitu* moisture conservation, surplus runoff water collection, storage and recycling. Further, the importance of rainwater harvesting for agriculture is now more urgent with increased climatic variability and higher frequency of extreme weather events. Extremes, untimely and high intensity rainfall experienced in recent years are likely to continue and cause surplus runoff. There is a scope for utilize this surplus runoff water through storage structure for supplementary irrigation in semi arid region and increase the cropping intensity in high rainfall region. Over the recent decades, interventions around rainwater harvesting have been an important component of rural and agricultural development programmes in India and many water harvesting structures were created with the public funding from schemes like Mahatma Gandhi National Rural Employment Guarantee Scheme (MNREGS), Integrated Watershed Management Programme (IWMP), National Agricultural Development Programme (RKVY) and National Horticultural Mission (NHM) and Pradhan Mantri Krishi Sinchai Yojana (PMKSY). High rainfall variability (AICRPDA, 1991-2011) in the selected seven study districts further makes an important case for rainwater harvesting for agriculture.

Although rainfall in high rainfall regions is sufficient to meet the water demand of crops, its spatial and temporal distribution makes rainfed farming a risky proposition. Water harvesting can reduce the risk substantially by facilitating early planting by taking maximum advantage of the rainfall, thereby insuring the crop against rainfall aberrations. The proper design of a water harvesting system in a high rainfall region should take into account the spatial and temporal behavior of rainfall, water requirement of the crops, in addition to catchment characteristics. Srivastava *et al.* (2001) reported that for a rice-based cropping system in eastern India, a catchment/command ratio of 3.0 and tank size of 1750 m^3/ha command area is required, which facilitates desirable moisture regime for rice and two irrigations to succeeding crop. At watershed level, Srivastava *et al.* (2009) and Kannan *et al*. (2006) evaluated the tank cum open dug well system suitable for plateau region of eastern India has been developed for providing reliable irrigation to croplands. The system comprises of a series of tanks with open dug wells in the recharge zone of the tank that re harvest back the seepage water. Thus, the rainwater remaining in the tank as well as partial seeped water is used for providing round the year full irrigation. This system was evaluated in field in Keonjhar district of Orissa of eastern India with six tanks and five wells in two drainage lines. The total command area of the system of six tanks and five wells in both drainage lines is 23 ha and the total irrigation potential is 44.5 ha. The system increased the rice yields from 1.92 t ha^{-1} to a range of 2.25 to 3.8 t ha^{-1} depending upon the package of practices or the amount of inputs. The farmers went for crops in post-monsoon and summer season and the cropping intensity rose to 112% in the first year, 126% in the second year and 132% in the third year.

D. Agro forestry systems for resource conservation

The extreme weather events occurred due the climate change impact during the last decade caused an enormous negative impact on agriculture in addition to the existing problems like water scarcity/stress, depletion of soil health and crop productivity stagnation. Traditional adaptations and management practice, such as agroforestry systems, may potentially offer options for improving farmer adapting to climate change through synchronised production of wood, food and fodder as well as moderation of the impact of climate change. The historical studies on agroforestry showed that, practice of agroforestry system (AFS) can maintain / improve the crop and land productivity level during the extreme weather events while sustaining soil health and maintaining ecological balance. Trees in the agriculture lands have multifunctional role like biodiversity and natural resource conservation, and these systems require less input and provide a more stable and diversified income due to provision of multiple goods and services for farmers (Tscharntke *et al.*, 2011).

Agroforestry practices are based on the idea that trees increase nutrient cycling, improves soil fertility and microclimate that support the growth of annual crops. AFS provides more profitable and less risky than the traditional agriculture systems because of diversified products and services. The root systems of trees are capable to explore deep soil for water and nutrients, which will help in overcoming the droughts. Additionally, tree increases through fall and soil porosity, increased soil cover and reduced runoff lead to increased water infiltration and soil moisture in the soil profile which can reduce moisture stress during less rainfall years.

Table 11. Agroforestry practices with potential for soil erosion control (Adopted from Young 1989)

Agroforestry practice	Suitable climatic condition	Notes
Plantation crop combinations	Humid to moist sub-humid climate	Densely planted combinations of plantation crops with multipurpose

		trees appear to control erosion effectively on at least moderate slopes and improves soil fertility
Multi-storey tree gardens, including homegardens	Mainly developed in humid and moist sub-humid climates, but possible potential in drier regions	Possess an inherent capacity to control erosion through multi-storey canopy in combination of herbaceous cover with abundant litter
Hedgerow intercropping (alley cropping) and barrier hedges	Humid, sub-humid and possibly semi-arid climates	A considerable apparent potential to combine erosion control with stable use on gentle to moderate slopes, more speculative potential on steep slopes
Trees on erosion-control structures	Any	Supplementary use of trees stabilizes earth structures and gives production from land they occupy
Windbreaks and shelterbelts	Semi-arid zone	Proven potential to reduce wind erosion
Silvo-pastoral practices	Semi-arid and sub-humid climates, plus some humid	Opportunities for inclusion of trees and shrubs as part of overall programme of pasture improvement
Reclamation forestry leading to multiple use	Any	Potential for planned design and development
Combination of the above in integrated watershed management	Any	Substantial opportunities include agroforestry with other major kinds of land use in integrated planning and management

Major advantages of AFS

It is widely recognized that establishing trees in degraded ecosystems improve soil quality and enhance soil productivity through biological nitrogen fixation, efficient nutrient cycling, and deep capture of nutrients and water from soils. AFS are effective at conserving soil by reducing erosion. The tree canopy and through fall reduces the high energy rain drops and allows slow movement of water, which helps in improving the infiltration there by it reduces erosion losses. The erosion control effect of AFS is most pronounced in steeply sloping land with intense rainstorm events. In hedgerow AFS, the contour bund planted hedgerows significantly reduce the runoff and soil loss while stabilizing the bunds (Hombegowda *et al.,* 2020). Crop yield increases in fields adjacent to agroforestry systems have been reported in many studies. AFSs help in crop production through the microclimate modification, reduced wind speeds, improved soil moisture availability and improvement of soil health (Ng *et al.,* 2008). Hombegowda *et al.,* (2020) recorded a 30% increase in the finger millet grain yield under Gliricidia hedgerow intercropping system in the sub-humid climate in Eastern Ghats, India. In recent years AFSs have become popular for its carbon sequestration potential. In regard to climate change, the important regulating service offered by AFSs on a global scale helps in mitigation of atmospheric CO_2 concentration through its sequestration in AFSs. In a review article Nair *et al.*, 2009 reported that, the wood carbon sequestration potentials (CSP) of AFS are ranged from 0.29 to 15.21 Mg ha^{-1} y^{-1}. The CSP is basically linked to the ecosystem productivity of the AFS which intern depending on tree species composition, stand age, site characteristics and management practices. In general, AFS in the low rain fall regions have relatively lower CSP than the high rainfall region.

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CLIMATE SMART AGRICULTURE AND CARBON SEQUESTRATION

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Climate Smart Agriculture (CSA):

Introduction

Climate Smart Agriculture is defined by three objectives:

1. Increasing Agricultural productivity to support increased incomes, food security and development

2. Increasing Adaptive Capacity at multiple levels (from farm to nation)

3. Decreasing Greenhouse gas emissions (GHG's) and increasing Carbon sinks (Campbell *et al*., 2014)

Food and Agricultural Organization (FAO) defines Climate Smart Agriculture (CSA) as "Agriculture that sustainably increases productivity, resilience (adaptation), reduces/ removes GHG's (Mitigation) and enhances achievement of national food security and development goals".

Main Reasons for GHG Emission:

Burning of fossils fuels:

The burning of fossil fuels such as coal, gas and oil produces carbon dioxide and nitrous oxide which are the major GHGs in the atmosphere.

Agricultural practices:

The haphazard use of chemical fertilizers during crop production releases different types of greenhouse gases. Rice cultivation is the main source of methane production through anaerobic fermentation in soil when the field is continuously flooded.

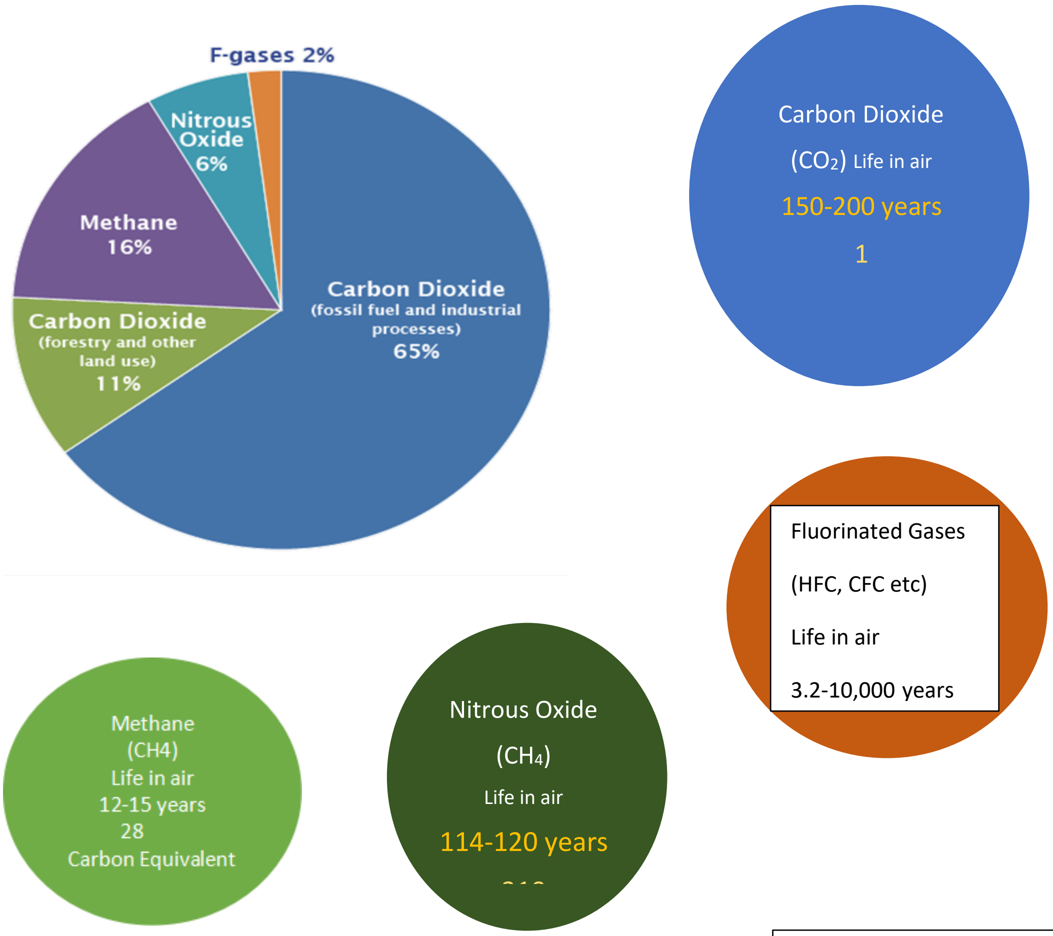
Intensive farming/Livestock:

The animals like cattle and sheep produce a large amount of methane during their process of digestion of food (enteric fermentation). Manure management is another key source of GHGs like methane and nitrous oxide.

Deforestation:

Trees absorb carbon dioxide from the atmosphere mainly for photosynthesis. When trees are cut down, the carbon stored in the trees is also released into the atmosphere. Carbon dioxide, carbon monoxide, nitrogen oxides and sulfur oxides are released when the trees are cut down.

Green House Gases (GHGs)



Source: IPCC

Agriculture contributes to climate change due to high use of energy, agrochemicals and water. India is one of the top GHG emitters. It accounts for 7.32% of global emission.19 per cent of the GHG emission is from Agriculture in India.

Ways to reduce greenhouse gases:

Avoiding emissions by maintaining existing carbon storage in trees and soils, increasing carbon storage by tree planting or conversion from conventional to conservation tillage practices on agricultural lands.

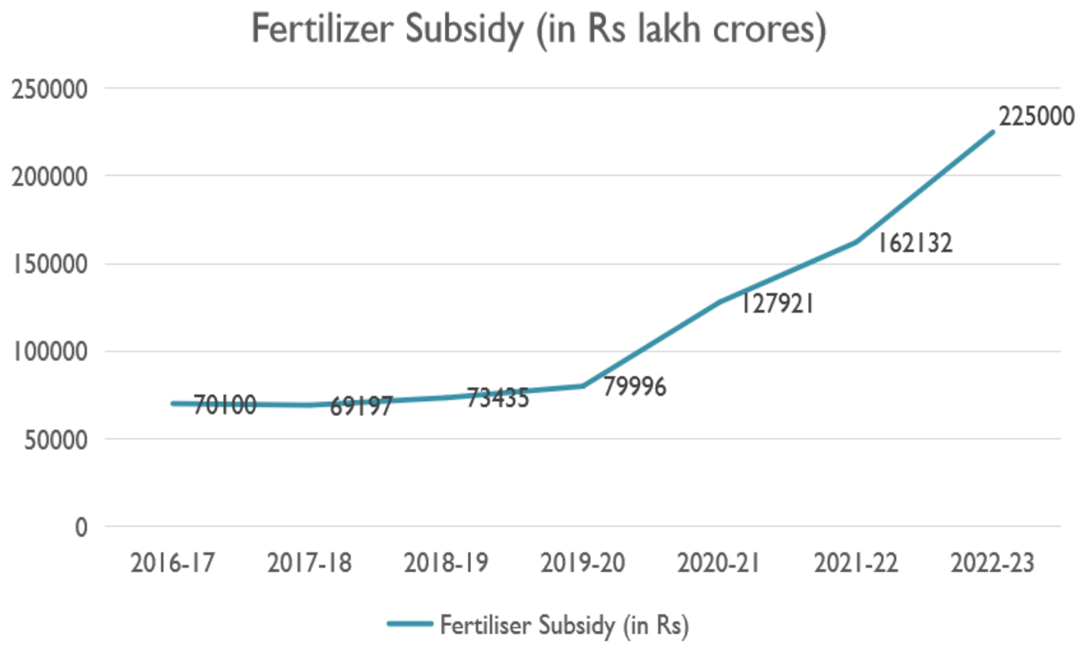
The following table gives the different types of adaptation and mitigation strategies that we can follow to overcome the climate risks that we are facing due to Climate change. This is a part of Climate Smart Agriculture.

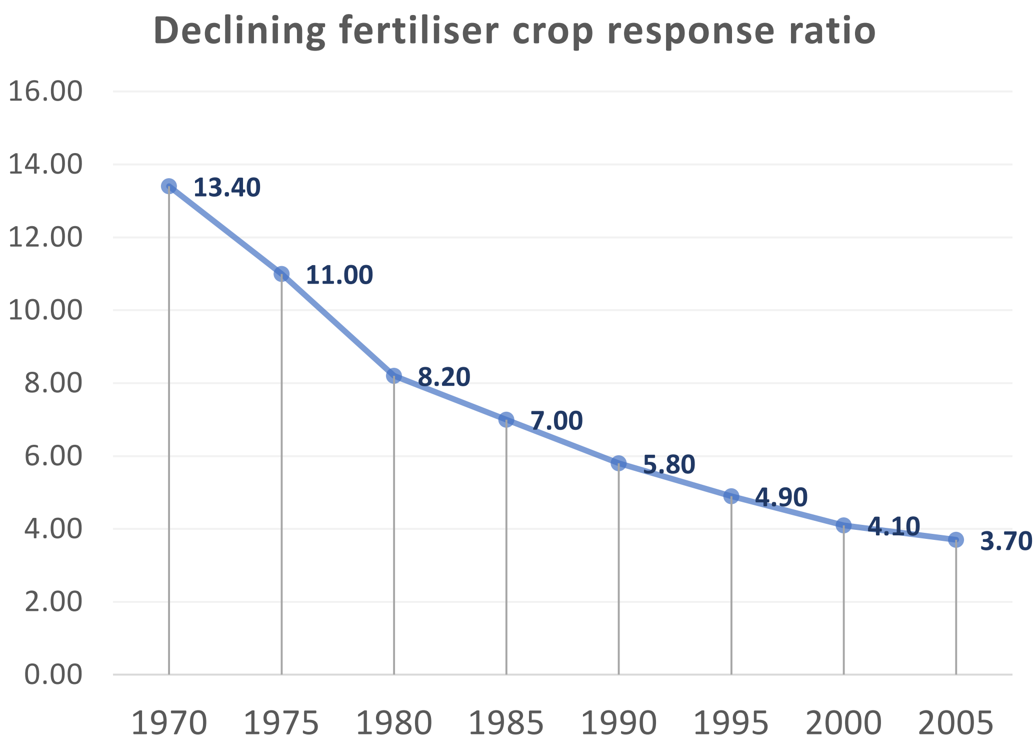
Climate Risk Management:

Adaptation strategies	Mitigation strategies
• Increasing crop diversity • Water harvesting and efficient water management • Promotion of climate-resilient technologies such as drought, flood and disease/pest tolerant crop varieties particularly in stress -prone areas; • Promotion of local, indigenous knowledge and practices • Improving awareness of communities through education and information dissemination • Improving the institutional capacity and efficiency of the communities/organizations.	• Reduction in chemical fertilizer and pesticide use and promotion of organic and ecological agriculture; • Reducing deforestation and promote reforestation; • Increasing use of renewable energy including solar energy, electrification and reduction in the use of fossil fuel-based vehicle and promotion of electrical energy

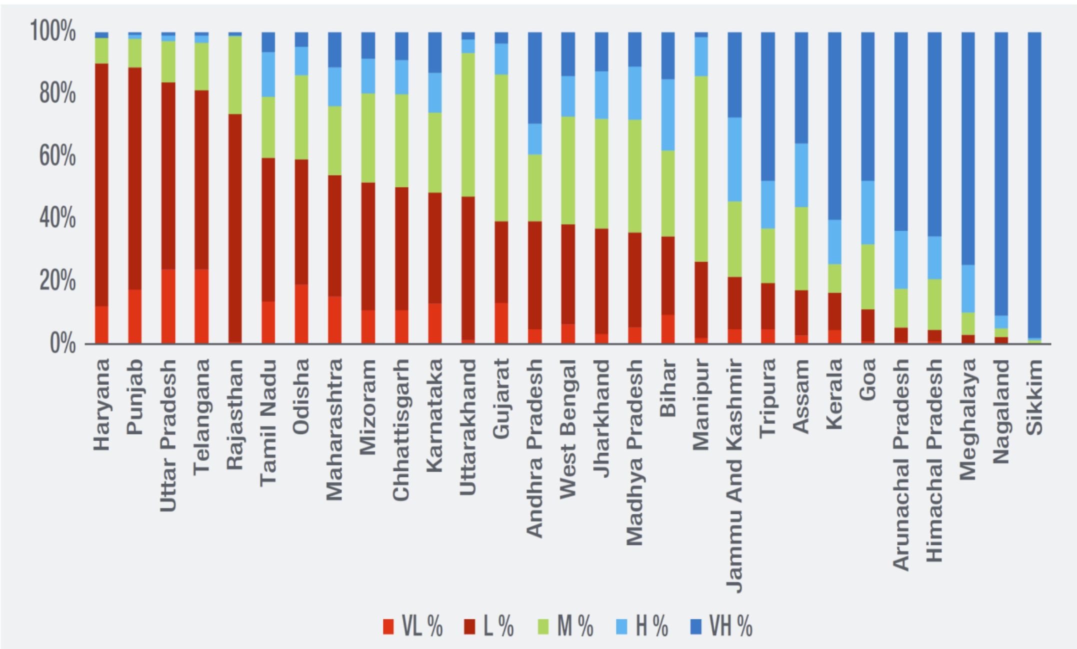
Issues with Chemical fertilizer application:

1. There is a severe imbalance In Punjab with the inorganic fertilizer application. The fertilizers are applied exorbitantly at the rate of 35:8:1 (N : P : K) as against a prescribed ratio of 4.05:1.60:1.00 of fertilizer application (2019-20).
2. In 2022-23: Fertiliser subsidy touched Rs. 2.25 lakh crores.
3. The fertilizer crop response ratio has also declined.





The soil organic carbon content of Indian soils are also very low (i.e.) around 67 per cent of the Indian soils have low organic carbon status (2017-19 data)



Soil Organic Carbon Status based on SHC Scheme: 2017-19

Source: Soil Health Card Portal, Ministry of Agriculture & Farmers Welfare, Government of India

Climate Smart Interventions to be adopted:

1.Regenrative Agriculture.

2.PM Promotion of Alternate Nutrients for Agriculture Management Yojana

3.To reduce the subsidy burden on chemical fertilisers from Rs 2.25 lakh crore in 2022-2023

4.50% subsidy savings will be passed on as a grant to the state that saves the money,

5.National Innovation on Climate Resilient Agriculture (NICRA).

6.National Mission on Sustainable Agriculture.

7.Paramparagath Krishi Vikas Yojana (Soil health Management)

Regenerative Agriculture:

Regenerative agriculture is a way of farming to build and improve soil fertility, whilst sequestering and storing atmospheric CO_2, increasing on farm diversity and improving water and energy management.

Regenerative agriculture focusses on working with nature, limiting costly artificial inputs and mimicking natural ecosystems within an agricultural setting. It draws its practices from Agroecology, Permaculture and Conservation Agriculture; its objective is to restore soil health.

There is no single methodology for regenerative agriculture, as it is highly dependent on working with the unique environmental conditions of each farm. However, there are some key principles which are consistent no matter where in the world it is being implemented:

Limit soil disturbance:

While tillage has been widely used in agriculture for many years, this practice represents a direct threat to soil organic matter, a key element for soil fertility and carbon stocks. By limiting soil disturbance and introducing other agricultural practices such as cover cropping and direct drilling, the soil ecosystem can develop and provide key ecosystem services. Very quickly you can see a drastic reduction of soil erosion, maximisation of soil's biodiversity and associated increase in nutrient cycling capacity and improved water retention.

Cover the soil:

Leaving bare soil, especially after tillage, greatly increases CO_2 emissions from the land. Sunlight shining on bare soil oxidises organic matter causing CO2 to be released, and generating a direct loss of fertility. The adoption of cover crops: temporary crops seeded between the main rotations, represents a cost effective, natural way to avoid bare soil. Covering the soil also prevents soil erosion and runoff entering water systems.

Integrate livestock:

Historically livestock and crops have been deeply intertwined. With the over specialisation of intensive methods many farms moved away from livestock or brought them into indoor systems. The separation of animals and plants is a great source of bio-chemical inefficiency, and CO_2 emissions. By re-integrating crops and livestock through planned grazing and manure application, we can increase soil fertility whilst reducing the need for artificial fungicides, pesticides and fertilisers.

Keep living roots in the ground:

Healthy root systems build soil biodiversity, cycle nutrients and help the soil to retain water. Perennial crops are highly beneficial for maintaining a living root system in the soil. However intensive agriculture focuses annual species which do not leave living roots in the ground, degrading the soil structure and nutrient levels. Reintroducing perennials into the agricultural system is a quick way of re-establishing year round living root systems which also has the added benefits of reducing disease and providing a home for nature.

Green finance:

These regenerative practices are a return to what some might say is a traditional way of farming, but they also represent a very modern opportunity for farmers. The recent focus on the reduction of Green House Gas emissions and the potential for soils to sequester carbon has lead to the creation of carbon market. When farmers implement regenerative practices, they can sequester and reduce carbon, improve local biodiversity and increase natural capital. These actions, when verified, will give them access to a new source of funding through the Green Finance Market, such as environmental impact bonds and payment for environmental services schemes.

Climate smart Rice production Practices:

Adopting of Aerobic Rice cultivation is a Climate smart Rice production practice. This will help in conserving water to the tune of 2350 litres/kg of Rice than the conventional practice of Rice cultivation.

Reducing the Ecological footprint:

The ecological footprint is a method that determines how dependent humans are on natural resources. It is a measure that indicates how much resources from the environment are required to support a specific way of life or business. Educating the farmers to adopt Decentralised production is a method by which we can reduce the ecological footprints.
Eg: Sahaja Aharam Institute at Andrapradesh.

Carbon Sequestration:

Introduction:

Carbon sequestration is also termed as Carbon Capture. It is a geoengineering technique for the long-term storage of carbon dioxide (or other forms of carbon) for the mitigation of global warming. More than 33 billion tons of carbon emissions (annual worldwide).

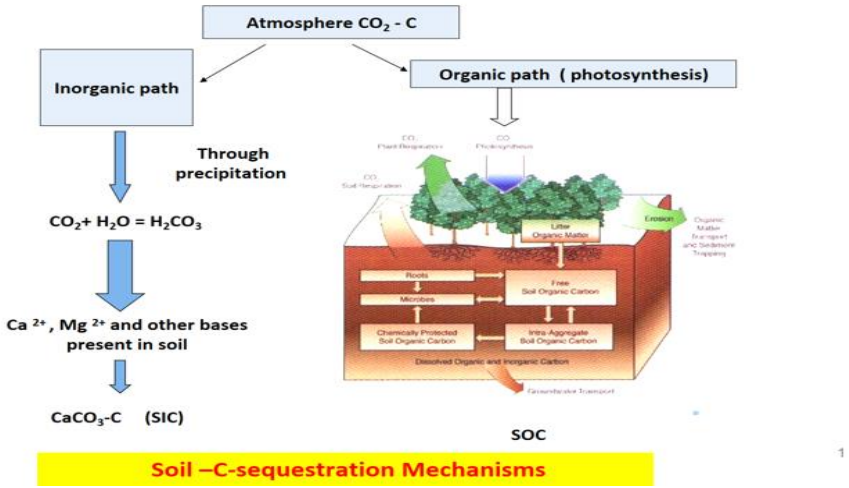
Ways that carbon can be stored (sequestered):

- In plants and soil as “terrestrial sequestration” (“carbon sinks”)
- Underground “geological sequestration”
- Deep in ocean “ocean sequestration”

The process of transferring of atmospheric carbon into a pedologic/soil C pool is called soil C sequestration (Lal *et al.* 2004). As nation has progressed, we have been emitting carbon or gases which results in global warming. The climate change has emerged as the leading environmental threat facing the world today.Highly intensive agriculture in the name of green revolution not withstanding the alarming depletion in soil organic C and increasing the production of major green house gases and enhancing the contamination of ground water.Emission of green house gases is concern of global warming and relative effect on biological life (IPCC, 2001).Under such situation carbon sequestration play a key role to conserve natural resources and achieve sustainability in agricultural production.

Practices like Conservation agriculture, agroforestry, application of mulching and biochar, introduction of covercrops and improved crop varieties, application of organic and inorganic fertilizers and residue management, practices in cropland ecosystem can enhance the carbon sequestration in both plants and soil (CSAS 2012). The Carbon sequestration capacity depends upon tree species, their growing condition and management practices under agroforestry.

Mechanisms of Soil C Sequestration:



Why Carbon Sequestration…...?

The important mitigation strategy to cope up with the negative impact of climate change to restore degraded soils and ecosystem and increase agronomic productivity to achieve food security. The potential of soil carbon sequestration in India is estimated at 10-14 Tg C/y for restoration of degradable soils and ecosystem (Lal *et al.* 2004).Soil carbon sequestration is a natural, cost effective and environment friendly process

Soil Carbon and Soil Health:

Key indicator of soil health because it plays a role in number of ways. Key functions 3 types

1.Biological functions

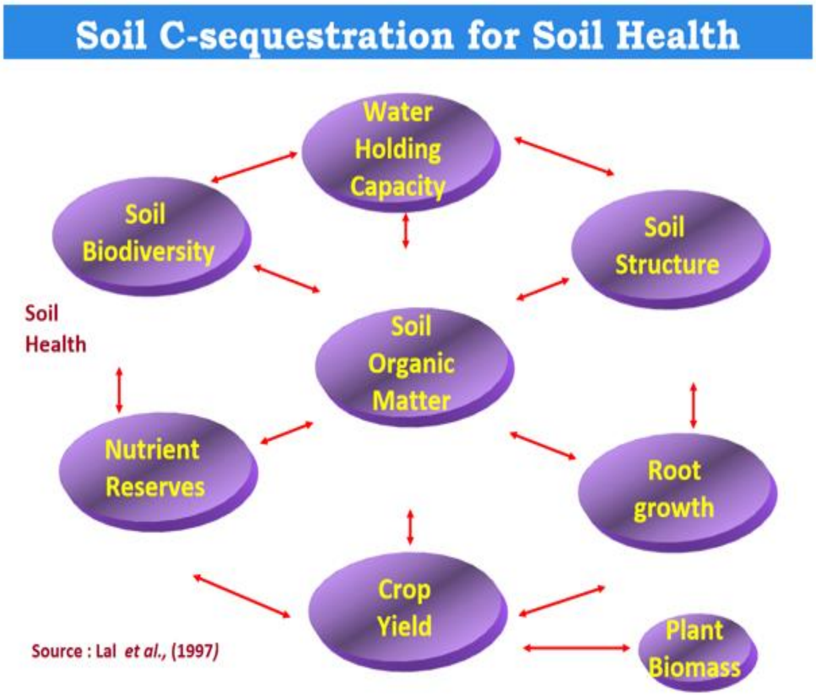
Provide nutrient and habitat for microbes, provide energy for biological processes and contributes to soil resilience.

2.Chemical functions

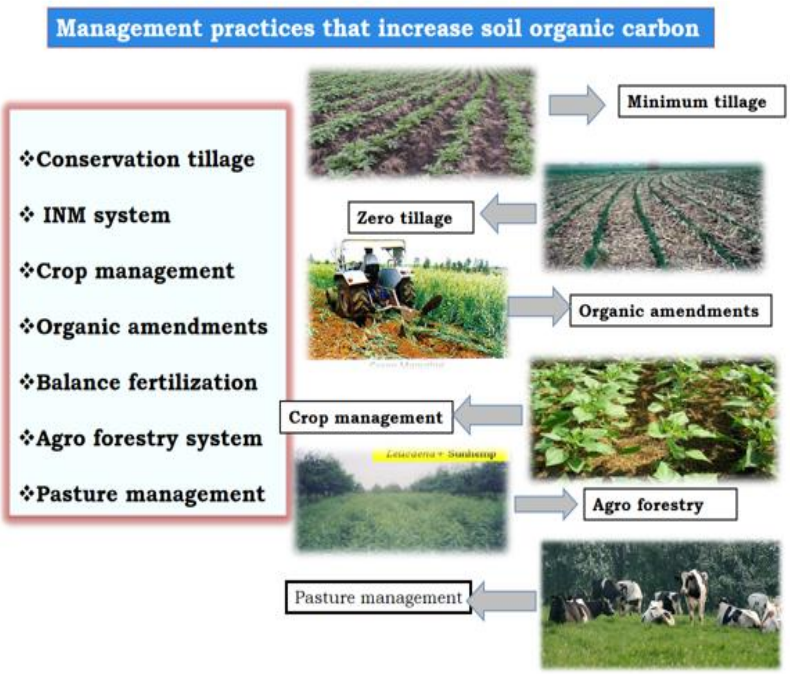
Measure of nutrient retention capacity, provides resilience against pH change and Main store of key elements viz., N and K

3.Physical functions

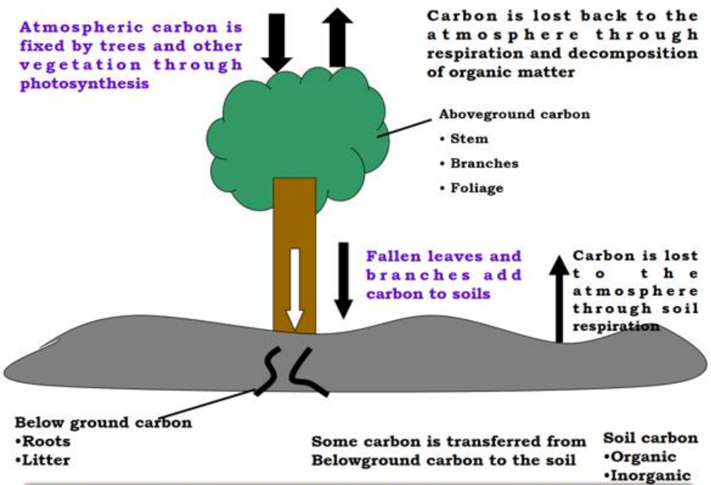
Binds soil particles into aggregates improving soil structural stability. Enhances water holding capacity of soil. Moderates changes in soil temperature



Management Practices that increase Soil Organic Carbon:



Carbon Pools in Forestry and Agriculture:



Carbon pools in forestry and agriculture (Source: EPA, 2008)

Different Pools of Soil Organic Carbon:

Pool I (CVL, very labile)	Organic C oxidisable under 12.0 *N* H_2SO_4;
Pool II (CL, labile)	The difference in C oxidisable under 18.0 *N* and that under 12.0 *N* H_2SO_4;
Pool III (CLL, less labile)	The difference in C oxidisable under 24.0 *N* and that under 18.0 *N* H_2SO_4 (the 24.0 *N* H_2SO_4 is equivalent to the standard Walkley and Black method); and
Pool IV (CNL, non-labile)	Residual organic C after oxidation with 24.0 *N* H_2SO_4 when compared with the Ctot. Walkley, (1947)

Carbon Stock and Carbon Sequestration Potential in Indian soils:

Carbon stock in Indian soils (Order -wise)

Soil order	Soil depth (m)	Carbon stock (Pg)		
		SOC	SIC	TC
Entisols	0-0.3	0.62	0.89	1.51
	0-1.5	2.56	2.86	5.42
Vertisols	0-0.3	2.59	1.07	3.66
	0-1.5	8.77	6.14	14.90
Inceptisols	0-0.3	2.17	0.62	2.79
	0-1.5	5.81	7.04	12.85
Aridisols	0-0.3	0.74	1.40	2.14
	0-1.5	2.02	13.40	15.42
Mollisols	0-0.3	0.09	0.00	0.09
	0-1.5	0.49	0.07	0.56
Alfisols	0-0.3	3.14	0.16	3.30
	0-1.5	9.72	4.48	14.20
Ultisols	0-0.3	0.20	0.00	0.20
	0-1.5	0.55	0.00	0.55
Total	0-0.3	9.55	4.14	13.69
	0-1.5	29.92	33.98	63.90

Bhattacharyya *et al.*, 2000

The potential of carbon sequestration in soils of India

Region	Area (M ha)	C sequestration potential ($Tg\ C\ yr^{-1}$)
Arid	52.0	0.67-1.34
Semi-arid	116.4	2.33-4.66
Sub-humid	86.4	3.46-5.18
Sub-humid/humid	33.3	2.06-2.72
Per humid	20.2	2.42-3.03
Sub-humid/semi-arid	8.5	0.34-0.51
Humid/Perhumid	11.9	1.43-1.79
Total	328.7	12.71-19.23
Secondary carbonates	328.7	21.78-25.6
Erosion control	--	4.80-7.20
Total	328.7	39.29-52.03

Tg = Tera gram

Source : Lal (2004)

Factors influencing C sequestration or C build up in soil:

1.**Climatic factor**: The Climatic factors include Temperature and Moisture and the Soil factors include Texture and Soil pH

2.Tillage and CO_2 retention: Soil CO_2 retention is less in the conventional tillage, whereas in the no tillage plot the soil CO_2 retention is more.

Effect of tillage practices on carbon sequestration

Soil depth (cm)	Soil organic carbon stock ($g\ kg^{-1}$)	
	CT	NT
0-5	6.17	9.52
5-10	5.13	5.08
10-20	10.41	10.01
20-30	7.75	7.22
30-40	3.56	4.92
0-40	33.03	36.84

CT= conventional tillage,
NT= no tillage

Source: Lal (2009)

Carbon Sequestration under Forest ecosystem:

Carbon sequestration rates differ based on the species of tree, type of soil, regional climate, topography & management practice. Pine plantations in SE United States can accumulate almost 100 metric tons of carbon per acre after 90 years (~ 1 metric ton : 1 year).

Carbon accumulation eventually reaches saturation point where additional sequestration is no longer possible (when trees reach maturity, or when the organic matter in soils builds back up to original levels before losses occurred)

After saturation, the trees or agricultural practices still need to be sustained to maintain the accumulated carbon and prevent subsequent losses of carbon back to the atmosphere. Carbon Sequestration ranges from 3Gt in croplands to 212 Gt in tropical forests. The Inter-Govermental Panel on Climate Change (IPCC) has projected the temperature increase to be between 1.1 ℃ and 6.4℃ by the end of 21^{st} century (IPCC 2007). For every 1℃ rise in night temperature rice yields are also expected to go down upto 10 percent (Peng *et al.*, 2004) by decreasing photosynthesis and increasing respiration losses (Pathak *et al.*, 2003). Agroforestry plays an important role in climate change mitigation through long term carbon sequestration (Sudha *et al.* 2007).

Types of Soil C Sequestration:

Terrestrial Carbon Sequestration:

The process through which CO_2 from the atmosphere is absorbed naturally through photosynthesis & stored as carbon in biomass & soils. Tropical deforestation is responsible for 20% of world's annual CO_2 emissions, though offset by uptake of atmospheric CO_2 by forests and agriculture.

Geological Carbon Sequestration:

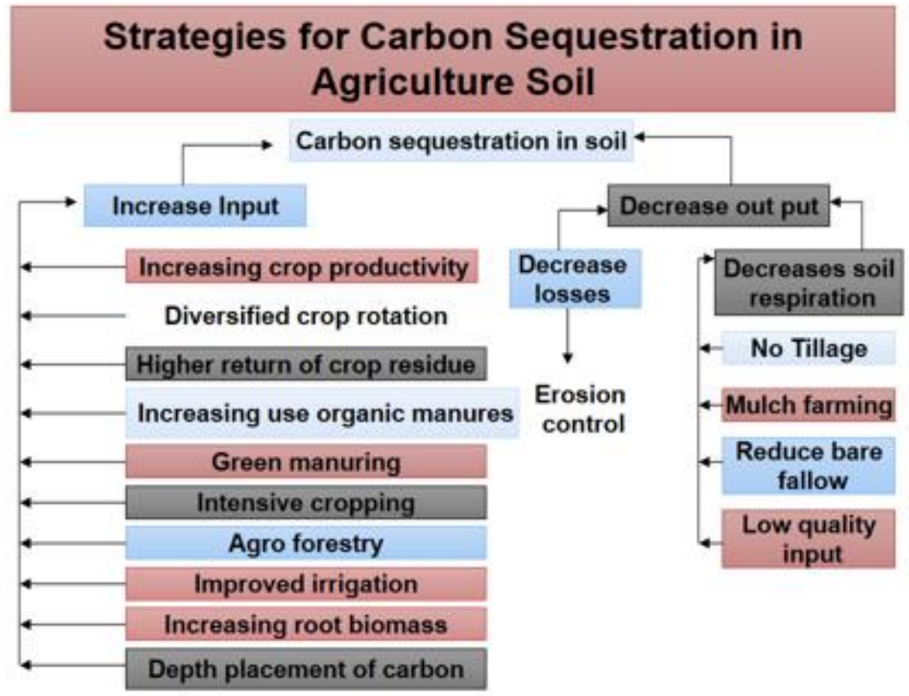
Storing of CO_2 underground in rock formations able to retain large amounts of CO_2 over a long time period. Held in small pore spaces (have held oil and natural gas for millions of years)

Oceanic Carbon Sequestration:

"Carbon is naturally stored in the ocean via two pumps, solubility and biological, and there are analogous man-made methods, direct injection and ocean fertilization, respectively. Eventually equilibrium between the ocean and the atmosphere will be reached with or without human intervention and 80% of the carbon will remain in the ocean. The same equilibrium will be reached whether the carbon is injected into the atmosphere or the ocean. The rational behind ocean sequestration is simply to speed up the natural process."

Carbon sequestration by direct injection into the deep ocean involves the capture, separation, transport, and injection of CO_2 from land or tankers. 1/3 of CO_2 emitted a year already enters the ocean. Ocean has 50 times more carbon than the atmosphere

Strategies for Carbon Sequestration in Agriculture soil:



Major constraints for C sequestration

A major constraint in adopting conservation tillage and mulch farming in India is the non-availability of crop residues for returning to the soil. Most of the crop residues are removed from fields for use as a fodder and fuel. Dung is also used as fuel for cooking. Thus, adoption of mulch farming techniques is possible only if economic sources of fuel and alternative sources of fodder are identified. Lack of awareness among the farmers regarding importance of carbon sequestration and its role in soil productivity.

Carbon trading:

Carbon sequestration is one of the important mitigation strategies to cope with the impact of climate change. The kyoto protocol brought the mechanism of trading carbon unit as a global mechanism to address the issue of reducing emission by various countries to meet the mandatory requirement.

What is Kyoto protocol?

The Kyoto protocol is an international agreement which lays down targets for industrialize countries to cut their green house emission which include CO_2, CH_4, N_2O, HFCs. Accepted by several developed and developing countries in 1997.Australia the latest signatory. USA refuse to sign the convention (world biggest green house emitter).

Carbon credit

Carbon credit is a concept that a incentivizes countries which reduce their GHG emission and disincentivises those who do not reduce their GHG emission. Under the kyoto protocol each company that shifts to cleaner technologies obtains to it account one credit per tone of CO_2 emission reduction. This credit to the company obtain is called carbon credit. The protocol imposes target commitment upon a country who in turn set emission quota on companies in their country. In order to fulfill their quota.

Conclusion

Soil carbon sequestration is an effective resource to sequester atmospheric CO_2 with better practical application than other approaches. Crop and land use management practices can be employed to sequester more carbon in plant and soil to enhance soil health, and sustainability and secure food productivity with changing climate in rainfed areas.

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ORGANIC MATTER DYNAMICS AND MICROBES ON SOIL HEALTH, CROP PRODUCTIVITY AND ENVIRONMENTAL QUALITY

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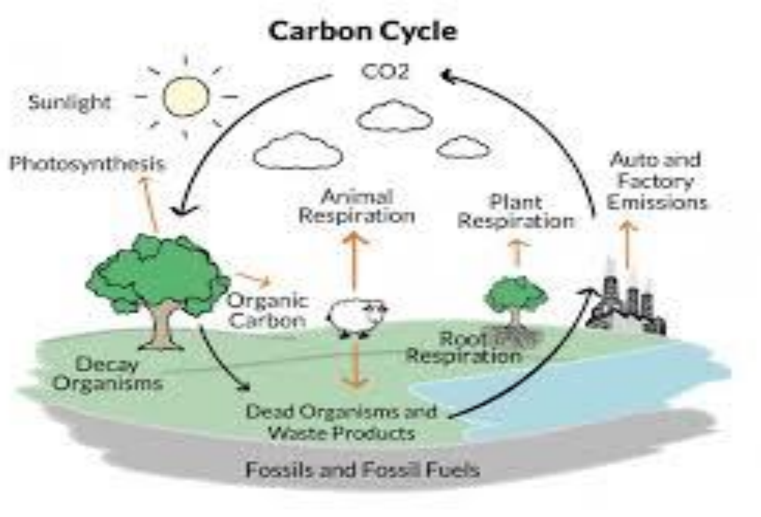
Climate Smart Agriculture (CSA) is an integrated approach to manage landscapes, cropland, livestock, forests and fisheries that address the interlinked challenges of food security and climate change. It is also a set of agricultural practices and technologies which simultaneously boost productivity enhance resilience and reduce GHG emissions.

According to FAO's definition on Climate Smart Agriculture is an approach that helps to transform agri-food systems towards green and climate resilient practices.

Carbon cycle:



The carbon cycle is the bio-geochemical cycle by which carbon is exchanged among the biosphere, pedosphere, geosphere, hydrosphere, and atmosphere of the Earth. Carbon is the main component of biological compounds as well as a major component of many minerals such as limestone. It describes the movement of carbon as it is recycled and reused throughout the biosphere, as well as long-term processes of carbon sequestration to and release from carbon sinks.

Carbon in the Earth's atmosphere exists in two main forms: carbon dioxide and methane. Both of these gases absorb and retain heat in the atmosphere and are partially responsible for the greenhouse effect.

The terrestrial biosphere includes the organic carbon in all land-living organisms, both alive and dead, as well as carbon stored in soils. About 500 gigatons of carbon are stored above ground in plants and other living organisms.

The dissolved inorganic carbon (DIC) in the surface layer is exchanged rapidly with the atmosphere, maintaining equilibrium

The largest human impact on the carbon cycle is through direct emissions from burning fossil fuels, which transfers carbon from the geosphere into the atmosphere. The rest of this increase is caused mostly by changes in land-use, particularly deforestation.

Carbon sequestration

Carbon sequestration (CS) or **carbon dioxide removal** (CDR) is the long-term removal, capture or sequestration of carbon dioxide from the atmosphere to slow or reverse atmospheric CO_2 pollution and to mitigate or reverse global warming. Carbon dioxide (CO_2) is naturally captured from the atmosphere through biological, chemical, and physical processes.

These changes can be accelerated through changes in land use and agricultural practices, such as converting crop and livestock grazing land into land for non-crop fast growing plants.

Artificial processes have been devised to produce similar effects,[5] including large-scale, artificial capture and sequestration of industrially produced CO_2 using subsurface saline aquifers, reservoirs, ocean water, aging oilfields, or other carbon sinks, bio-energy with carbon capture and storage, biochar, ocean fertilization, enhanced weathering, and direct air capture when combined with storage.

Carbon sequestration is the process involved in carbon capture and the long-term storage of atmospheric carbon dioxide (CO_2).

CS in different Eco-systems

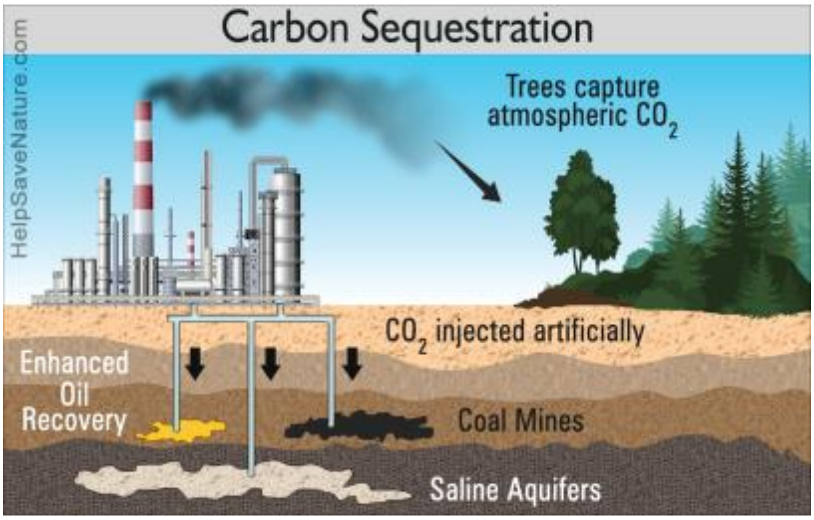
Peat bogs act as a sink for carbon due to the accumulation of partially decayed biomass that would otherwise continue to decay completely.

Afforestation is the establishment of a forest in an area where there was no previous tree cover. Reforestation is the replanting of trees on marginal crop and pasture lands to incorporate carbon from atmospheric CO_2 into biomass.[15] For this carbon sequestration process to succeed the carbon must not return to the atmosphere from mass burning or rotting when the trees die.

Wetland soil is an important carbon sink; 14.5% of the world's soil carbon is found in wetlands, while only 6% of the world's land is composed of wetlands

Compared to natural vegetation, cropland soils are depleted in soil organic carbon (SOC). When a soil is converted from natural land or semi natural land, such as forests, woodlands, grasslands, steppes and savannas, the SOC content in the soil reduces by about 30–40%

Bamboo plantation sequesters carbon at a much faster rate than a mature forest or a tree plantation. Therefore the farming of bamboo timber may have significant carbon sequestration potential.



Significance of carbon sequestration on soil and environment

Carbon sequestration is the process involved in carbon capture and the long-term storage of atmospheric carbon dioxide (CO_2)

Significance

Carbon sequestration, the long-term storage of carbon in plants, soils, geologic formations and the ocean. Carbon sequestration occurs both naturally and as a result of anthropogenic activities and typically refers to the storage of carbon that has the immediate potential to become carbon dioxide gas. In response to growing concerns about climate change resulting from increased carbon dioxide concentrations in the atmosphere, considerable interest has been drawn to the possibility of increasing the rate of carbon sequestration through changes in land use and forestry and also through geo-engineering techniques such as carbon capture and storage.

Anthropogenic activities such as the burning of fossil fuels have released carbon from its long-term geologic storage as coal, petroleum and natural gas and have delivered it to the atmosphere as carbon dioxide gas.

Carbon dioxide is also released naturally, through the decomposition of plants and animals. The amount of carbon dioxide in the atmosphere has increased since the beginning of the industrial age, and this increase has been caused mainly by the burning of fossil fuels. Carbon dioxide is a very effective greenhouse gas that is, a gas that absorbs infrared radiation emitted from Earth’s surface. As carbon dioxide concentrations rise in the atmosphere, more infrared radiation is retained and the average temperature of Earth’s lower atmosphere rises. This process is referred to as global warming.

Some policy makers, engineers and scientists seeking to mitigate global warming have proposed new technologies of carbon sequestration. These technologies include a geo engineering proposal called carbon capture and storage (CCS).

In CCS processes, carbon dioxide is first separated from other gases contained in industrial emissions. It is then compressed and transported to a location that is isolated from the atmosphere for long-term storage. Suitable storage locations might include geologic formations such as deep saline formations (sedimentary rocks whose pore spaces are saturated with water containing high concentrations of dissolved salts), depleted oil and gas reservoirs, or the deep ocean. Although CCS typically refers to the capture of carbon dioxide directly at the source of emission before it can be released into the atmosphere, it may also include techniques such as the use of scrubbing towers and "artificial trees" to remove carbon dioxide from the surrounding air.

Organic matter

Organic material or natural organic matter refers to the large source of carbon-based compounds found within natural and engineered, terrestrial and aquatic environments. It is mattercomposed of organic compounds that have come from the remains of organisms such as plants and animals and their waste products in the environment

Basic structures are created from cellulose, tannin, cutin, and lignin, along with other various proteins, lipids, and carbohydrates. Organic matter is very important in the movement of nutrients in the environment and plays a role in water retention on the surface of the planet.

The composition of natural organic matter depends on its origin, transformation mode, age, and existing environment, thus its bio-physico-chemical functions vary with different environments

The organic matter in soil derives from plants, animals and microorganisms. The *priming effect* is characterized by intense changes in the natural process of soil organic matter (SOM) turnover, resulting from relatively moderate intervention with the soil (Kunal Ghosh et al, 2012)

Decomposition

One suitable definition of organic matter is biological material in the process of decaying or decomposing, such as humus. A closer look at the biological material in the process of decaying reveals so-called organic compounds (biological molecules) in the process of breaking up (disintegrating).

The main processes by which soil molecules disintegrates are by bacterial or fungal enzymatic catalysis. If bacteria or fungi were not present on Earth, the process of decomposition would have proceeded much slower.

Organic matter is heterogeneous and very complex. Generally, organic matter, in terms of weight, is: 45-55% carbon, 35-45% oxygen, 3-5% hydrogen, 1-4% nitrogen. Decomposition of organic matter involves four component processes: photo-oxidation, leaching, comminution, and mineralization (Sahai, 1999)

Chelation- metal – organic complex

Chelation is a chemical process in which a substance is used to bind metals or minerals.

Chelation is a type of bonding of ions and molecules to metal ions. It involves the formation or presence of two or more separate coordinate bonds between a polydentate ligand and a single central atom. These ligands are called chelants, chelators, chelating agents, many investigations have been carried out during the last ***50*** years on the composition of soil organic matter, but, largely because of the difficulty of isolating the organic matter from the inorganic fraction of the soil, they have met with comparatively little success. Dilute aqueous alkali and salt solutions have commonly been used to extract organic matter, from soils and have yield humic acid and fulvic acid fractions on acidification of their extracts. Although based on this arbitrary and rather unsatisfactory extraction procedure, humic acid/fulric acid concept still dominates much of the work on soil organic matter and numerous attempts have been made to elucidate the composition of these fractions.

The primary source of the organic matter in soils is vegetation, although the micro-organisms and soil fauna which feed on plant residues also make significant contributions to the supply of fresh tissues available for decomposition.

Approximate composition of mature plant residues of dry matter (%)

Cellulose 20-50

Hemi cellulose (including pectin) **10-30**

Lignin 10-30

Tannin 0-4

Oil, wax, resin, cutin 1- 6

The transformations of these biological tissues in the soil can be grouped in five stages:5

(I) The hydrolytic decomposition of the large molecular polysaccharides, proteins, nucleic acids, oils and waxes to simple sugars, amino-acids, nucleotides, aliphatic acids and alcohols and the slower oxidative breakdown of lignin and tannin to smaller aromatic molecules.

(2) The metabolic breakdown of the small molecular products from stage (I) to carbon dioxide, water and inorganic salts.

(3) The metabolic synthesis of microbial cells and faunal tissues.

(4) The production of relatively stable humus compounds by

(a) the accumulation of the more resistant residues of plants, micro-organisms and soil fauna,

(b) the recombination of certain intermediate decomposition products from stage (I).

(5) The slow decomposition of humus to carbon dioxide, water and inorganic salts.

'Humus' is usually defined as that portion of the soil organic matter which is completely amorphous and has no cellular structure characteristic of plants, micro-organisms or animals.

In considering possible processes for the formation of humus, account must be taken of its known characteristics. For example, while plant protein is readily decomposed in the soil with the release of ammonium and nitrate nitrogen, the nitrogen content of humus, which amounts to about 5%, is much more resistant to microbial attack and is also largely resistant to chemical extraction and hydrolysis. Bremner has reported that, of the nitrogen in soil organic matter, about 40% is liberated as amino-acids by hydrolysis with hydrochloric acid, and about 51% as amino sugars, but that there is no direct evidence for the nature of the remainder. As by far the greatest proportion of the nitrogen in biological tissues occurs in the peptide linkages of proteins, considerable conversion to more stable forms must occur during humus formation.

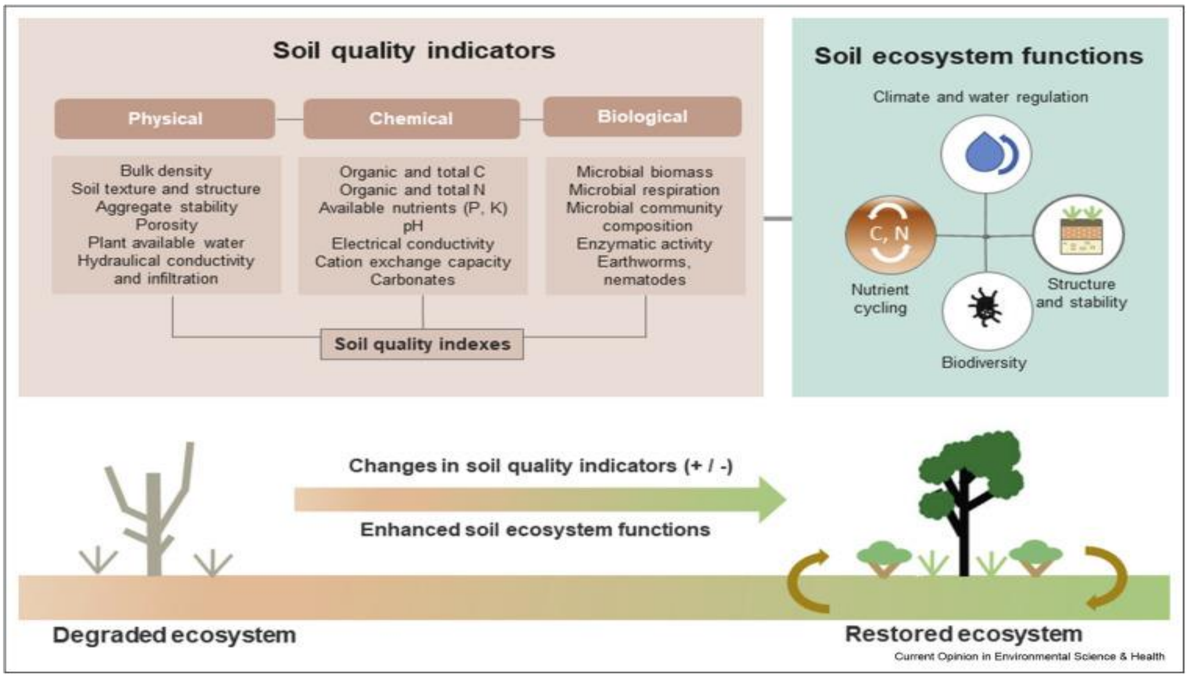
Soil resilience and O.M

SR = SOC+CEC+SMB

- ✓ Soil resilience is determined by combination of SOC content, CEC & microbial biomass
- ✓ Soil resilience is a measure of functionality of whole ecosystem
- ✓ Soils with a greater microbial diversity were more resistant and resilient to perturbations than soils with less diverse communities

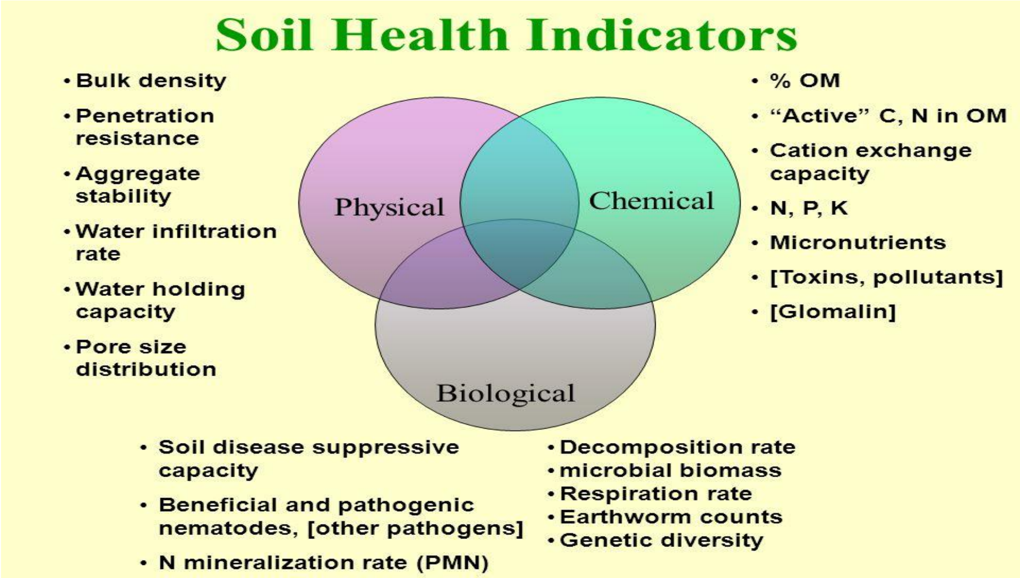
Soil Quality (Doran & Parkin, 1994) – It is the soil conditions to predict productivity

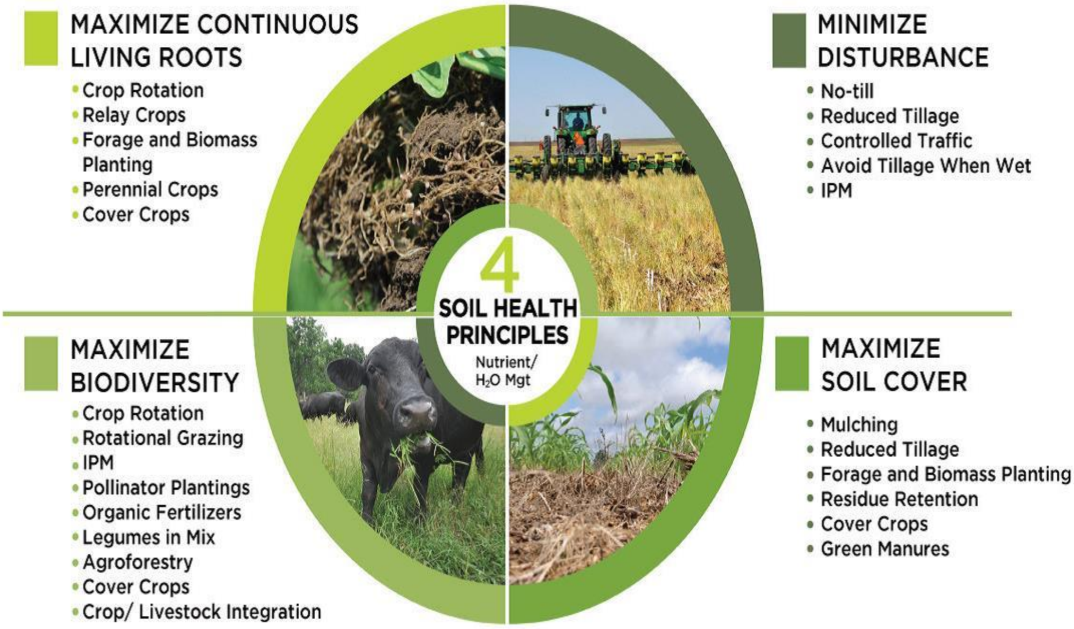
Soil Quality defined as the "capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality and promote plant and animal health"



Soil Health (Doran & Safley, 1997) – It is the soil conditions to predict how soil functions – Good functioning does not imply good productivity

Soil Health is defined as the " continued capacity of soil to function as a vital living system within ecosystem and land use boundaries to sustain biological productivity, promote the quality of air , water and environments and maintain plant, animal and human health".





Impact of climate change on soil health

Deterioration of soil	
Increasing Temperature	Reduction in labile pool of SOM
	Reduction in moisture content
	Increase in mineralization rate

	Loss of soil structure
	Increase in soil respiration rate
Increasing CO_2 concentration	Increase in soil organic matter
	Increase in water use efficiency
	More availability of carbon to soil microorganisms
	Accelerated nutrient cycling
Increasing rainfall	Increase in soil moisture or soil wetness
	Nutrient leaching
	Increased volatilization loss of nitrogen
	Increase in soil organic matter
Reduction in Rainfall	Reduction in soil organic matter
	Reduction in nutrient availability

SOM - Measured

SOM is usually measured in the laboratory as organic carbon. Soil organic matter is estimated to contain 58% organic carbon (varies from 40 to 58%) with the rest of the SOM comprising of other elements (eg, 5% N, 0.5% P and 0.5% S).

A conversion to SOM from a given organic carbon analysis requires that the organic carbon content be multiplied by a factor of 1.72 (1.00/0.58). Thus, 2% SOM is about 1.2% organic carbon.

Organic Carbon Stock

- The organic carbon stock expressed in t ha^{-1}, is the mass of organic carbon in the soil (layer) and is derived from the organic carbon content and the weight of the soil.
- The soil organic carbon content is the fraction of organic carbon in soil expressed as weight percentage (weight organic carbon/weight soil).
- The weight of the soil (t ha^{-1}) is derived from the depth of the soil (cm) and the bulk density or specific weight (g cm^{-3}) of the soil.
- For a soil with different layers the carbon stock in the soil is the sum of the carbon stock in the soil layers.

Example: If the organic carbon content of a topsoil layer of 10 cm is 1.3% and the bulk density is 1.2, then the carbon stock is 15.6 ton carbon per ha.

Convert % to weight for a given depth and area

SOC stock in tonnes of carbon per hectare (tC/ha) = (soil organic carbon %) x (mass of soil in a given volume)

For example, a soil with a SOC of 1.3% (0.013) and a bulk density of 1.2 grams per cubic centimetre (equivalent to 1.2 tonnes per cubic metre), would have SOC to a depth of 10 cm (0.1 m) per hectare (10 000 m^2) of (0.013) x (1.2 x 0.1 x 10 000) = 15.6 tC/ha.

Using the conversion factor of 1.72, the amount of SOM would be: 15.6 x 1.72 = 26.8 tonnes of organic matter.

1000 kg/m^3 is equivalent to 1 g/cm^3

Soil organic matter fractions

Fractions	**Size**	**Turnover Time**	**Decomposition**
Dissolved organic matter (DOM)	<45µm	Very rapid (minutes – days)	Composed of soluble root exudates, simple sugars and decomposed by-products (<1% total SOM)
Particulate organic matter (POM)	<53µm – 2 mm	(month – decade)	Composed of fresh, decomposition plant and animal matter with an identifiable cell structure (2-25% total SOM)
Humus	<53µm	(10 – 100 years)	Made up of older, decayed organic compound – resisted decomposition. It includes structural and non-structural organic molecules. (50 % total SOM)
Resistant organic matter (ROM)	<53µm < 2 mm	(100 – 1000years)	It is relatively inert material – made up of chemically resistant material – charcoal (burnt organic matter) (30 % SOM)

Effect of microbes on soil health

Microbes are essential for soil health, as they facilitate decomposition of organic matter, nutrient cycling and nitrogen fixation. They improve soil structure by forming aggregates that increase water retention and reduce erosion. Additionally, microbes suppress plant diseases, promote growth and help plants tolerate stress. A diverse microbial community indicates a healthy, resilient soil that can better store carbon and resist environmental changes.

- **Nutrient cycling and availability:** Microbes decompose organic matter, releasing essential nutrients for plants. They also fix nitrogen and solubilize phosphorus making them accessible to plants.
- **Soil structure and water management:** Microbial activity, particularly the production of extracellular polymeric substances (EPS), binds soil particles together to form stable aggregates. This improves soil structure, make it "crumb" and increases its WHC
- **Plant health and stress tolerance:** Microbes provide plants with immunity against pathogens and suppress diseases. They also help plants to manage abiotic stresses - drought and salinity.

- **Growth promotion:** Through symbiotic relationships, microbes can promote root growth and produce hormones that stimulate plant development.
- **Soil resilience and carbon storage:** A diverse and abundant microbial community makes the soil more resilient to environmental stress and is a major driver of soil carbon storage.
- **Pollutant degradation:** Microbes break down pollutants, pesticides, plastics by biodegradation.

Factors that impact microbial communities

- Use of chemical fertilizers, pesticides and herbicides: The extensive use of these chemicals can reduce microbial growth and diversity.
- Soil conditions: Soil – moisture, temperature, pH significantly influence microbial populations.
- Plant-microbe relationship: This is a symbiotic relationship where microbes feed plants and plants feed microbes through root exudates.

Soil Enzymes and Microbes as an Indicators of Soil Health

Enzymes, are catalyst, that breaks up long, complex waste molecules into small - simple pieces - then, it can be digested directly by bacteria. They are involved in the main cycles of C, N, P & S. Degradation of organic wastes, oxidation of organic matter in soil are carried out by enzymes

Soil enzymes are bio-indicators of the potential of a soil to carry out specific bio-chemical reactions in order to maintain soil fertility. They are continuously playing an important role in maintaining soil ecology, soil physical, chemical properties, soil fertility and soil health.

They are directly involved in soil structure stabilization, decomposition of organic wastes, organic matter formation and nutrient cycling. They are catalyzing several vital reactions - necessary for the life processes of M.O in soil

Enzymes - oxidise SOM and release inorganic nutrients. Hence, they are playing an important role in agriculture. All soils contain a group of Enzymes that determines soil metabolic processes - increase the reaction rate. The enzyme levels in soil is vary - primarily due to the fact that different amount of O.M content, O.M composition, Activity of its living organisms and intensity of biological processes. Enzymes in soil - synthesized by microbes – vegetal animal cells (Dotaniya et al., 2019)

Origin of soil enzymes

(a) Microorganisms-living and dead

(b) Plant roots and plant residues and

(c) Soil animals

State of soil enzymes

a. Most activity associated with clay

b. Enzymes attached to insoluble organic matrices exhibit pH and temperature changes

c. Enzymes are bound to organic matter - then bound to clay

Importance of soil enzymes

- Release of nutrients into the soil by means of organic matter degradation
- Identification of soils, Identification of microbial activity
- Enzymes are sensitive indicators of ecological change. Enzymes activity in soil was demonstrated in 100 years ago. There are 60 soil enzymes have been identified so far in various soils. High enzyme activity is observed in clay soil (< 5 µ).
- Enzyme – clay interaction is a highly complex process. There is a +ve soil enzyme activity and soil B.D. here is a -ve soil enzyme activity and water infiltration. Urease inhibitors – reduce NH_3 volatilization – increase plant recovery of fertilizer nitrogen.
- Some Enzymes are activated only when they interact with additional chemical components are called 1. Co – enzymes – vitamins (complex organic molecules), 2. Co – factors – Mg, Fe, Zn, Cu, Mn, Ni, Co

Enzymes may include

1. amylases
2. b-glucosidase
3. cellulase
4. chitinase
5. dehydrogenase
6. phosphatase
7. protease
8. urease released from plants-animals- organic compounds – M.O - soils
9. arylsulphatases

Oxido – reductases – catalyzing electron – transfer reactions

Transferases – catalyzing molecular group (NH_2, R, CO) – transfer reactions

Hydrolases – catalyzing bond hydrolysis

Role of soil enzymes

Enzyme	**Acted On**	**End Product**	**Significance**	**Function**
Beta glucosidase	C - compounds	glucose (sugar)	Energy for M.O	O.M decomposition
FDA hydrolysis	organic matter	C - Nutrients	Energy-Nutrients for M.O	O.M decomposition - Nutrient cycling
Amidase	C-N compounds	NH_4	plant available NH_4	Nutrient cycling

Urease	nitrogen (urea)	NH_3, CO_2	plant available NH_4	Nutrient cycling
Phosphatase	phosphorus	PO_4	plant available P	Nutrient cycling
Sulfatase	Sulphur	SO_4	plant available S	Nutrient cycling

SOIL MICROBES

The biological activity in soil is largely concentrated in the topsoil. The biological components occupy a tiny fraction (<0.5%) of the total soil volume and make up < 10% O.M in soil.

Despite of their small volume in soil, M.O are key players in the cycling of N, S, P & decomposition of org. residues. M.O are further associated with the transformation and degradation of waste materials & synthetic organic compounds (Chhonkar et al., 2012)

M.O respond quickly to changes - they rapidly adapt to environmental conditions and function as an excellent indicator of change in soil health

Soil Flora	**Soil Fauna**
Soil Bacteria	Protozoa
Soil Fungi	Nematodes
Soil Actinomycetes	Insects and mites
Algae	Rodents and earthworms
Root, rhizoid, rhizome of higher plants	Borrowing vertebrates

Bacteria

Bacteria and Archaea are the smallest organisms in soil apart from viruses. They are prokaryotic - simple cell structure with no internal organelles. All the other microorganisms are eukaryotic- have a more advanced cell structure with internal organelles and the ability to reproduce sexually.

A bacterial genus called *Pseudomonas*, metabolize a wide range of chemicals and fertilizers. Another genus known as *Nitrobacter* can only derive its energy by turning nitrite into nitrate. The genus *Clostridium* - can grow in the absence of oxygen, respiring anaerobically.

Nitrogen fixation

Bacterias are responsible for the process of nitrogen fixation (which is the conversion of atmospheric nitrogen into nitrogen-containing compounds (such as ammonia) that can be used by plants.

Autotrophic bacteria derive their energy by making their own food thrugh oxidation, like the *Nitrobacters* species, rather than feeding on plants or other organisms. These bacteria are responsible for nitrogen fixation. The amount of autotrophic bacteria is small compared to heterotrophic bacteria. Heterotrophic bacteria acquire energy by consuming plants or other microorganisms

Fungi

Fungi are abundant in soil, but bacteria are more abundant. They are important in the soil as food sources for other organisms and soil health. The quality as well as quantity of organic matter in the soil has a direct correlation to the growth of fungi, because most fungi consume organic matter for nutrition. Fungi thrive in acidic environments, while bacteria and actinomycetes cannot survive in acid, which results in an abundance of fungi in acidic areas. Fungi also grow well in dry, arid soil because fungi are aerobic or dependent on oxygen and the higher the moisture content in the soil, the less oxygen is present for them.

Blue-green algae - are responsible for nitrogen fixation

Protozoa are eukaryotic - reproduce sexually - It can be split up into three categories: flagellates, amoebae and ciliates

Flagellates - are smallest members of the protozoa- it again divided based on whether they can participate in photosynthesis.

Non-chlorophyll-containing flagellates are not capable of photosynthesis because chlorophyll is the green pigment that absorbs sunlight. These flagellates are found mostly in soil. Flagellates that contain chlorophyll typically occur in aquatic conditions. Flagellates can be distinguished by their flagella, which is their means of movement.

Amoebae

Amoebae are larger than flagellates and move in a different way. Amoebae - distinguished from other protozoa by their slug-like properties and pseudopodia (false foot). It does not have permanent appendages

Ciliates

Ciliates are the largest - protozoa group - move by means of short, numerous cilia (resemble small, short hairs)

Actinomycetes

Actinomycetes are SMO. They are a type of bacteria, but have some characteristics with fungi - shape and branching properties, spore formation and secondary metabolite production.

Antibiotics

It has ability to produce antibiotics. Streptomycin, neomycin, erythromycin and tetracycline. Streptomycin is used to treat tuberculosis and infections caused by certain bacteria Neomycin is used to reduce the risk of bacterial infection during surgery.

Erythromycin is used to treat certain infections caused by bacteria, such as pneumonia and ear, intestine, lung, urinary tract and skin infections. Microbes can make nutrients and minerals in the soil available to plant. They produce hormones that spur growth, stimulate the plant immune system and trigger or dampen stress responses. More diverse soil microbiome results in fewer plant diseases and higher yield

Farming can destroy soil's rhiziobiome (microbial ecosystem) by using soil amendments such as fertilizer and pesticide. Healthy soil can increase fertility in multiple ways, including supplying nutrients such as N and protecting against pests and disease, while reducing the need for water and other inputs. The group of bacteria called rhizobia - live inside the roots of legumes and fix nitrogen from the air into a biologically useful form.

Mycorrhizae or root fungi form a dense network of thin filaments that reach far into the soil, acting as extensions of the plant roots they live on or in. These fungi facilitate the uptake of water and a wide range of nutrients. Up to 30% of the carbon fixed by plants is excreted from the roots as so-called exudates-including sugars, amino acids, flavonoids, aliphatic acids, and fatty acids, that attract and feed beneficial microbial species while repelling and killing harmful ones *Stenotrophomonas rhizophila* increases drought tolerance in crops such as sugar beets and maize.

The microbe excretes molecules that help plants withstand stress, including osmoprotectants, which prevent the catastrophic outflux of water from plants in salty environments. Microbes can affect the flavor of food plants. A bacterium called *Methylobacterium extorquens* increases the production of furanones, a group of molecules that gives strawberries their characteristic flavor. One approach is to apply microbes to plant seeds before planting instead of directly into soil.

Commercial activity - Almost all registered microbes are biopesticides, producing - $1 billion annually, < 1% of the chemical amendment market, estimated at $110 billion. Some microbes have been marketed for decades, such as *Trichoderma* fungi that suppress other, pathogenic fungi, and the caterpillar killer *Bacillus thuringiensis.* Serenade is a biopesticide - contains *Bacillus subtilis* - has antifungal and antibacterial properties - promotes Pl. growth. It can be applied in a liquid form on plants and to soil to fight pathogens. It has found acceptance in both conventional and organic agriculture.

Conclusion

Organic matter dramatically boosts soil health by improving structure, water retention, and nutrient supply, reducing compaction and erosion and feeding beneficial microbes, creating a resilient, fertile medium that supports robust plant growth and sequesters carbon. It enhances soil's physical properties (better water flow, aeration), chemical properties (nutrient holding), and biological activity (microbial food source), making soil more productive and resistant to drought and stress. It also significantly boosts crop yield and quality

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HARNESSING OF INDIGENOUS RICE AND MILLETS - A BOON FOR SUSTAINABLE CLIMATE RESILIENCE, FOOD AND HUMAN WELL-BEING

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Introduction

Rice is said to be the oldest domesticated grain crop (around 10000 years) and the most consumed cereal grain grown on the planet. Rice is grown in 11% of the world's arable land which accounts for third highest worldwide production of food crop after maize and wheat (FAOSTAT, 2023). In terms of global human nutrition and calorific intake, 21% of per capita energy and 15% of per capita protein is provided by rice (with the percentage in developing countries being 27% and 20%, respectively), ranking it as the most important food crop among the crops that feed the world (Khush and Virk, 2000). Growing rice is the important livelihood activity of millions of households around the world and forms the major source of revenue and foreign exchange for several Asian and African countries. The climate change induced natural catastrophes; along with the environmental (biotic and abiotic) stresses pose a great threat to the food security and the economic development of world's 60% population. Realizing this fact, the United Nation has set 'reducing hunger and poverty' as one of the 'Millennium Development Goals' and declared 2004 as the International Year of Rice. The food demand of the growing population was met by the first green revolution in rice production, which however, tend to diminish in recent years due to biotic and abiotic stresses.

Current scenario of nutritional security:

Climate-smart agriculture (CSA) presents a viable pathway for enhancing agricultural productivity, resilience, and sustainability in the face of climate change. Unlike conventional sustainability models, regenerative agriculture not only mitigates environmental degradation but also revitalizes ecosystems, making it a critical component of climate adaptation and mitigation strategies. At this juncture have to remember the utilization and importance of indigenous landraces for the crop improvement programmes.

Around the world, especially in India, nutritionists have been outspoken in their opposition to the harmful junk food trend and in favour of more nutrient-dense, biologically friendly, and functional meals. Additionally, several studies are being conducted to find new food-based methods to lessen the frequency and severity of lifestyle choices associated with disease. The primary emphasis is on the food's glycaemic index, mineral content, and nutritional qualities. Considering all these factors, rice has the potential to be a health food that has therapeutic and nutraceutical qualities (Ahuja et al., 2008).

Nutraceuticals are functional foods that offer health advantages beyond disease prevention and protection. Similarly, items with therapeutic qualities focus on the development of remedial agents and the treatment of sickness (Aruna et al., 2024). For instance, rice bran or its constituents have several pharmacological properties, such as anti-inflammatory, antioxidant, anticancer, cardiovascular protection, antihyperlipidemic, hepatoprotective, nephroprotective, immunomodulatory, antidiabetic, and antimicrobial properties. These properties make them potential components that could function as a therapeutic nutraceutical (Sen et al., 2020).

Additionally, the anthocyanin pigment that is deposited on the rice coat gives the rice its various colours, including brown, red, black, and purple (Huang and Lai, 2016, Lekshmi et al., 2023). In recent years, traditional rice grains have gained increased attention from consumers, health advisors, and nutritionists because of their significant impact on human health, nutritional value, and biological activity. Rice is considered the queen of cereals because of its superior biological activity, nutritional value, possible health benefits, and digestibility (Verma et al., 2017).

Modern varieties vs Indigenous landraces

The polishing procedure eliminates all dietary fiber and important fatty acids, as well as 67% of vitamin B3, 80% of vitamin B1, 90% of vitamin B6, 50% of manganese and phosp horus, and 60% of iron (Devraj et al., 2020). Ashok kumar et al. (2020) state that traditional unpolished rice, which is rich in all the elements-carbohydrates, protein, iron zinc, folate, vitamin B12 and bioactive components possesses medicinal properties that help prevent disease. Currently, many people today suffer from undernutrition due to poor food choices. However, although traditional rice is a potential diet for various diseases, it is replaced by other food by neglecting its medicinal values. Hence there is a need to review and spread the knowledge on the nutraceutical significance of traditional rice, its therapeutic properties, and its physiological effects on the human body.

Kowsalya *et al.* (2022) emphasised the antioxidant potential of some medicinal rice such as *Kattuyanam, Mapillai samba, Navara, Karunguruvai, Kavuni, Kichadi samba, Illupaipoo samba, Kalanamak, Karudan samba,* and *Seeraga samba* can treat human ailments, and it causes various physiological changes in the human body. Unpolished traditional rice has additional properties compared to ordinary polished rice since the bran layers contain high bioactive components like polyphenols, phytochemicals, antioxidants, vitamins, and minerals. These components can control several biological diseases such as carcinoma, cardiovascular disease, neurological disorder, nephrological disorder, and diabetes.

Meanwhile commercial rice varieties play a critical role in ensuring food security through high yields, traditional rice varieties offer superior nutritional benefits and contribute to the preservation of biodiversity and cultural heritage (Vennila et al. 2025). Integrating traditional varieties into modern agricultural practices and diets can help address nutritional deficiencies and promote sustainable farming. Traditional landraces of rice are indigenous varieties that have been cultivated and selected by farmers over generations. These landraces are adapted to local environmental conditions and possess unique genetic traits that contribute to their resilience nutritional and nutraceutical value (Vennila et al. 2022). Unlike modern high-yielding varieties, traditional landraces often contain higher levels of essential nutrients, such as vitamins, minerals, and antioxidants. Their nutritional significance lies in their potential to enhance dietary diversity and combat lifestyle disorders and diseases. Preserving and utilizing these landraces in breeding programs can help improve the nutritional quality of rice, contributing to better health outcomes for communities dependent on this staple crop.

Though the nutrient profile of traditional rice varieties is exceptional and rich in antioxidants and other compounds that help neutralize harmful free 4 radicals in the body and reduce the risk of chronic diseases, proper phytochemical composition of those traditional landraces is unknown or known meagre. In the context of metabolic health, traditional rice varieties have shown promising effects in managing conditions such as diabetes, dyslipidemia, arthritis, osteoporosis neurodegenerative disorders and obesity (Kowsalya et al. 2022). Their lower glycemic index compared to refined grains helps regulate blood glucose levels and insulin sensitivity, reducing the risk of insulin resistance and type 2 diabetes. Furthermore, the presence of bioactive compounds in traditional rice varieties, such as flavonoids and phenolic acids, contributes to their antioxidant and anti- inflammatory properties, which may protect against cardiovascular disease and certain types of cancer. Research has shown that consuming traditional rice varieties rich in nutraceutical components can help mitigate the risk of chronic diseases and enhance overall health. Regular consumption of antioxidant-rich foods has been associated with a lower incidence of cardiovascular disease, cancer, and. Similarly, anti-inflammatory compounds found in traditional rice varieties may help alleviate symptoms of arthritis, asthma, and inflammatory bowel disease.

Despite their cultural and nutritional significance, traditional rice varieties face numerous challenges that threaten their preservation and cultivation. Modern agricultural practices, such as monocropping and the use of chemical fertilizers and pesticides, have led to the erosion of traditional farming systems and the loss of biodiversity (Vennila et al. 2023). Additionally, economic pressures and market demands favouring high-yielding hybrid varieties have marginalized traditional rice farming communities, leading to the abandonment of traditional varieties and the loss of indigenous knowledge.

Indigenous Rice - A Nutraceutical

Rice, one of the most widely consumed staples globally, is not only essential for its caloric contribution but also for its diverse nutraceutical properties that significantly contribute to human health. Rice provides essential carbohydrates, proteins, and micronutrients necessary for human health. Nutraceuticals are bioactive compounds that provide health benefits beyond basic nutrition. Nutraceuticals are food-derived products that provide additional health benefits especially to combat lifestyle diseases.

Ahuja *et al.* (2008) enlightened the medicinal uses of rice in Ayurveda which balances the tridoshas and heals the human body from various diseases. Indian pharmacopoeia recommended rice water as an excellent drink in febrile and inflammatory diseases and dysuria.

Umadevi *et al.* (2012) described rice not only provides nutritional and therapeutic benefits, but its byproducts are also useful. Growing rice produces a variety of valuable and worthwhile byproducts. Rice can be used to treat several skin diseases. To treat boils, sores, swellings, and skin blemishes, use rice paste balls. Other herbs are occasionally added to the rice balls to enhance their therapeutic properties. Sticky rice is commonly used to relieve stomach distress, heartburn, and indigestion. Brown rice extracts help treat breast and stomach cancer, as well as warts and also help to relieve indigestion, nausea, and diarrhea.

Due to increasing awareness among people about the side effects of synthetic drugs used to increase the glucose uptake in tissues and the benefits of consuming functional foods, research is focused on natural compounds as therapeutic agents. The anthocyanin in rice are chemically flavonoids which serves as an antioxidant, antidiabetic, antihyperlipidemic and anti-ageing agents. Zhu Shoumin (2005) and Sung *et al.* (2019).

Indigenous Rice - Reservoir of nutraceuticals:

Krishnan *et al.* (2021), characterized pigmented rice in terms of nutraceutical starch (NS) and phenolic content. Further the effect of rice phenolics on carbolytic enzyme inhibition, glucose uptake, hepatic glucose homeostasis and anti-glycation ability was analyzed *in vitro*. The most relevant effect on enzyme inhibition (α-amylase: IC_{50}-42.34 µg/mL; α-glucosidase: IC_{50}:63.89 µg/mL), basal uptake of glucose (>39.5%) and anti-glycation ability (92%) was found in red rice (RR), than black rice (BR). The role of RR phenolics in regulating glucose homeostasis was deciphered using hepatic cell line system, which found up-regulation of glucose transporter 2 (GLUT2) and glycogen synthase 2 (GYS2); while expression of gluconeogenic genes were found down regulated.

Indigenous Rice - Abiotic stresses:

By the traditional breeding initiatives, the natural variability in the global rice germplasm, notable progress has been made in the development of high yielding, salt-tolerant rice varieties. This involves, for the most part, using the readily available, widely adapted sources-such as Pokkali, Nona-Bokra, SR26B, and M 40-to transfer salt tolerance to more elite lines in order to produce high yielding salt-tolerant rice varieties (Singh *et al.,* 2021). Many rice types that can withstand salt have been released consequently (Balasubramanian and Vennila, 2024a). To address the needs of salt-affected areas, several attempts were also undertaken to increase the rice hybrids' resistance to salt (Hoang *et al.,* 2016).

The comparative analysis between stress and non-stress conditions reveals interesting patterns in ion homeostasis. The general reduction in potassium concentration and increase in sodium uptake under stress conditions aligns with current understanding of salt stress responses in rice (Zhou et al., 2024). However, the ability of certain lines, particularly ABL-146 and ABL-125 which is a derivative of ADT 43 x Kalurundai (Balasubramanian and Vennila, 2024b), to maintain relatively stable K+/Na+ ratios under stress indicates the presence of robust salt tolerance mechanisms, which could be attributed to enhanced expression of ion transporters and channels (Usman et al., 2023).

Millets scenario in India

Currently, this is the age of an agrarian crisis which has called for crop improvement under the detrimental effects of climate change. Intensive agriculture of a few crops for food requirements has led to inadequate nutrition, and genetic erosion, and has forced to neglect local nutritionally-rich crops (Gull et al, 2014). These are known as poor man's crops and sustain about one-third of the world's population. The problems created by climate change can be primarily solved using naturally stress resistant plants (NSRP's), which ensures yield stability, global food security, and health. Millets are agronomically beneficial because they are tolerant to drought, heat, salt, and biotic stresses, and survive in marginal lands under rainfed conditions (Kaur et al., 2024).

Millets are commonly known as “Coarse cereals or poor man’s cereals”.

Millets also known as “climate-smart crops” and “smart -food” as these foods are good for us, the planet as well as the farmers. The *2030 Agenda for Sustainable Development*, adopted by all United Nations members in 2015, created 17 world Sustainable Development Goals (SDGs). The aim of these global goals is “peace and prosperity for people and the planet”. Good health and well-being (SDG 3). Traditionally Proso millet is used in the cure of gonorrhoea; Foxtail millet as a sedative and laxative; Barnyard millet is used in the disease of spleen; Finger millet in the “Tridosha” blood disease; Kodo millet in constipation, Little millet as a blood purifier (Kaur et al. 2024).

Proso contains a very high level of minerals and dietary fiber. It is a rich source of various minerals and vitamins. It contains potassium, iron, phosphorus, calcium, magnesium, zinc, vitamin B-complex, niacin, and folic acid. Pearl millet has less amount of carbohydrates as compared to other staple cereals, and it is mainly composed of starch and insoluble dietary fiber. It is gluten-free and high in omega-3 fatty acids; the amino acid score is also good (Zhang et al 2014) further it contains fatty acids (alpha-linolenic acid, eicosapentaenoic acid, and docosahexaenoic acid), other micronutrients (iron, zinc, copper, potassium, magnesium, phosphorous, manganese), and B vitamins (Sabuz et al. 2023)

Table 1. Nutritional index of millets (per 100 g)

Name of millet	Energy (kcal)	Protein (g)	Carbohy -drates	Fat	Calcium	Dietary Fiber	Starch
Sorghum	334	10.4	67.6	1.9	27	10.2	59
Pearl millet	363	11.6	61.7	5	27	11.4	55
Finger millet	320	7.3	66.8	1.3	364	11.1	62
Proso millet	341	12.5	70.0	1.1	14	-	-
Foxtail millet	331	12.3	60.0	4.3	31	-	-
Kodo millet	353	8.3	66.1	1.4	15	6.3	64
Little millet	329	8.7	65.5	5.3	17	6.3	64
Barnyard millet	307	11.6	65.5	5.8	14	-	-

(Source: Indian Food Composition Table, IIMR 2017)

Kodo millet provides gluten-free protein. It contains B-complex vitamins such as B6, niacin, and folic acid and minerals including magnesium, iron, potassium, calcium, and zinc.

Moreover, it is highly digestible. Foxtail millet contains vitamins, minerals, high dietary fiber content, resistant starch, and essential amino acids.

Finger millet has the highest carbohydrate level; it is primarily of slowly digestible starch, dietary fiber, and resistant starch. Around 7% protein is present in finger millet, which is less as compared to other millets (IIMR 2017). It contains various micronutrients such as calcium, potassium, magnesium, iron, and zinc, as well as B vitamins, especially B6, niacin, and folic acid, which are abundantly present.

Foxtail Millet (Kangni/Kakum): Foxtail millet is cultivated in several states across India, including Tamil Nadu, Andhra Pradesh, Karnataka, and Maharashtra. It is often used to make rice dishes, idlis (steamed rice cakes), and dosas.

Little Millet (Kutki/Sama): Little millet is grown in different parts of India, including Karnataka, Andhra Pradesh, Tamil Nadu, and Odisha. It is used to make khichdi, upma (a savory dish made with semolina), and porridge. In little millet, there is availability of around 8.7% of protein and amino acids (cysteine and methionine) (Neeharika et al. 2020) The little millet also contains various micronutrients. (iron, niacin, phosphorous, zinc) and also the proteins (Birania et al.2020).

Barnyard Millet (Sanwa/Jhangora): Barnyard millet is cultivated in various regions of India, including Uttar Pradesh, Maharashtra, and Uttarakhand. It is used to make porridge, kheer (sweet pudding), and upma.

Conclusion

Rural livelihoods are severely hampered by climate change and weather-related disasters, which are frequently affected by erratic rainfall, droughts and floods. Awareness should be created to the farmers and consumers about the importance of traditional landraces and millets for cultivation and consumption. Several challenges faced by breeders in developing biofortified varieties with photo-insensitive, higher yield coupled with cooking quality using traditional rice landraces and millets.

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EFFECTIVE CLIMATE-SMART PRACTICES TO MITIGATE GLOBAL WARMING AND GREENHOUSE GASES IN AGRICULTURE

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Introduction

Agriculture plays a vital role in the global economy, providing food, fiber, and livelihoods to millions. However, it also contributes significantly to greenhouse gas (GHG) emissions, which exacerbate global warming. As the global population continues to grow, there is an increasing need for sustainable agricultural practices that can meet the rising food demand without compromising the environment. Climate-smart agriculture (CSA) refers to a set of practices designed to improve agricultural productivity, enhance resilience to climate change, and reduce GHG emissions. This write-up explores effective CSA practices that help mitigate global warming and reduce GHG emissions, with a focus on methods suitable for different agricultural systems.

1. Conservation Agriculture

a. Minimum Tillage

Conservation agriculture (CA) involves practices that minimize soil disturbance, enhance soil structure, and promote biodiversity. Minimum tillage, where farmers disturb the soil as little as possible, reduces CO_2 emissions from the soil and helps in carbon sequestration. It also improves soil health, leading to greater water retention and nutrient availability, which can enhance crop productivity. Traditional ploughing and tilling methods disturb the soil structure, breaking it up to prepare for planting. In contrast, minimum tillage leaves most of the soil surface undisturbed, often with only small areas being opened for planting seeds.

Traditional tillage releases large amounts of CO_2 into the atmosphere as soil organic matter is exposed to oxygen and breaks down. In contrast, minimum tillage reduces this release of CO2 by leaving the soil relatively undisturbed. Additionally, minimum tillage reduces the use of heavy machinery, which in turn reduces fuel consumption and the associated CO_2 emissions. Minimum tillage also helps reduce nitrous oxide (N_2O) emissions by improving soil structure and reducing the compaction that can lead to poor aeration. Well-aerated soils promote more efficient nutrient cycling and reduce the conditions that favor N_2O production, particularly in waterlogged or compacted soils.

One of the key challenges facing agriculture is water management, especially in the context of climate change, where rainfall patterns are becoming more erratic. Minimum tillage helps improve the soil's ability to retain moisture by enhancing its structure and increasing organic matter. This leads to better water infiltration and reduced evaporation, making crops more resilient to drought conditions.

Soil erosion is a major concern in many agricultural systems, particularly in areas with sloping terrain or poor land management practices. Minimum tillage helps reduce erosion by maintaining a protective cover of crop residues on the soil surface. The residue acts as a buffer, reducing the impact of rain and wind on the soil and preventing it from being washed or blown away. Erosion not only leads to the loss of fertile topsoil but also contributes to the release of CO_2 from the organic matter that is eroded. By minimizing soil disturbance and maintaining soil cover, minimum tillage reduces erosion, contributing to both improved soil health and lower carbon emissions.

b. Crop Residue Management

Crop residue management is a key practice in climate-smart agriculture (CSA) that involves leaving the remains of harvested crops, such as stalks, leaves, and roots, on the field rather than burning or removing them. This approach contributes to sustainable farming by improving soil health, enhancing water retention, and reducing greenhouse gas emissions.

Benefits of Crop Residue Management in CSA:

1. **Soil Health Improvement:** Residue left on the soil surface decomposes and adds organic matter, which enhances soil structure, fertility, and microbial activity.
2. **Carbon Sequestration:** By leaving organic material in the field, crop residues help capture and store carbon in the soil, mitigating the release of CO_2 into the atmosphere.
3. **Erosion Control:** Crop residues act as a protective cover, reducing soil erosion caused by wind and water. This preserves fertile topsoil, crucial for long-term productivity.
4. **Moisture Conservation:** Residues act as mulch, reducing soil evaporation and improving water infiltration, which is particularly beneficial in drought-prone areas.
5. **Reduced GHG Emissions:** Avoiding the burning of crop residues lowers the release of harmful emissions like carbon dioxide (CO_2) and methane (CH_4), contributing to climate change mitigation.

Overall, crop residue management aligns with CSA goals by promoting sustainability, resilience to climate variability, and reducing agriculture's carbon footprint.

c. Crop Rotation and Diversification

Crop rotation involves alternating the species or varieties of crops grown in a particular field across different seasons or years, while diversification refers to the practice of growing multiple crops or varieties within a farming system. These practices not only improve soil health and productivity but also enhance the adaptability of agricultural systems to climatic variations. Rotating crops helps break pest cycles and enhances soil fertility. By alternating crops with legumes, for example, farmers can reduce their dependence on chemical fertilizers, thereby lowering nitrogen-related GHG emissions. Diversifying crops also makes farming systems more resilient to extreme weather events.

Crop rotation plays a crucial role in improving soil health by preventing the depletion of specific nutrients. Different crops have varying nutrient requirements and rooting depths. For instance, legumes such as soybeans or alfalfa fix atmospheric nitrogen through symbiotic relationships with nitrogen-fixing bacteria in the soil. When legumes are included in the rotation, they enrich the soil with nitrogen, reducing the need for synthetic fertilizers in subsequent crops like corn or wheat. By alternating deep-rooted and shallow-rooted crops, rotation also improves soil structure. Deep-rooted crops break up compacted soil layers, enhancing water infiltration and root penetration. This leads to better water retention and nutrient availability, fostering a more fertile and resilient soil ecosystem.

Crop diversification is the practice of growing multiple crops or varieties within a farm or field. Diversifying crops can improve farm resilience to climate-related stresses such as droughts, floods, and temperature extremes. Different crops have varying tolerance levels to environmental conditions, and growing a mix of crops reduces the risk of complete crop failure in the face of adverse weather events. For example, a diversified system that includes drought-tolerant crops like sorghum or millet alongside water-intensive crops such as rice or maize can balance water requirements and enhance overall productivity under variable climate conditions. This reduces the vulnerability of farming systems to unpredictable weather patterns, making them more adaptable to climate change.

Diversification provides farmers with more options for marketable crops, which can enhance income stability and reduce economic risks. A monoculture system, where farmers rely on a single crop for income, is highly vulnerable to market fluctuations and crop failures. In contrast, a diversified system provides multiple income streams, ensuring that farmers are less affected by poor market prices or crop losses due to pests or climate-related events. This economic resilience is essential in regions where smallholder farmers are especially vulnerable to the impacts of climate change. Diversified cropping systems can help stabilize farm income, providing a buffer against climate shocks and market volatility, and contributing to food security.

Both crop rotation and diversification contribute to reducing GHG emissions from agricultural systems. Crop rotation minimizes the need for synthetic fertilizers, reducing nitrous oxide emissions, while diversified systems optimize the use of natural resources, enhancing carbon sequestration in soils and plants. Additionally, by promoting efficient nutrient cycling, integrated pest management, and water conservation, these practices contribute to the overall sustainability of agricultural production. Furthermore, diversified systems that include agroforestry or silvopastoral elements can enhance carbon storage aboveground by incorporating trees and shrubs. These systems are capable of sequestering significant amounts of carbon, thereby playing an important role in climate change mitigation.

2. Agroforestry Systems

Agroforestry is the intentional integration of trees and shrubs into agricultural landscapes. This practice can take several forms, including alley cropping (growing crops between rows of trees), silvopasture (combining trees with livestock grazing), and forest farming (growing shade-tolerant crops under a tree canopy). Each of these systems has unique advantages, but all share common benefits for both the environment and agricultural productivity.

One of the most critical contributions of agroforestry systems to mitigating climate change is their ability to sequester carbon. Trees absorb CO2 from the atmosphere through photosynthesis and store it as carbon in their biomass (trunks, branches, leaves) and in the soil. This carbon storage reduces the concentration of CO_2, a major GHG, in the atmosphere.

Aboveground Carbon Sequestration: The trees in agroforestry systems can store large amounts of carbon in their trunks, branches, and leaves. The larger and older the tree, the more carbon it can sequester. Perennial tree crops, such as fruit trees or timber species, can store carbon for decades, making them an essential part of long-term carbon storage strategies.

Belowground Carbon Sequestration: Agroforestry systems also enhance soil carbon sequestration. Tree roots contribute organic matter to the soil, improving its carbon content and overall health. Additionally, the presence of trees reduces soil erosion and helps maintain stable soil carbon levels, which are crucial for mitigating GHG emissions from agricultural lands.

a. Silvopasture

Silvopasture is a form of agroforestry that integrates trees with pasturelands and livestock. This practice enhances carbon sequestration while improving forage production. It also reduces methane emissions from livestock by improving the quality of the forage.

b. Alley Cropping

In alley cropping, crops are grown in the spaces between rows of trees or shrubs. The trees act as windbreaks, reducing soil erosion, while the crops benefit from the organic matter contributed by tree litter. Alley cropping systems can also be used to diversify farm outputs and provide additional income sources for farmers. Agroforestry also helps reduce GHG emissions from agricultural activities in several ways. Traditional farming practices, such as intensive monocropping and frequent tillage, often release large amounts of CO_2 and N_2O into the atmosphere. Agroforestry reduces these emissions by creating more sustainable, low-input farming systems.

Nitrous oxide (N_2O) is a potent greenhouse gas, mainly released through the excessive use of synthetic nitrogen fertilizers. Agroforestry systems reduce the need for these fertilizers by improving nutrient cycling. Leguminous trees, such as acacias or gliricidia, are often used in agroforestry systems because they fix atmospheric nitrogen, enriching the soil with natural nitrogen that benefits both crops and trees. This reduces dependence on synthetic fertilizers and lowers N_2O emissions. Livestock farming is a major source of methane (CH_4) emissions, especially from enteric fermentation in ruminant animals such as cows and sheep.

c. **Silvopastoral systems**, a form of agroforestry that integrates trees with pastureland, can help mitigate methane emissions by improving the quality of forage and the overall health of grazing animals. Trees in silvopasture systems provide shade, which reduces heat stress in animals and improves their productivity, potentially lowering methane emissions per unit of livestock output.

- **Carbon Sequestration:** Trees in silvopastoral systems capture and store carbon in both their aboveground biomass (trunks, branches, leaves) and in the soil. This carbon sequestration helps offset methane and nitrous oxide emissions from livestock, making the system more climate-friendly.
- **Improved Animal Health and Productivity:** The presence of trees provides shade and shelter for livestock, reducing heat stress and improving overall animal health and productivity. Healthier, more productive animals tend to have lower GHG emissions per unit of output (e.g., meat or milk).

Despite its benefits, agroforestry faces challenges that may hinder its widespread adoption. These include:

- **Land Tenure Issues:** In some regions, farmers may lack secure land tenure, making them hesitant to invest in long-term agroforestry systems that take years to fully mature.
- **Knowledge and Training:** Successful agroforestry requires specific knowledge about tree species, planting techniques, and management practices. Farmers need training and extension services to implement these systems effectively.
- **Initial Costs:** Establishing an agroforestry system can involve high initial costs for planting trees and managing the land. However, these costs are typically offset by long-term benefits such as increased yields, reduced input costs, and ecosystem services.

d. Opportunities for Scaling Agroforestry: Governments, NGOs, and international organizations are increasingly recognizing agroforestry as a key strategy for climate-smart agriculture. Providing financial incentives, technical support, and secure land tenure can encourage farmers to adopt agroforestry systems. Additionally, promoting market access for agroforestry products (such as timber, fruits, or nuts) can provide farmers with economic incentives to integrate trees into their farming systems.

3. Improved Livestock Management

Livestock farming is a major contributor to global greenhouse gas (GHG) emissions, accounting for about 14.5% of total anthropogenic GHGs. The primary sources of emissions in livestock systems include methane (CH_4) from enteric fermentation in ruminants, nitrous oxide (N_2O) from manure management, and carbon dioxide (CO_2) from land-use changes related to feed production and deforestation. With the increasing demand for animal products driven by population growth and changing dietary patterns, there is a critical need to implement climate-smart practices in livestock management to mitigate the environmental impact of the sector while ensuring food security and economic viability.

Improved livestock management within the framework of Climate-Smart Agriculture (CSA) seeks to increase productivity, enhance the resilience of farming systems to climate variability, and reduce GHG emissions.

a. Improved Feed Quality

One of the most effective ways to reduce methane emissions from livestock is by improving the quality of animal feed. Low-quality, fibrous feed leads to higher methane production, as it is more difficult for animals to digest. By providing higher-quality forage, grain-based supplements, or improved pasture species, farmers can enhance animal nutrition, resulting in more efficient digestion and lower methane emissions per unit of animal output.

- **Feed Additives:** The use of specific feed additives, such as fats, oils, tannins, and nitrates, has been shown to reduce methane emissions from ruminants. For example, dietary oils can inhibit methane-producing microbes in the rumen, while nitrates help redirect hydrogen, which would otherwise form methane, towards the production of non-methane compounds.
- **Precision Feeding:** Matching nutrient supply to the specific requirements of animals at different stages of growth or lactation can also optimize feed efficiency and reduce GHG emissions. Precision feeding ensures that animals are not overfed or underfed, which can reduce both methane emissions and nitrogen losses from manure.

b. Breeding and Genetics

Breeding livestock for improved productivity and lower methane emissions is another promising approach. Selective breeding programs that focus on traits such as higher feed conversion efficiency, faster growth rates, and improved health can reduce methane emissions per kilogram of animal product (e.g., meat, milk, or wool).

- **Genetic Selection for Low Methane Production:** Some studies have shown that certain animals naturally produce less methane than others. By identifying and breeding these animals, farmers can create herds with lower overall methane emissions.

c. Improved Manure Storage and Handling

Manure management practices can greatly influence GHG emissions. Proper storage and handling of manure can help reduce both methane and nitrous oxide emissions.

- **Anaerobic Digesters:** One of the most effective technologies for reducing methane emissions from manure is the use of anaerobic digesters. These systems capture methane produced from the anaerobic breakdown of manure and convert it into biogas, which can be used as a renewable energy source for electricity, heat, or transportation fuel. By capturing methane, anaerobic digesters prevent its release into the atmosphere and provide an alternative to fossil fuels.
- **Composting:** Composting manure under aerobic conditions (with oxygen) reduces methane production and helps convert nitrogen into stable organic forms, minimizing nitrous oxide emissions. Well-managed composting can also produce a valuable soil amendment that improves soil health and fertility, further enhancing the sustainability of livestock farming systems.

d. Precision Application of Manure as Fertilizer

Manure is an excellent source of nutrients for crops, but improper application can lead to significant GHG emissions. Climate-smart practices include the precision application of manure, where it is applied at the right time, in the right amount, and in the right place to maximize nutrient use efficiency and minimize GHG emissions.

- **Manure Injection:** Injecting liquid manure into the soil rather than spreading it on the surface reduces ammonia volatilization, which in turn reduces the potential for nitrous oxide emissions. This practice also improves nutrient uptake by crops and reduces the risk of nutrient runoff into water bodies.
- **Covered Manure Storage:** Covering manure storage facilities (e.g., lagoons or pits) with impermeable covers can reduce methane emissions by limiting the anaerobic conditions that favor methane production. The captured methane can then be flared or used as a renewable energy source.

4. Precision Agriculture

Precision agriculture is a farming management system that uses advanced technology to monitor and manage variations in crop and livestock production, applying inputs (such as water, fertilizers, and pesticides) precisely where and when they are needed. This data-driven, technology-enhanced approach is highly aligned with the goals of Climate-Smart Agriculture (CSA), which seeks to increase productivity, enhance resilience to climate change, and reduce emissions. This write-up explores how precision agriculture can contribute to mitigating global warming and reducing GHG emissions, while also enhancing the sustainability of agricultural systems.

a. Optimizing Fertilizer Use and Reducing Nitrous Oxide Emissions

Nitrous oxide (N_2O) is one of the most potent greenhouse gases, with a global warming potential approximately 300 times greater than carbon dioxide (CO_2). A significant portion of N_2O emissions in agriculture comes from the overuse and inefficient application of nitrogen-based fertilizers. Precision agriculture can play a key role in reducing these emissions by improving the precision with which fertilizers are applied.

b. Variable Rate Technology (VRT)

One of the core tools of precision agriculture is **Variable Rate Technology (VRT)**, which allows farmers to apply fertilizers at varying rates across a field based on the specific nutrient needs of different areas. VRT systems rely on data collected from soil sensors, satellite imagery, and GPS-guided machinery to map out nutrient deficiencies or surpluses in the field. This enables farmers to apply just the right amount of fertilizer where it is needed, reducing excess nitrogen that would otherwise contribute to N_2O emissions.

c. Soil Nutrient Monitoring

Precision agriculture involves the use of advanced soil sensors and testing technologies that provide real-time information about soil nutrient levels. By accurately assessing the nutrient status of the soil, farmers can avoid over-fertilization, which reduces the risk of nutrient runoff and volatilization into the atmosphere as N_2O. This also improves overall soil health, which contributes to long-term agricultural sustainability.

d. Timing of Fertilizer Application

Precision agriculture tools also allow farmers to optimize the timing of fertilizer application. By using weather forecasting models and real-time data, farmers can apply fertilizers when soil and climatic conditions are most favorable, minimizing nutrient losses through leaching or volatilization. This reduces the environmental impact of fertilizer use and enhances the efficiency of nutrient uptake by crops, lowering N_2O emissions.

e. Soil Moisture Sensors

Soil moisture sensors measure the water content in the soil, providing real-time data to farmers about when and how much to irrigate. This prevents over-irrigation, which not only conserves water but also reduces the risk of nutrient leaching and the emissions of N_2O from waterlogged soils. These sensors can be integrated into automated irrigation systems that apply water only when needed, reducing unnecessary water use.

f. Precision Irrigation with Remote Sensing

Remote sensing technology, such as drones or satellite imagery, can monitor crop health and water stress across large areas. This allows farmers to target irrigation more precisely, applying water only where crops need it most. By reducing over-irrigation and improving water efficiency, precision irrigation can help lower the carbon footprint of agricultural systems.

g. GPS-Guided Machinery

Precision agriculture uses **GPS (Global Positioning System)** and **autonomous machinery** to enhance the efficiency of field operations. GPS-guided tractors and sprayers allow farmers to optimize the movement of machinery across fields, reducing overlaps and minimizing the number of passes required to complete tasks. This not only reduces fuel consumption but also limits soil compaction, which can improve soil health and productivity in the long term.

- **Reduced Fuel Consumption:** With more efficient machinery use, farmers can reduce the total amount of fuel burned during planting, fertilization, and harvest operations. This directly lowers CO_2 emissions from fossil fuel combustion, contributing to climate change mitigation.

5. Integrated Pest Management (IPM)

IPM is an approach that combines biological, cultural, and chemical control methods to manage pests with minimal environmental impact. It reduces the need for synthetic pesticides, which are often associated with high energy use and GHG emissions during their production and application.

a. Biological Control

Biological control involves the use of natural predators, parasites, or pathogens to control pest populations. By relying on these natural enemies, farmers can reduce or eliminate the need for chemical pesticides, thereby reducing emissions associated with their production, transport, and application. Examples include:

- Releasing beneficial insects such as ladybugs or predatory mites to control aphid populations.

- Using bacteria, fungi, or viruses that specifically target pest species, such as the bacterium *Bacillus thuringiensis* (Bt), which is effective against certain caterpillars.

This method not only decreases GHG emissions but also promotes biodiversity and ecosystem resilience, which are key goals of climate-smart agriculture.

b. Cultural Practices

Cultural control methods involve modifying farming practices to reduce pest pressure. These include crop rotation, intercropping, and adjusting planting dates to avoid peak pest periods. By preventing pest infestations, cultural practices reduce the need for chemical treatments and associated emissions.

- **Crop Rotation:** Rotating crops can break pest life cycles, reducing pest populations and the need for pesticides.
- **Intercropping:** Growing different crops in proximity can confuse pests or attract beneficial insects, lowering pest pressure without the need for chemicals.

These practices enhance the sustainability of farming systems by promoting soil health and reducing the carbon footprint of pest management.

6. Organic Farming

Organic farming is an agricultural system that avoids the use of synthetic fertilizers, pesticides, and genetically modified organisms (GMOs). Instead, it relies on natural processes such as composting, crop rotation, and biological pest control.

a. Composting and Organic Fertilizers

Organic farming relies on organic fertilizers, such as compost, animal manure, and green manure, which contribute to building soil organic carbon. Unlike synthetic fertilizers, which can contribute to GHG emissions, organic inputs improve soil structure, increase microbial activity, and enhance the soil's ability to store carbon over the long term.

- **Composting:** The use of compost as a natural fertilizer helps sequester carbon in the soil by converting organic waste into stable organic matter. This process not only reduces methane emissions from organic waste decomposition but also enhances soil fertility, reducing the need for synthetic inputs.

b. No-Till and Reduced Tillage Practices

In organic farming, reduced tillage or **no-till practices** are often employed to prevent soil degradation and promote carbon sequestration. Tillage disturbs the soil, releasing stored carbon into the atmosphere as CO_2. By minimizing soil disturbance, organic farming helps retain carbon in the soil, contributing to long-term carbon storage.

- **Cover Cropping:** Organic systems often use cover crops to protect and enrich the soil. Cover crops increase biomass and organic matter in the soil, which helps to store more carbon while also improving soil health.

7. Water-Smart Practices

Efficient water management is critical for both productivity and climate change mitigation. Poor irrigation practices can lead to water waste, land degradation, and methane emissions from waterlogged soils.

a. Drip Irrigation

Drip irrigation is one of the most water-efficient irrigation methods. It delivers water directly to the plant roots through a network of tubes and emitters, minimizing water loss through evaporation or runoff. By providing water in precise amounts where it is needed most, drip irrigation significantly improves water-use efficiency and reduces the energy required for water pumping.

- **GHG Reduction:** Drip irrigation systems reduce energy consumption for water pumping, which, in turn, lowers the associated CO_2 emissions. This method also decreases the amount of water applied to crops, which can reduce methane (CH_4) emissions from waterlogged soils, particularly in crops like rice.

b. Sprinkler Irrigation with Sensors

Sprinkler irrigation systems, particularly those equipped with soil moisture sensors, can optimize water usage by irrigating only when necessary. Sensors measure soil moisture levels in real-time and signal when irrigation is required, ensuring that crops receive adequate water without over-irrigating.

- **Energy Efficiency:** By reducing unnecessary irrigation, sensor-based systems cut down on the energy used for water distribution, contributing to lower GHG emissions.

c. Alternate Wetting and Drying (AWD)

AWD is a water management practice used in rice production that alternates between wet and dry periods, reducing methane emissions from flooded rice paddies. This method can also improve water-use efficiency and reduce irrigation costs.

8. Climate-Smart Crop Varieties

Developing and adopting climate-smart crop varieties can help mitigate GHG emissions while improving crop resilience to climate change.

a. Drought-Resistant Crops

Crops such as maize, wheat, rice, and sorghum have been bred to withstand periods of drought by improving water-use efficiency and maintaining yields under water-limited conditions. These varieties are designed to have deeper root systems, better water retention, and improved physiological mechanisms to cope with water stress.

- **Water Conservation and GHG Reduction:** By reducing the need for irrigation, drought-tolerant crops help lower the energy consumption and CO_2 emissions associated with water extraction and distribution. In addition, maintaining productivity in water-scarce conditions helps reduce the pressure to expand agricultural land, which can prevent deforestation and protect carbon-rich ecosystems.

b. Nutrient-Efficient Crops

Nitrogen-efficient crop varieties can absorb nitrogen more effectively, reducing the need for synthetic fertilizers. This can lower N2O emissions, which are a potent greenhouse gas. **Nitrogen-use efficient (NUE)** crop varieties are capable of absorbing and utilizing nitrogen more effectively, leading to higher yields with reduced fertilizer inputs. These varieties are developed for crops such as maize, wheat, and rice, where nitrogen use is typically high.

- **GHG Reduction:** By reducing the amount of nitrogen fertilizer needed, these crops help lower N_2O emissions from agricultural soils. In addition, they reduce the energy required for the production, transportation, and application of synthetic fertilizers, further cutting down CO_2 emissions.

Phosphorus is another critical nutrient, and overuse of phosphorus fertilizers can lead to environmental degradation. Breeding crops that are more efficient at using phosphorus can reduce the need for phosphorus fertilizers, conserving natural resources and minimizing the environmental impact of phosphorus mining and use. Legumes play a key role in sustainable agriculture by fixing nitrogen from the atmosphere, reducing the need for synthetic nitrogen fertilizers. Climate-resilient legume varieties are bred to tolerate drought, heat, and poor soil conditions, making them an essential part of climate-smart farming systems.

9. Bioenergy and Biofuels

The use of bioenergy and biofuels in agriculture can reduce the reliance on fossil fuels and lower GHG emissions. By converting agricultural waste into energy, farmers can create a renewable source of energy while also reducing methane emissions from organic waste decomposition.

a. Biogas Production

Biogas is produced through the anaerobic digestion of organic materials such as manure, crop residues, and food waste. It can be used as a renewable energy source to power farms or generate electricity, reducing dependence on fossil fuels.

b. Ethanol and Biodiesel

Ethanol and biodiesel are renewable fuels made from crops like corn, sugarcane, and soybeans. They can replace traditional fossil fuels in farm machinery and transportation, leading to lower carbon emissions.

10. Policy Support and Financial Mechanisms

For Climate smart agriculture practices to be widely adopted, supportive policies and financial mechanisms are necessary. Governments, international organizations, and the private sector play important roles in promoting climate-smart agriculture.

a. Carbon Credits and Incentives

Farmers can benefit from carbon credits by adopting practices that sequester carbon or reduce GHG emissions. Carbon credit programs provide financial incentives for farmers to engage in sustainable practices, making CSA more economically viable.

b. Research and Extension Services

Governments and research institutions need to invest in agricultural research to develop new technologies and climate-smart practices. Extension services should be strengthened to ensure that farmers have access to the knowledge and resources they need to implement CSA practices effectively.

Conclusion

Mitigating global warming and reducing GHG emissions in agriculture requires a comprehensive approach that includes conservation agriculture, improved livestock management, agroforestry, precision agriculture, and the adoption of climate-smart technologies. By implementing these practices, farmers can not only reduce their environmental impact but also enhance their resilience to the effects of climate change. However, widespread adoption of these practices will require strong policy support, financial incentives, and continued investment in research and education. Sustainable agriculture is essential for ensuring food security in a changing climate while protecting the planet for future generations.

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WARMING WORLD, BOOMING BUGS - A GROWING THREAT TO GLOBAL FOOD SECURITY AND SUSTAINABLE SOLUTIONS

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ABSTRACT

Climate change is reshaping agricultural pest dynamics, posing significant threats to crop production. Elevated CO_2 levels enhance plant growth, indirectly benefiting herbivorous pests. Altered precipitation patterns and rising temperatures create favorable conditions for pest proliferation and expanded habitats. Warmer climates accelerate pest development, leading to more generations per year and increased crop damage. Additionally, milder winters improve overwinter survival rates, resulting in larger pest populations in subsequent seasons. The disruption of natural predator-prey relationships further exacerbates pest infestations, necessitating greater reliance on chemical pesticides, which carry environmental and health risks. Effective pest management strategies must integrate resistant crop varieties, biological control agents, and predictive modeling to anticipate and mitigate pest outbreaks. Understanding the multifaceted impacts of climate change on agricultural pests is crucial for developing sustainable farming practices and safeguarding global food security in an evolving climate. Future research should focus on adaptive management approaches to address these emerging challenges.

1. Introduction

Agriculture is an art, science, and technology with added-on credentials that feed humans, which would face tonnes of problems from sowing to harvest and famous problems related to insect pests are triple R- Resistance, Residue, and Resurgence along with lack of proper surveying or monitoring of insect pests infestation, improper utilization of IPM management strategies, lack of trained extension workers, scam related to biocontrol agents and so on. On the other indebtedness returned by humankind to the ecosystem is an irreversible change in climatic factors which created diverse issues such as changes in cropping patterns, crop physiology, increased insect and disease pests infestation, collapsed biodiversity, failure of pest management strategies, increase in the introduction of alien insect species which pave the way for failure of the newer formulation of pesticides eventually resulting in the resistance development of native insect pests species and make the minor pests gain superpowers and attain the status of major pests and give out the endemic pest outbreak and, there is no room to talk about natural enemies. With this, the impact of climate change on insect pests in various aspects is discussed.

2. Global Climatic Status

Climate change is the long-term alteration of Earth's temperature and weather patterns. While natural factors like solar cycles and volcanic eruptions can influence climate, human activities have been the primary cause of the current warming trend. Burning fossil fuels, deforestation, and industrial processes release greenhouse gases, such as carbon dioxide and methane, into the atmosphere (United Nations, 2023). Greenhouse gases which would absorb and re-emit the infrared radiation eventually heating the earth's surface. The major greenhouse gases, carbon dioxide, methane, and nitrous oxide, have both anthropogenic and natural sources of origin, the rest of them, such as chlorofluorocarbons and Sulfur hexafluoride, are resulted by anthropogenic origin. In 2022 atmospheric levels of greenhouse gases reached new observed highs with globally averaged concentrations of carbon dioxide (CO_2) at 417.9 ± 0.2 parts per million (ppm), methane (CH_4) at 1 923 ± 2 parts per billion (ppb) and nitrous oxide (N_2O) at 335.8 ± 0.1 ppb (Fig 1.) (World Meteorological Organization, 2023a. download (wmo.int)).

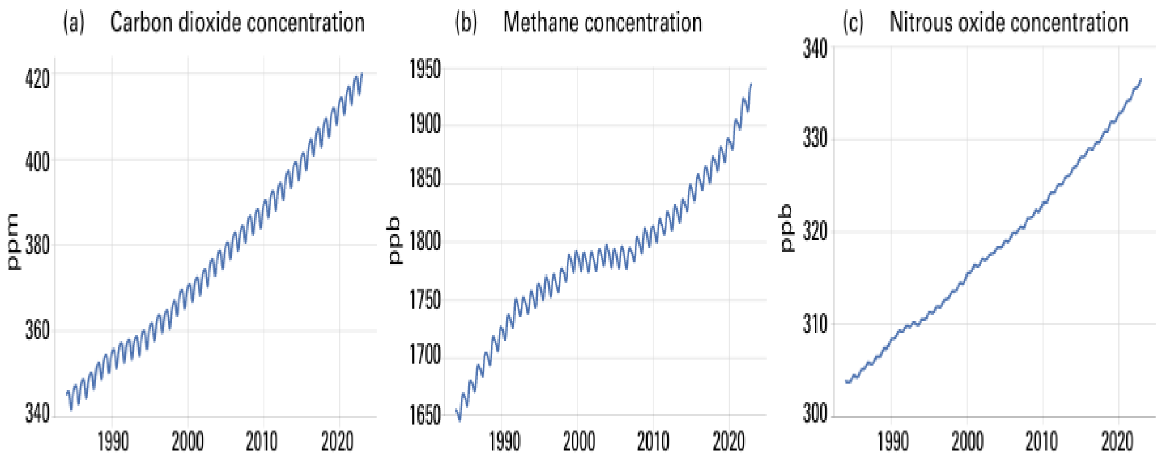

Fig 1. Monthly globally averaged mole fraction (a measure of atmospheric concentration), from 1984 to 2022, of (a) CO_2 in ppm, (b) CH_4 in ppb, and (c) N_2O in ppb. (Source: World Data Centre for Greenhouse Gases (WDCGG))

With this consequence of greenhouse gas emissions, the global mean near-surface temperature in 2023 was increased by 1.45 ± 0.12 °C and for the past 174 years, 2023 was recorded as the warmest year (World Meteorological Organization, 2023a).

In 2023, the global mean sea level was recorded and the highest value reflects continued ocean warming as well as the melting of glaciers and ice sheets. The long-term rate of sea-level rise has more than doubled, increasing from 2.13 mm yr^{-1} in 1993-2002 to 4.77 mm yr^{-1} in 2014 -2023 (World Meteorological Organization, 2023b). Glaciers measured around the world and thinned by an average of approximately 1m from 2011 to 2020 (Priya *et al.*, 2019).

Regarding precipitation, it varied from place to place and year to year, some regions faced dry spells and others received heavy downpours during the same period resulting in the loss of socioeconomic status of humans. Extremities such as wildfires, flooding, and drought ultimately result in the loss of life, biodiversity, and resources and completely vanish away the life needs. With concern to agriculture, global food insecurity was exacerbated by the climate, and weather extremities, where 149 million people faced food insecurity before 2023 it has increased to 333 million people (World Meteorological Organization, 2023b). With these issues, the mission of attaining Sustainable Developmental Goals remains questionable.

3. Consequences of climate change on Agricultural Insect pests

3.1 Impact of Elevated Temperature

With the rise in global temperature, it was reported that the global food production capacity will decrease by 10% in the mid-21st century as an impact of elevated temperature on crop growth, development, yield, and geographical distribution (Priya *et al.*,2019; Tai *et al.*, 2014). The increase in temperature leads to loss of soil moisture resulting in water scarcity, dry spells, and ultimately decreased crop yield (Dai *et al.*, 2018).

Insects, as poikilothermic organisms, are highly sensitive to temperature fluctuations. Temperature variations influence their behavior, distribution, development, and reproductive rates, with metabolic rates doubling for every 10°C increase (Skendžić *et al.*, 2021). Elevated temperatures can accelerate insect feeding, performance, and dispersal, potentially leading to population shifts and earlier infestations, resulting in crop damage (Shrestha 2019). Research indicates that rising temperatures may contribute to earlier emergence and extended insect life cycles. These shifts in insect behavior and distribution could pose significant challenges for farmers as host plants may migrate to new growing regions (Skendžić *et al.*, 2021).

3.1.2 Impact of elevated carbon dioxide

Elevated carbon dioxide enables faster growth due to rapid carbon assimilation as it is the key element in the plant system. The main effects of elevated CO_2 on plants include a reduction in transpiration and stomatal conductance, improved water and light-use efficiency, and thus an increase in photosynthetic rate. C_3 plants under elevated CO_2 concentration of 550ppm from 353ppm increased the yield by 19% (Kimball, 2016). On the other hand, C_4 plants resulted in a positive, neutral, and negative impact on yield, with a reduction in evapotranspiration they exhibited higher drought-tolerant capacity (Manderscheid *et al.*, 2016).

Elevated CO_2 offers better crop productivity but renders poor quality food i.e., reduced protein, mineral, and vitamin concentration (Zhu *et al.*, 2018; Loladze, 2014). The differential effects of elevated atmospheric CO_2 on C_3 and C_4 plants may lead to asymmetrical impacts on herbivory. C_3 plants, which tend to be positively influenced by elevated CO_2, may experience increased herbivory due to their enhanced growth and nutritional quality. Conversely, C_4 plants, less responsive to CO_2 enrichment, may be less affected by changes in insect feeding behavior. These differential responses could alter plant-insect interactions and affect ecosystems. Under elevated CO_2 plant's chemical constituents affect herbivores' nutrient quality and palatability. Increased CO_2 enhances the herbivore to consume more food by 17% to compensate for the lack of nutrition, therefore increasing the damage to the crop; a decrease in pest abundance by 22%; relative growth rate decreases by 9% (Stiling & Cornelissen, 2007) (Fig 2.).

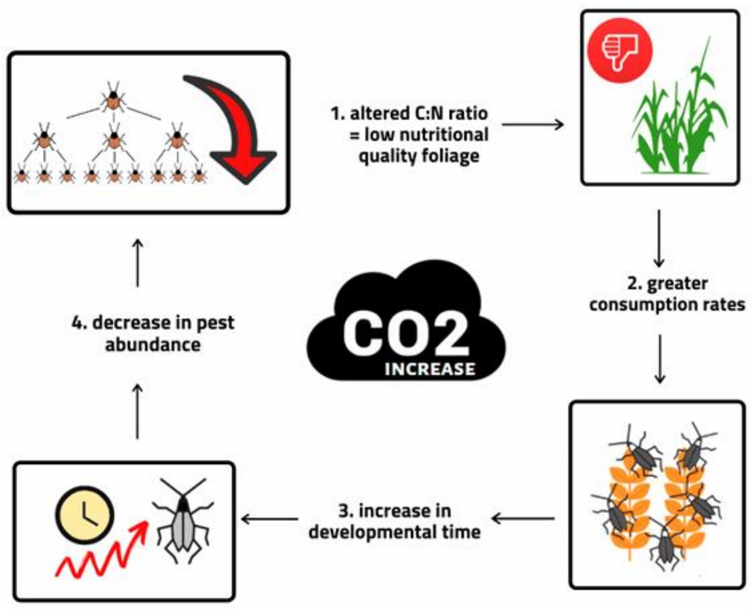

Fig 2. Elevated CO_2 impact on agricultural insect pests
Source: Skendzic *et al.* 2021

3.1.3 Impact of precipitation

Climate change has a tremendous impact on precipitation, soil moisture, and evaporation. Rainfall plays a crucial role in global food production. The hydrological cycle is highly influenced by temperature rise (Haddeland *et al.*, 2014; Huntington, 2010), it results in hot and dry spells with an increase in evapotranspiration and water demand for irrigation also increases gradually. Lobell *et al.* reported there was a decrease in maize yield by 2% when the temperature was more than 30˚C (Lobell *et al.*, 2011).

Precipitation plays a sensitive role in the population of insect pests. In case of sucking pest heavy downpour vanish or wash out them, under water stress conditions the nutritional composition and biological process of the plants are declined hence the population of insect pests increased with decrease in parasitism as result of the undergrowth of host insect (Skendžić *et al.*, 2021; Gregory *et al.*, 2009).

3.2 Climatic change influence on the life cycle and population of Insect pests

Climate change significantly impacts insect pests by altering their distribution, behavior, and population dynamics. The ambient temperature exerts a significant influence on the physiological functions of insects, encompassing respiration, immunity, metabolism, growth, reproduction, behavior, locomotion, dispersal, longevity, and survival (Adamo *et al.*, 2012; Roitberg & Mangel, 2016). Rising temperatures can expand the geographic range of pests, increase their overwintering survival rates, and accelerate their life cycles, leading to more generations per year (Parmesan, 2006).

Elevated levels of CO_2 and temperature significantly impact the overwintering survival of insect pests (Jasrotia *et al.*, 2023). Warmer winters enhance pest survival rates, leading to larger populations emerging in the spring (Björkman *et al.*, 2011; Klapwijk *et al.*, 2012). Research findings indicate that a 2°C temperature increase causes insects to go through more life cycles within a single season than expected (Battisti & Larsson, 2023; Kocmánková *et al.,* 2010). Additionally, higher temperatures accelerate insect metabolism and development, resulting in increased generations per year.

3.2.1 Consequences on insect pest life cycle and population

Climate change especially because of global warming, significantly impacts insect pest populations. These changes can lead to larger populations, more frequent infestations, and increased crop damage.

For instance, insects can become more resistant to heat after experiencing brief periods of high temperatures, a process known as "heat hardening"(Colinet *et al.,* 2015). As a result, early season heat exposure may have a greater impact than later exposure, as insects have not yet developed heat tolerance. Additionally, there exists significant genetic variation in heat tolerance within the same insect species population (van Heerwaarden *et al.,* 2016; Kellermann *et al.,* 2017). A finding reveals that both acute and chronic temperature exposure can significantly enhance the upper thermal limits of *Manduca sexta* larvae. These results suggest that repeated or continuous exposure to elevated temperatures during development can confer greater heat tolerance than a single heat shock (Kingsolver *et al.,* 2016). This adaptive plasticity in thermal tolerance is likely a crucial mechanism enabling insects to cope with the increasing temperatures associated with climate change. However, numerous researchers have indicated that plants cultivated under elevated temperatures or increased CO_2 concentrations will exhibit reduced nutritional quality (Coviella & Trumble, 1999). Consequently, insects that feed on these plants will experience prolonged larval development periods and increased mortality rates.

While increased temperatures and humidity often correlate with higher whitefly populations and subsequent crop damage, this relationship is not always straightforward (Pathania *et al.,* 2020). Similarly, aphids, known for their small size and rapid life cycles, can exhibit significant shifts in migration patterns due to rising temperatures (Pollard & Yates, 1993). This can lead to sudden and substantial outbreaks, causing significant economic losses in both agriculture and forestry. For example, the green peach aphid, *Myzus persicae,* exhibits a flexible life cycle influenced by temperature (Cheng *et al.,* 2002). In colder regions, aphids undergo a cyclical parthenogenetic cycle, alternating between sexual and asexual reproduction. They overwinter as eggs on primary host plants, hatch in spring, and migrate to secondary host plants during the summer (Wu *et al.,* 2020). In warmer regions, they may also reproduce continuously through asexual parthenogenesis. The migration of aphids can lead to sudden outbreaks, causing significant economic losses in agriculture and forestry (Dixon, 2012). Analyzing historical aphid trends can provide valuable insights for forecasting and effectively managing these pests.

Tropical insects are often assumed to be more susceptible to warming than their temperate counterparts. However, this perception is primarily based on macro climate data and may overlook the specific adaptations of temperate species (Deutsch *et al.,* 2008; Johansson *et al.,* 2020). When considering the developmental stages and seasonal activity patterns of insects, the differences in thermal tolerance between tropical and temperate regions become less pronounced. In temperate biomes, while heat waves are increasing in frequency, their unpredictability can hinder the evolution of specific heat tolerance adaptations (Thakur *et al.*, 2020). To mitigate heat stress, insects employs various strategies, such as reducing activity levels, seeking cooler microclimates such as burrowing into the soil, or temporarily retreating to sheltered areas like moving to lower parts of their food plants (Hemmings & Andrew, 2017).

3.3 Consequence on insect pest Infestation rate

Climate change is having a profound impact on the dynamics of insect pest populations. Rising temperatures are facilitating the expansion of pest ranges, accelerating their development, and increasing their reproductive rates. These factors contribute to heightened crop damage from 10% to 25%, increased pesticide usage, and plant disease transmission risks (World Economic Forum, 2024).

Recent research examines the factors associated with the population dynamics of cereal aphids and armyworms feeding on wheat. The study found that the factors most strongly associated with the population dynamics of cereal aphids are fertilizer input and mean temperature, while the population dynamics of armyworms is significantly related to precipitation (Wang *et al.,* 2015). The results provide insights into developing ecologically-based pest management strategies for these agricultural pests under global change. Climate anomalies, such as heat waves and droughts, are contributing to increased outbreaks of bark beetles (Curculionidae: Scolytinae) in Europe and the United States (Bentz *et al.*, 2010). These outbreaks are exacerbated by human activities that create warm microclimates, further facilitating the proliferation of these destructive pests.

The impact of environmental change on the effectiveness of insecticides against insects is a subject of ongoing debate. It is crucial to identify general trends and investigate the underlying mechanisms driving these changes in the context of global climate change (Marini *et al.*, 2017; Jamieson *et al.*, 2012). Increasing temperatures can overall increase the insecticidal activity by 1.33 times, with the activity of some insecticide classes and insect groups being more sensitive to temperature changes (Boullis *et al.,* 2015). Additionally, humidity changes were found to have a positive relationship with insecticidal activity, while no significant effects were observed for changes in CO_2 concentration (Li *et al.*, 2024).

3.4 Consequences on Tri-trophic Interaction:

Tritrophic interactions are crucial in pest management as they involve the dynamic relationships between plants, herbivores, and natural enemies, which collectively influence the effectiveness of biological control strategies depicted in Table 1. Climate change is profoundly altering the complex relationships between insect pests, their host plants, and natural enemies. Phytophagous insect species are regulated by both top-down mechanisms (natural enemies) and bottom-up mechanisms (host plant availability and quality) (Welch & Harwood, 2014; Bharathi *et al.,* 2023). These interactions collectively shape insect population dynamics, performance, and behaviour. In agricultural, forestry, and other ecosystems, phytophagous insects are crucial components of the tri-trophic relationships involving host plants, insect pests, and natural enemies (War *et al.*, 2016).

Will Changes in Greenhouse Gas Emissions Heighten the Susceptibility of Herbivorous Insects to Their Natural Enemies? As temperatures rise and precipitation patterns shift, these tri-trophic interactions are undergoing significant changes, which will impact the effectiveness of biological control programs (Walther *et al.,* 2002). In the absence of natural enemies, herbivores may escape top-down control, enabling them to establish large populations in new habitats.

The effectiveness of natural enemies hinges on their capacity to withstand adverse or novel environmental conditions and to keep pace with their prey and hosts (Thomson *et al.,* 2010; Evans *et al.,* 2013). A study found that warmer spring temperatures led to earlier egg-laying and larval development in the cereal leaf beetle, while parasitism by the wasp *Tetrastichus julis* was less affected. This resulted in reduced parasitism during warmer springs, suggesting that climate change could weaken the biological control of cereal leaf beetle by the parasitoid wasp (Ahmed *et al.,* 2017). Furthermore, empirical studies have demonstrated that aphids reared on water-stressed plants exhibit lower parasitism rates, likely attributable to the diminished size or availability of the host (Crossley *et al.,* 2024). To mitigate these negative consequences, it is crucial to adopt integrated pest management strategies, conserve biodiversity, develop climate-resilient crop varieties, and implement effective monitoring and forecasting systems (Monticelli *et al.*, 2018; Kansman *et al.*, 2021).

Table 1. Selected natural enemies frequently utilized in biological control programs (Sehgal *et al.*, 2006)

Insect Pest	**Species**	**Predominant Regions**	**Natural Enemies**
Aphids	Various species (e.g., *Myzus persicae*)	Worldwide	Lady beetles (Coccinellidae), Parasitic wasps (Aphidiinae), Green lacewings (Chrysopidae), Hoverflies (Syrphidae)
European Corn Borer	*Ostrinia nubilalis*	North America, Europe	Trichogramma wasps, Lady beetles (Coccinellidae), Lacewings (Chrysopidae)
Mountain Pine Beetle	*Dendroctonus ponderosae*	North America	Woodpeckers, Parasitic wasps (Braconidae), Predatory beetles (Cleridae)
Diamondback Moth	*Plutella xylostella*	Worldwide	Parasitic wasps (Trichogrammatidae), Predatory beetles (Carabidae), Spiders (Araneae)
Cotton Bollworm	*Helicoverpa armigera*	Asia, Africa, North America	Parasitic wasps (Braconidae), Predatory bugs (Hemiptera), Spiders (Araneae)
Colorado Potato Beetle	*Leptinotarsa decemlineata*	North America, Europe	Parasitic wasps (Braconidae), Predatory beetles (Carabidae), Spiders (Araneae)

Fall Armyworm	*Spodoptera frugiperda*	North America, Africa, Asia	Parasitic wasps (Braconidae), Predatory beetles (Carabidae)
Asian Citrus Psyllid	*Diaphorina citri*	Asia, North America	Parasitic wasps (Encyrtidae), Lady beetles (Coccinellidae), Spiders (Araneae)
Brown Marmorated Stink Bug	*Halyomorpha halys*	Asia, North America, Europe	Parasitic wasps (Scelionidae), Predatory stink bugs (Pentatomidae)
Spotted Lanternfly	*Lycorma delicatula*	Asia, North America	Parasitic wasps (Dryinidae), Spiders (Araneae)
Locusts	*Schistocerca gregaria* (Desert Locust)	Africa, Middle East Asia	Parasitic flies (Tachinidae), Fungal pathogens
Japanese Beetle	*Popillia japonica*	North America, Japan	Parasitic wasps (Tiphiidae), Predatory beetles (Carabidae)
Red Imported Fire Ant	*Solenopsis invicta*	Americas, Australia, Asia	Parasitic flies (Phoridae), Predatory beetles (Carabidae)
Western Corn Rootworm	*Diabrotica virgifera virgifera*	North America, Europe	Parasitic wasps (Braconidae), Predatory beetles (Carabidae)
Gypsy Moth	*Lymantria dispar*	North America, Europe, Asia	Parasitic wasps (Braconidae), Predatory beetles (Carabidae)

3.5 Case Studies

3.5.1 Case Study 1- Pest status of cotton under the influence of climate change

The insect pest complex of cotton has undergone significant changes due to various factors, including the expansion of American cotton cultivation, the adoption of Bt cotton, alterations in the ecological landscape, the cultivation of diverse cotton cultivars, the misuse of insecticides, and the excessive application of fertilizers and pesticides.

Historically, leafhopper was the primary sucking pest affecting cotton in India (Dhawan & Simwat, 2001). However, the widespread use of synthetic pyrethroids to control bollworms has led to the emergence of whitefly as a major pest, causing substantial yield losses. Additionally, whitefly serves as a vector for the cotton leaf curl virus, further exacerbating crop damage.

Beyond leafhopper and whitefly, other sucking pests, such as thrips and aphids, have gained prominence in recent years. The mealybug, *Phenacoccus solenopsis*, has emerged as a serious pest in certain regions, causing significant damage to cotton crops (Dhawan *et al.*, 2009). The mirid bug, *Creontiades biseratense*, has also become a major pest in some areas like Dharwad and Coimbatore (Udikeri *et al.*, 2010).

These shifts in the insect pest complex have resulted in increased challenges for cotton growers, necessitating effective pest management strategies to mitigate yield losses and maintain cotton production (Table 2.). Elevated global temperatures have created favorable conditions for the proliferation of various insect pests, including cotton sap-sucking pests such as whiteflies, thrips, aphids, and mealybugs. The increased temperatures have significantly impacted the population dynamics of these pests, particularly the whitefly, which has emerged as a major vector of cotton leaf curl viral disease.

Studies have indicated that elevated CO2 levels can lead to a decrease in the efficacy of Cry toxins produced by Bt cotton, potentially compromising its resistance to certain insect pests. Additionally, higher temperatures have been found to reduce the effectiveness of insecticides, such as synthetic pyrethroids and Spinosad (Central Institute for Cotton Research, 2024).

Table 2. Status of Cotton insect pests in India

Year	**Major Pest**	**Minor Pest**	**New Pest Detected**	**Pest Outbreak**
Up to 1970	Leafhopper, pink bollworm	Whitefly, aphids, thrips	Spotted bollworm	American Bollworm in some pockets (1978)
1971-1980	Leafhopper, pink bollworm, spotted bollworm	Whitefly, aphid, thrips	American bollworm	American bollworm (1983)
1981-1990	Leafhopper, pink bollworm, spotted bollworm	Whitefly, aphid, thrips	Tobacco caterpillar	American bollworm (1990, 1995)
1991-2000	Leafhopper, whitefly, American bollworm, spotted bollworm, pink bollworm	Aphid, thrips	Leaf miner, CLCuV	Whitefly (1995), American bollworm (1997, 1998)
2001-2010	Leafhopper, whitefly, mealybug, tobacco caterpillar, spotted bollworm, American bollworm	Aphid, thrips	Mealybug	American bollworm (2001), Tobacco caterpillar (2005), Mealybug (2007)
2011-2019	Whitefly, leafhopper, thrips	Aphid, mealybug	-	Whitefly (2015)

Source: Shera *et al.* (2020)

Leafhopper populations on cotton plants experience increased protection during both the reproductive and vegetative phases as temperatures rise. While morning relative humidity positively impacts the larval population of pink bollworm, higher evening relative humidity has a detrimental effect. (Sankaranarayanan *et al.,* 2010)

From 2005-2014, the infestation rate of sap feeders in the selected regions of North India (Vennila *et al.,* 2018),

- Faridkot, Punjab- *Amrasca biguttula biguttula* > *Thrips tabaci* > *Bemisia tabaci*

In Faridkot, during 2013-2014 *Amrasca biguttula biguttula* population was doubled when compared to 2005-2011, *Thrips tabaci* was reported more in 2011 and faced a downfall in 2012 and *Bemisia tabaci* was higher in 2014 as maximum (higher) temperature favored their population growth.

- Ludhiana, Punjab- *Amrasca biguttula biguttula* > *Bemisia tabaci* > *Thrips tabaci*

In Ludhiana, *Amrasca biguttula biguttula* was recorded higher in 2005-2010 as rainfall favored their growth, *Bemisia tabaci* infestation decreased in 2005 and increased in 2010 and *Thrips tabaci* population was low, as the minimum temperature and rainfall didn't cope up their development. *Amrasca biguttula biguttula* and *Bemisia tabaci* were recorded tremendous in 2009, maximum, and minimum temperature and rainfall enhanced their development.

- Hisar, Hariyana- *Bemisia tabaci* > *Amrasca biguttula biguttula* > *Thrips tabaci*

In this region, *Bemisia tabaci* infestation was enhanced by minimum temperature and rainfall, and also increased usage of insecticides promoted their growth over *Amrasca biguttula biguttula* because of resistance development.

- Siganganagar, Rajasthan- *Thrips tabaci* = *Bemisia tabaci*

Both thrips and whiteflies have increased populations because of favorable temperature and rainfall. Whereas, *Amrasca biguttula biguttula* lost its pest status in that particular study period.

3.5.2 Case Study 2- Climate Change and the Invasion Ecology of Insect Pests in India: A Review

Climate change significantly impacts the dynamics of invasive insect pests in India, which leads to geographic range shifts, increased reproductive success, and altered ecological relationships (Bisht & Giri, 2019). This, in turn, leads to increased crop damage, economic losses, and increase in the introduction of new species as shown in the Fig.2. The Convention on Biological Diversity identifies invasive alien species as the most significant threat to global biodiversity, imposing substantial costs on agriculture, forestry, and aquatic ecosystems (Shrestha, 2019; Convention on Biological Diversity, 2023). It is generally believed that only a small fraction of introduced invasive alien species (IAS) become established, and an even smaller fraction of these established species spread and become economic pests. This concept is often referred to as the "rule of 10," which posits that approximately 1 in 10 introduced species escape into the environment, 1 in 10 of these escapees become established, and 1 in 10 of the established species become economic pests (KOMNENIC, 2023).

Rising temperatures and changing precipitation patterns facilitate the spread of pests like the fall armyworm (*S. frugiperda*) (Sani *et al.*, 2020), exacerbating their impact on agriculture. Enhanced survival and reproductive cycles under warmer conditions, as observed in the whitefly (*B. tabaci*), result in higher pest pressures (Tariq, 2020). Additionally, rising temperatures in North India are likely to cause earlier-than-usual infestations of *H. armigera*, leading to increased crop losses in pigeon pea and chickpea (Sujith & Bharthisha, 2024). These shifts necessitate the adaptation of Integrated Pest Management (IPM) strategies to effectively address the evolving pest dynamics and mitigate their detrimental effects on crop production.

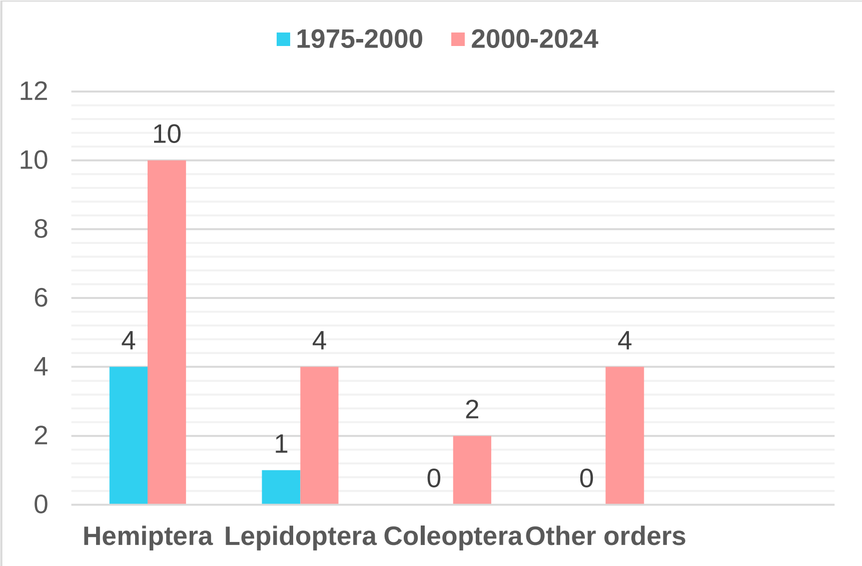

Fig 2. Invasive insect pests introduced in India

(National Biodiversity Authority, n.d; Gupta *et al.*, 2019; Dara, 2019)

3.6 Optimizing pest management for climate-driven Insect pest challenges:

The combined effects of climatic changes on insect pests present significant challenges for future pest management. The escalating frequency of native and invasive pests, driven by the combined forces of global trade and climate change, necessitates a rapid capacity for adaptation to both biotic and abiotic pressures (Overton *et al.*, 2021; Juroszek& Tiedemann, 2011). Traditional scouting methods based on historical data may become unreliable, necessitating more intensive monitoring programs to track population fluctuations (Deguine *et al.*, 2021).

A comprehensive analysis of regional temperature, precipitation, and pest activity patterns will enable farmers to accurately identify specific climate-related challenges and implement targeted mitigation measures. Regular monitoring of agricultural pests is a critical component of effective pest management under changing climate conditions (Singh, 2023).

Climate change causes unpredictable weather, higher temperatures, and altered precipitation, affecting insect pest behaviour and distribution. Developing robust models that integrate the interactions between CO_2, temperature, plant physiology, and insect pest population dynamics is crucial for proactive pest management in a changing climate (Dolker *et al.*, 2017; Choudhary *et al.*, 2019). For example, CLIMEX modeling software to predict the future distribution ranges of two Central European Forest pests, the nun moth and the gypsy moth, under three different climate warming scenarios (Vanhanen *et al.,* 2007). Using temperature-based life cycle modeling and spatial mapping, another study simulated the future population dynamics of *S. litura* under warmer climate conditions projected for the year 2050 (Fand *et al.,* 2015). Likewise, the life history parameters of *B. tabaci* were studied in a climatic chamber simulation of the future climate of Central Europe which shows significant changes in development time and fecundity under future climatic conditions (Milenovic *et al.,* 2023). Therefore, climate forecasting and modeling are poised to become indispensable tools for managing agricultural insect pests in the future.

4. Conclusion

Climate change is significantly altering agricultural pest dynamics, posing new challenges for farmers globally. Rising temperatures and shifting weather patterns enable pests to thrive in new regions, leading to increased infestations and crop damage. Warmer climates accelerate pest life cycles, causing more frequent and severe outbreaks. Additionally, the disruption of ecological balances favors pests over their natural predators, often resulting in greater reliance on chemical pesticides, which can harm human health and the environment. To address these challenges, sustainable strategies such as Integrated Pest Management (IPM) are crucial. IPM combines biological controls, cultural practices, and selective pesticide use to manage pest populations effectively. Developing pest-resistant crop varieties and enhancing pest monitoring and forecasting systems can also help farmers anticipate and mitigate pest pressures. By adopting these innovative approaches, we can build resilient agricultural systems that ensure food security and environmental sustainability in the face of climate change.

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CLIMATE-SMART PEST MANAGEMENT PRACTICES

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ABSTRACT

Climate change is a major challenge for agriculture, causing higher temperatures, irregular rainfall, and extreme weather events that increase pest dynamics and crop losses. In countries such as India, where a significant portion of the population depends on farming, these impacts are severe. Conventional use of chemical pesticides has limitations due to resistance, environmental damage, and greenhouse gas emissions. The Food and Agriculture Organisation introduced the concept of Climate-Smart Agriculture (CSA) to enhance productivity, resilience, and climate change mitigation. Within CSA, Climate-Smart Pest Management (CSPM) offers strategies to reduce pest damage while supporting sustainable agriculture. CSPM combines approaches such as pest-resistant crop varieties, biological control, semiochemicals, biopesticides, pest monitoring, and cultural practices like crop rotation and intercropping. These methods lower pesticide use, conserve biodiversity, and enhance ecosystem services. Advanced technologies like remote sensing, GIS-based pest mapping, AI-driven forecasting models, RNA interference (RNAi) techniques, and gene-edited crop varieties help to mitigate climate-related pests. Despite its benefits, CSPM faces challenges including limited awareness, lack of resources, and policy gaps. Strengthening research, extension services, and multi-stakeholder collaboration is essential. CSPM provides a pathway to secure food production, enhance resilience, and promote sustainable farming under changing climatic conditions.

Keywords: *Climate change, Climate-smart agriculture, Climate-smart pest management, Food security, Integrated pest management, Sustainable agriculture*

1. Introduction

Climate change has emerged as a major global issue, with rising temperatures, erratic rainfall, prolonged droughts, and severe weather events impacting ecosystems and human livelihoods. These changes strongly influence pest occurrence, survival, and distribution (IPCC, 2013; Skendžić et al., 2021). In countries like India, where agriculture supports nearly two-thirds of the population, the impacts are especially critical (Gupta & Pathak, 2016). Already, pests account for the loss of up to 40% of global food production each year. Although chemical pesticides have been widely used to control them, this strategy is unsustainable due to the resistance development, ecological damage, and contributions to greenhouse gas (GHG) emissions (Oerke, 2006).

Climate change impacts crop yields directly while also influencing pest dynamics, their distribution, abundance, and severity. Pests, defined as “any species, strain, or biotype of plant, animal, or pathogenic agent harmful to plants or plant products” (FAO, 2013b), including invasive species, are spreading into new areas as changing climates create favorable conditions for their survival, further intensifying crop losses (Juroszek et al., 2011; Lamichhane et al., 2015; Macfadyen et al., 2018; IPPC, 2021).

Changes in temperature, rainfall, and CO_2 concentration alter insect biology, ecology, and interactions with crops. Elevated temperatures enhance the rate of pest growth and reproduction, often leading to more frequent outbreaks (Bale et al., 2002). Rainfall variability affects survival and migration, while elevated CO_2 changes plant physiology and nutritional quality, indirectly influencing herbivores (Lincoln et al., 1986; Lindroth, 2010). These changes collectively affect host–pest synchrony, species distribution, and community structure. For example, severe weather conditiond have triggered large-scale locust swarms capable of devastating crops (CIMMYT, 2024). Similarly, *Helicoverpa armigera* and *Chilo partellus* have expanded their ranges under warming climates, threatening staple crops in Asia and Africa (Sharma et al., 2005).

To address these challenges, Climate-Smart Agriculture (CSA) was introduced by the Food and Agriculture Organization (FAO), a framework designed to ensure food security by promoting sustainable, resilient, and adaptive farming systems under climate stress (Lipper and Building, 2018). An integral part of CSA is Climate-Smart Pest Management (CSPM). This approach emphasizes reducing chemical pesticide use, sustaining crop productivity, and adapting pest control to climate variability. While CSPM offers several benefits for promoting agricultural sustainability, it also has certain limitations (Bouri et al., 2023). This review examines the role of CSPM in relation to climate change. It highlights areas where more efficient interventions are needed and explores how pest management strategies can be adapted to extreme weather events to enhance the resilience of global agricultural systems.

2. Climate-Smart Agriculture

The Food and Agriculture Organization (FAO) formally introduced the concept of Climate Smart Agriculture (CSA) in 2010 (FAO, 2010). Since then, the CSA has been further developed and refined by multiple stakeholders, including international organizations, national governments, research institutions, and development agencies, to integrate climate considerations into agricultural planning and practice (Lipper et al., 2014; FAO, 2013a). CSA provides a framework for applying globally relevant agricultural management principles that simultaneously address food security and climate change challenges.

CSA relies on three interconnected pillars: (i) improving agricultural productivity and household incomes sustainably; (ii) enhancing adaptation and resilience at farm and community levels to address climate change; and (iii) minimizing greenhouse gas emissions where feasible (Sekabira et al., 2022). These pillars highlight the dual challenge of meeting rising food demand while maintaining environmental sustainability in response to climate change. In context, CSA encourages agricultural systems to produce more food without degrading soil, water, or biodiversity, thereby balancing productivity, adaptation, and mitigation in a holistic framework (Thornton et al., 2018).

Many components of Integrated Pest Management (IPM) practices naturally align with the goals of CSA, providing synergies that contribute to resilience and sustainability. Practices such as biological control, habitat management, crop diversification, and the use of resistant crop varieties directly enhance productivity and adaptation, while also reducing pesticide use, thereby lowering GHG emissions (Pretty & Bharucha, 2015; CABI, 2025). Some interventions contribute explicitly to CSA outcomes, while others support them indirectly by strengthening ecosystem services and improving the adaptive capacity of farming systems. These connections emphasize the role of climate-smart pest management (CSPM) as a vital component of the CSA framework, providing strategies to manage pest pressures while also contributing to food security and sustainable agricultural development under climate change (CABI, 2025).

3. Climate-Smart Pest Management

Climate-smart pest management (CSPM) is a cross-sectoral approach designed to reduce pest-related crop losses, increase ecosystem services, decrease greenhouse gas (GHG) emissions per unit of food produced, and improve the resilience of agriculture systems under changing climates. The pest management strategy adopted under Climate-Smart Agriculture (CSA) is frequently characterized as a specialized form of Integrated Pest Management (IPM) since CPSM is not commonly used in the literature as a specific term. The FAO describes IPM as "the careful consideration of all available pest control techniques and the integration of appropriate measures that discourage pest population growth while minimizing pesticide use and other interventions to economically justified levels, thereby reducing risks to human health and the environment" (FAO, 2022). IPM-related agricultural practices focus on rational and limited use of chemical pesticides to mitigate environmental and health impacts (Egan et al., 2022).

CS-IPM (Climate-smart integrated pest management), or CSPM, is a recently introduced concept that adapts traditional IPM to the challenges of climate change by applying sustainable and innovative practices to support agricultural development. CSPM combines interdisciplinary approaches to improve primary production under changing climatic conditions. Effective pest management requires synchronizing knowledge of pest biology with cost-effective, environmentally safe control methods. According to Egan et al. (2022), CS-IPM is an integrated approach that promotes conservation-oriented and ecologically compatible practices for managing insect pests, pathogens, and weeds, while reducing dependence on chemical pesticides. Such practices lessen risks to human health, biodiversity, and ecosystems. Among them, biologically based products and pest-resistant crop varieties are viewed as the most promising alternatives (Heeb et al., 2019).

3.1 Key Strategies of CSPM:

Climate change affects pest dynamics by altering their diversity, abundance, and distribution, increasing overwintering survival, accelerating population growth and the number of generations, enabling the use of alternative host plants, weakening host plant resistance, raising the threat of invasive species, and facilitating the spread of pest-transmitted diseases (Shrestha, 2019). To overcome these problems, CSPM is a holistic framework that integrates ecological, technological, and socio-economic dimensions of pest management. It encompasses a range of ecological based and technology supported interventions. Its main strategies involve adopting resistant crop varieties, utilizing biological control agents, conducting pest monitoring and surveillance, and incorporating climate-based decision tools. CSPM is embedded within CSA and aims to balance productivity, adaptation, and mitigation outcomes. Its success relies on farmer participation, extension services, supportive policies, and coordinated stakeholder action (FAO, 2017).

3.1.1 Resistant Varieties

Planting pest-resistant varieties reduces crop vulnerability and input dependency. Such varieties are essential under climate stress, as they enhance yield stability and lower pesticide demand (Sharma & Ortiz, 2000). However, climate stress can weaken plant defenses, increasing vulnerability. Transgenics such as Bt cotton have provided breakthroughs, though their efficacy declines under elevated temperatures and drought (Chen et al., 2005). This necessitates breeding climate-resilient resistant varieties.

3.1.2 Pest Surveillance and Early Warning Systems

Monitoring and early warning systems provide timely information on pest outbreaks, allowing farmers to act preventively. Digital innovations and GIS-based models improve the accuracy of predictions, empowering extension workers and smallholders to respond effectively (Sharma et al., 2005).

3.1.3 Biological Control

Biological control using parasitoids, predators, and microbial agents such as fungi and viruses reduces reliance on chemical pesticides. These eco-friendly options strengthen ecosystem services and align directly with CSA's adaptation and mitigation goals (Thomson et al., 2010).

3.1.4 Semiochemicals and Biopesticides

Semiochemicals such as pheromones and allelochemicals are integral to monitoring, trapping, and mating disruption. Their volatility under warmer climates, however, reduces efficacy, requiring innovation in formulations (Heuskin et al., 2011). Biopesticides based on fungi, bacteria, viruses, and nematodes are effective alternatives but sensitive to UV radiation and temperature extremes.

3.1.5 Cultural and Agronomic Practices

Cultural control measures, including crop rotation, intercropping, adjusted planting dates, and diversification, can buffer pest outbreaks (Lin, 2011). These strategies increase system resilience while reducing reliance on chemical inputs. GIS-based pest risk mapping is increasingly applied to forecast outbreaks and inform farmers (Sharma et al., 2005).

4. Benefits of Climate-Smart Pest Management

CSPM delivers multiple benefits across social, economic, and environmental dimensions. It increases food security by reducing pest-induced losses, enhances resilience, reduces greenhouse gas emissions through rational input use and reduced pesticide reliance, and promotes biodiversity conservation. CSPM directly contributes to the UN Sustainable Development Goals (SDGs), particularly Zero Hunger, Climate Action, and Life on Land (FAO, 2017). Importantly, it empowers smallholder farmers by providing knowledge-based, cost-effective solutions.

4.1 Food Security

CSPM practices support higher agricultural productivity by minimizing losses caused by pests and enhancing farm incomes. The adoption of pest-resistant crop varieties, biological control agents, and advanced pest monitoring systems ensures effective crop protection while reducing dependence on synthetic chemicals (FAO, 2017). Implementing economic threshold based pesticide applications allows for precise use of inputs, optimizing costs and safeguarding crops. Additionally, integrating precision agriculture tools such as drones and smart sensors enables real-time pest monitoring and crop health, further increasing yield and reducing resource wastage.

4.2 Adaptation

Adaptation strategies under CSPM focus on helping farmers adjust to changing pest dynamics caused by climate change. Early warning systems, continuous pest surveillance, and ecological farming practices enable timely interventions, reducing the vulnerability of smallholder farmers. Crop diversification, rotating pest resistant varieties and integrating soil crop management further strengthen resilience against extreme weather conditions (Chandana et al., 2024). Moreover, practicing intercropping, hedgerow planting, and habitat conservation for natural enemies, further strengthens the adaptive capacity of farming systems.

4.3 Mitigation

CSPM aids climate change mitigation by lowering greenhouse gas emissions resulting from the overuse of pesticides and fertilizers. Promoting biological control, cultural practices, and organic amendments lowers the carbon footprint while maintaining or enhancing biodiversity (Heeb & Jenner, 2017). Advanced technologies such as remote sensing, GIS-based pest mapping, AI-driven forecasting models, RNA interference (RNAi) techniques, and gene-edited crop varieties enable precise, environmentally responsible pest management (Manideep et al., 2025). These innovations help to mitigate climate-related pest challenges but also enhance overall sustainability by reducing chemical inputs, conserving soil health, and promoting ecosystem services.

5. Initiatives for Climate Smart Agriculture

In India, several government initiatives have been launched to promote Climate-Smart Agriculture (CSA). These include The National Adaptation Fund for Climate Change (NAFCC), National Innovation on Climate Resilient Agriculture (NICRA), Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), Soil Health Mission, Biotech-KISAN, Paramparagat Krishi Vikas Yojana (PKVY), and Climate Smart Village Model. In addition to these government-led programs, various public and private sector stakeholders, including farmer-producer organizations, cooperatives, and non-governmental organizations (NGOs), are actively supporting CSA adoption. At the international level, several initiatives also play an important role. It includes the CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), the World Bank Group and the Global Alliance for Climate-Smart Agriculture (GACSA). Similarly, the Climate-Smart Agriculture Youth Network (CSAYN) engages young people worldwide in raising awareness and promoting action on CSA.

6. Integration with other Climate-Smart Agriculture practices

CSPM cannot be considered a stand-alone approach as it closely interacts with existing Climate-Smart Agriculture (CSA) practices at both farm and national levels. Farmers adopting CSPM often face additional challenges and therefore require integrated adaptation and mitigation strategies. The relationship between CSPM and CSA is strong because CSPM addresses not only biotic factors like pests and diseases but also abiotic aspects such as crop nutrition and soil management. CSA practices that enhance the effectiveness of CSPM include site-specific nutrient management, integrated soil fertility management, conservation agriculture, breeding for climate-resilient crops, and crop diversification. For instance, a study on climate-smart push–pull technology in East Africa, a cost-effective method to control maize stemborers (*Chilo spp*., Lepidoptera: Crambidae) and witchweed (*Striga spp*., Orobanchaceae) while improving soil fertility, showed that farmers were more willing to adopt and expand this practice (Murage et al., 2015).

6. Challenges of CPSM

Despite its potential, CSPM adoption faces barriers including lack of awareness, limited financial access, weak extension services, and insufficient policy support. Many smallholders lack access to resistant varieties, biological agents, and reliable forecasting tools. Moreover, institutional gaps hide the scaling of CSPM innovations (Parsa et al., 2014). To overcome these challenges, policies must incentivize adoption through subsidies, training programs, gender-inclusive approaches, and investment in research and extension services. Strengthening multi-stakeholder collaboration is key to mainstreaming CSPM within national agricultural plans (Sekabira et al., 2019).

7. Conclusion

CSPM represents an essential pathway for achieving sustainable agricultural development under climate change. By aligning IPM strategies with the CSA pillars, CSPM reduces pest risks, improves resilience, and mitigates environmental impacts. Addressing the challenges posed by climate change and pests requires more than technological solutions alone. It also necessitates policy support, capacity building, and stakeholder engagement at local, national, and global levels. Research institutions and universities contribute through innovations such as AI-based pest forecasting, RNA interference (RNAi) technologies, and the development of climate-resilient crop varieties Levelling up CSPM requires governments, research institutions, non-governmental bodies, and farming communities to design and implement policies that encourage sustainable agriculture, strengthen farmer education and extension, and promote the process of climate-smart pest management practices. Its process ensures food security, climate resilience, and sustainable farming for future generations.

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CLIMATE CHANGE AND ITS IMPACT ON PLANT DISEASES

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ABSTRACT

The change in global climate is because of expanding convergence of greenhouse gases (GHG) in the atmosphere. Climate changes observed on Earth in recent years are mostly the result of various human activities. The global temperature has risen by around 0.8 °C over the past hundred years and is expected to ascend by between 0.9 and 3.5 °C by 2100. Climate change does not only affect the holistic crop growth but also influence the spread, multi plication, incidence and severity of many phytopathogenic agents. These effects will be seen not only on the other elements of the agroecosystem but also on plants and other organisms. Climate change involving rise in temperature and CO2 level in the atmosphere, and other weather events such as drought and flooding, all affects the host plant resistance to pathogens. Climate change has the potential to alter host-pathogen interactions and ultimately pose great impact on development of disease epidemics. Such changes will not only have a great effect on the growth and cultivation of different crops but also affect the reproduction, spread and severity of many plant pathogens. Various plant disease models have been created to integrate modern climate forecasts at different levels. At the level, the adaptive potential of plant and pathogen populations may prove to be one of the most important predictors of the magnitude of climate change effects. This review highlights various influences of climate change on plant diseases and their effects with suitable examples.

Keywords: *Climate change, GHG, plant diseases, moisture*

Introduction

Nowadays, all agricultural industries are significantly impacted by the problem of climate change. Impacts of climate change are already becoming apparent for both natural and human systems, with most crops experiencing more negative than positive effects on yields. The earth's sur face is heated by greenhouse gases in the atmosphere, which capture the reflected energy. Green house gases (GHG) viz., water vapour (H_2O), carbon dioxide (CO_2), Methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs) and Ozone (O_3) in the atmosphere trap reflected radiation to warm the earth surface (Mahato, 2014).

According to the Intergovernmental Panel on Climate Change (IPCC), climate change resulted in increase in atmospheric CO_2 by 30% and temperature by 0.3 to 0.6 °C (Chakraborty et al. 2000). The host, pathogen, and environment components of the disease triangle are all impacted by the world's changing climate (Pachauri et al. 2014) (Figure 2). A model was used to study the impact of climate change on Phoma (*Leptosphaeria maculans*) in rapeseed, that foresee temperature and precipitation under CO_2 discharge situations for the years 2020 and 2050s in UK (Evans et al. 2007) and spore production by teleomorphs on climate change (Kaczmarek et al. 2016). Human activities are widely involved in increasing global climate changes that directly influences the ecology (Pachauri and Reisinger, 2007 and Ahanger et al., 2013). This global climate changes by various factors (Pachauri and Reisinger, 2007 and Pachauri et al., 2014) and change orinfluence all the 3 major elements of disease triangle, viz., host, pathogen and environment (Legreve and Duveiller, 2010).

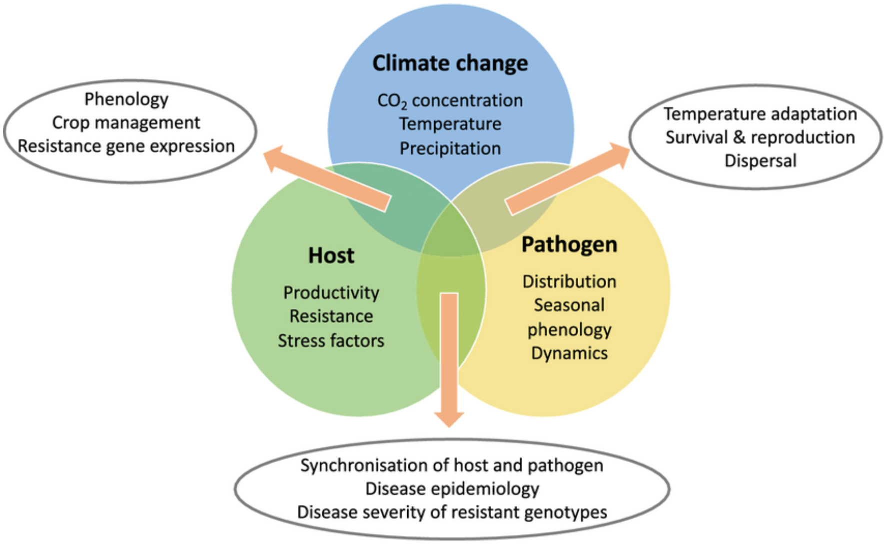

Fig. 1. Impacts of Climate Change on components of disease triangle

Crop growth and production can be significantly affected due to high atmospheric CO_2 concentration, temperature, changes in precipitation patterns and frequency of extreme weather phenomena and diseases presence will altered under these condition (Rosenzweig and Tubiello, 2007, Ghini et al., 2008 and Chakraborty, 2011). When the host present pathogens with short life cycles, reproduction rates are high and dispersion mechanisms respond quickly and adapt faster to climate change (Coakley et al., 1999). In order to obtain sustainable food production in a changing climate, disease management procedures should be updated

Effect of temperature on plant diseases:

Certain minimum temperature is required by both plants and pathogens to grow. Temperature affects the chain of events in disease cycles such as survival, dispersal, penetration, development and also reproduction rate for many pathogens. With increasing temperature spore germination of rust fungus *Puccinia substriata* increases (Tapsoba and Wilson, 1997). Altered temperatures favour over wintering of sexual propagules which increased the evolutionary potential of a population (Pfender and Vollmer (1999). Generally high moisture and temperature favours and initiate disease development, as well as germination and proliferation of fungal spores of diverse pathogens (Agrios, 2005). Conidia of powdery mildew have the ability to germinate even at 0% relative humidity (RH) (Yarwood, 1978). Conidia of *Erisiphe cichoracearum* germinate at temperature from 7 to 32°C with a RH of 60 to 80% (Khan and Khan, 1992); and spores of *Erysiphe necator* germinate at temperatures from 6 to 23°C with a RH from 33 to 90 % (Bendek et al., 2007).

Likewise, wheat leaf rust resistance genes viz., Lr2a, Lr210 and Lr217 are temperature sensitive. Only Lr2a gene shows resistance at temperature beyond 25°C. In contrast, lignification in forage crops increases with higher temperature (Wilson et al., 1991). Moderate temperature is the best for fungal growth that cause plant disease. Phytophthora infestans, late blight of potato and tomato, infects and reproduces most successfully at high moisture when temperatures are between 7.2°C and 26.8°C. Infection of Eucalyptus sp. by *Phytophthora cinnamomi* due to increased soil temperature of 12-30°C (Podger et al., 1990). Temperature also plays a vital role for the occurrence of bacterial diseases such as *Ralstonia solanacearum, Acidovorax avenae* and *Burkholderia glumea* and bacteria also proliferate in the areas where temperature dependent diseases have not been previously observed (Kudela, 2009). Even the incidence of virus and other vector borne diseases also alter. Mild and warmer winters make aphids easy to survive thus spreading Barley yellow dwarf virus (BYDV) and also increase viruses of potato and sugar beet (Thomas, 1989; Mackerron et al., 1993).

Fig. 2. Effect of temperature on plant diseases

The incidence of bacterial pathogens i.e. *Ralstonia solanacearum, Acidovorax avenae*, and *Burkholderia glumea* is greatly influenced by temperature. Moreover, bacteria thrive in places where temperature-dependent diseases have not yet been reported (Kudela, 2009). High temperature (34.5 °C), reduced virulence of soft rot bacterium (*Erwinia carotovora* subsp. *carotovora*) except in strain EC153, which generated large amounts of rRNA, N-acyl homoserine lactone and extracellular proteins causing widespread maceration of Chinese cabbage and celery petioles (Hasegawa et al. 2005). Temperature also influence the prevalence of viruses and vector-borne diseases. A mild winter increases the survival of aphids and thus increase the incidence of viral diseases of sugar beet and potato and spread of Barley Yellow Dwarf Virus (Thomas, 1989; Mackerron et al. 1993). Future forecasts indicate that in the years 2020, 2050, and 2080, regions that are favourable to the Black Sigatoka (*Mycosphaerella fijiensis*) disease of banana would substantially decline, although some areas will still favour the occurrence of the disease (Ghini et al. 2007).

Impact of CO_2 on plant disease:

Both the host and the pathogen are influenced by increased CO_2 levels in various ways. Increased size of plant organs, leaf area, leaf thickness, more numbers of leaves, higher total leaf area/plant, stems and branches with greater diameter are resulted from increased CO_2 levels (Bowes, 1993 and Pritchard et al., 1999). Dense canopy favours the incidence of rust, powdery mildew, *Alternaria* blight, *Stemphylium* blight and anthracnose diseases. Higher CO_2 concentrations induce greater fungal spore production. Increased CO_2 also enhances photosynthesis, increased water use efficiency and reduced damage from ozone (von Tiedmann and Firsching, 2000); and leaf area, plant height and crop yield are increased at higher doses of CO_2 (Eastburn et al., 2011). Increased CO_2 inhibited resistance against PVY in tobacco plants (Matros et al. 2006), and tomato YLCV (Huang et al. 2012) and TMV in tomato plants (Zhang et al. 2015). High CO_2 levels may also reduce pathogen-induced viral resistance (Garrettt et al. 2006). As a result, while rising temperatures affect the duration, frequency and development, virus epidemics by modifying host resistance, altering virus multiplication rates and physiology of host-virus interactions, rising CO_2 concentrations may lessen the impact of temperature on epidemics by boost

Effect of changed moisture regime on plant pathogens:

With increased temperature various models on climate change predict frequent and extreme rainfall events and higher atmospheric water vapour concentrations. These encourage the crops to produce healthier and larger canopies that retain moisture as leaf wetness and RH for longer periods and results in condition conducive for pathogens and diseases such as late blights and vegetable root diseases including powdery mildews (Coakley et al., 1999). High moisture favours foliar diseases and some soil borne pathogens such *Phytophthora, Pythium, R. solani* and *Sclerotium rolfsii*. Drought stress affect the incidence and severity of viruses such as Maize dwarf mosaic virus (MDMV) and Beet yellows virus (BYV) (Olsen et al., 1990 and Clover et al., 1999). At low soil moisture, *Ralstonia solanacearum* exhibits reduced growth in tomatoes (Islam et al. 2004). In apple, the incidence of various canker diseases caused by fungal pathogens is increasing as a result of less rain during the rainy season and more severe summers (Paul, 2000). Likewise, the incidence of apple scab (*Venturia inaequalis*) has also decreased as a result of less rainfall in the winter and in March and April, which is required for the maturation of the disease spreading sexual spores.

Effect due to UV radiation:

Increased UV radiation may have positive as well negative impact on pathogen population (Caldwell et al. 2007; Sharma et al. 2012). Even at lower doses, the most potent radiation, UV-C, kills microorganism isms more effectively but frequently damages plants. Indirect effects such as regulation of plant defence mechanisms, ROS accumulation and production of secondary metabolites like phenolic compounds can be attributed to UV-B-specific pathways (Vanhaelewyn et al. 2019). UV inactivates microorganism isms by framing pyrimidine dimers in RNA and DNA, that obstruct gene expression process (Goosen and Moolenaar, 2008; Cutler and Zimmerman, 2011). UV rays harms structure of pathogens and bio-control agents directly and interferes with host resistance. UV radiations are the result of depletion of ozone layer because of release of greenhouse gases (Ghini et al. 2012).

Effect of climate change on vector-borne diseases:

Plant viruses operate in association with their host plants and vectors. The risk of vector-borne disease at the local and regional level is limited by the climatic requirements of disease vectors (Malmstrom et al., 2011). Both host plant and insect vector populations are affected by climate change and spread the plant viruses (Jones, 2009). Global warming also influences the primary infection of the host, the spread of the infection within the host and/or the horizontal transmission of the virus to new hosts by the vector. Phenology and physiology of the host also affected by climate change, thereby affect its virus susceptibility and virus ability to infect. In turn, effects on host physiology may affect the attractiveness of the host to vectors and/or viral transmissibility. Climate change has various effects on vectors like modification of vector phenology, vector's over-wintering, density, migration and its stability. There is a little effect by elevated CO_2 levels on natural enemies of insect herbivores. This elevated CO_2 have indirect effect on third trophic level, by changing the size and composition of insect's prey populations. Any changes either in host plant or insect vector population due to climate change could spread plant viruses (Canto et al., 2008).

Climate change and microbial interactions:

The three principle greenhouse gases that microorganisms produce and consume are carbon dioxide, methane, and nitrous oxide. Climate change can accelerate the diseases that certain bacteria can spread to people, animals, and plants. Significant effects on the carbon cycle and the functioning of many ecosystems are caused by elevated CO_2 levels in the atmosphere. Key parameters impacting soil microbial populations include temperature, CO_2 con centration, and nitrogen deposition amount (Garrettt et al. 2006). Alteration in abiotic environments over the short and long terms have an impact on both the populations of microorganism isms that live on plant surfaces as well as plant development and production. Every modification in the phyllo sphere's microbiota has an impact on plant development and resistance to aggressive disease attack.

Plant pathosystems models:

To study the effects of climate change on both plant pathogens and diseases, pathosystem are examined (Elad and Pertot, 2014). Predictive models have been developed for a few plant-pathogen systems. Powdery mildew (*Erysiphe necator*) is one of the most important diseases of grapevine and European grapevine moth (*Lobesia botrana*) is one of the most noxious vineyard pests in the European and Mediterranean regions. Phenological models of grapevine with phenological models of grape powdery mildew and the European grapevine moth applied the models to climate change scenarios for the eastern Italian Alps and considered potential changes in the interactions between these species (Caffarra et al., 2012).

They simulate decrease powdery mildew epidemics in disease severity, especially in years where disease symptoms first appear at a later date and in the presence of increased temperatures. They also suggested that in the warmer region with profitable viticulture areas, increased temperatures might have a detrimental effect on yield because of increased asynchrony between the growth stages of resistant larvae of grapevine and European grapevine moth larvae. On the other hand, the increase in pest pressure caused by the increased number of generations might not be as severe as expected on the basis of the pest model only, because of the earlier harvest dates, which would limit the damage caused by late-season generations. Moisture allows for infection by zoosporangia and dry periods kill the pathogen (Gessler et al., 2011).

Conclusion:

Climate change is a significant phenomenon that has an influence on agricultural productivity. Due to the fact that crucial to locate areas where crop production have been affected by the temporal and spatial changes brought on by climate change. We couldn't find any data on how elevated levels of the greenhouse gases nitrous oxide or me thane might affect any of the biological factors related to infectious plant diseases. First, there is need to evaluate under climate change the efficacy of current physical, chemical and biological control tactics, including disease-resistant cultivars, and secondly, to include future climate scenarios in all research aimed at developing new tools and tactics. Disease risk analyses based on host–pathogen interactions should be performed, and research on host response and adaptation should be conducted to understand how an imminent change in the climate could affect plant diseases. The initiation of disease forecasting must be prioritized to protect the farmers from bearing loss. We can also contribute in reducing crop yield losses by adopting different climate resilient technologies and practices of climate resilient farming.

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SUSTAINABLE FARMING AND ENVIRONMENTAL CONSERVATION THROUGH MICROBES IN THE ERA OF CLIMATE CHANGE

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INTRODUCTION:

Since the late 1970s, scientists have recognized the connection between rising carbon dioxide (CO_2) levels and global climate change. The National Academy of Sciences stated in 1979 that continued CO_2 increases would inevitably lead to significant climatic shifts (National Research Council). Decades of research have since confirmed this prediction-anthropogenic activity such as fossil fuel combustion, deforestation, and population growth have intensified greenhouse gas concentrations, resulting in a measurable rise in global temperatures and widespread climate disruption. The Intergovernmental Panel on Climate Change (IPCC), established in 1988, compiles and assesses scientific data to guide global climate policy, and its 2021 report documented unprecedented changes to Earth's climate in every region, including rapid surface warming over the past two centuries (Intergovernmental Panel on Climate Change). Similarly, the World Health Organization (WHO) has declared climate change the greatest health threat facing humanity (World Health Organization), as its effects extend to water quality, food security, public health, and global economies. These findings accentuate that climate change is not only an environmental issue but also a profound challenge to all forms of life on Earth, demanding urgent, coordinated global action.

Microbes contribute significantly to solving climate change by regulating greenhouse gases through biogeochemical cycles (like the carbon and nitrogen cycles), enhancing carbon sequestration in soils, producing clean energy through bio-based products like biofuels, and aiding in the bioremediation of pollutants. Harnessing these natural microbial capabilities through targeted management of ecosystems and soil health holds immense potential for reducing greenhouse gas emissions and achieving a sustainable energy future. Microbes are responsible for many historical environmental changes that shaped the earth. These tiny generators of life have survived for billions of years, and further research may hold the answers we have been looking for all along. Microbes, including bacteria and fungi, are crucial to maintaining healthy soil and combating climate change. Understanding the role of microbes in climate change is therefore critical to protecting the health of the planet. Around the world, scientists from multiple disciplines, including ecology, microbial engineering and medicine, are engaging in important research and developing microbe-based techniques and frameworks to address the problem. Many of these scientists convened in Houston at ASM Microbe 2023 to participate in a special "Climate Change and Microbes (CCM)".

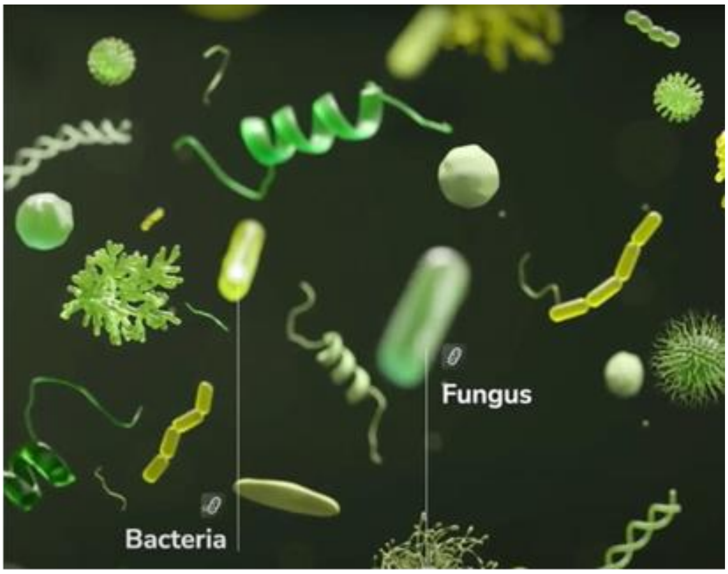
Microbial Adaptation to Climate Change

Microbes respond rapidly to environmental changes because they grow quickly, exist in huge numbers and can exchange genetic material. According to Dr. Mengting “Maggie” Yuan of UC Berkeley, climate change—particularly warming and reduced precipitation—reshapes microbial activity, diversity and interactions in soil ecosystems. Her research focuses on how grassland soil microbes respond to these shifts and how their interactions influence the processing of carbon fixed by plants. Understanding these below-ground food webs is essential for improving climate predictions.

Microbes adapt in multiple ways. For example, warming can increase bacterial respiration but reduce bacterial cell size. Viruses in cold ocean environments have evolved proteins that help them withstand low temperatures. Changes in temperature and moisture also alter microbial community composition in soils and oceans, which can impact carbon and nutrient cycling.

Viruses themselves play a role in these ecological changes. Some, like cyanophages that infect cyanobacteria, can halt carbon dioxide fixation during infection, increasing the amount of greenhouse gases that remain in the atmosphere. However, scientists still need to better understand the full influence of viral communities on microbial responses to climate change.

Because microbes strongly influence carbon fluxes and greenhouse gas emissions, studying their behavior under changing environmental conditions is critical. As Yuan puts it, microbes may be small, but they have powerful effects on Earth’s climate. Her work was featured in the ASM Microbe 2023 session on how microbial communities ecologically and evolutionarily respond to climate Change



Therefore microbe-based innovations to help humans adapt to and sustainably mitigate climate change in terms of its pace and deleterious consequences mainly focusing on the following.

➢ Microbes for a non-fossil carbon economy.

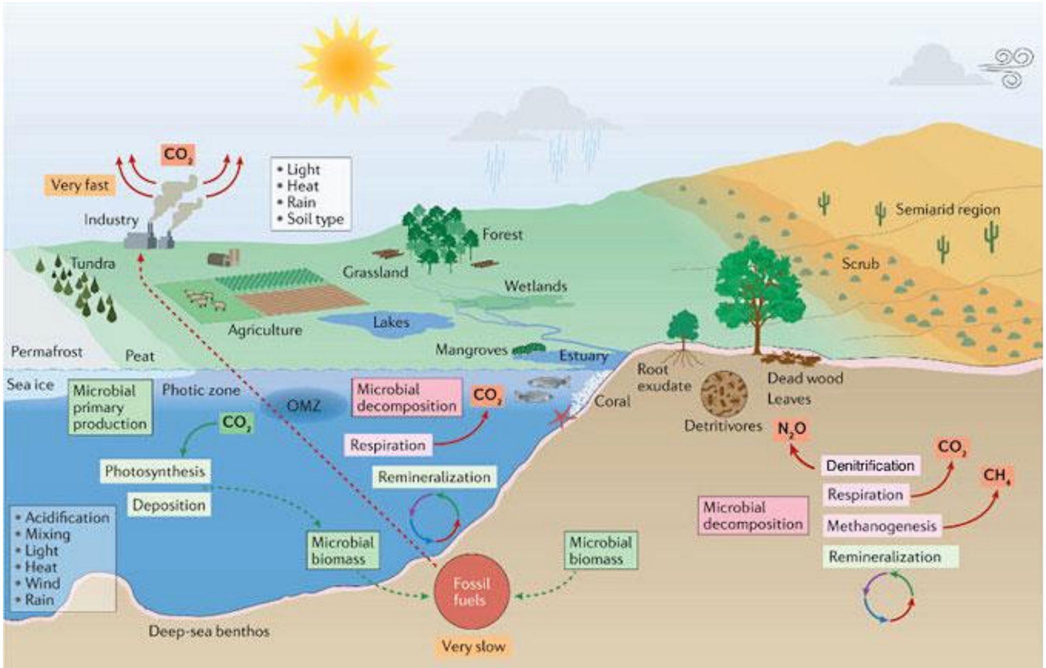
➢ Microbes for food security and ecosystem resilience.

➢ Microbes for urgent methane mitigation**.**

These solutions scientifically sound, economically sustainable, safe and scalable in a 5-to-15-year period. It is also confident that these solutions will promote social equity and societal well-being more generally and that they can be tailored to the needs and capacities of local communities, countries and regions.

How do Microbes help Mitigate Climate Change?

1. **Greenhouse Gas Regulation:** Microorganisms are central to the global cycles of greenhouse gases (carbon dioxide, methane, and nitrous oxide). They can act as both producers and consumers of these gases, and by managing and stimulating microbial processes in terrestrial and aquatic environments, we can reduce net emissions.



Microbes in aquatic and terrestrial environments produce and consume the greenhouse gases CO_2, CH_4 and N_2O. Soil and aquatic microbes produce these gases when decomposing organic matter to provide nutrients for plants and marine life, respectively. Source: National Library of Medicine.

2. **Carbon Sequestration:** Soil microbes are essential to carbon sequestration. Microbial communities, particularly in soils, help to store carbon. Microbes form biofilms that bind soil particles, which helps to prevent erosion and retain moisture, while the carbon from dead microbes in these biofilms can remain in the soil for long periods. Certain bacteria and algae convert carbon dioxide into organic matter, which is then stored in the soil. This helps remove excess carbon dioxide from the atmosphere, mitigating the effects of global warming.

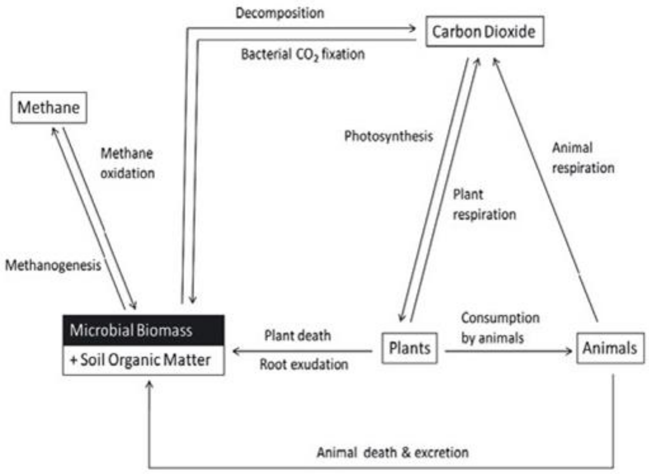
Some of the key soil microbes involved in carbon sequestration include:

a. **Mycorrhizal fungi:** These fungi form mutualistic relationships with plant roots, helping plants to absorb nutrients and water from the soil. They also play a role in carbon sequestration by increasing the amount of carbon stored in the soil.

b. **Actinobacteria:** These bacteria are known to decompose plant litter and other organic matter, releasing carbon dioxide in the process. They also play a role in carbon sequestration by producing organic compounds that help to stabilize soil organic matter.

c. **Rhizobia:** These bacteria form symbiotic relationships with legume plants, fixing nitrogen from the air and making it available to the plant. This process also helps to increase the amount of carbon stored in the soil.

d. **Proteobacteria:** These bacteria play a role in decomposing plant litter and other organic matter, releasing carbon dioxide. However, they can also play a role in carbon sequestration by producing compounds that help to stabilize soil organic matter.

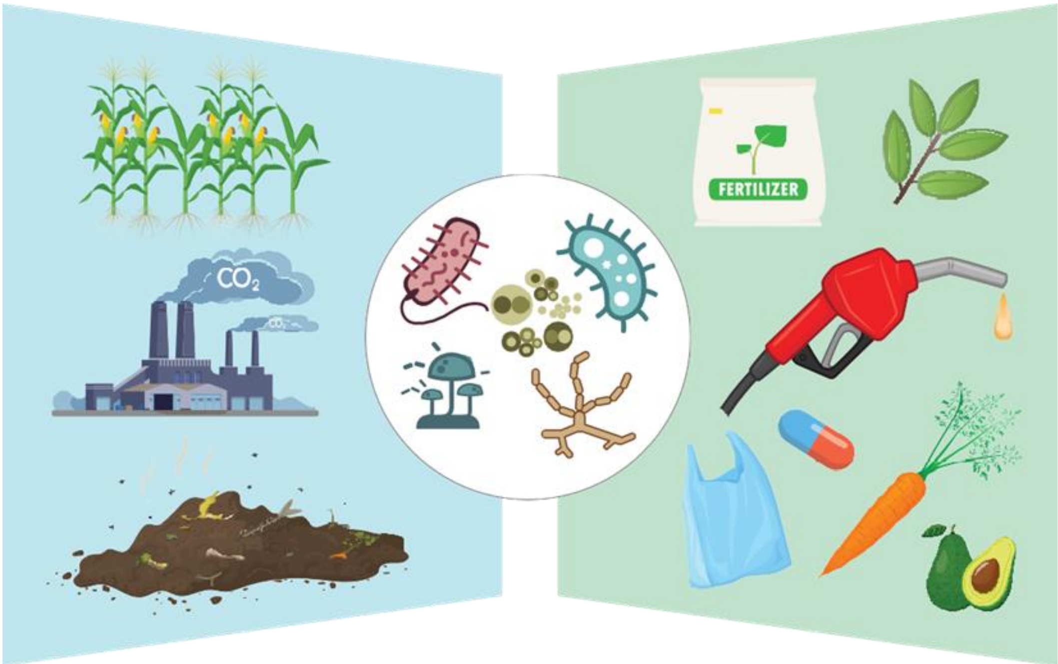


3. **Bioenergy and Sustainable Products:** Microbes are used to produce clean energy sources, such as bioethanol, biogas, and bio butanol. These bio-based alternatives to fossil fuels can help reduce carbon emissions and support a low-carbon economy.

- **Bioenergy:** This involves generating energy from organic matter rather than fossil fuels. Bioenergy production from microbial bioconversion of a variety of feedstocks, coupled with carbon capture and storage, is modeled to be able to deliver nearly 245 exajoules of energy per year by 2050. Anaerobic digestion, which uses consor- tia of bacteria to break down organic matter in the absence of oxygen to produce biogas, can convert up to 60%-80% of the organic matter in feedstocks to biogas (Weiland 2010). Microbial fermentation can convert feedstock sugars into ethanol or other biofuels. The United States alone generated over 15 billion gallons of ethanol through primary fermentation of corn in 2022 (eia.gov).

- **Biomanufacturing:** Renewable and sustainable carbon sources are used as feed-stocks for microbially converted value-added products. The goal is to offset the use of petrochemicals, and thus greenhouse gas emissions, and create a robust supply route to the commodity market. Over 70% of CO_2 emissions are attributed to transporta- tion and the chemical industry (Net Zero America 2021). Microbial production of fuels not only can substantially reduce greenhouse gas emissions but also can be used to produce new advanced fuels with higher energy density and fuel blend properties (e.g. 1,4-dimethylcyclooctane) (Baral et al. 2021). It is estimated that over 60 billion gallons of renewal carbon liquid fuels could be manufactured from currently available biomass (BETO Billon-Ton Report 2023).

Microbial bioconversion is an essentially modular and widely implementable technology that can be tailored to a geographic location, market or community. This can be a source of equity and opportunity worldwide and to a range of communities. Thus, each region can develop a system that is tailored to their starting materials as well as desired products based on the local need and availability of resources. Bioproduction of fertilizers, foods and even therapeutics can also indirectly ameliorate problems in food shortage, ecological preservation and disease spread that are all exacerbated by global warming and climate change.



The overall net benefits of microbial conversion of waste products are dependent on the efficiency of the conversion, the sustainability of the feedstock and the offset of the product. Agricultural residues, energy crops, wood processing and municipal waste are all common types of waste feedstocks. For example, agricultural residues, such as corn stover, wheat straw and rice husks, could provide up to 5.2 billion tons of biomass annually for bioenergy production (Bentsen et al. 2014) while municipal solid waste, such as food scraps and yard trimmings, is projected to reach 3.4 billion tons by mid-century (Kaza et al. 2018). Large markets represented by fuels, materials and platform chemicals provide the obvious bioproduction targets that stand to have an immediate effect on greenhouse gas reduction.

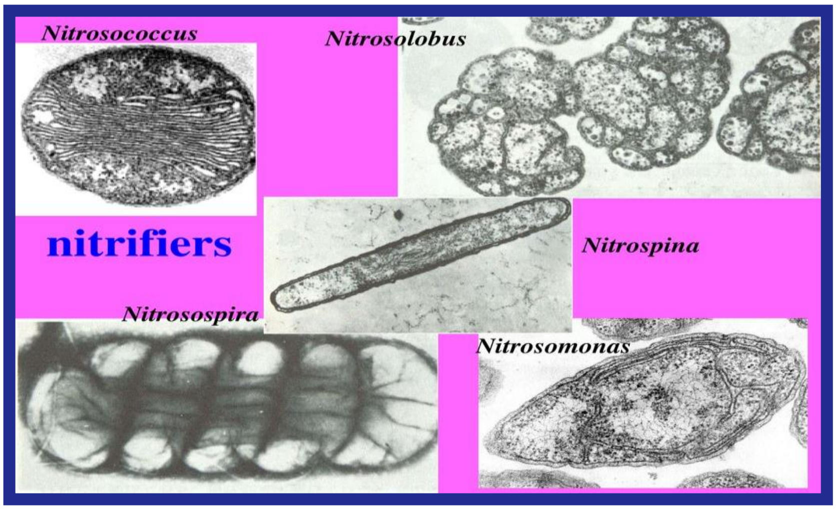
4. **Nutrient Cycling:** Soil microbes play a critical role in the nutrient cycling process. Microbes break down complex organic molecules such as cellulose and lignin, into simpler compounds that plants can readily use. This process known as decomposition,

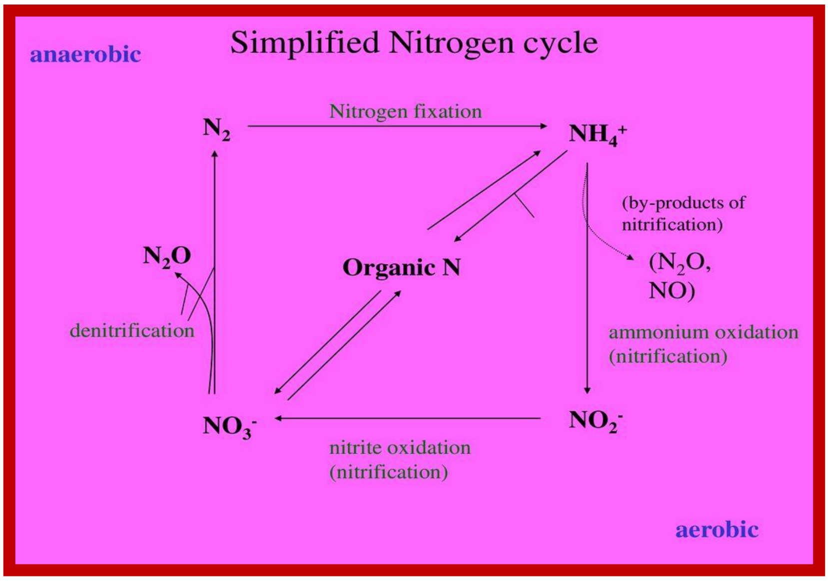
releases nutrients like carbon and nitrogen back into the environment. This supports plant growth and overall soil health, which indirectly contributes to climate change mitigation. Nitrogen is a crucial nutrient for plant growth, but it must be in the proper form for plants to use it. These nutrients can then be taken up by plants and used for growth and development. This process is known as nutrient cycling and helps maintain the health and fertility of the soil.

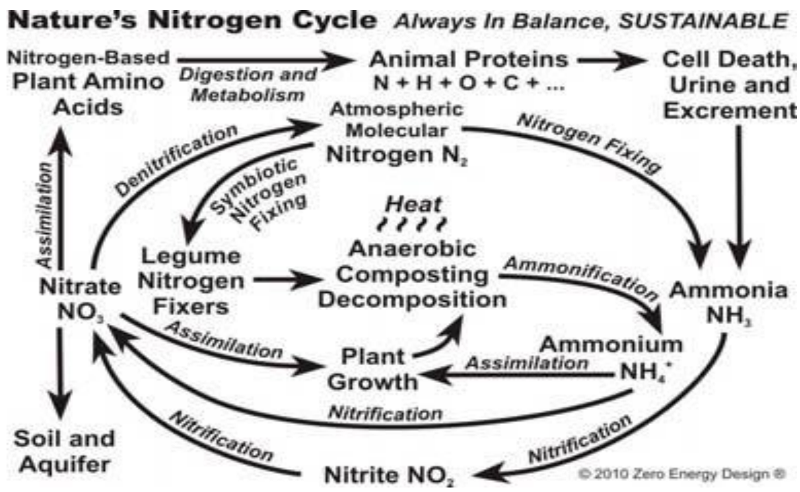
For example, nitrogen-fixing bacteria, such as Rhizobium, convert atmospheric nitrogen into a form that plants can use, such as ammonia or nitrite. This process, called nitrogen fixation, is essential for the growth of many plants, as nitrogen is a critical component of proteins and other cellular structures.

Here are some of the key microbes involved in the nitrogen cycle:

- **Nitrogen-fixing bacteria:** These bacteria, such as Rhizobia and *Azotobacter*, can convert atmospheric nitrogen into a form that plants can use. This process, called nitrogen fixation, is critical for plants' growth and the ecosystem's health.
- **Ammonia-oxidizing bacteria:** These bacteria, such as *Nitrosomonas* and *Nitrosococcus*, convert ammonia into nitrite, which is an intermediate form of nitrogen.
- **Nitrite-oxidizing bacteria:** These bacteria, such as *Nitrobacter*, convert nitrite into nitrate, which is another intermediate form of nitrogen.
- **Denitrifying bacteria:** These bacteria, such as *Pseudomonas* and *Paracoccus*, convert nitrate back into nitrogen gas, which is released into the atmosphere.
- **Decomposers:** These microbes, such as fungi and bacteria, break down dead organic matter and recycle its nutrients back into the soil.
- **Phosphorus-solubilizing bacteria:** These bacteria, such as *Bacillus* and *Pseudomonas*, can recycle phosphorus from insoluble sources, making it available for plants and other organisms.
- **Sulfur-oxidizing bacteria:** These bacteria, such as *Thiobacillus* and *Beggiatoa*, play a crucial role in the sulfur cycle by oxidizing sulfur compounds, making sulfur available for other organisms in the ecosystem.







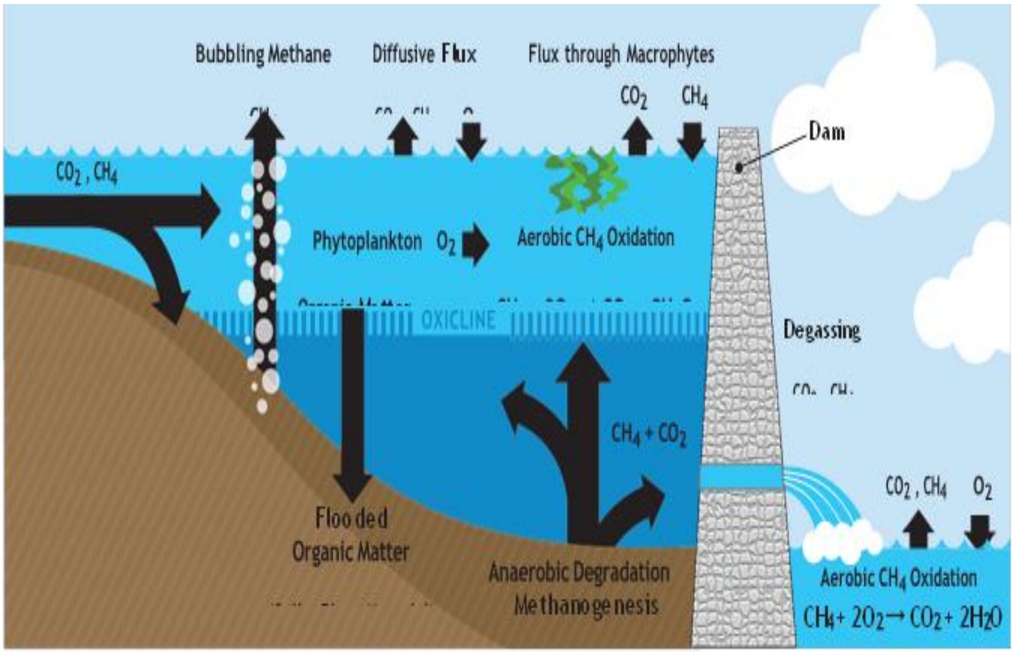
5. **Bioremediation:** Microorganisms can degrade, detoxify, and absorb hazardous substances, which helps to clean up polluted environments. This process can alleviate the environmental hazards caused by anthropogenic activities and reduce associated emissions.

   a. Soil Pollution Reduction: Soil microbes can reduce soil pollution. Many industrial processes and consumer products release harmful chemicals into the environment, contaminating the soil. But some soil microbes can break down these pollutants, helping to clean up contaminated soil and protect the ecosystem.

   b. When waste breaks down, it releases methane, another potent greenhouse gas. Methane is a potent greenhouse gas that contributes to global warming and can negatively impact carbon sequestration efforts.

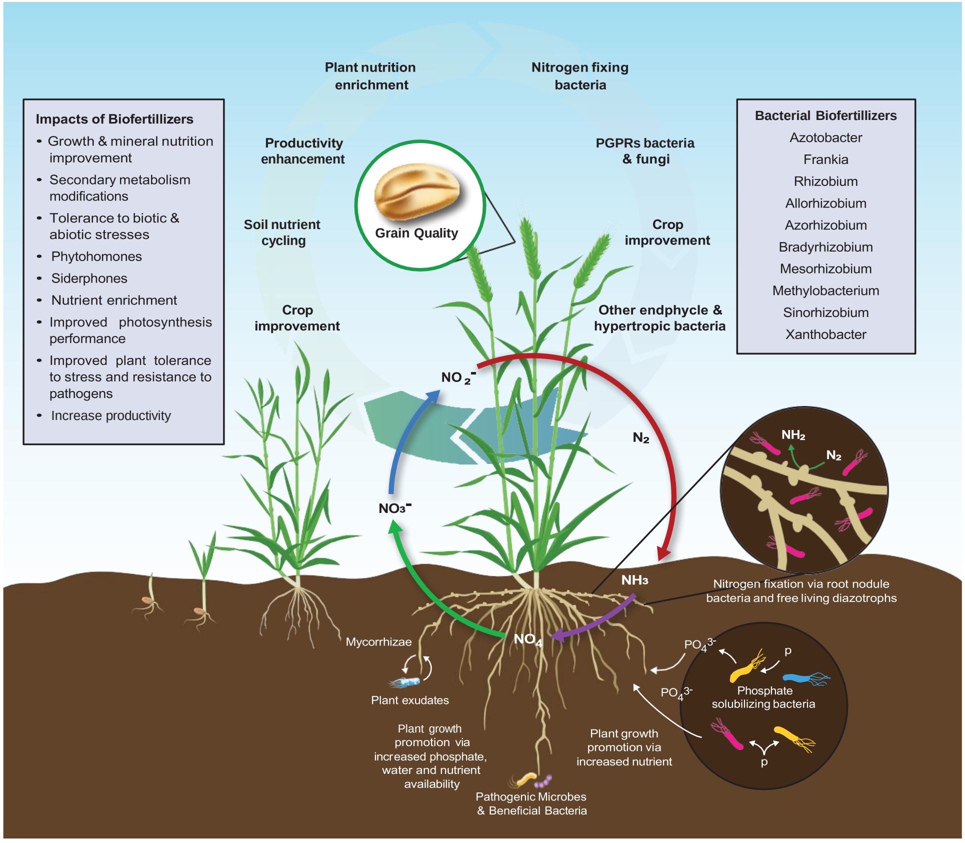
   c. Microbes both consume and produce methane, making them key allies to mitigating this greenhouse gas. Methane is approximately 80 times as potent as carbon dioxide at trapping heat in the atmosphere over a 20-year period. Thus, reducing overall methane emissions is an effective means for reducing global warming in the near future. Over 150 countries have signed the Global Methane Pledge to reduce global methane emissions at least 30% from 2020 levels by 2030. Some microbes, particularly certain types of archaea and bacteria, are involved in producing methane. One example of this is Methanogenic archaea. These microbes are responsible for most methane production in anaerobic environments, such as wetlands, rice paddies, and the digestive tracts of ruminants. They produce methane as a byproduct of their metabolic activities, which involve breaking down organic matter.

d. The production of methane by these microbes can release significant amounts of the gas into the atmosphere, which can negatively impact the climate and carbon sequestration efforts. However, it is important to note that not all microbes involved in producing methane are harmful. Some microbes, such as those involved in the production of biogas, can be harnessed to produce renewable energy while reducing greenhouse gas emissions. Microbes, such as methanotrophic bacteria, can break down methane before it can escape into the atmosphere. This process not only reduces methane emissions but also creates a source of clean energy. Effective way of utilizing the methane producers and enhancement of methane consumers are promising options to reduce global methane emissions.



Methane consuming microbes in freshwater reservoirs can reduce overall greenhouse gas emissions

6. **Sustainable Agriculture:** A healthy soil microbiome is essential for maintaining soil health and promoting sustainable agriculture. Microbes play a crucial role in supporting a healthy soil microbiome in several ways:



Microbial biofertilizers improve agricultural yield, promote soil health and increase soil carbon sequestration.

a. Practices like composting, using plant growth promoting rhizobateria (PGPR), and inoculation with mycorrhizal fungi can improve plant health and productivity while also increasing soil carbon and reducing the need for chemical inputs.

b. **Soil structure:** Microbes, such as mycorrhizal fungi, can help improve the soil's structure by forming networks of hyphae that bind soil particles together. This can help improve water retention, reduce erosion, and increase the soil's overall health.

c. **Disease suppression:** Microbes can help to suppress diseases in plants by competing with pathogens for resources, producing antibiotics, and supporting the growth of healthy roots.

d. **Pest control:** Microbes can play a role in controlling pests by producing toxins that are toxic to insects and other pests and by supporting the growth of plants that are resistant to pests.

e. **Rhizosphere microbes improves plant stress tolerance:** The plant rhizosphere is occupied with various microbes such as plant growth- promoting bacteria (PGPB) and plant growth promoting fungi (PGPF). Mycorrhizae supply phosphate and nitrate to plants and rhizobacteria play a role in fixing atmospheric nitrogen. Some beneficial microbes can provide resistance to environmental stress factors. Growth of crops under abiotic stress conditions can be improved by different bacterial families. Co-inoculation of Rhizobium/Pseudomonas with *Zea mays* can increase its salt tolerance due to decreased electrolyte leakage and balance of leaf water contents. Various microorganisms produce plant growth hormones such as indole acetic acid and gibberellic acid, which promote root growth.

PGPBs can also promote the plant's immune system to fight with many pathogens. Certain PGPF, such as mycorrhizal and endophytic fungi, significantly enhance stress tolerance of the plants against a variety of conditions, i.e., drought, heat, pathogens, herbivores, or limiting nutrients. Some PGPF can have beneficial effects on certain host plants and exerts pathogenicity to nonhost plants, for example, Colletotrichum acutatum, which is a pathogenic ascomycete for strawberry but beneficial when colonizing with pepper, eggplant, bean, and tomato. Microbes help to improve plant stress responses to an abiotic environment by influencing plant physiologically.

f. **Microorganisms in Controlling Carbon Emission:** Carbon sequestration by microbial processes is yet to be explored. Two important sinks of carbon are soil and the ocean can play a major role to mitigate anthropogenic carbon emission. There is a huge potential of the carbon sequestration process which can be modified by microbial community engineering, i.e., a shift in land use from arable land to grassland entails an average 18% higher carbon sequestration, with a yearly carbon input of 0.75 tonnes C/ha/year. A limited degree of soil manipulation could bring a higher degree of microbial homeostasis for sequestration. The addition of charcoal or biochar to the soil as a long-term carbon source improves soil quality and adsorption of nutrients to increase their bioavailability to the plants. The concept of carbon sequestration can also be approached by using concentrated CO_2 sources. Microbial electro-synthesis generates valuable products from electricity, using CO_2 or other organic feed stocks as carbon sources. In this process, acetate butyrate and other commodity chemicals have been produced. These chemicals can be converted to medium-chain fatty acids like caproate and caprylate that can serve as bio-based building blocks for the chemical industries. An energy efficient harvesting of carbon sources could lead to microbial carbon sequestration.

g. **Improving Salinity Tolerance:** Soil salinity could decrease national agricultural crop production in arid and coastal regions in climate change situations. Azospirillum inoculation can alter salt- stressed maize variety. Osmotic stress of pepper can be decreased by inoculation with Bacillus sp.TW4. For the salt-stressed plants, secondary inoculation with Azospirillum can result in prolonged root exudation of plant flavonoids following inoculation with Rhizobium. Thus, co-inoculation of plants with various bacterial species can improve abiotic stress tolerance.

h. **Drought Stress Tolerance:** The drought stress on plants can result in stomatal closure to minimize water loss by increased abscisic acid (ABA) levels in leaves with some other compounds such as ethylene, salicylic acid, etc. PGPR has a beneficial effect on plant's drought tolerance caused by changes in hormonal contents, mainly of ABA, ethylene, and cytokinins. *Azospirillum lipoferum* strains when inoculated with wheat seedlings can reduce drought stress. Root morphology can be changed by beneficial bacteria and hormone- like matters produced to excite the endogenous plant hormones. It was also evident that a significant amount of nitric oxide is produced as a diffusible gas by *A. brasilense* in aerobic conditions signaling an IAA-induced pathway for root growth. Inoculation of plant species with certain bacterium species can increase its drought stress tolerance by isolating its drought-responsive gene, ERD15, from *A. thaliana* when inoculated with *Paenibacillus polymyxa* Prasannakumar *et al.,* (2020).

7. **Innovation and Collaboration:** Continued scientific research and innovation are needed to fully realize the potential of microbial solutions. Global collaboration, interdisciplinary training, considerations for policy makers and industry engagement are essential for developing and implementing these solutions on a larger scale.

Mitigation options used for solving climate change

1. Less chemical consumption on farms through a reduced need to spray crops.
2. Minimize introducing synthetic chemical fertilizer in agriculture and using plant promoting microorganisms which act as a biofertilizer in a form of bio inoculation. Finally, can easily stop GHSs emission.
3. Avoiding the use of fossils raw materials and fuel (wood) through replacement the use of enzymes and microorganisms helps to make bio based products in adverse variety of industry sectors.
4. Using biofuel and apply bio based strategies and targets. For example, bioethanol. Biofuels are made from living things or the waste that they produce. One of the most common biofuels is ethanol, it is produced from plants. As a result biofuels from food stuffs such as sugar cane are not likely to provide a long term solution as a replacement to fossil fuels. The sugar can then be fermented (broken down) to ethanol by microbes such as the yeast Saccharomyces cerevisiae, Sulfolobus solfataricus and Trichoderma reesei.
5. Using potential bio based chemicals and plastics because of can replace their fossil based counter parts with significant and proven in greenhouse gases emission reduction.
6. Introducing novel species in the ecosystem
7. Improving drought tolerance biotic organisms
8. Minimizing and reducing water loss from agriculture
9. Applying afforestation program all over the world. Then carbon sequestration can easily managed
10. Creating public awareness, partnerships across sectors and countries will be vital for building a sustainable future and bring together to save nature and protect ecosystem.

Conclusion:

Climate change is a monumental threat that needs innovative solutions. Microbes have traditionally been seen as problems, but microbes offer many solutions for climate change. Microbes can mitigate climate change by reducing greenhouse gas emissions, replacing fossil fuels and increasing carbon sequestration. In addition, microbes can help increase food and energy security while also promoting biodiversity as we adapt to a changing climate.

Ultimately, an effective and sustainable portfolio of climate change mitigation technologies will have multiple components that should have both decreased dependability on fossil fuels and greenhouse gas sequestration through the use of microbes as well as harnessing the microbial potentiality to increase food and energy security while promoting biodiversity.

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INSTITUTIONALIZING CLIMATE SMART AGRICULTURAL STRATEGIES: POLICIES AND PROGRAMMES TO PROMOTE CLIMATE SMART AGRICULTURE IN INDIA

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ABSTRACT

To be climate smart, agriculture has to achieve the three conflicting objectives of sustainably increasing agricultural productivity and income, adapting and building resilience to climate change, and reducing and/or removing greenhouse gases emissions. But, for pursuing Climate Smart Agricultural strategies, farmers require additional resources in the form of capital, labour, information, service, market, credit, land rights *etc*. which is beyond their affordability. Hence, certain institutional mechanism spanning from international level to grass root level is put in place to provide an enabling environment for farmers to adopt CSA strategies. There are various schemes/programmes like PMKSY to provide capital for installing micro-irrigation system, PM-KUSUM to replace diesel pump with solar powered irrigation pump, GKMS to provide weather advisory, PMFBY to insure the crop, RKVY to encourage crop diversification, SHC to test the soil health status, PKVY to promote organic farming, KCC for low cost institutional credit to meet out the additional expenditure, NMAET to guide on IPM, INM,IWM, varieties and decisions, FPO to achieve economies of scale, and provision for tenant farmers in all of them. National Mission for Sustainable Agriculture (NMSA) has been recognized as the umbrella programme to execute all these schemes/programmes, to support farmers in adopting Climate Smart Agricultural strategies.

Keywords: *Climate Smart Agriculture, Institutionalization, policies, programmes, schemes, strategies.*

Introduction

Agriculture has to become more efficient in utilization of its resources *viz*. land, labour, seed, water, fertilizers, pesticides and machinery; and in pursuing various farm management practices to be resilient against the emerging challenges of climate change. While striving to fulfil the humungous task of ensuring the food security of burgeoning global population, agriculture should be smart enough to address the twin challenges of mitigating Green House Gas (GHG) emissions and adapting to climate change. To be climate smart, agriculture has to achieve the three conflicting objectives of a) sustainably increasing agricultural productivity and income; b) adapting and building resilience to climate change; and c) reducing and/or removing greenhouse gases emissions, where possible (Singh and Hassan, 2023) (Figure 1). Thus, Climate Smart Agriculture (CSA) is defined as agriculture that sustainably increases productivity, enhances resilience (adaptation), reduces/removes green house gases (mitigation) where possible, and enhances achievement of national food security and development goals (FAO, 2013).

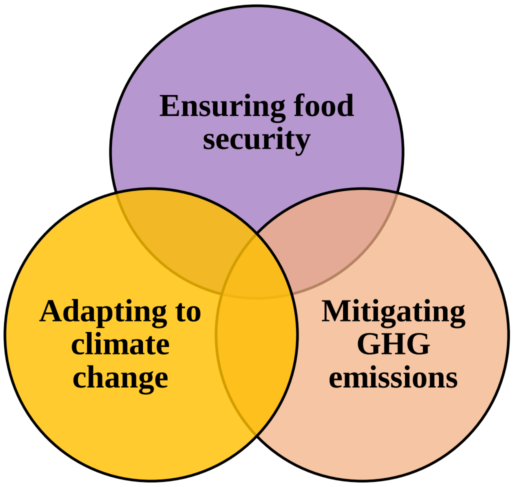

Figure 1. Conflicting objectives of Climate Smart Agriculture

The importance of pursuing CSA lies in the fact that agriculture as an occupation is highly vulnerable to natural calamities *viz*. changing temperature and rainfall patterns, floods, droughts and hailstorms; 86% of farmers who are marginal and small holders with low income level, limited resources, lack of alternate livelihoods and low crisis management capability will be worse affected by climate related stresses; agriculture as a sector provides employment and livelihood to around 60% of the country's population and contribute more than 10% to the country's GDP; and it is also a significant emitter of GHG due to fertilizers, livestock, residue burning *etc*. (Khan et. al., 2022).

Agriculture should be climate smart in six different ways which form the six pillars of Climate Smart Agriculture (Figure 2) (Kishore et. al., 2018; Kumar et. al., 2018):

1) **Water smart:** An intervention is said to be water smart, if it improves the efficiency of water use in agriculture. Eg. underground pipeline irrigation, and micro irrigation.
2) **Nutrient smart:** An intervention is said to be nutrient smart, if it improves the efficiency in application and uptake of nutrients. Eg. soil health-based integrated nutrient management.
3) **Crop smart:** An intervention is said to be crop smart, if the adoption of improved varieties of seeds and different crop combinations are productive and tolerant to various climatic stresses. Eg. drought/submergence tolerant varieties, short duration varieties, contingent crops, and crop diversification.
4) **Weather smart:** An intervention is said to be weather smart, if it helps farmers to forecast the weather in advance and plan their farm operations accordingly. Eg. ICT-based weather advisory, and weather-based crop insurance.
5) **Energy smart:** An intervention is said to be energy smart, if it reduces the fossil fuel consumption and improve the energy efficiency of equipment used in agriculture. Eg. solar powered irrigation system, and energy efficient machinery.

6) **Knowledge smart:** An intervention is said to be knowledge smart, if it strengthens the capacity of farmers to adapt to climate change. Eg. Trainings, and exposure visits.

This chapter aims to explore how the climate smart agricultural strategies practiced by farmers are institutionalized in the form of policies and programmes in order to scale up and scale out their adoption on a large scale, with the specific objectives a) to know the requirements of farmers or the constraints they face in adopting CSA strategies; b) to identify the institutional mechanism in place to fulfil the farmers' requirements of implementing CSA strategies; c) to brief about the existing schemes/programmes that support CSA strategies; and d) to study in detail the modalities of National Mission for Sustainable Agriculture, an umbrella programme to address the impacts of climate change on Indian agriculture and farmers.

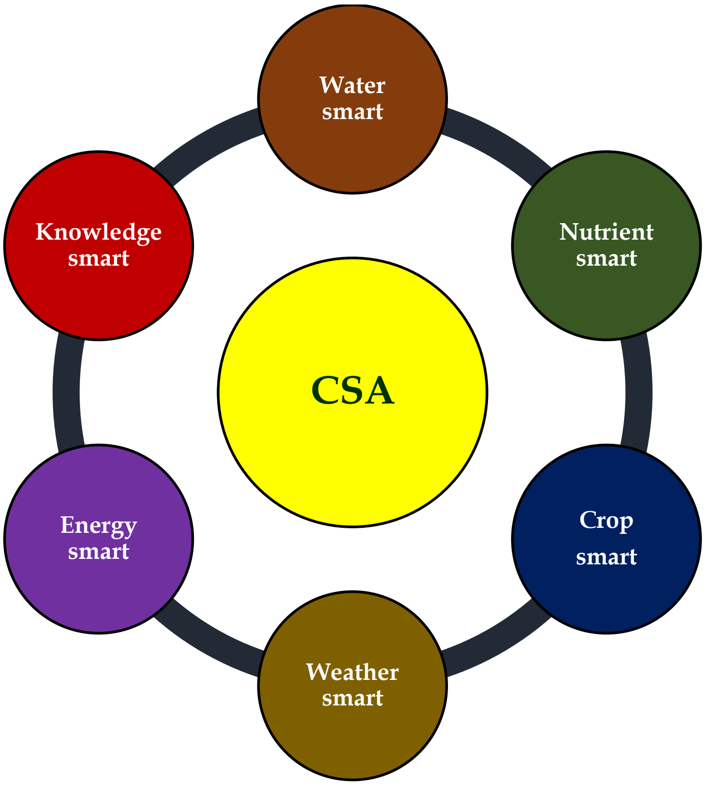

Figure 2. Six pillars of Climate Smart Agriculture

Requirements or constraints in adopting CSA strategies

While some CSA strategies can be implemented by farmers with the available resources, adopting many CSA strategies requires additional resources in the form of capital, labour, information, service, market, credit, land rights *etc*. which is beyond the affordability of farmers (FAO, 2017; van Asseldonk et. al., 2023). For example, installing a micro irrigation unit or a solar powered pump for irrigation requires considerable capital (Table 1). Tenant farmers will be hesitant to invest in improving the irrigation infrastructure by laying underground pipelines, digging farm pond or broad bed and furrow system as they do not have the land rights and not to annoy the landlord. Farmers require efficient weather advisory services to plan their farm operations in advance under the changing climatic conditions. If a farmer wants to insure his crop against weather anomalies, there should be an insurance service provider having an insurance product that could efficiently capture the weather parameters.

Crop diversification which is an indigenous strategy practiced by farmers from time immemorial to overcome the adversities of climate variability essentially needs more man-days of labour round the year which is a huge constraint in locations where farmers face labour shortage and high wage rates due to urbanization, industrialization and lack of family labour.

Similarly, assessing the soil health of the farm requires the services of a soil testing laboratory in the vicinity. A farmer who wants to pursue organic farming needs a proper institutional guidance to comply with National Programme for Organic Production (NPOP) norms and adhere to the National Standards for Organic Production (NSOP) for obtaining organic certification. Moreover, as organic farming produces a high-quality produce but at low quantity, the farmer needs a dedicated marketing outlet where either the organic produce can be sold at a premium price or the reduced yield is compensated in the form of an incentive. Indigenous production or purchased organic inputs is the cornerstone of organic farming which attracts additional cost of cultivation, time and labour. Practices like integrated pest management (IPM), integrated nutrient management (INM), integrated weed management (IWM), cultivation of climate resilient varieties requires extension support. In fact, a farmer should have a larger landholding for implementing these CSA strategies so as to achieve economies of scale.

Table 1. Requirements / constraints in adopting CSA strategies

Sl.No.	Strategy	Requirement/constraint
1.	Micro irrigation, solar powered pump	Capital
2.	Irrigation infrastructure, soil reclamation	Land rights
3.	Modification in farm operations	Weather advisory
4.	Crop insurance	Insurer
5.	Crop diversification	Labour
6.	Soil health assessment	Soil testing laboratory
7.	Organic farming	Knowledge, certification, market
8.	Additional cost of cultivation	Credit
9.	IPM, INM,IWM, varieties, decisions	Extension service
10.	All strategies	Economies of Scale

Institutional mechanism to fulfil the farmers' requirements of implementing CSA strategies

Certain institutional mechanism spanning from international level to grass root level should be in place in order to provide an enabling environment for farmers to adopt CSA strategies. At the international level, the issue of climate change was institutionalized through the United Nations Framework Convention on Climate Change (UNFCCC) and the Intergovernmental Panel on Climate Change (IPCC) (Figure 3). Further, Sustainable Development Goal (SDG) No.13 emphasizes the integration of climate change mitigation and adaptation into national policies (Patra and Babu, 2023). Having signed the UNFCCC in 1992 and acceding to the Kyoto Protocol in 2002, India has formulated its National Action Plan on

Climate Change (NAPCC) in 2008 which provides an overarching policy framework for climate action in the country (Rosmann et. al., 2021).

Within this broad national policy framework, eight missions were implemented on different strategies areas among which National Mission for Sustainable Agriculture (NMSA) being implemented by the Ministry of Agriculture and Farmers Welfare with an aim to evolve and implement strategies to make Indian agriculture more resilient to the changing climate (GoI, 2024). Aligning with NAPCC, all the States in India have formulated their State Action Plan on Climate Change (SAPCC) to make provision for State-wide and cross-sectoral climate change impact and vulnerability assessment; and to formulate adaptation and mitigation strategies to be carried out by the State Government Departments. Within this state policy framework, various schemes/programmes of Central and State Governments are being implemented through designated implementing agencies and allocation of adequate resources to promote CSA strategies among farmers.

For example, Tamil Nadu has launched its Tamil Nadu State Action Plan on Climate Change (TNSAPCC) in 2015 by adopting all the eight National Missions except for National Mission for Sustaining the Himalayan Ecosystem (NMSHE) (GoT, 2015). In 2023, it has formulated the Tamil Nadu Organic Farming Policy to promote organic farming in the State and Department of Agriculture was identified as the Implementing Agency of the Centrally Sponsored Scheme (CSS) Paramparagat Krishi Vikas Yojana (PKVY). The scheme aims to promote organic farming through a cluster approach of 20 ha and facilitate farmers to obtain Participatory Guarantee System (PGS) Certification which will help them to certify their organic produce, label and market their products domestically.

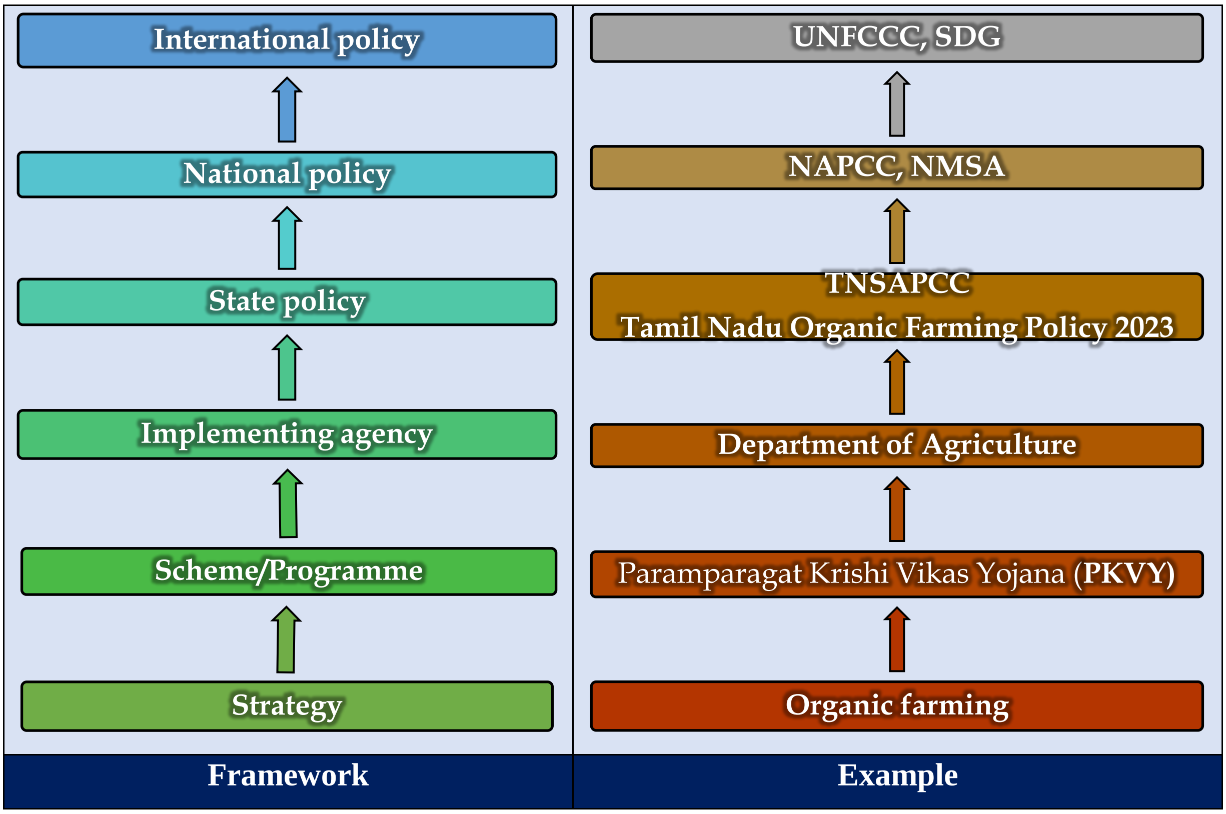

Figure 3. Institutional framework for implementing CSA strategies

Schemes/Programmes that support CSA strategies

Over the years, Government of India has implemented various schemes / programmes to promote CSA strategies among farmers (GoI, 2024a). The schemes/programmes that fulfil the resource requirements or remove the constraints of farmers in adopting the above discussed CSA are detailed in Table 2.

1. Micro irrigation:

On 1st July, 2015, Government of India launched the *Pradhan Mantri Krishi Sinchayee Yojana* (PMKSY) with the vision of extending the coverage of irrigation and improving water use efficiency in a focused manner with end to end solution on source creation, distribution, management, field application and extension activities. Under the *Har Khet ko Pani* component of the scheme i.e. extending the coverage of irrigation, activities *viz*. rain water conservation, construction of farm pond, water harvesting structures, small check dams, contour bunding, diversion canals, field channels, water diversion/lift irrigation are funded. Under the "per drop more crop" component, farmers are encouraged to set up micro irrigation facility in their farm (drip and sprinkler irrigation system) through financial assistance of 100% to small and marginal farmers; and 75% subsidy to big farmers up to 5 ha. Tamil Nadu Horticulture Development Agency (TANHODA) is the implementing agency of this scheme in Tamil Nadu.

2. Solar powered pump:

In March 2019, Government of India launched the *Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan* scheme (PM-KUSUM) which supports individual farmers to install standalone solar agriculture pumps of capacity up to 7.5 HP for replacement of existing diesel agriculture pumps / irrigation systems in off-grid areas, where grid supply is not available (GoI, 2024b). Financial assistance of 80% subsidy is provided to small and marginal farmers belonging to SC and ST categories, 70% subsidy for other small and marginal farmers, and 60% subsidy for other farmers. Agricultural Engineering Department is the implementing agency of this scheme in Tamil Nadu.

3. Crop diversification:

Tamil Nadu Irrigated Agriculture Modernization Project (TNIAMP) is a multi disciplinary project funded by World Bank and implemented by the Government of Tamil Nadu (GoT, 2024). The main objective of the programme is to accelerate crop diversification from crops requiring more water to high remunerative and less water requiring horticultural crops like vegetables, fruits, spices and flowers. Individual demonstrations will be conducted in farmers' field varying from 0.2 to 1.0 acre depending upon nature of the crop - about 0.2 acre for flowers, 0.2-0.5 acre for vegetables and up to 1.0 acre for fruits. Based on the performance of the crop under demonstration, farmers will be encouraged to take up the crop without expecting any financial assistance from the project. The required technical guidance will be given from sowing to harvest of the crop by the Department of Horticulture.

4. Soil health assessment:

On 19th February 2015, Government of India launched the Soil Health Card scheme to give each farmer soil nutrient status of his holding and advice him on the dosage of fertilizers and the needed soil amendments to maintain soil health in the long run. A soil health card will be handed over to the farmer which contains the status of his holding's soil with respect to 12 parameters *viz*. N, P, K (macro-nutrients); S (secondary- nutrient); Zn, Fe, Cu, Mn, Bo (micro-nutrients); and pH, EC, OC (physical parameters). The particular holding will be assessed every 3 years and the farmer will be given revised card. Agriculture Department is the implementing agency of this scheme in Tamil Nadu.

5. Organic farming:

In 2015, Government of India launched the *Paramparagat Krishi Vikas Yojana* (PKVY) to support and promote organic farming through a cluster approach of 20 ha and facilitate farmers to obtain Participatory Guarantee System (PGS) Certification which will help them to certify their organic produce, label and market their products domestically. A total assistance of Rs.14.95 lakh is provided per cluster for mobilization, adoption of PGS certification and manure management. In that, Rs.10.00 lakh is allocated to farmers subject to Rs.50,000/ha for manure management and biological nitrogen harvesting; and Rs.4.95 lakh for the implementing agency for mobilization and adoption of PGS Certification and Quality Control. Agriculture Department is the implementing agency of this scheme in Tamil Nadu.

6. Credit requirement:

In August 1998, Kisan Credit Card scheme (KCC) was introduced by the National Bank for Agriculture and Rural Development (NABARD) for implementation by all Commercial banks, Regional Rural Banks, and state co-operative banks. The scheme aims to provide adequate and timely credit to farmers for their agricultural operations at a differential interest rate (DIR) of 4% per annum. The scheme was further extended in 2004 for investment credit requirement of farmers in allied and non-farm activities; and Electronic Kisan Credit Cards are being issued since 2012.

7. Economies of scale:

In 2020, Government of India launched the Central Sector Scheme for "Formation and Promotion of 10,000 Farmer Producer Organizations (FPOs)" enabling farmers to enhance their bargaining power, leverage economies of scale, reduction in cost of production and enhancing their incomes through aggregation of agricultural produce. FPOs will be provided financial assistance up to Rs.18.00 lakh for 3 years. In addition, provision has been made for matching equity grant up to Rs.2,000 per farmer member of FPO with a limit of Rs.15.00 lakh and a credit guarantee facility up to Rs.2.00 crore of project loan from eligible lending institution to ensure institutional credit accessibility to FPOs. Further, Rs.25.00 lakh will be given to Cluster Based Business Organizations (CBBO) for hand holding each FPO over a period of 5 years. In Tamil Nadu, this Scheme is jointly implemented by the Department of Agricultural Marketing and Agri Business, Government of Tamil Nadu and NABKISAN, a subsidiary of NABARD.

8. Weather forecasting:

India Meteorological Department (IMD) runs an operational Agrometeorological Advisory Services (AAS) called *Gramin Krishi Mausam Sewa* (GKMS) scheme for the benefit of farming community in the country (IMD, 2020). Under the scheme, medium range weather forecast at district and block level for next five days is generated and based on the forecast, 130 Agromet Field Units (AMFU) located at State Agricultural Universities (SAU), Institutes of Indian Council of Agricultural Research (ICAR), Indian Institute of Technology (IIT) and District Agromet Units (DAMU) at Krishi Vigyan Kendras (KVK) prepare Agromet Advisories on every Tuesday and Friday for the districts under their jurisdiction and for the blocks of the district of their location and communicate to the farmers to take decision on day-to-day agricultural operations through print and electronic media, Door Darshan, radio, internet, SMS, Kisan Portal *etc*. Farmers can also access the weather information including alerts and related agromet advisories relevant to them through the mobile App 'Meghdoot' launched by Ministry of Earth Sciences, and 'Kisan Suvidha' launched by Ministry of Agriculture & Farmers Welfare, Government of India.

9. Crop insurance:

On 18th February 2016, Government of India launched the *Pradhan Mantri Fasal Bima Yojana* (PMFBY) to provide a simple, affordable, and comprehensive crop insurance product to Indian farmers. This scheme covers all non-preventable natural risks from pre-sowing to post-harvest, ensuring financial support in the event of crop failure due to natural calamities, pests, or diseases. As per provisions, the premium share of the farmer is capped at 2% for *kharif* crops, 1.5% for *rabi* crops and 5% for commercial/horticultural crops. Some States have further waived off farmer's share of premium due to which there is very less burden on farmers. The scheme employs remote sensing, smartphones, and drones for rapid crop loss assessment and claim settlements. The National Crop Insurance Portal (NCIP) digitizes processes for seamless farmer-insurer-bank interaction. YES-TECH (Yield Estimation System Based on Technology) ensures remote sensing based accurate yield estimation, while CROPIC (Collection of Real-time photos and Observations of Crops) uses geotagged photos to verify crops for precise damage assessment. This tech integration empowers farmers and streamlines insurance operations.

10. Extension service:

In 2010, the Modified Extension Reforms Scheme was introduced for strengthening extension machinery and utilizing it for synergizing interventions under the umbrella of Agriculture Technology Management Agency (ATMA). Agricultural Technology, including the adoption/promotion of critical inputs, and improved agronomic practices were being disseminated under 17 different schemes of the Department of Agriculture & Cooperation. In 2014, the National Mission on Agricultural Extension and Technology (NMAET) was introduced by amalgamation of these schemes. The aim of the Mission is to restructure and strengthen agricultural extension to enable delivery of appropriate technology and improved agronomic practices to farmers. This is envisaged to be achieved by a judicious mix of extensive physical outreach and interactive methods of information dissemination, use of ICT, popularisation of modern and appropriate technologies, capacity building and institution strengthening to promote mechanisation, availability of quality seeds, plant protection *etc*. and encourage aggregation of Farmers into Interest Groups (FIG) to form Farmer Producer Organisations (FPO).

11. Land rights:

All the above discussed schemes which directly benefit individual farmers, have provision for the participation of tenant farmers up on submission of valid land tenancy agreement.

Table 2. Various schemes/programmes that support CSA strategies

Sl.No.	Strategy	Requirement/constraint	Scheme/Programme
1.	Micro irrigation, solar powered pump	Capital	PMKSY, PM-KUSUM
2.	Irrigation infrastructure, soil reclamation	Land rights	All schemes
3.	Modification in farm operations	Weather advisory	GKMS
4.	Crop insurance	Insurer	PMFBY
5.	Crop diversification	Labour	RKVY
6.	Soil health assessment	Soil testing laboratory	SHC
7.	Organic farming	Knowledge, certification, market	PKVY
8.	Additional cost of cultivation	Credit	DIR, KCC
9.	IPM, INM, IWM, varieties, decisions	Extension service	NMAET
10.	All strategies	Economies of Scale	FPO

National Mission for Sustainable Agriculture (NMSA)

National Mission for Sustainable Agriculture (NMSA) was implemented in 2014-15 for making agriculture more productive, sustainable, remunerative and climate resilient by promoting location specific integrated/composite farming systems; soil and moisture conservation measures; comprehensive soil health management; efficient water management practices and mainstreaming rainfed technologies (GoI, 2014). It aims to promote sustainable agriculture through a series of adaptation measures focusing on 11 key dimensions:

1) Improved crop seeds
2) Livestock and fish cultures
3) Water use efficiency
4) Pest management
5) Improved farm practices
6) Nutrient management
7) Agricultural insurance

8) Credit support

9) Markets

10) Access to information

11) Livelihood diversification

Mission objectives

a) To make agriculture more productive, sustainable, remunerative and climate resilient

b) To conserve natural resources through appropriate soil and moisture conservation measures

c) To adopt comprehensive soil health management practices

d) To optimize utilization of water resources

e) To develop capacity of farmers

f) To pilot model in select blocks for improving productivity of rainfed farming

g) To establish an effective inter and intra Departmental/Ministerial co-ordination

Mission strategies

a) IFS

b) Resource conservation technologies

c) Efficient water utilization through application of technologies

d) Improved agronomic practices

e) Soil-specific crop management

f) INM

g) Involving knowledge institutions and professionals

h) Convergence and leveraging investments from other schemes like MGNREGS, IWMP, RKVY, NFSM, MIDH, NMAE&T *etc*.

i) A consortium approach with SAU, KVK, ICAR Centres, professional organisations *etc*. by the State Government.

j) Engaging NGOs for implementation of cluster/village development plan in case of limited government infrastructure.

k) Strong monitoring and feedback systems. Capacity building of the implementing agencies would be steered by MANAGE.

l) Establishing platform to liaison, review and coordinate implementation

Mission interventions

NMSA has 4 components:

1. Rainfed Area Development (RAD)

- Promotes IFS.
- Supports income generating activities.
- Adopts cluster approach of 100 ha to utilize the potential of created common resources.
- To qualify, a farmer must introduce at least one component/activity to the existing cropping system and water management.
- Support to each farm family up to 2 ha limited to Rs.1.00 lakh.
- FPO can develop the clusters.
- Suitable linkage for agro-processing and marketing will be established for the cluster.

2. Soil Health Management (SHM)

- Promotes location as well as crop specific sustainable soil health management through residue management, organic farming, macro-micro nutrient management, appropriate land use, judicious application of fertilizers and minimizing the soil erosion / degradation.
- provides support to reclamation of problem soils.

3. On Farm Water Management (OFWM)

- Focuses on drip and sprinkler technologies, efficient water application and distribution system, secondary storage and drainage development.
- Micro irrigation support to each farm family up to 5 ha.
- Training on appropriate water management technologies.

4. Climate Change and Sustainable Agriculture: Monitoring, Modeling and Networking (CCSAMMN)

- Supports climate change adaptation/mitigation research/pilot/model projects to develop suitable sustainable management practices and IFS models suitable to specific agro-climatic conditions.
- Supports trainings and demonstrations on various aspects of climate change adaptation in agriculture based on research findings.
- Supports knowledge networking through web portal/information system, studies, documentation, conferences, workshops *etc*., in the area of climate change.
- SAUs, ICAR Institutes, National/International Institutes, KVKs, Private/Public sector R&D organizations are eligible.

Mission Structure

NMSA has three tier structure for planning, implementation and monitoring of various components (Figure 4):

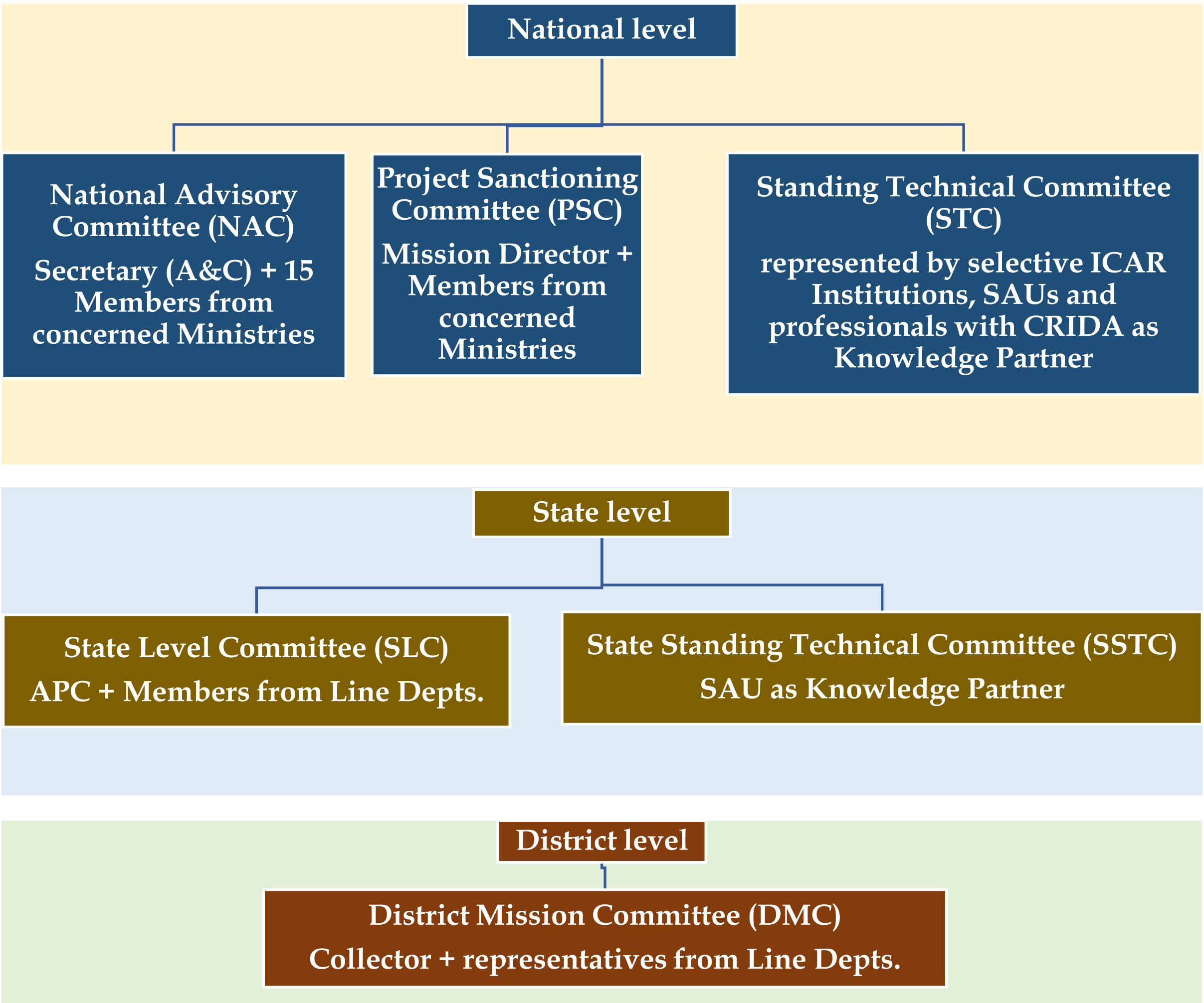

Figure 4. Three tier structure of National Mission for Sustainable Agriculture

Fund flow mechanism

Department of Agriculture & Cooperation, Government of India will communicate tentative annual outlay to each State, who in turn will prepare respective component-wise allocation for Annual Action Plant (AAP). The AAP will be scrutinized by the National level Committees and approved. Consequent to approval of AAP, funds will be released to State Nodal Department or designated implementing agency notified by the State. The State Level Implementing Agency will ensure implementation in a time bound manner in accordance with their approved AAP. Funds will be released in instalments based on physical and financial progress report, submission of utilization certificates and other necessary documents as per provisions of General Financial Rules, specific emergent need *etc*. At least 50% of the allocation is to be utilized for small and marginal farmers of which at least 30% are women beneficiaries/farmers. Further 16% and 8% of the total allocation or in proportion of SC/ST population in the district will be utilized for Special Component Plan (SCP) and Tribal Sub Plan (TSP) respectively (Figure 5).

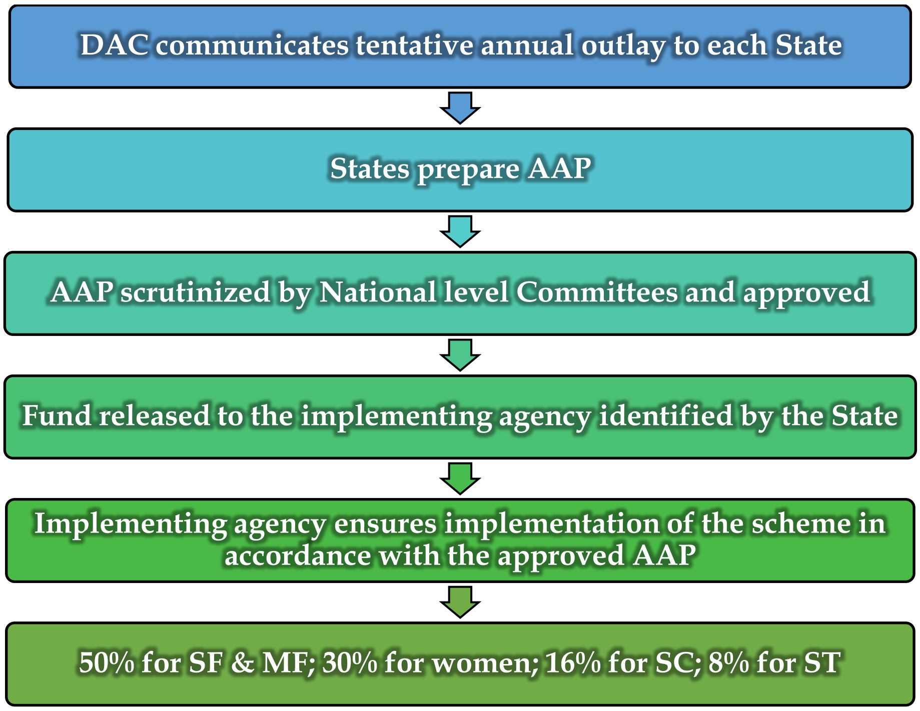

Figure 5. Fund flow mechanism of National Mission for Sustainable Agriculture

Evaluation, Reporting and Impact Assessment

NMSA envisages concerted mechanism for monitoring and evaluation with involvement of all implementing agencies including line departments. A bench marking exercise is taken up before taking up any cluster/project under NMSA. Physical and financial progress under each sub components of NMSA is updated every month and uploaded in the website. ICT will be deployed extensively for ensuring transparency in the implementation process and effective monitoring. NMSA will be evaluated on bi-annual basis through 'third party agency' for assessing efficacy, performance, outcome and shortcomings to facilitate mid course corrections

Activities funded by NMSA

A. Rainfed Area Development (RAD)

Sl.No.	**Item**	**Assistance**
I. IFS		
1.	Cropping system	50% limited to Rs.10,000/ha for inputs up to 2 ha per beneficiary
2.	Horticulture based farming system	50% limited to Rs.25,000/ha for inputs up to 2 ha per beneficiary
3.	Agroforestry	50% limited to Rs.15,000/ha for inputs up to 2 ha per beneficiary
4.	Livestock based farming system (cow / buffalo)	50% limited to Rs.40,000/ ha with 2 milch animals up to 2 ha per beneficiary

Sl.No.	Item	Assistance
5.	Livestock based farming system (small ruminants / poultry)	50% limited to Rs.25,000/ ha with 10 animals / 50 birds up to 2 ha per beneficiary
6.	Fishery based farming system	50% limited to Rs.25,000/ha up to 2 ha per beneficiary
II. Value addition and farm development activities		
1.	Bee keeping	40% limited to Rs.800/colony of 8 frames and Rs.800/hive up to 50 colonies/hive per beneficiary
2.	Silage making	100% limited to Rs.1.25 lakh per farm family
3.	Green house (Tubular structure)	50% limited to Rs.422/sq.m. up to 4,000 sq.m. per beneficiary
4.	Green house (wooden structure)	50% limited to Rs.270/sq.m. up to 20 units of 200 sq.m. each per beneficiary
5.	Green house (bamboo structure)	50% limited to Rs.225/sq.m. up to 20 units of 200 sq.m. each per beneficiary
6.	Green house (plastic tunnels)	50% limited to Rs.30/sq.m. up to 1000 sq.m. per beneficiary
7.	Ponds/tanks	50% limited to Rs.125/cum limited to Rs.75,000 including lining
8.	Lining of ponds/tanks	50% limited to Rs.25,000
9.	Community tanks / ponds / check dam / reservoirs on public land	100% limited to Rs.20 lakh/unit
10.	Tube wells / Bore wells	50% limited to Rs.25,000/unit
11.	Small tank renovation	50% limited to Rs.15,000/unit
12.	Recharge of defunct bore well	50% limited to Rs.5,000/unit
13.	Pipe/pre-cast distribution system	50% limited to Rs.10,000/ha up to 4 ha per beneficiary
14.	Water lifting devices	50% limited to Rs.15,000/electric or diesel unit and Rs.50,000/solar or wind unit
15.	Electricity connectivity to community water sources	50% limited to Rs.1.25 lakh/unit
16.	Land shaping	50% limited to Rs.4,000/ha up to 2 ha
17.	Vegetative fencing	50% limited to Rs.4,000/ha up to 2 ha

Sl.No.	Item	Assistance
18	Contour bunding	50% limited to Rs.5,000/ha up to Rs.10,000/beneficiary
19.	Bench terracing	50% limited to Rs.20,000/ha up to 2 ha/beneficiary
20.	Upper reach gully control bund	50% limited to Rs.3,000/structure up to Rs.15,000 per beneficiary; 100% limited to Rs.3,000/structure up to Rs.1.2 lakh/common property/village
21.	Middle reach gully control bund	50% limited to Rs.12,000/structure upto Rs.24,000 per beneficiary; 100% limited to Rs.12,000/ structure upto Rs.1.2 lakh/common property/village
22.	Lower reach gully control bund	50% limited to Rs.20,000/structure upto Rs.40,000 per beneficiary; 100% limited to Rs.20,000/ structure upto Rs.2.4 lakh/common property/village
23.	Spill ways	50% limited to Rs.40,000/structure upto Rs.40,000 per beneficiary; 100% limited to Rs.40,000/ structure upto Rs.1.6 lakh/common property/village
24.	Organic input production unit	50% limited to Rs.125/cu.ft. up to Rs.50,000/unit for permanent structure and Rs.8,000/unit for HDPE bed
25.	Storage / packaging / processing unit	50% limited to Rs.4,000/sq.m. upto Rs.2.0 lakh per unit
26.	FPO	As per the Ministry guidelines
27.	Reclamation of alkali / saline soil	50% limited to Rs.25,000/ha up to 2 ha
28.	Reclamation of acid soil	50% limited to Rs.3,000/ha up to 2 ha
29.	Capacity building	Rs.10,000/training; Rs.20,000/demonstration

B. On Farm Water Management (OFWM)

Sl.No.	Item	Assistance
1.	Drip irrigation for wide spaced crops	35% for SF & MF; 25% for others limited to Rs.37,200 normative cost/ha up to 5 ha per beneficiary
2.	Drip irrigation for close spaced crops	35% for SF & MF; 25% for others limited to Rs.90,000 normative cost/ha up to 5 ha per beneficiary
3.	Micro sprinkler	35% for SF & MF; 25% for others limited to Rs.58,900 normative cost/ha up to 5 ha per beneficiary

Sl.No.	Item	Assistance
4.	Mini sprinkler	35% for SF & MF; 25% for others limited to Rs.85,200 normative cost/ha up to 5 ha per beneficiary
5.	Portable sprinkler	35% for SF & MF; 25% for others limited to Rs.19,600 normative cost/ha up to 5 ha per beneficiary
6.	Semi-permanent irrigation system	35% for SF & MF; 25% for others limited to Rs.36,600 normative cost/ha up to 5 ha per beneficiary
7.	Rain gun	35% for SF & MF; 25% for others limited to Rs.31,600 normative cost/ha up to 5 ha per beneficiary
8.	Training	Rs.50,000/training
9.	On-farm water distribution system	50% limited to Rs.12,000/ha up to 5 ha per beneficiary
10.	Secondary storage structures	50% limited to Rs.100/cum up to Rs.2.0 lakh per beneficiary
11.	Drainage system in waterlogged farm land	50% limited to Rs.25,000/ha up to Rs.1.0 lakh per beneficiary

C. Soil Health Management

Sl.No.	Item	Assistance
I. Soil Health Component		
1.	New Soil Testing Labs	75% limited to Rs.56 lakh
2.	Strengthening existing STL	75% limited to Rs.30 lakh
3.	Capacity building of staff and farmers	Rs.25,000/training of staff; Rs.10,000/training of farmers; Rs.10,000/demonstration
4.	Creation of data bank for site specific balanced use of fertilizer	Rs.10 lakh per State
5.	Adoption of village by STLs	Rs.20,000/Frontline Field Demonstration (FFD)
6.	Digital district soil maps	Rs.6.0 lakh per district up to Rs.50 lakh per State per annum
7.	Portable soil testing kits	Rs.15,000/kit
8.	Distribution of micronutrient	50% limited to Rs.500/ha up to 2 ha

Sl.No.	Item	Assistance
9.	Strengthening Fertilizer Quality Control Labs	Rs.30 lakh
10.	New FQCL	Rs.75 lakh
II. INM component		
1.	Compost production unit	100% limited to Rs.190 lakh/unit for Government agencies; 33% limited to Rs.63 lakh/unit for individuals/private agencies
2.	Biofertilizer / biopesticide unit	100% limited to Rs.160 lakh/unit for Government agencies; 25% limited to Rs.40 lakh/unit for individuals/private agencies
3.	Biofertilizer and organic fertilizer testing quality control lab	Rs.85 lakh for new; Rs.45 lakh for strengthening
4.	Promotion of organic inputs	50% limited to Rs.5,000/ha up to 2 ha per beneficiary
5.	Organic farming under Participatory Guarantee System	Rs.20,000/ha limited to 2 ha per beneficiary
6.	Organic village adoption	Rs.10 lakh/village
7.	Training and demonstration	Rs.20,000/demonstration

D. CCSAMN

Sl.No.	Item	Assistance
1.	Dissemination of rainfed Technologies by State	Rs.10 crore/Block
2.	Research/model/pilot projects	As per project
3.	Capacity building, training and networking projects	As per project

Conclusion

Many CSA practices / strategies / technologies are identified to overcome the adverse impacts of climate change. But, their adoption by farmers needs external support in the form of capital, land rights, labour, service, market, credit, scale and knowledge. Various programmes / schemes are implemented to support the farmers with the required inputs. These programmes are backed by different levels of policy framework. Devising appropriate policies and programmes are important to adopt CSA strategies to overcome the emerging challenges of climate change.

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AGROFORESTRY BASED CLIMATE SMART STRATEGIES TO ADDRESS CLIMATE CHANGE CAUSES AND CONSEQUENCES

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Introduction

Climate change represents one of the most pressing global challenges of the 21st century, threatening environmental stability, human health, and sustainable economic development. Rising global temperatures have intensified extreme weather events, accelerated sea-level rise, and disrupted ecosystems that provide essential services such as food production, water regulation, and biodiversity conservation (IPCC, 2021). These environmental changes elevate public health risks through heat stress, the spread of vector-borne diseases, and deteriorating air quality, while also imposing substantial economic costs due to infrastructure damage, declining agricultural productivity, and livelihood losses (WHO, 2018; Stern, 2007). If left unmitigated, climate change will exacerbate socio-economic inequalities and undermine progress towards the Sustainable Development Goals (SDGs), necessitating urgent and coordinated mitigation and adaptation efforts.

Climate change refers to statistically significant and persistent changes in the mean state or variability of the climate system, typically observed over periods of three decades or longer. While natural processes contribute to climate variability, the current trend is predominantly driven by anthropogenic activities, particularly the emission of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). CO_2 remains the most significant anthropogenic GHG, accounting for approximately 72% of total emissions and contributing substantially to radiative forcing and global warming. The sharp increase in atmospheric GHG concentrations over the past century is largely attributed to fossil fuel combustion, deforestation, industrialization, and unsustainable agricultural practices.

Agriculture is both a contributor to and a victim of climate change. The sector accounts for a significant share of global GHG emissions (22% of global greenhouse gas emissions which includes from forestry and other land use (Jia et al., 2019) while being highly vulnerable to temperature variability, erratic precipitation, droughts, and floods. In this context, Climate-Smart Agriculture (CSA) has emerged as an integrated framework aimed at achieving three interlinked objectives: sustainably increasing agricultural productivity and incomes, enhancing resilience and adaptive capacity, and reducing or removing GHG emissions where feasible (FAO, 2013; Lipper et al., 2014). CSA promotes innovative land-use practices, resource-efficient technologies, and enabling policy environments to ensure food security while minimizing environmental degradation.

Within the CSA paradigm, agroforestry has gained recognition as a transformative land-use system capable of addressing both the causes and consequences of climate change. Agroforestry integrates trees with crops and/or livestock in spatially or temporally diversified arrangements, thereby enhancing productivity, ecological stability, and livelihood security (Young, 1997). The integration of perennial woody components into agricultural landscapes strengthens carbon sequestration, improves soil structure and fertility, moderates microclimates, and reduces pressure on natural forests. In India, where timber productivity (0.7 m^3 ha^{-1} $year^{-1}$) remains significantly lower than the global average (2.1 m^3 ha^{-1} $year^{-1}$) (Lal, 2011), agroforestry plays a critical role in meeting domestic wood demand and reducing reliance on imports. Approximately 45 million m^3 of India's annual roundwood production is sourced from trees outside forests, underscoring the importance of farm forestry and agroforestry systems (Kant & Nautiyal, 2021).

Agroforestry systems (AFS) provide multiple ecosystem services, including food, fuel, fodder, timber, biodiversity conservation, soil fertility enhancement, erosion control, and watershed protection (Jose, 2009; Sileshi et al., 2007; Tambat et al., 2025). In India, agroforestry contributes nearly half of the country's fuelwood requirements, two-thirds of small timber needs, and a substantial proportion of raw materials for the paper and plywood industries, in addition to supplying 9-11% of green fodder (NRCAF, 2013). Beyond livelihood support, AFS function as effective carbon sinks due to the high biomass accumulation of tree components. However, their carbon sequestration potential varies depending on species composition, system design, management intensity, and site-specific socio-ecological conditions.

Given its multifunctional benefits, agroforestry represents a robust climate-smart strategy that simultaneously mitigates greenhouse gas emissions, enhances adaptive capacity, and strengthens rural livelihoods. Integrating agroforestry more systematically into CSA frameworks offers a practical pathway for achieving climate resilience, sustainable land management, and environmental conservation goals. This paper examines agroforestry-based climate-smart strategies and evaluates their potential to address both the drivers and impacts of climate change, particularly in the context of developing countries such as India.

Public Perceptions of Climate Change

Public perceptions of climate change vary significantly across countries and influence the adoption of climate-smart practices, including agroforestry. A YouGov survey conducted in June 2015 reported relatively high levels of skepticism in the United States (32%) and the United Kingdom (26%), where respondents stated that climate change "is not a serious problem" (Figure 1). In contrast, only 2-4% of respondents in countries such as China, Indonesia, and Malaysia expressed similar views, highlighting notable cross-national differences in climate risk perception.

Recent survey, indicated increasing recognition of climate change as a serious issue in both the US and UK, thus, now in US ad UK GHG emissions are reduced (Jones et al., 2025). Thes, variations and shifts in public opinion underscore the need for context-specific awareness programs, policy measures, and incentive structures to promote climate-smart land-use systems such as agroforestry.

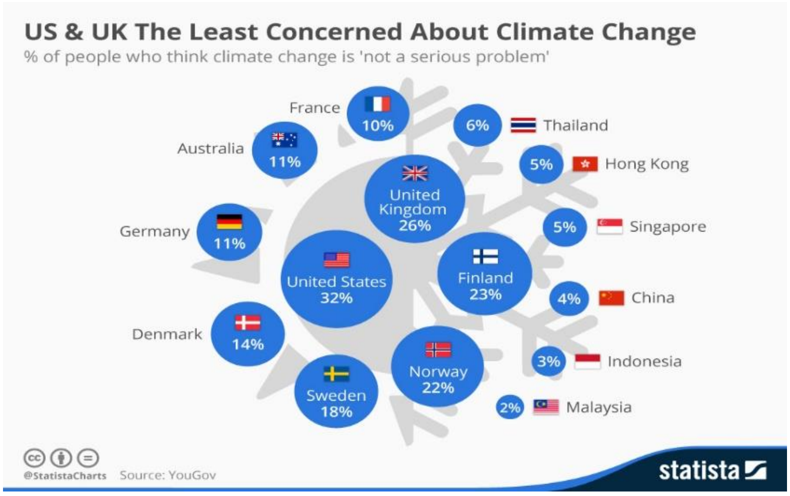

Figure 1. Public Perception about the climate change in selected countries

Causes of climate change

Climate change results from both natural processes and anthropogenic activities. Natural drivers include volcanic eruptions, fluctuations in solar radiation, and long-term variations in Earth's orbital parameters (Milankovitch cycles), which have influenced climatic patterns over geological time scales. However, their contribution to the rapid warming observed since the mid-20th century is minimal (IPCC, 2021). Contemporary climate change is predominantly driven by human activities that increase atmospheric concentrations of greenhouse gases (GHGs), particularly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The combustion of fossil fuels, deforestation, industrial processes, and intensive agricultural practices enhance radiative forcing by trapping heat in the atmosphere, resulting in accelerated global warming (IPCC, 2021; NASA, 2023).

Role of Land-Use Practices in Greenhouse Gas Emissions

Land-use change represents a major source of global GHG emissions. Deforestation for agriculture, logging, and urban expansion releases substantial quantities of CO_2 by removing forest biomass that functions as a critical carbon sink. The carbon stored in vegetation and soils is subsequently emitted into the atmosphere, intensifying the greenhouse effect. Similarly, conversion of wetlands and grasslands disrupts soil carbon stocks and microbial processes, leading to increased emissions of CH_4 and N_2O gases with significantly higher global warming potential than CO_2.

Agriculture is a principal contributor to land-use-related emissions. Application of synthetic fertilizers and manure elevates N_2O emissions, while enteric fermentation from ruminant livestock is a major source of CH_4. Unsustainable practices such as intensive tillage, monocropping, and excessive agrochemical use degrade soil organic matter, thereby reducing the soil's capacity to sequester carbon. Expansion of cropland often involves clearing natural vegetation, compounding carbon losses. Urban land-use change further reduces vegetative cover and increases energy demand, indirectly contributing to GHG emissions.

Addressing these challenges requires sustainable land management strategies that enhance carbon sinks while maintaining productivity. Practices such as agroforestry, reforestation, conservation agriculture, and ecosystem restoration can significantly reduce emissions and strengthen resilience to climate variability.

Global Greenhouse Gas Emissions

Global GHG emissions remain unevenly distributed across countries. According to the Global Carbon Project (2023), China was the largest emitter in 2022, contributing approximately 11.5 billion tons (Bt) of CO_2. The United States followed with around 5 Bt, while India emitted approximately 2.5 Bt. Germany and Brazil each emitted less than 1 Bt. These disparities underscore the need for both global cooperation and nationally tailored mitigation strategies, including sustainable land-use interventions such as agroforestry.

Consequences of Climate Change

Climate change exerts profound impacts on ecosystems, human societies, and economies through interconnected physical, biological, and socio-economic pathways. Rising global temperatures have increased the frequency, duration, and intensity of heat waves, contributing to elevated mortality and morbidity, particularly among vulnerable populations. Accelerated melting of glaciers and polar ice caps has intensified sea-level rise, placing low-lying coastal regions and small island states at heightened risk of flooding, erosion, and displacement.

Climate change also amplifies extreme weather events, including hurricanes, floods, droughts, and wildfires, resulting in large-scale damage to infrastructure, livelihoods, and natural ecosystems. Increased atmospheric CO_2 concentrations have led to greater oceanic absorption of carbon, causing ocean acidification that threatens coral reefs and calcifying marine organisms. Furthermore, shifts in temperature and precipitation regimes disrupt ecological balance, accelerate biodiversity loss, reduce agricultural productivity, and exacerbate food and water insecurity. Health impacts are similarly significant, including increased air pollution, expanded distribution of vector-borne diseases, and psychological stress associated with climate-induced displacement and disasters.

Projected Impacts on Indian Agriculture

Indian agriculture is particularly vulnerable to climate variability due to its dependence on monsoon rainfall and the dominance of smallholder farming systems. Projections indicate substantial adverse impacts on cereal production and livestock systems by the end of the 21st century. Studies suggest that cereal productivity may decline by 10–40% under future climate scenarios characterized by rising temperatures and altered precipitation patterns.

Yield reductions are expected to be more severe during the rabi (winter) season, with wheat identified as highly temperature-sensitive; an increase of 1°C could reduce national wheat production by approximately 4–5 million tonnes. However, adaptive measures such as timely sowing and improved agronomic management could potentially limit these losses to 1–2 million tonnes.

Livestock systems are also at risk, as rising temperatures increase heat stress, thereby elevating water, shelter, and energy requirements. Heat stress negatively affects animal health, reproduction, and milk productivity, compounding risks to rural livelihoods and national food security. Collectively, these impacts pose significant challenges to the sustainability of India's agricultural sector.

Projected Crop-wise Yield Changes

Climate simulations indicate heterogeneous impacts across crops and time horizons. According to Birthal et al. (2014), yield declines are projected to intensify progressively by 2035, 2065, and 2100 under scenarios of maximum temperature and rainfall change. Higher temperatures are expected to shorten crop growth duration and increase thermal stress, while erratic rainfall patterns may reduce soil moisture availability and increase the frequency of droughts and floods.

By 2100, maize, among the least affected rainy-season crops, is projected to experience yield reductions of approximately 4.2%, compared to a 1.2% decline by 2035. Pigeon pea may face more substantial losses, with yields declining by 10.1% in the near term and up to 23.3% by the end of the century. In the rabi season, chickpea appears highly vulnerable, with projected reductions of 10.0% by 2035 and 26.2% by 2100. In contrast, rapeseed–mustard shows marginal positive yield responses (approximately 0.5–0.7%) across projected periods, reflecting crop-specific climatic sensitivities.

These projections highlight the urgency of developing and scaling climate-resilient crop varieties, improving water management, and adopting adaptive agronomic practices to safeguard food security and farm incomes.

Climate Change Mitigation and Adaptation Framework

Climate Change Mitigation

Climate change mitigation addresses the root causes of global warming by reducing atmospheric concentrations of greenhouse gases. In land-use and agricultural systems, mitigation operates through two principal pathways: emission reduction and enhancement of carbon sinks.

Emission reduction strategies aim to minimize GHG releases from deforestation, land-use conversion, soil degradation, and unsustainable farming practices. Key measures include improving energy efficiency, reducing methane emissions from livestock, optimizing fertilizer use to limit nitrous oxide, and preventing vegetation clearance.

Carbon sequestration complements these efforts by capturing and storing atmospheric carbon dioxide in biomass and soils. Forests, agroforestry systems, and well-managed agricultural lands function as critical carbon sinks. Afforestation, reforestation, ecological restoration, and tree-based farming systems enhance biomass accumulation and soil organic carbon stocks, generating mitigation benefits alongside biodiversity conservation and livelihood support.

Climate Change Adaptation

Climate change adaptation involves adjustments in ecological, agricultural, and socio-economic systems to reduce vulnerability and enhance resilience to climatic variability. In land-use systems, adaptation focuses on maintaining productivity and ecosystem stability under rising temperatures, erratic rainfall, and extreme weather events.

Strengthening soil resilience through improved organic matter, soil structure, and nutrient cycling enhances water retention, reduces erosion, and buffers crops against drought and heat stress. Diversified and integrated farming systems, crop diversification, and resource-efficient land management further distribute production risks and sustain output under climate uncertainty. Enhancing net primary productivity (NPP) also contributes to long-term resilience by supporting biomass accumulation, ecosystem functioning, and food security.

Adaptation remains essential even under stringent mitigation scenarios, as past emissions have already locked in a degree of warming (IPCC, 2022). However, adaptation has limits, particularly where climate impacts exceed ecological or socio-economic coping capacity. Priority sectors include water resources, agriculture, infrastructure, health, energy, and disaster risk management. Despite its importance, adaptation financing especially in developing countries remains insufficient (World Bank, 2010; UNEP, 2021).

Integrated Strategies to Combat Climate Change

Effective climate action requires a complementary approach combining mitigation and adaptation. Mitigation strategies include transitioning to renewable energy sources, improving energy efficiency, promoting sustainable transportation, implementing carbon capture and storage technologies, and enhancing forest-based carbon sequestration (IPCC, 2022; UNFCCC, 2021). In agriculture, climate-smart practices such as agroforestry, conservation farming, and precision nutrient management reduce emissions while improving resilience (FAO, 2018).

Adaptation strategies encompass technological measures (e.g., climate-resilient infrastructure), administrative interventions (e.g., land-use planning and building codes), and behavioral changes (e.g., disaster preparedness and water conservation) (IPCC, 2022; UNDRR, 2019).

At the individual level, actions such as energy conservation, sustainable transport choices, reduced meat consumption, waste minimization, and tree planting complement systemic efforts (EPA, 2021; WWF, 2020). While policy and institutional frameworks are central, widespread behavioral change strengthens overall mitigation outcomes.

Ecosystem-Based Adaptation (EBA)

Ecosystem-based adaptation utilizes natural systems as “green infrastructure” to enhance resilience to climate impacts. By conserving and restoring wetlands, forests, grasslands, and coastal ecosystems, EBA reduces vulnerability to floods, storm surges, droughts, and erosion. Beyond risk reduction, EBA provides co-benefits including carbon sequestration, water purification, biodiversity conservation, and livelihood enhancement (Munang et al., 2013; UNEP, 2021).

By integrating ecological processes with land-use planning, EBA offers a multifunctional and cost-effective pathway for achieving climate resilience while advancing environmental sustainability.

Regional Examples of Climate Change Adaptation

Countries across Africa, Asia & Oceania, and the Americas have implemented a variety of climate change adaptation strategies tailored to their local environmental challenges. In Africa, Egypt addresses sea-level rise through national action plans, environmental impact assessments, and coastal infrastructure protection, while Sudan combats drought using traditional rainwater harvesting, shelter-belts, and livestock monitoring. Botswana supports subsistence farmers by providing post-drought re-employment programs and crop production assistance (UNFCCC, 2020).

In Asia & Oceania, Bangladesh incorporates climate considerations into water management, builds flow regulators, and cultivates alternative crops to adapt to sea-level rise and saltwater intrusion. The Philippines addresses droughts and floods by shifting to drought-resistant crops, installing shallow tube wells, and constructing fire lines; for storm surges and sea-level rise, it builds cyclone-resistant housing, enhances shoreline defence capacity, and restores mangrove forests (World Bank, 2018).

In the Americas, Canadian Inuit communities adapt to permafrost melt and changing ice cover by altering hunting practices and using GPS navigation, while cities like Toronto implement heat-health alert plans with cooling centers and hotlines. In the United States, programs such as New Jersey's Coastal Blue Acres and Texas's rolling easements encourage proactive land-use planning for sea-level rise. Farmers in Mexico and Argentina adapt to drought by adjusting planting dates, cultivating drought-tolerant crops, accumulating commodity stocks, and establishing crop insurance or financial pools (IPCC, 2022). These region-specific strategies demonstrate the diversity and context-specific nature of adaptation measures worldwide.

India's Climate Commitments

Following the Paris Agreement, the Prime Minister of India announced a set of ambitious climate pledges aimed at mitigating greenhouse gas emissions and promoting sustainable development. India plans to increase its non-fossil fuel energy capacity to 500 GW by 2030 and to meet 50% of its energy requirements from renewable sources by the same year, highlighting a strong commitment to clean energy transition (Government of India, 2021). In addition, India aims to expand its forest cover to absorb an estimated 2.5 billion tonnes of CO_2, while reducing total projected carbon emissions by one billion tonnes by 2030. The long-term goal is to achieve net-zero carbon emissions by 2070, reflecting India's commitment to balancing economic growth with environmental sustainability and global climate objectives (Ministry of Environment, Forest and Climate Change, 2021)

Key Issues in Climate Change Mitigation

Energy production and consumption remain the dominant sources of global greenhouse gas emissions. Fossil fuel combustion for electricity, heat, and transport is the primary contributor, releasing substantial amounts of carbon dioxide, methane, and other GHGs into the atmosphere. Although natural carbon sinks such as oceans and terrestrial ecosystems absorb a portion of these emissions, their capacity is limited and insufficient to offset current emission levels.

Mitigation opportunities exist at multiple decision points across the energy system, from production to end-use consumption. Transitioning from fossil fuels to renewable and low-carbon energy sources, improving energy efficiency in industrial and household sectors, and deploying carbon capture and storage (CCS) technologies are critical interventions. Strategic investments in research, development, and innovation across these nodes can significantly reduce emissions while maintaining energy security and supporting economic growth (IEA, 2021; IPCC, 2022).

Reforestation and ecosystem restoration further complement energy-sector mitigation by strengthening natural carbon sinks. The importance of tree-based climate solutions was notably emphasized by Nobel Laureate Dr. Wangari Maathai, founder of the Green Belt Movement (1976), which promoted large-scale tree planting, environmental conservation, and community empowerment. Such initiatives underscore the vital role of biological carbon sequestration in comprehensive climate mitigation strategies.

Policy Options for Reducing Greenhouse Gas Emissions

Reducing greenhouse gas emissions requires a mix of policy instruments that provide economic and regulatory incentives for low-carbon behavior. Market-based approaches include carbon taxes, where a fixed fee is levied per tonne of CO_2 equivalent, as exemplified by Australia's AUD 23/tCO_2e tax and emissions trading schemes (ETS), which cap total emissions and allow permit trading, as implemented in the European Union covering ~ 40% of regional emitters (World Bank, 2021; European Commission, 2020). Regulatory measures set mandatory standards, such as energy-efficient building codes, vehicle emission limits, or electricity generation controls. Subsidies further incentivize low-carbon practices by supporting renewable energy adoption, energy-efficient technologies, and research and development in emission reduction innovations. When applied in combination, these instruments create complementary pathways for sustained GHG reduction.

Carbon Pricing in Climate Mitigation

Carbon pricing is a critical strategy for internalizing the environmental costs of emissions, creating economic incentives for producers and consumers to adopt low-emission technologies and practices. Economic modeling suggests that achieving the European Union's 2°C warming target may require carbon prices of ~100 US$/t$CO_2$eq by 2030, substantially above the current European Union's - emission technologies price of ~25 US$/t$CO_2$eq (World Bank, 2021). Beyond emissions reduction, carbon pricing yields co-benefits including improved air quality, public health gains, increased investment in renewable energy, and accelerated innovation in clean technologies (Stiglitz et al., 2017).

Technology-Driven Mitigation

Effective mitigation policies aim to reduce GHG emissions while minimizing administrative and compliance costs. Well-designed policies consider redistribution effects, balancing sectoral gains and losses to ensure net societal benefits (IPCC, 2022). Long-term stabilization of atmospheric GHGs depends on a portfolio of both current and emerging technologies. Incentives for research, development, deployment, and diffusion are essential to ensure timely adoption at scales required to meet global climate targets (UNEP, 2021).

Carbon Capture and Storage (CCS) exemplify technology-driven mitigation by combining biological and geological approaches. Industrial CO_2 is captured, compressed, and transported to secure storage sites, such as deep saline aquifers, depleted oil and gas reservoirs, unmoveable coal seams, or porous rock formations sealed by caprock. Complementary biological sequestration—through forests, crops, and biomass-enhances carbon uptake in soils and vegetation, contributing to net negative emissions (IPCC, 2022; Global CCS Institute, 2021).

Collaboration, Policy, and Monitoring

Robust climate action depends on collaboration across national and international platforms. Knowledge sharing, financial support, and technology transfer from developed to developing nations are critical to support mitigation and adaptation initiatives (UNFCCC, 2021). Policy advocacy engages governments, research institutions, and communities to coordinate climate solutions (IPCC, 2022). Monitoring mechanisms, including environmental impact assessments and regular performance reviews, ensure compliance with regulations, assess intervention effectiveness, and enable adaptive management for improved accountability and efficiency (Government of India, 1986).

Land Management Strategies for Addressing Climate Change

Land management strategies for climate change encompass mitigation and adaptation, highlighting the dual role of terrestrial ecosystems in reducing greenhouse gas concentrations while enhancing resilience to climate variability.

Carbon Sequestration Potential of Land-Use Systems

Land-use and management interventions offer substantial carbon sequestration potential, complementing energy and technological mitigation strategies. By 2040, agroforestry is projected to provide the highest sequestration (~580 Mt C y^{-1}), owing to the combination of tree planting and agricultural productivity. Grazing management follows (~330 Mt C y^{-1}) through rotational grazing, pasture improvement, and soil carbon enhancement. Forest and cropland management contribute moderately (~190 Mt C y^{-1} and ~130 Mt C y^{-1}, respectively), while wetlands, degraded land restoration, and rice management offer smaller yet complementary contributions (Nair et al., 2021; FAO, 2021). These findings underscore the central role of sustainable land management in achieving global carbon reduction goals.

Soil Organic Carbon Across Land-Use Systems

Soil organic carbon (SOC) stocks and distribution vary widely across land-use systems (Saha et al., 2010). Forests maintain high total SOC (~176.6 Mg C ha^{-1}) with dominant labile fractions (250–2000 µm and 53–250 µm), reflecting continuous organic inputs. Rice-paddy systems record the highest total SOC (~220 Mg C ha^{-1}), enriched in the <53 µm fraction, promoting long-term carbon stabilization under anaerobic conditions. Other system - coconut, home gardens, rubber plantations, show lower SOC, indicating depletion following forest conversion. Overall, SOC losses occur with land-use change, while wetland rice systems partially offset these losses through fine-fraction carbon stabilization.

Agroforestry Systems (AFS)

Agroforestry delivers multiple environmental, economic, and social benefits, including food, fuelwood, fodder, timber, erosion control, watershed protection, soil fertility enhancement, and biodiversity conservation (Jose, 2009; Sileshi et al., 2007). In India, agroforestry meets roughly half of fuelwood demand, two-thirds of small timber needs, 70-80% of plywood wood, 60% of paper pulp raw material, and 9–11% of livestock fodder (NRCAF, 2013; Deeksha raj et al., 2025). Trees in AFS serve as significant carbon sinks due to rapid growth and high biomass accumulation. Co-benefits include enhanced food security, diversified incomes, secured land tenure, and restoration of degraded lands. Carbon sequestration potential varies with species, system design, and management, emphasizing the need for site-specific planning and supportive policies.

Land use and management strategies offer significant potential for carbon sequestration, contributing to climate change mitigation alongside energy and technological interventions. By 2040, agroforestry is projected to provide the highest sequestration potential, capturing approximately 580 Mt C y^{-1}, due to its combination of tree planting and agricultural productivity (Figure 2). Grazing management follows, with an estimated 330 Mt C y^{-1}, achieved through improved pasture management, rotational grazing, and soil carbon enhancement. Forest management and cropland management offer moderate contributions, with potential sequestration of around 190 Mt C y^{-1} and 130 Mt C y^{-1}, respectively. Other measures such as wetland restoration, restoration of degraded lands, and rice management contribute comparatively smaller amounts but still play a complementary role in integrated land-based mitigation strategies (Nair et al., 2021; FAO, 2021). Collectively, these practices underscore the critical role of sustainable land management in achieving global carbon reduction goals.

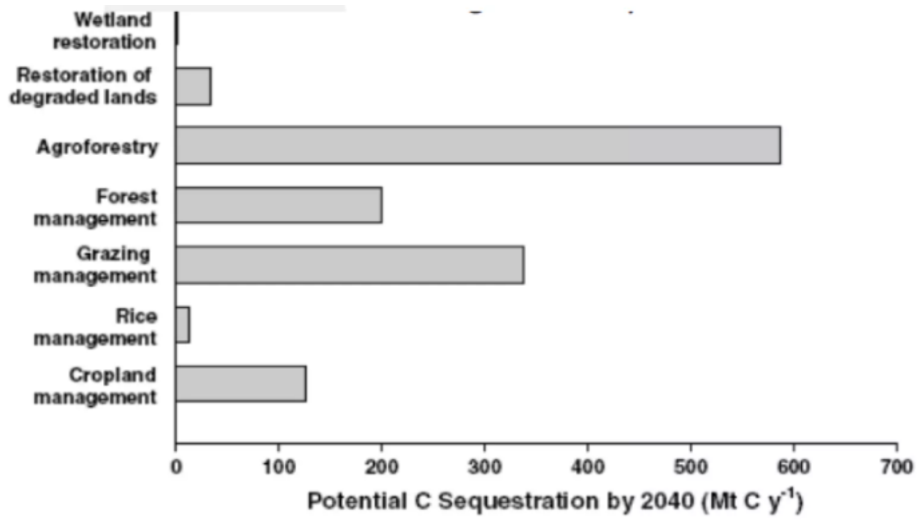

Figure 2. Carbon sequestration potential of various land use and management options (Source: Adopted from IPCC 2000)

These patterns indicate that forest maturity, structural complexity, and species diversity drive carbon storage. While natural forests remain top reservoirs, well-managed agroforestry provides significant sequestration while supporting livelihoods and productivity.

Grazing Land and Dryland Management

Grazing lands (~3.4 billion ha globally) can act as carbon sinks when managed sustainably via rotational grazing, optimized stocking, and fire management. Improved vegetation cover and root biomass enhance SOC, while also increasing soil fertility, water retention, and resilience to climate extremes.

Drylands (~40% of global land) are vulnerable to degradation but offer large-scale mitigation potential. Restoration programs like Africa's Great Green Wall and China's Three-North Shelter Forest Program employ afforestation, agroforestry, and ecosystem restoration to increase carbon storage in biomass and soils. While sequestration rates are lower than in humid ecosystems, the extensive area makes drylands a crucial component of landscape-level climate mitigation.

Conceptual Framework for Agroforestry in Climate Change Mitigation and Adaptation

Agroforestry, a cornerstone of Climate-Smart Agriculture, integrates trees and shrubs with crops and livestock to enhance farm resilience to climate extremes, including droughts, floods, and heatwaves. Simultaneously, it mitigates greenhouse gas emissions by sequestering CO_2 in tree biomass and soil organic carbon (Nair et al., 2021; Verchot et al., 2007). Agroforestry improves nutrient cycling, reduces erosion, optimizes land and water use, and diversifies income, reducing dependence on external inputs while supporting long-term productivity. Its multifunctionality is particularly relevant for smallholder farmers in tropical regions, who are among the most climate-vulnerable (Table 1).

Table 1: Agroforestry as tool for agriculture models in mitigation and adaptation of climate change

Climate change activity*	Major climate change functions	Agroforestry functions that support climate change mitigation and adaptation
Mitigation		
Activities that reduce GHGs in the atmosphere or enhance the storage of GHGs stored in ecosystems	Sequester carbon	Accumulate C in woody biomass Accumulate C in soil
	Reduce GHG emissions	Reduce fossil fuel consumption: Reduce equipment runs in areas with trees Reduce farmstead heating and cooling Reduce CO_2 emissions from farmstead structures Reduce N_2O emissions: By greater nutrient uptake through plant diversity By reduced N fertilizer application in tree component Enhance forage quality, thereby reducing CH_4
Adaptation		
Actions to reduce or eliminate the negative effects of climate change or take advantage of the positive effects	Reduce threats and enhance resilience	Alter microclimate to reduce impact of extreme weather events on crop production Alter microclimate to maintain quality and quantity of forage production Alter microclimate to reduce livestock stress Provide greater habitat diversity to support organisms (e.g., native pollinators, beneficial insects) Provide greater structural and functional diversity to maintain and protect natural resource services Create diversified production opportunities to reduce risk under fluctuating climate
	Allow species to migrate to more favorable conditions	Provide travel corridors for species migration

* Definitions from Ontario Ministry of Natural Resources, http://www.mnr.gov.on.ca/en/Business/ClimateChange/2ColumnSubPage/STDPROD_090121.html.

Notes: GHG = greenhouse gas. C = carbon. CO_2 = carbon dioxide. N_2O = nitrous oxide. CH_4 = methane.

(**Source:** Adopted from Schoeneberger et al., 2012)

India’s agroforestry heritage-encompassing scattered multipurpose trees, community forestry, ethno-forestry, and farmer-managed natural regeneration demonstrates substantial mitigation potential, with carbon sequestration rates ranging from 19.6 Mg C ha^{-1} yr^{-1} in Uttar Pradesh to 23.5–47.4 Mg C ha^{-1} yr^{-1} in arid Rajasthan (Pandey, 2002). Agroforestry buffers farms against climate shocks by enhancing microclimates, improving water-use efficiency, and providing year-round products such as fruits, fodder, and fuelwood.

Mitigation Functions

Agroforestry sequesters carbon in both biomass and soils while reducing emissions through improved nitrogen use efficiency and enhanced forage quality, which lowers N_2O and CH_4 emissions (Thevasthasan et al., 2004; Allen et al., 2009). Carbon stocks follow a clear gradient: primary forests (~300 Mg C ha^{-1}) > managed forests (≤200 Mg C ha^{-1}) > agroforestry systems (50–150 Mg C ha^{-1}) > croplands/pastures (<50 Mg C ha^{-1}) (Verchot et al., 2011). Agroforestry thus provides an intermediate yet substantial carbon reservoir, balancing productivity with ecosystem service provision (Figure 3).

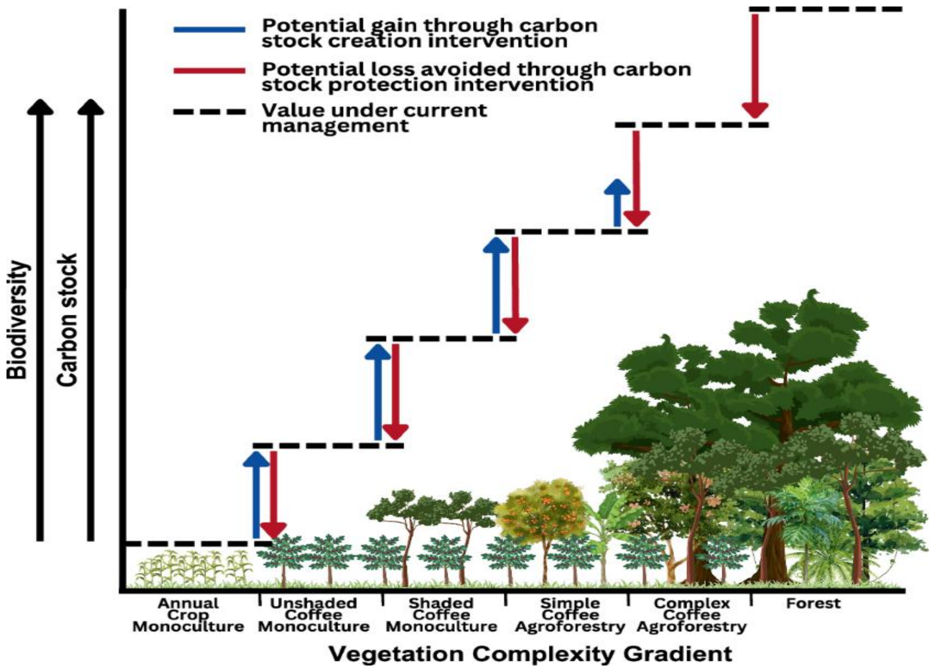

Figure 3. Relationship between Vegetation Complexity and Carbon Stock (Source: Adopted from Verchot et al., 2011)

Green House Gases (GHG) Dynamics

Studies in tropical landscapes reveal that high-input croplands emit the most N_2O, while forests act as CH_4 sinks with low N_2O emissions (Table 2). Agroforestry systems occupy an intermediate position, demonstrating reduced N_2O emissions and moderate CH_4 uptake, highlighting their role in mitigating potent greenhouse gases while sustaining productive land use (Mutuo et al., 2005).

Table 2. Average fluxes of N_2 and CH_4 in different land systems in Sumatra, Indonesia

Land use system	N_2O (µg N m^{-2} h^{-1})	CH_4 (µg CH_4 m^{-2} h^{-1})
High Input cropping	31.2	15.2
Low input cropping	15.6	-17.2
Cassava/Imperata	7.1	-14.2
Multistrata Agroforestry	5.8	-23.3
Rubber Agroforestry	3.3	-27.5
Forest	5.0	-31.0

(**Source:** Adopted from Mutuo et al., 2005)

Adaptation Functions

Agroforestry enhances microclimatic stability, soil and water conservation, and resilience against climatic variability. Trees provide shade, reduce wind speed, prevent soil erosion, and improve water infiltration and storage, which is critical during droughts. Diversified production within these systems buffers against crop failure and market shocks, while multiple income streams from timber, fruits, fodder, and medicinal products strengthen livelihood security. Collectively, agroforestry enhances adaptive capacity, food security, and long-term resilience of smallholder farming systems under climate change.

Classification of Agroforestry Systems and Associated Management Factors

Agroforestry systems are classified based on structural and functional attributes, as well as management factors that govern productivity, soil conservation, and ecosystem services (Figure 4) (Nair, 2012). Common system types include:

Alley Cropping Systems

Practiced in tropical and temperate regions, these systems integrate woody perennials with annual crops. Key management factors include residue management, nutrient cycling, plant diversity, species mixture, erosion control, and reduced tillage. These interactions enhance soil fertility, reduce degradation, and optimize land productivity.

Multi-strata Systems

Examples include shaded coffee plantations and homegardens. Characterized by vertical stratification and high structural complexity, management emphasizes species diversity, nutrient cycling, residue management, erosion control, and reduced tillage, mimicking forest ecosystems while providing ecological and livelihood benefits.

Protective Systems

Riparian buffers, windbreaks, and live fences focus on safeguarding soil and water resources. Management prioritizes erosion control, nutrient cycling, and residue management, with plant diversity supporting stability and functionality.

Silvopastoral Systems

Integrating trees with grazing or browsing livestock, these systems are managed through species mixture, reduced tillage, nutrient cycling, and erosion control to balance forage production, soil protection, and nutrient redistribution.

Woodlots and Fodder Banks

These simpler systems emphasize soil fertility and biomass production, relying primarily on nutrient cycling and erosion control.

Agroforestry Interventions and Adoption

Brown et al. (2018) classify agroforestry interventions based on mechanisms of action, including farmer capacity development, material support, financial incentives, community advocacy, market linkage facilitation, and institutional/policy reforms. Effective scaling requires integrating technical, social, financial, and policy measures:

- **Capacity development:** Training, extension services, and participatory learning equip farmers with propagation and management skills.
- **Material support:** Ensures access to quality seedlings and planting material.
- **Incentives:** Payments for ecosystem services and premiums for certified products encourage adoption.
- **Community advocacy:** Collective action through outreach and events strengthens adoption norms.
- **Market linkages:** Connect producers to buyers, improving economic viability.
- **Institutional reforms:** Secure land tenure and enabling policies promote long-term investment.

Together, these strategies enhance productivity, adoption, and sustainability while maximizing agroforestry's contributions to climate mitigation, adaptation, and rural livelihoods.

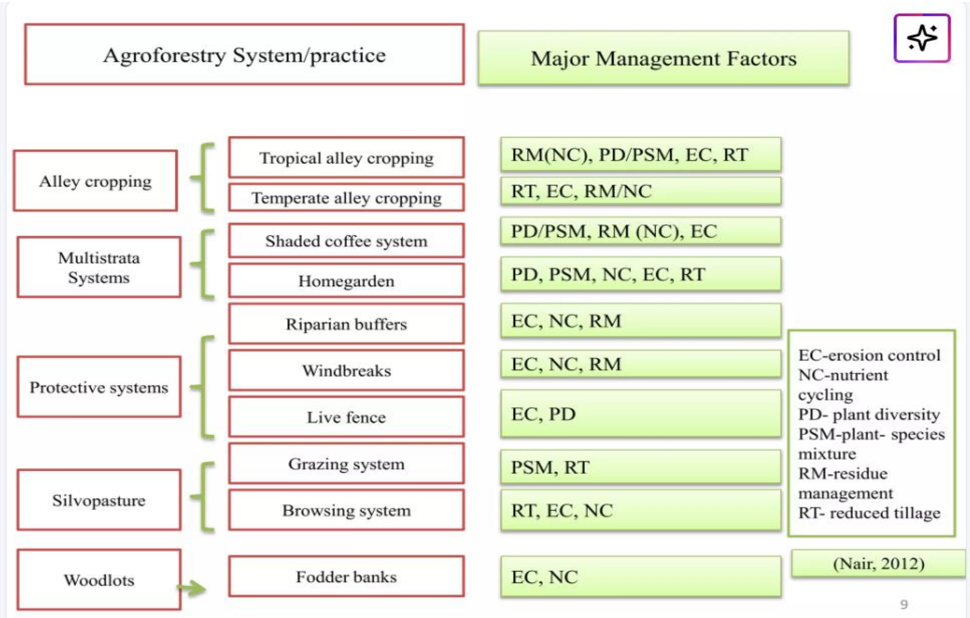

Figure 4. Classification of Agroforestry Systems and Associated Management Factors (Source: Adopted from Nair 2012)

Agroforestry and Carbon Sequestration

Agroforestry systems have greater carbon sequestration potential than croplands, pastures, or natural grasslands (Young, 1997). Tree integration improves soil properties and contributes to net carbon gains, while reducing soil-derived GHG emissions. In India, diverse systems are practiced across climatic regions (Table 3):

- Shifting cultivation, homegardens, plantation-based cropping: Predominant in humid tropics, Kerala, and Andaman & Nicobar Islands.
- Tree-spice gardens and crop combinations: Coastal Karnataka and southern states.
- Boundary plantations: Uttar Pradesh, Gujarat, Haryana, Bihar, and Odisha.
- Woodlots and shelterbelts: Hilly and wind-prone regions.
- Scattered trees on farmlands: Arid and semi-arid regions.
- Agro-silvo-pastoral systems: Semi-arid zones.

Total carbon sequestration potential (CSP) across 15 Indian states ranges from 0.032 to 1.849 million t C per state, totaling 7.230 million t C (Table 4). Monocropping of trees and crops sequesters 40–84% less carbon than agri-silviculture, emphasizing the advantages of integrated systems.

Globally, SOC sequestration in agroforestry systems ranges from 12 to 228 Mg ha^{-1}, with median values around 95 Mg ha^{-1}. Mixed-species stands in Puerto Rico (15.21 Mg C ha^{-1} yr^{-1}) and cacao-based systems in Costa Rica (12.04 Mg C ha^{-1} yr^{-1}) demonstrate the high potential of multi-strata systems in humid tropics. Indian woodlots (Kerala) sequester 11.08 Mg C ha^{-1} yr^{-1}, while silvopastoral systems record 6.55 Mg C ha^{-1} yr^{-1}. Arid systems, such as Mali's fodder banks and live fences, show lower rates (0.29–0.59 Mg C ha^{-1} yr^{-1}), highlighting climatic limitations on biomass accumulation.

Table 3: The carbon absorption capacity of different agroforestry models

Region	Agroforestry model	Carbon storage capacity	Reference
Semi-arid region	Agri-silviculture system	26.0 tC/ha	NRCAF(2005)
Himachal Pradesh	Silvopasture	31.71 tC/ha	Verma et al., (2008)
Central India	Block Plantation	24.1-31.1 tC/ha	Swamy et al., (2003)
Himachal Pradesh	Agrisilviculture	13.37 tC/ha	Verma et al., (2008)
Kerala	Silvipastoral	6.55 Mg/ha/yr	Kumar et al.,(2002)
Himachal Pradesh	Agri-Horticulture	12.28 tC/ha	Vermak et al., (2008)
Sumantra	Indonesia Home-gardens	8.00Mg/ha/yr	Roshetko et al., (2002)

(**Source:** Adopted from Rohit Kumar et al., 2019)

Table 4: Agroforestry area, and carbon sequestration potential (CSP) in different states

States	Agroforestry area (million /ha)	Total CSP (million tones/ha)
Uttar Pradesh	1.971	0.472
Gujarat	1.089	0.119
Bihar	0.795	0.199
West Bengal	0.405	0.050
Rajasthan	2.051	0.482
Punjab	0.420	0.108
Haryana	0.352	0.032
Himachal Pradesh	0.327	0.309
Maharashtra	1.916	1.849
Madhya Pradesh	1.346	0.248
Karnataka	1.293	0.455
Tamil Nadu	0.688	0.412
Orissa	0.804	0.499
Chhattisgarh	0.601	1.140
Andhra Pradesh & Telangana	1.673	0.853
Total/Mean	**15.73**	**7.230**

(**Source:** Adopted from Rohit Kumar et al., 2019)

Carbon Storage Potential in Agroforestry Systems

Agroforestry represents a particularly effective land-use strategy for carbon sequestration in both grazing lands and drylands. Estimates of SOC sequestration in agroforestry systems range from 12 to 228 Mg ha^{-1}, with a median value of approximately 95 Mg ha^{-1}. Converting degraded or unproductive lands into agroforestry systems can therefore generate substantial carbon gains annually, while also delivering co-benefits such as diversified income sources, improved soil health, and enhanced ecosystem services.

Mean Vegetation Carbon Sequestration Potential of Agroforestry Systems: Mean vegetation carbon sequestration potential varies widely among agroforestry systems and across climatic regions, as synthesized from multiple studies. The highest sequestration rate is reported for mixed-species agroforestry stands in Puerto Rico, reaching 15.21 Mg C ha^{-1} yr^{-1}, reflecting favorable climatic conditions and high biomass productivity. Similarly high values are observed in cacao-based agroforestry systems in Costa Rica, with a mean sequestration rate of 12.04 Mg C ha⁻¹ yr⁻¹, underscoring the effectiveness of multi-strata perennial systems in humid tropical environments.

Agroforestry systems in India also demonstrate substantial carbon sequestration potential. Agroforestry woodlots in Kerala sequester an average of 11.08 Mg C ha^{-1} yr^{-1}, while silvopastoral systems in the same region record 6.55 Mg C ha^{-1} yr^{-1}, highlighting the role of tree integration in enhancing biomass accumulation even in production-oriented landscapes.

In contrast, agroforestry systems located in arid and semi-arid regions exhibit markedly lower sequestration rates. Fodder banks and live fences in Mali sequester only 0.29 and 0.59 Mg C ha^{-1} yr^{-1}, respectively, reflecting climatic limitations on plant growth and biomass production.

Overall, the compiled data from studies such as Takimoto et al. (2008) and Parrotta (1999) illustrate the strong influence of climate, species composition, and management intensity on vegetation carbon sequestration. These findings emphasize that the carbon mitigation potential of agroforestry systems is highly context-dependent, reinforcing the need for site-specific system design and management to maximize climate change mitigation benefits.

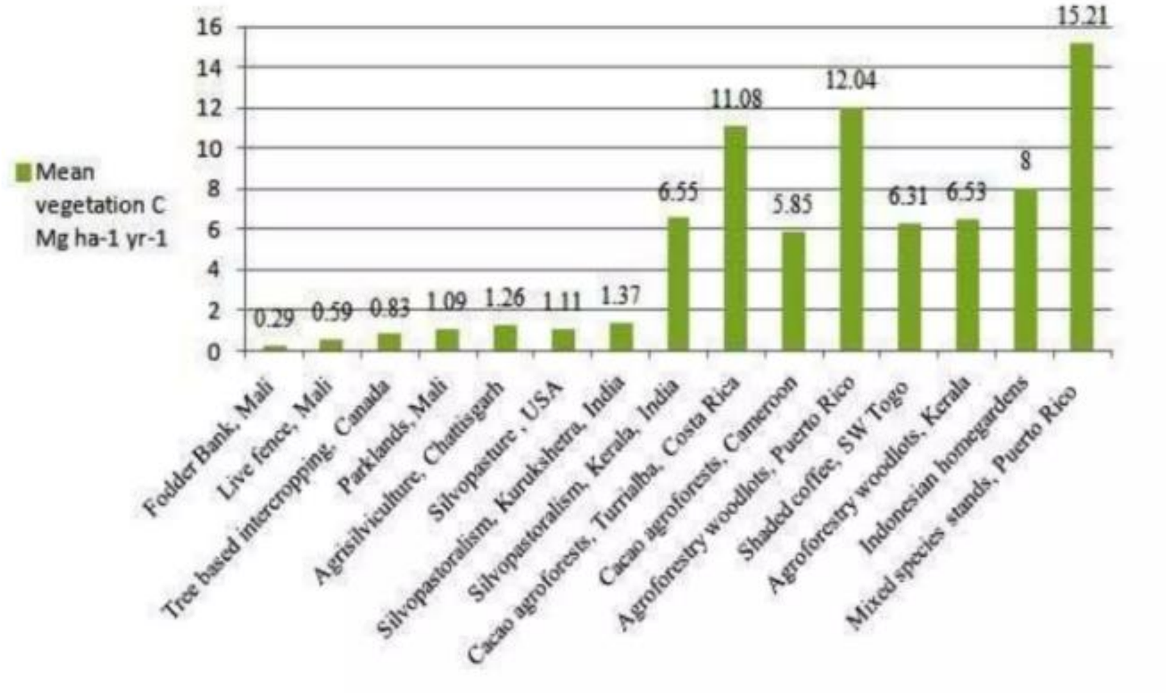

Figure 5. Mean Vegetation carbon sequestration potential (Mg per ha per year) of Agroforestry systems (Source: Nair et al. 2009)

Biomass and Carbon Stock in Agroforestry Systems

Carbon stocks vary with system composition and structural complexity:

- Taungya system (*Gmelina arborea*, 3-5 years): Highest total carbon stock (174 Mg C ha^{-1}), driven by herbaceous biomass (40.5%).
- Mixed multi-storey system: Highest tree biomass (67-89 Mg ha^{-1}), aboveground biomass (83 Mg ha^{-1}), and total carbon stock (162 Mg C ha^{-1}).

- Falcata-coffee system (5-year-old *Paraserianthes falcataria*): Lowest biomass and carbon stock (92 Mg C ha^{-1}).

In Benguet, Philippines, carbon density and CO_2 sequestration vary significantly with system design. Chayote-coffee-vegetable systems achieve ~780 tCO_2 ha^{-1}, dominated by soil carbon, whereas baseline systems store ~250 tCO_2 ha^{-1}. Tree biomass contributions vary, emphasizing the importance of diverse plant components for maximizing carbon storage (Lasco et al., 2014).

These findings underscore that climate, species composition, management intensity, and system design critically determine carbon sequestration potential, highlighting the need for site-specific agroforestry strategies to optimize climate mitigation benefits.

Socio-Economic and Market Dimensions of Agroforestry

White and Minang (2011) showed the trade-offs between economic profitability measured as net present value (NPV, \$ ha^{-1}) and carbon stocks (Mg C ha^{-1}) across tropical land-use systems (Figure 6). Land uses with high short-term economic returns, such as intensive annual crops and tree crop plantations (e.g., oil palm, coffee, cocoa), typically sustain lower carbon stocks. This is due to management practices emphasizing frequent harvesting, high productivity, and limited retention of large, mature trees. Conversely, primary and production forests store the highest carbon stocks but generate comparatively low immediate NPV to landowners.

Agroforestry systems occupy an intermediate position, offering a strategic balance between carbon storage and economic returns. They sequester significantly more carbon than conventional annual cropping systems or pastures while generating diversified income streams from fruits, timber, fodder, and crops. This dual functionality not only contributes to climate mitigation through carbon sequestration but also provides an economic buffer against climate variability, addressing key drivers of deforestation. The framework presented by White and Minang highlights the opportunity costs associated with conserving high-carbon ecosystems, illustrating potential income foregone when forests are not converted to high-profit, low-carbon land uses.

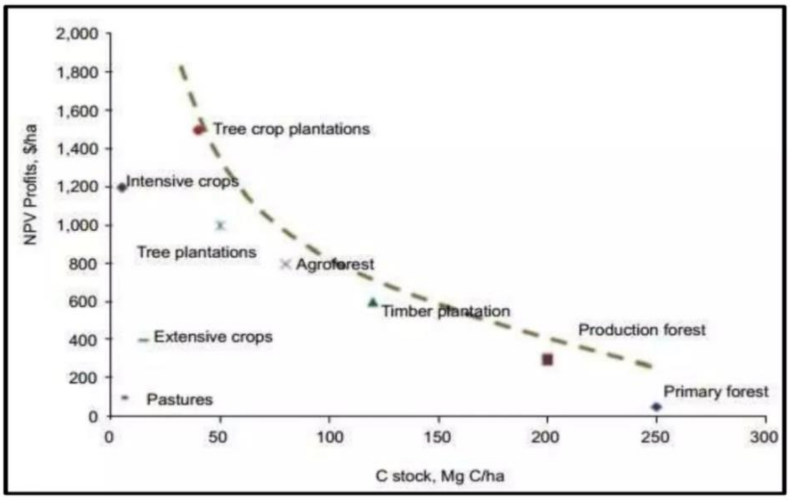

Figure 6. Relationship between NPV profit and carbon stock across different land uses systems NPV-Net present value C-carbon stock (Source: White and Minang 2011)

Agroforestry and the Clean Development Mechanism (CDM)

Smallholder agroforestry systems (AFS) demonstrate considerable variation in tree density, structure, and carbon sequestration potential, making them well-suited for climate mitigation under the Clean Development Mechanism. According to Roshetko et al. (2002), AFS can be broadly categorized as:

- **Agroforests and community forests:** High tree densities and substantial carbon stocks, with time-averaged storage of ~175 Mg C ha^{-1} over 60 years (e.g., home gardens, rubber, coffee, natural forests).
- **Plantations:** Moderate to high tree density systems storing 50–150 Mg C ha^{-1}, including timber, rubber, oil palm, and coffee plantations.
- **Row or scattered tree systems and improved fallows:** Low to medium tree densities, with correspondingly low carbon stocks, including silvopastoral systems and developing fallows.

Key principles for CDM carbon projects include:

- **Additionality:** Carbon sequestration must occur due to the project and would not happen under baseline management.
- **Leakage:** Emissions reductions in one area must account for potential displacement elsewhere, such as deforestation in other locations.
- **Permanence:** Long-term retention of sequestered carbon is critical, as agroforestry systems may be vulnerable to harvest, land-use changes, or disturbances.

A clear understanding of these categories and principles is essential for designing effective, verifiable, and sustainable carbon mitigation projects in smallholder landscapes.

Role of Agroforestry in REDD+

Agroforestry can support REDD+ (Reducing Emissions from Deforestation and Forest Degradation) objectives by contributing to both carbon conservation and substitution. REDD+ incentivizes developing countries to reduce emissions from deforestation and forest degradation, sustainably manage forests, and enhance forest carbon stocks.

Carbon Conservation

By integrating trees into agricultural landscapes, agroforestry maintains and enhances carbon stored in biomass and soils. Avoiding complete forest clearance prevents carbon release and aligns directly with REDD+ goals. Tree-based farming systems improve soil organic carbon, increase aboveground biomass, and enhance ecological stability, further supporting forest conservation.

Carbon Substitution

Agroforestry products, such as timber and fuelwood, can replace more emission-intensive alternatives, including fossil fuels, concrete, or steel. For example, using on-farm wood for cooking reduces pressure on natural forests and lowers fossil fuel consumption, simultaneously supporting REDD+ objectives and promoting sustainable forest management.

Through these mechanisms, agroforestry functions as a nature-based, multifunctional strategy that simultaneously delivers climate mitigation, forest conservation, and livelihood benefits for rural communities.

Case Studies

Several case studies across diverse global regions demonstrate the effectiveness of agroforestry as a climate change adaptation strategy, particularly for smallholder farmers.

In Costa Rica, Oelbermann et al. (2011) evaluated a payment for ecosystem services (PES) program employing a silvopastoral system that integrated trees with livestock. Prior to implementation, farmers experienced decreased productivity, livestock weight loss, reduced harvestable products, and lower milk yields. Following the adoption of *Brachiaria brizantha* within the silvopastoral system, milk production during the dry season increased by up to 70%. Additionally, grasslands were better managed, grazing pressure was reduced, and livestock carrying capacity improved. Trees within the system provided multiple ecological functions, and all participating landowners reported enhanced drought resilience and higher livestock density per unit area.

In Tanzania, Charles et al. (2013, 2014) documented that agroforestry in the Mwanga District enhanced system resilience by diversifying products and income streams. This diversification reduced farmers' vulnerability to climate variability and mitigated the risk of total crop failure, highlighting agroforestry's role in stabilizing livelihoods under uncertain climatic conditions.

In India, Rao et al. (2011) reported that agroforestry systems in hot, semi-arid regions not only contributed to carbon sequestration and reduced nitrogen losses but also delivered a suite of socio-economic and ecological benefits. These included improved soil fertility, enhanced water retention, and supplementary income sources, emphasizing the multifunctionality of tree-based farming systems in supporting climate adaptation.

Collectively, these case studies underscore that agroforestry enhances productivity, ecosystem services, and livelihood resilience, making it a robust and scalable strategy for adapting to the increasingly unpredictable impacts of climate change.

Engaging Farmers in Climate-Smart Agriculture

Engaging farmers is central to advancing climate-smart agriculture (CSA), enhancing resilience, reducing greenhouse gas emissions, and sustaining productivity under changing climatic conditions. Adoption of renewable energy technologies such as solar-powered irrigation pumps, biogas plants, and small-scale wind turbines - reduces dependence on fossil fuels while providing reliable energy for agricultural operations (Kumar et al., 2020). Effective waste management practices, including composting of agricultural residues, in-field decomposition of organic matter, and biogas production, simultaneously minimize environmental pollution and enrich soil fertility, providing additional energy sources (FAO, 2018).

Promoting genetically improved crop varieties, including drought-tolerant and high-yielding cultivars, allows farmers to maintain or increase productivity on the same land while coping with climate stressors such as heat, water scarcity, and erratic rainfall (Varshney et al., 2018). Integrating these technological interventions with training and extension services ensures that farmers acquire the knowledge and tools necessary for sustainable, climate-resilient agriculture.

The Indian Context - Land-Based Climate Mitigation Potential

India presents significant opportunities for land-based climate mitigation. Over 40% of the country's land area is potentially suitable for interventions such as grazing land improvement, agroforestry expansion, and dryland restoration. Approximately 70 million hectares of wastelands could be rehabilitated through sustainable land management practices. Incorporating these approaches into national climate strategies simultaneously addresses climate mitigation, land degradation, food security, and rural livelihoods.

Climate-Smart Agriculture and Agroforestry

Climate-Smart Agriculture is an integrated approach aimed at achieving three interrelated objectives: (i) increasing agricultural productivity, (ii) enhancing resilience to climate change, and (iii) reducing or removing greenhouse gas emissions. CSA promotes resource-efficient, adaptive, and environmentally sustainable farming systems.

Agroforestry, a key component of CSA, involves the deliberate integration of trees with crops and/or livestock. Incorporation of woody perennials into agricultural landscapes improves soil fertility, enhances water retention, moderates microclimates, and sequesters atmospheric carbon. Agroforestry systems diversify farm income, strengthen ecosystem services, and enhance overall system sustainability. By combining mitigation and adaptation benefits, agroforestry provides a practical climate-smart strategy, contributing to food security, rural livelihoods, and national climate commitments.

Agriculture is among the sectors most vulnerable to climate change, particularly in tropical and sub-tropical regions where smallholder farmers dominate. Limited adaptive capacity renders subsistence farmers especially susceptible to climate variability. Agroforestry offers dual benefits: mitigating atmospheric GHG accumulation and enhancing adaptive capacity. Verchot et al. (2007) demonstrated the significant mitigation potential of agroforestry in humid and sub-humid tropics, while also highlighting its role in strengthening smallholder resilience through diversified production and improved ecosystem stability.

Agroforestry in India

India has a long-standing tradition of agroforestry, with scattered multipurpose trees on farmlands providing fodder, fuelwood, fruits, timber, shade, and medicinal products. Agroforestry practices in India include farm forestry, community forestry, and diverse indigenous forest management systems.

Carbon sequestration potential varies across agro-ecological zones. Pandey (2002) reported sequestration rates of 19.56 Mg C ha^{-1} yr^{-1} in Uttar Pradesh, with carbon pools ranging between 23.46 and 47.36 Mg C ha^{-1} in tree-based arid agro-ecosystems of Rajasthan. These findings underscore the significant role of agroforestry in India's climate mitigation strategies.

Collectively, grazing land management, dryland restoration, and agroforestry emerge as scalable, cost-effective, and multifunctional climate solutions. By enhancing carbon storage in vegetation and soil organic matter, these nature-based approaches can make a meaningful contribution to global mitigation efforts while simultaneously supporting ecosystem resilience and socio-economic development.

Agroforestry as a Climate-Smart Land-Use Strategy

Agroforestry stands out as a practical and multifunctional land-use strategy capable of addressing the dual challenges of climate change mitigation and adaptation. In a country like India, with its vast rural populations and diverse agro-ecological zones, integrating trees with crops and livestock provides multiple ecological, economic, and social benefits. Within the broader framework of Climate-Smart Agriculture, agroforestry can enhance agricultural productivity, secure livelihoods, restore degraded ecosystems, and function as a critical carbon sink. With supportive policies, targeted research, and robust extension services, agroforestry has the potential to transform India's agricultural landscapes, making them more sustainable, resilient, and climate-adaptive.

Conclusion

Agroforestry represents a multifunctional approach that simultaneously integrates climate change mitigation and adaptation, offering a pathway toward high-carbon, productive, and resilient landscapes. Effective climate strategies must leverage the synergy between mitigation and adaptation, promoting land-use practices that generate economic returns while maximizing carbon storage in both biomass and soils. The success of these strategies, however, depends on managing trade-offs between carbon sequestration and emissions of other potent greenhouse gases, such as nitrous oxide and methane.

By combining tree-based interventions with crops and livestock, agroforestry systems can enhance ecosystem resilience, improve soil and water management, and buffer smallholder farmers against climate variability, while simultaneously contributing to global climate mitigation objectives.

Future research and implementation priorities include:

1. Buffering against disasters: Quantifying the role of agroforestry in protecting crops, livestock, and communities from climate-related extremes, including floods, heatwaves, and droughts.
2. Standardized impact assessment: Developing robust, widely accepted methodologies for measuring carbon sequestration, greenhouse gas fluxes, and co-benefits in agroforestry systems, enabling integration into formal carbon accounting frameworks and incentive mechanisms such as REDD+ and CDM.
3. Biological pest control: Investigating how diversified agroforestry systems influence pest dynamics and natural enemy populations under changing climatic conditions.
4. System vulnerability: Assessing the resilience of different agroforestry configurations to heat stress, water scarcity, and extreme weather, ensuring long-term productivity and sustainability under future climate scenarios.

Addressing these knowledge gaps will strengthen the role of agroforestry in climate-smart land management, providing scalable, evidence-based solutions that simultaneously enhance carbon sequestration, reduce greenhouse gas emissions, and improve the adaptive capacity of vulnerable smallholder farming communities.

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IMPERATIVE ADAPTION OF ANIMAL HUSBANDRY IN CLIMATE SMART AGRICULTURE TO REDUCE HUNGER AND IMPROVE NUTRITION

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Introduction:

India is an agricultural country. Most of the country's population depends on agriculture as their main source of income and employment. Animal Husbandry is one of the most important parts of the agricultural system of our country. Most of the farmers in our country work in an integrated farming system where livestock is an important activity. India has the largest animal population in the world. Cattle and buffalo make up more than half of the animal population. In this way, milk production is the backbone of the livestock sector and the agricultural GDP. Studies show that farmers have more equal access to livestock than they do to land, making livestock distribution a more balanced and fair process. In addition, there will be opportunities for entrepreneurship in processing, value creation and food production (Kothandaraman *et al*., 2019). In a time when the soil is degraded and the increase in agricultural production seems to be on the horizon, Animal Husbandry has emerged as a profitable enterprise to increase the income of the farmers along with following benefits:

- Synergies with crop production: Animal husbandry can complement crop production by providing organic fertilizer, improving soil health, and reducing pest and disease pressure.
- Diversified farming systems: Integrating animal husbandry into farming systems can promote biodiversity, reduce reliance on single crops, and enhance ecosystem services.
- Nutrition-sensitive agriculture: Animal husbandry can contribute to nutrition- sensitive agriculture by providing nutrient-dense foods, improving dietary diversity, and enhancing food quality.
- Supporting vulnerable populations: Animal husbandry can provide a safety net for vulnerable populations, such as smallholder farmers, women, and youth, by offering a reliable source of income and food.
- Climate-smart agriculture: Animal husbandry can be adapted to climate change by implementing climate-resilient practices, such as agroforestry, silvopasture, and conservation agriculture.
- Livestock value chains: Developing livestock value chains can enhance the economic benefits of animal husbandry, improve market access, and increase the availability of animal products.

- Animal health and welfare: Ensuring animal health and welfare is critical to maintaining productive and sustainable animal husbandry systems, reducing antimicrobial resistance, and promoting ethical farming practices.
- Policy and institutional support: Strengthening policies, institutions, and capacity-building initiatives can help support the development of sustainable animal husbandry systems, promote investment, and enhance food security.

Food insecurity, particularly regarding milk, is a pressing issue in many parts of the world (Radeny *et al*., 2022). Here are some key points: 1. Global milk demand: The global demand for milk is increasing, driven by population growth, urbanization, and rising incomes. 2. Milk availability: However, milk availability is limited in many regions, particularly in sub-Saharan Africa and South Asia. 3. Food insecurity: Milk is an essential source of protein, calcium, and other nutrients, making milk insecurity a significant contributor to food insecurity. 4. Malnutrition: Inadequate milk consumption can lead to malnutrition, stunted growth, and development issues in children.5. Rural-urban disparities: Milk availability and access often vary greatly between rural and urban areas, exacerbating existing health disparities. 6. Seasonal fluctuations: Milk production can be seasonal, leading to fluctuations in availability and price.7. Affordability: Milk can be unaffordable for many households, particularly in low-income communities. 8. Supporting small-scale dairy farmers: Empowering small-scale dairy farmers, especially women, can enhance milk availability, improve livelihoods, and increase food security. 9. Dairy value chains: Strengthening dairy value chains can improve milk quality, safety, and distribution, increasing access to this essential nutrient. 10. Nutrition education: Promoting nutrition education and awareness about the importance of milk and dairy products can stimulate demand and support food security initiatives.

Addressing milk insecurity requires a comprehensive approach that includes supporting dairy farmers, improving dairy value chains, and promoting nutrition education to ensure equitable access to this essential nutrient. Food insecurity affects over 820 million people worldwide, with 1 in 9 people facing hunger. Food insecurity is a complex issue requiring comprehensive solutions to ensure equitable access to nutritious food for all. Food insecurity in India is a significant concern, despite the country's progress in food production and economic growth.

Animal Husbandry is imperative for hunger alleviation owing to the under mentioned points:

- ✓ Animal husbandry offers vast potential for adopting innovative technologies to boost production and income, unlike the stagnant crop production sector.
- ✓ The emerging trend of pet animal rearing presents a new opportunity for farmers to breed and sell pets, increasing their income.
- ✓ The expansion of veterinary education and services through colleges, universities, and institutes enhances the effectiveness of animal healthcare and extension services.
- ✓ Governments prioritize animal husbandry to secure rural livelihoods, recognizing its importance.

- ✓ Self-Help Groups (SHGs), predominantly led by women, focus on animal husbandry as a primary occupation, promoting empowerment and income growth.
- ✓ Intensification methods in animal husbandry lead to increased productivity and efficiency.
- ✓ Information and Communication Technologies (ICTs) facilitate faster dissemination of technologies, marketing information, and other essential data, driving growth in the animal husbandry sector.
- ✓ Growing demand for organic and desi livestock products, driven by health consciousness, offers farmers a niche opportunity to increase their income.
- ✓ Implementing Integrated Farming Systems (IFS) can significantly enhance farm family income in a short period, making training in IFS crucial for farmers.

Soil organic Carbon:

Soil organic carbon (SOC) depletion is a significant concern globally, and animal husbandry can play a crucial role in increasing SOC levels. Its mainly caused by 1. Intensive agriculture and tillage lead to SOC loss. 2. Soil erosion and degradation reduce SOC. 3. Climate change and rising temperatures accelerate SOC decomposition.

Animal Husbandry's Role in Increasing SOC:

- ➢ Grazing Management: Proper grazing practices can enhance SOC sequestration by promoting soil carbon storage.
- ➢ Manure Application: Animal manure adds organic matter, increasing SOC levels.
- ➢ Cover Cropping: Integrating cover crops into animal husbandry systems reduces soil erosion and increases SOC.
- ➢ Agroforestry: Integrating trees into animal husbandry systems promotes soil carbon sequestration.
- ➢ Regenerative Agriculture: Animal husbandry can be part of regenerative agriculture, focusing on soil health, biodiversity, and ecosystem services.

Benefits of Increased SOC:

- ✓ Carbon Sequestration: Mitigates climate change by storing carbon in soils.
- ✓ Soil Fertility: Enhances soil fertility, structure, and water-holding capacity.
- ✓ Biodiversity: Supports biodiversity by creating habitat for soil biota.
- ✓ Food Security: Improves crop yields and food security.

By adopting sustainable animal husbandry practices, we can increase SOC levels, mitigate climate change, and promote soil health, ultimately contributing to a more resilient food system.

The need for increased livestock production is pressing, given the rapidly growing demand for animal products and the important contribution of livestock to the incomes and welfare of the rural poor. Additional physical, or financial capital is needed for the introduction of a new livestock enterprise, but thereafter replacements may be home bred (Dhami *et al*., 2015). Human capital in the form of husbandry knowledge and skills is also needed. Technological innovations should be appropriate to the resource base, while access is needed to market outlets and input delivery systems. There is limited scope for increased offtake from grassland-based systems. Options for welfare improvement include provision of water supplies and drought relief. Mixed crop-livestock systems contribute most to ruminant production and income for the rural poor. Nutrient recycling and other beneficial crop-livestock interactions arise, though individual ownership of land and enclosure may be needed to confine livestock and protect crops. Options exist for technical improvements in animal health, nutrition and production systems. The latter may involve greater specialisation, for instance into dairy farming, with the introduction of exotic breeding material.

Poultry and pig production systems are the most intensive and fastest growing sources of meat. They are now more important than ruminant meats in developing country diets. Much of the growth derives from large-scale, commercial production companies in peri-urban locations. Concerns, over competition with poor livestock producers, reliance on feed grains, loss of genetic diversity and environmental pollution, must be recognised. However, these systems are the most economically efficient and cheapest sources of animal protein. There is considerable scope for import substitution and saving of foreign exchange. Improvements to traditional 'backyard' systems are needed, together with development of an institutional framework to promote equitable contracts between commercial processors and smallholder producers and joint action by smallholders in establishing processing and marketing facilities. Similar issues arise in relation to smallholder dairy development.

Livestock development policies include trade and pricing policies, to encourage the developed countries to reduce trade barriers, to reduce domestic protection of industrial sectors and to make limited use of subsidies and taxes. Subsidies may be used for disaster relief or to promote use of innovations. Taxes may be used to recover costs publicly financed services. Institutional development requires strengthening of rural roads and communications, property rights and contractual agreements, and organisations for the provision of credit, animal health services, and other inputs. Dissemination of timely market information is desirable and promotion of links between producers and processors or of producer groups for processing and marketing. The decline in funding for livestock research must be reversed.

More research is needed on animal and veterinary public health, forage crops and the utilisation of crop by-products, improved husbandry and production systems and possibly on breeding. In addition, socio-economic research is needed into existing production systems, and institutions for land tenure, credit, labour hire, input delivery and product marketing together with methods of research prioritisation (Zhang *et al*., 2017). Increased funding for well-designed policies for trade, pricing, institutional development, research and technological change should yield substantial returns in terms of growth in agricultural and national income, saving of foreign exchange and rural poverty relief.

In order to start dairying and doubling the income, the farmer can start with desi breeds or indigenous breeds (Sujith *et al*., 2024).

Breeds:

1. Gir: Originating from Gujarat, Gir cows are known for their distinctive hump and are prized for their high milk production (average 1,200 kg per lactation).

2. Sahiwal: Hailing from Punjab, Sahiwal cows are renowned for their heat tolerance and high milk production (average 2,100 kg per lactation).

3. Red Sindhi: From the Sindh region, Red Sindhi cows are recognized by their distinctive red coat and are valued for their milk production (average 1,500 kg per lactation).

4. Ongole: Originating from Andhra Pradesh, Ongole cows are known for their draft purposes and are also used for milk production (average 500 kg per lactation).

5. Tharparkar: Hailing from Rajasthan, Tharparkar cows are prized for their heat tolerance and milk production (average 1,000 kg per lactation).

6. Rathi: From Rajasthan, Rathi cows are recognized by their distinctive coat patterns and are valued for their milk production (average 1,200 kg per lactation).

7. Hariana: Originating from Haryana, Hariana cows are known for their high milk production (average 1,500 kg per lactation).

8. Deoni: Hailing from Maharashtra, Deoni cows are prized for their draft purposes and are also used for milk production (average 500 kg per lactation).

9. Kankrej: From Gujarat, Kankrej cows are recognized by their distinctive hump and are valued for their milk production (average 1,000 kg per lactation).

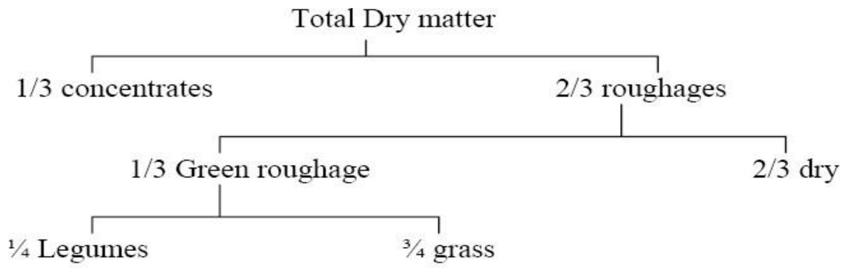
10. Hallikar: Originating from Karnataka, Hallikar cows are known for their draft purposes and are also used for milk production (average 500 kg per lactation).

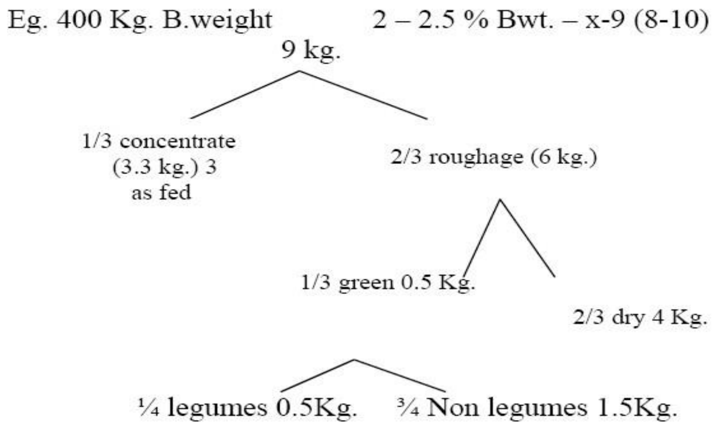
Nutrition of Cows:

Grass-based diet: Most Indian cow breeds are adapted to a grass-based diet, with a focus on high-fiber, low-concentrate feeding. Roughage: Provide high-quality roughage like hay, straw, or silage to meet fiber requirements. Concentrates: Supplement with concentrates like grains, pulses, or commercial cattle feed in limited quantities. Mineral and vitamin supplements: Ensure adequate mineral and vitamin intake through supplements or fortified feeds. Water: Ensure access to clean, fresh water at all times. Dry matter intake: Manage dry matter intake according to age, breed, and production stage.

Nutrient balancing: Balance nutrients like protein, energy, and fiber to meet individual needs. Seasonal variations: Adjust feeding strategies according to seasonal changes in temperature, humidity, and forage availability. Pregnancy and lactation: Provide additional nutrients and energy during pregnancy and lactation stages. Regular monitoring: Regularly monitor cow health, milk production, and reproductive performance to adjust nutritional strategies

Distribution of Total Dry matter Requirement in dairy animals





The main components of food are water and dry matter. The dry matter consists of organic material and inorganic material. On an average, a milch cow will consume concentrate feed equivalent to 2.5-3 per cent of its bodyweight. We need to provide adequate feed to meet the daily requirement of the animals to get the best milk yield. The concentrate feed can be prepared using grains, rice bran, oil cakes, common salt and mineral mixtures.

A variety of locally available raw material such as sorghum (jowar or Cholam), cumbu (pearl millet or bajra), tamarind seed, rice bran, tapioca residue, ragi (finger millet) husk, sunflower meal, groundnut oilcake, gingelly oilcake, cotton seedcake, neem cake and poultry droppings can be used judiciously to make the concentrate.

To make 100 kg of feed in an area where sorghum grains are easily available, a farmer will have to mix 30 kg sorghum, 1 kg cumbu, 23 kg cotton seedcake, 20 kg poultry droppings, 10 kg neem cake, 10 kg ragi husk, 4 kg sunflower meal, 1 kg salt and 2 kg mineral mixture. This 100 kg feed mixture will contain 14 per cent digestible crude protein (DCP) and 60 per cent total digestible nutrients (TDN), which are needed to meet the energy needs of the animals. These concentrates should be fed to the milch cows at a rate of about one kg for every 2.5 kg milk produced.

In the case of the buffaloes, the recommended rate is 1 kg feed for every two litres of milk yielded. Besides this, the animals should be fed with 5-6 kg of dry fodder and 15-20 kg green fodder to get good results.

Balanced Ration to Provide Complete Nutrition

Balanced ration

A balanced ration is a ration which provides the essential nutrients to the animal in such proportions and amounts that are required for the proper nourishment of the particular animal for 24 hours.

Desirable Characteristics of a Ration:

1. **The ration should be properly balanced**

With a correct and balanced ration the cow can get the best out of all the constituents present in her food.

2. **The feed must be palatable**

Whatever food is given to an animal it must be to its linking. For profitable production the animal should be able to eat to the maximum of its appetite which is possible only if the food is palatable. Mouldy, dusty, spoiled and inferior foods are unpalatable and must not be given to the animals.

3. **Variety of food in the ration**

By combing many feeds in a ration a better and balanced mixture of protein, vitamin and other constituents are furnished than by depending on only a few.

4. **The ration should contain enough mineral matter**

Milk contains large amount of minerals like calcium, phosphorus, etc. If the mineral matter in the ration is not sufficient to meet the demands in milk yield, cow will have to be drawn upon her own body supplies.

5. **The ration should be fairly laxative**

Otherwise the food will be incompletely digested. Constipation is often the cause of most of the digestive trouble.

6. **The ration should be fairly bulky but not two bulky**

Stomach of cattle is very capacious and they do not feel satisfied unless their stomach is filled up. If the ration is too bulky, the animal will fail to get all its nutrient requirements.

7. **Feed must be properly prepared**

Some feeds require special preparation before administration in order to render them more digestible and palatable. The feeds require special preparation before administration.

Importance of Green Fodder for Cattle Production and their Nutritive Value

Why Green Fodder?

1. The feeding of green fodder (grass, legume or cereal fodder) is always economical. The feeding of concentrates or compounded feed may give high output per unit of feed may

not be economically viable always for the countries like where grains, oilcakes and milling byproducts are scarce and costly.

2. In most of the farming situations, feeding concentrates or compounded feed will increase the cost of feeding which in turn raise the cost of production.
3. On the other hand, an animal yielding on average of 5-6 liters of milk per day can be comfortably maintained with feeding of green fodder only (grass or cereal fodder and legumes) without any supplementation of concentrates.
4. It is not economical for the farmer to have intensive dairy, sheep or goat farm without sufficient provision for green fodder or dry fodder throughout the year. If the land resource is scarce, a farmer can have suitable agroforestry models to increase the forage production per unit area.

How Fodders are classified?

1. There are different types of classification available. However, the following two classifications are easier to understand and adopt.
2. Classification of fodder on the basis of season of cultivation
    a. Kharif fodder (June – September): Eg. Cowpea, Field bean, Bajra, Sorghum, Maize.
    b. Rabi fodder (October – Dec/Jan): Eg. Berseem, Lucerne, Oats, Barley etc.,
    c. Summer fodders (April – June): Eg. cowpea, Maize, Field bean, Sorghum, Bajra etc.
3. Classification based on Plant family and duration of the crop
    a. Legumes (Annual and Perennial): Eg. Berseem, Cowpea, Stylo, Hedge Lucerne.
    b. Non – legumes (Annual and Perenial): Eg. Hybrid Napier, Guinea grass, Fodder maize, Fodder sorghum etc.

Legumes

1. Legumes are the most important component of animal fodder in view of their high content of crude protein (20 – 25%) compared to fodder cereals (8 – 12%) and fodder grasses (5 – 10%).
2. Non-leguminous fodders (Cereal and grass) provided much of the required energy (carbohydrates) for livestock while legumes improve the quality of fodders when mixed with non-leguminous fodders.
3. Green fodders of non-legumes are fed in bulk quantities (about 10% of body weight of the animal) whereas that of legumes is fed in small quantities (1-2% of body weight).
4. If legumes are fed in bulk, it may create problems like bloat in animals.

Non-legume

1. Non-legumes refer to all grasses belonging to the family of plants, gramineae comprising 450 genera and more than 6000 species distributed throughout the world.
2. Grasses considerably vary in their habits, size and habitat. Some grasses are annuals, while others are perennials.
3. Another group of non-legumes is the Cereal fodders. They play an important role in the feeding of dairy animals.
4. Farmers in general are not growing cereals exclusively for fodder purpose. Rather they grow them mainly (straw / stover) is used as cattle feed. But such straw/stover are very poor in their nutritive value compared to their value as green fodder.
5. However, there are varieties available in the cereal group exclusively meant for fodder purpose and in such a case the crop should not be allowed for grain setting.

Which green fodder to choose?

1. It is highly essential to select the right choice of crops to cultivate.
2. This depends on the soil type, soil fertility status, agro climatic conditions, water availability, kind and number of livestock reared etc.
3. However, it is advisable to grow legume as an intercrop along with grass or cereal fodder in order to make the fodder more nutritious.
4. Given below is the list of forage crops that are recommended for Tamil Nadu.
5. The other source for the livestock feed is the natural grazing resources available in the Common Property Resources. (ie. Lake, bunds, common grazing grounds, roadsides etc).

Improved Varieties for Forage Crops Suitable for Cattle

S. No	Name of the crop	Special features
Cereal Forages		
1	Sorghum CO FS - 29	Multicut variety (5-6 cuttings per year) Suitable for irrigated farming
2	Sorghum Co – 27 (60 – 65days)	Thin stem, ratoonability, drought tolerant
3	Bajra Co – 8 (50 -55 days)	Soft stem, high leaf stem ratio, highly palatable
Grasses		
1	Hybrid napier Co - 1	High yield and Drought tolerant
2	Hybrid napier Co - 2	High yield and Drought tolerant

3	Hybrid napier Co - 3	High yield, High leaf stem ratio and Highly palatable and low oxalate content
4	Guinea grass (Co - 1 & C0 -2)	Shade tolerant and thin stem
5	Kollukattai (Blue Anjan) Co - 1 *Cenchrus glaucus*	Highly suitable for rainfed and pasture lands, High bio mass yield and drought tolerant
6	Deenanath	Thin Stem and highly palatable
Cereal Forages		
1	Sorghum CO FS - 29	Multicut variety (5-6 cuttings per year) Suitable for irrigated farming
2	Sorghum Co - 27 (60 - 65days)	Thin stem, ratoonability, drought tolerant
3	Bajra Co - 8 (50 - 55 days)	Soft stem, high leaf stem ratio, highly palatable

Reproduction in cows

It is one of the most important aspects in dairy cows. In cows, release of ova from the Graffian follicle (Ovulation) takes place 12 hours after the end of oestrum. The optimum time for breeding the cattle is 12 hours after the onset of Oestrus (i.e. at Mid-heat).

Either Natural Service or Artificial Insemination can be performed in cows. The cows should be checked for pregnancy on day 40. A calf per year per cow is our government policy. Also, Vaccination against FMD, Anthrax etc., is a recommended practice before rainy season.

Conclusion

Dairy farming can be a profitable venture for doubling farmers' income, provided it is managed efficiently. With high-yielding breeds, proper feeding, breeding, and health management practices, farmers can increase milk production and quality, fetching better prices. Value addition through products like cheese, butter, or ghee can further boost revenue. By leveraging government initiatives, subsidies, and extension services, and exploring premium markets, farmers can enhance their earnings. Successful dairy farmers in India have reported average annual incomes ranging from ₹500,000 to ₹1,000,000, with net profit margins of 20-30%. However, it's crucial to address challenges like high initial investment, disease outbreaks, and market fluctuations to ensure sustainability and profitability. With careful planning and market awareness, dairy farming can indeed double farmers' income and contribute significantly to their economic well-being.

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EMERGING AQUACULTURE TECHNOLOGIES FOR CLIMATE CHANGE RESILIENCE

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Introduction

Climate change poses unprecedented challenges to global food systems, particularly in fisheries and aquaculture sectors that sustain millions of livelihoods. Rising sea surface temperatures, ocean acidification, habitat degradation, and unpredictable extreme events increasingly threaten capture fisheries and the biodiversity of aquatic ecosystems. In this context, aquaculture emerges as both an adaptation and mitigation strategy, offering opportunities to diversify production systems, reduce pressure on wild stocks, and enhance socio-economic resilience in vulnerable coastal and island communities.

India, endowed with diverse aquatic resources, has strategically advanced aquaculture innovations through its national research institutes. These institutes have each developed climate-resilient model addressing conservation, livelihood security, and sustainable resource management. Together, these initiatives exemplify how science-driven aquaculture technologies can function as practical climate adaptation strategies.

Aquaculture as a Climate Adaptation Strategy

The fisheries and aquaculture sector are among the most climate-sensitive food production systems. Climate change affects the habitat, fish distribution, reproductive cycles, and ecosystem productivity, while also intensifying risks of diseases also. Aquaculture, if appropriately designed, provides an effective adaptation strategy by buffering communities from the uncertainties of wild fisheries and securing aquatic germplasm resources.

Ecological Dimension: Conserving Germplasm and Reducing Wild Harvest

Aquaculture reduces direct pressure on coral reefs, mangroves, and estuaries by providing alternatives to wild collection. Captive propagation safeguards the germplasm resources and ensure continuity of production even when natural populations decline.

Technological Dimension: Controlled and Adaptive Production Systems

Innovations such as recirculatory aquaculture systems (RAS), biofloc technology, and integrated multi-trophic aquaculture (IMTA) minimize water use, recycle nutrients, and buffer against climate variability. Use of renewable energy, especially solar, reduces carbon emissions and enhances sustainability.

Socio-economic Dimension: Livelihood Diversification and Community Resilience

Community-based aquaculture provides a supplementary and often more stable income source for coastal and island populations, which is vulnerable to climate stress. Importantly, low-cost, small-scale technologies are accessible to women and marginalized groups.

Gender and Social Inclusion as Adaptation Pathways

Women's participation in aquaculture enterprises strengthens household resilience and promotes social equity. Training and cooperative models enhance local ownership of climate-smart practices.

Policy and Governance Perspective

Aquaculture aligns with the Paris Agreement, Nagoya Protocol, and SDGs, particularly SDG 13 (Climate Action) and SDG 14 (Life Below Water), making it a key component of India's national adaptation strategy.

Community Aquaculture: ICAR-NBFGR's Model for Climate-resilient Aquaculture

Community aquaculture links biodiversity conservation with livelihood enhancement in climate-vulnerable regions. By maintaining broodstock in captivity and standardizing captive breeding technologies, dependence on wild capture is minimized. The reduced harvesting stress allows ecosystems like reefs and mangroves to regenerate, while communities benefit from new income streams.

Importantly, aquaculture introduces species and system diversification, mitigating risks posed by climate variability. Low-cost, environmentally benign practices such as solar-powered hatcheries, indigenous feed formulations, and bivalve farming further reduce the ecological footprint. Community engagement also enhances social resilience by empowering women, building entrepreneurship, and fostering local stewardship of aquatic resources.

Ultimately, community aquaculture provides a unique model, where biodiversity conservation and socio-economic development is growing together. By involving local people directly in the management and sustainable utilization of aquatic resources, the approach transforms communities from passive resource users into active custodians of biodiversity. It illustrates how ecological resilience and human well-being can be achieved simultaneously when conservation strategies are embedded within livelihood frameworks, ensuring long-term sustainability of both natural resources and dependent human populations.

Successful model at Agatti Island, Lakshadweep

ICAR-NBFGR, with the funding support of the Department of Biotechnology and the Centre for Marine Living Resources and Ecology, established a Germplasm Resource Centre for marine ornamental invertebrates at Agatti Island. Broodstock of nine ornamental shrimp species *Gnathophyllum americanum, Saron marmoratus, S. neglectus, Ancylocaris brevicarpalis, Stenopus hispidus, Periclimenella agatii, Cuapetes purushothamani, Cinetorhynchus himanshui* and *Thor hainanensis* were developed and maintained, with successful captive breeding protocols standardized for *T. hainanensis* and *A. brevicarpalis,* a milestone achievement at the global level.

These technologies were transferred to local women beneficiaries, leading to the establishment of four community aquaculture units with the participation of 45 women powered primarily by solar energy. The units, now functional, generate a steady income for the islanders, while simultaneously reducing wild harvest and conserving fragile reef resources. This initiative represents a unique convergence of scientific innovation and societal benefit, where native resources are used sustainably for both conservation and livelihood development.

Cluster mode rearing units for marine ornamental fishes at Maharashtra

NBFGR also established a demonstration ornamental fish hatchery at the Coastal and Marine Biodiversity Centre, Thane, in collaboration with the Mangrove Foundation and Mangrove Cell, Government of Maharashtra. The facility focuses on the captive production of clownfishes and the same were supplied to the beneficiaries for rearing in cluster-based aquaculture units across three coastal districts of Maharashtra. Hatchery bred young ones of clownfish were supplied to these units for further rearing and marketing. The established rearing unit was successful in providing sustainable additional income to the beneficiaries and thereby, helped for their socio-economic upliftment.

Livelihood Development Programme at Tamil Nadu

In southern India, NBFGR initiated a livelihood development programme at the Pichavaram mangrove ecosystem, recently declared a Ramsar site and Pulicat region with the funding support of Tribal Dept., Govt. of Tamil Nadu. The programme engages local communities in ornamental aquaculture, thereby reducing pressure on mangrove-associated resources and enhancing conservation awareness.

Broader Impacts

The efforts of NBFGR, highlight how aquaculture technologies can reduce harvesting pressure on natural stocks, enhance biodiversity conservation, and generate supplementary income in climate-sensitive regions. These models particularly emphasize:

- **Gender empowerment**, with women's participation
- **Diversification of candidate species**, mitigating risks associated with climate variability
- **Eco-friendly practices**, including solar-powered units and low-carbon system
- **Alignment with global frameworks**, including the Nagoya Protocol, SDG 14, and India's Blue Economy vision

Way Forward

To scale-up this institutional model, which requires:

- Expansion of captive breeding technologies for new candidate species.
- Strengthened the public-private partnerships and cooperatives for technology dissemination.
- Policy frameworks that integrate access-and-benefit sharing mechanisms.
- Integration of biodiversity exploration with aquaculture enterprise development.

With sustained research, investment, and community participation, India can position itself as a global leader in climate-resilient aquaculture, contributing simultaneously to biodiversity conservation, livelihood generation, and sustainable development.

7. Conclusion

Indian research institutes have demonstrated how aquaculture technologies can be harnessed for climate change resilience. NBFGR's community-based ornamental model is a breakthrough in ornamental aquaculture, and diversification initiatives collectively provide replicable pathways, where conservation and livelihoods joining together. By embedding scientific innovation within community frameworks, India is building adaptive capacity against climate change, while safeguarding aquatic biodiversity and strengthening socio-economic resilience in coastal and island regions.

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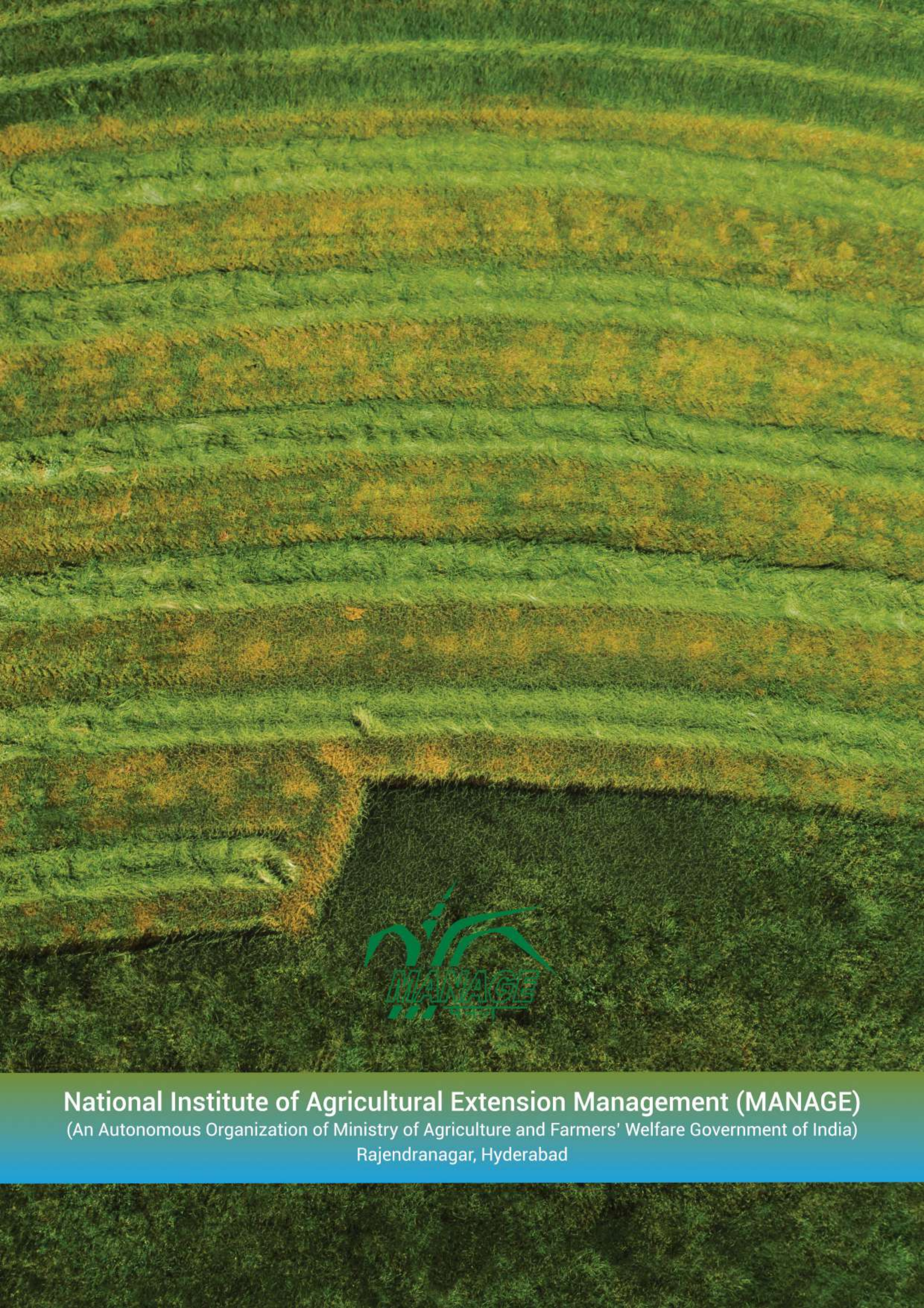

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