



Climate smart soil management strategies for sustainable soil health

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Abstract : Healthy soils are the cornerstone of sustainable food production, serving as a reservoir of essential nutrients that support biological productivity and mitigate environmental impacts. Soil health, characterised by its biological, chemical, and physical properties, is crucial for maintaining agricultural productivity and environmental quality. However, in regions such as the semi-arid tropics of India, poor soil health has led to suboptimal crop yields and nutrient imbalances. National soil fertility surveys reveal widespread deficiencies in both major and micronutrients, exacerbating soil degradation and reducing agricultural sustainability. Compounded by climate change, these challenges highlight the need for innovative, climate-smart management practices. Climate change intensifies threats to soil health through increased temperatures, erratic rainfall, and extreme weather events, which lead to erosion, compaction, and declining soil fertility. Climate-smart soil management strategies, such as conservation agriculture, organic farming, and agroforestry, are critical for enhancing soil organic carbon (SOC) levels, improving water retention, and mitigating greenhouse gas emissions. For instance, zero-tillage and crop residue management can significantly increase SOC sequestration, while agroforestry systems enhance biodiversity and carbon storage. Similarly, organic farming and integrated nutrient management can replenish soil fertility and sustain long-term productivity. Furthermore, implementing site-specific nutrient management and water conservation measures is essential to optimise resource use efficiency. Technologies such as precision irrigation and IoT-based tools offer additional avenues for sustainable soil-water management. These practices align with global efforts to mitigate climate change, enhance carbon sequestration, and secure food systems under changing climatic conditions. This paper underscores the critical role of soil health in achieving sustainable development goals, emphasising the need for interdisciplinary approaches to soil and climate-smart agriculture. Advancing these strategies will ensure resilient agro-ecosystems, higher productivity, and long-term environmental sustainability.

Keywords: *Agroforestry, Climate-smart agriculture, Organic farming, Soil health, Sustainability*

Introduction

It takes half a millennium to build two centimetres of living soil and only a few seconds to destroy it. Soil is the real essence of life on earth. It serves as a natural medium for plant growth that

sustains human and animal life. Healthy soils provide a range of ecosystem services, including resisting erosion, receiving, filtering, and storing water, retaining nutrients, promoting biodiversity, sequestering carbon, and acting as an environmental buffer in landscapes. Healthy soil is the foundation of production and sustainable agriculture.

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Unfortunately, soil health has undergone implacable degradation at an alarming rate under climate change scenario.

The agricultural system in the world has been facing tremendous pressure on the use of resources, largely due to climate change and environmental stresses. Increase of mean temperature, changes in rainfall patterns, increasing frequency and intensity of extreme events, sea level rise and salinisation, and perturbations in ecosystems are the clear indications of climate change and have profound impacts on agriculture (Thornton, 2012).

Shrink-swell soils, characterised by their high clay content and pronounced expansion and contraction in response to moisture variations, present unique challenges for sustainable soil management. These soils are found globally, particularly in semi-arid and tropical regions, and are integral to agricultural productivity and land management systems (Dinka and Lascano, 2012). The dynamic nature of these soils, characterised by significant structural instability and susceptibility to degradation, necessitates innovative management strategies to maintain their health and productivity while addressing the broader challenges of climate change.

The concept of climate-smart soils was put forth by Paustian et al. (2016). The key is that soils can sequester carbon and remove it from the atmosphere, thereby helping to combat climate change. The management strategy for climate-smart soils encompasses three key areas: soil carbon sequestration, soil management to mitigate N_2O emissions, and soil management to reduce CH_4 emissions. Climate-smart soil management (CSSM) strategies offer a promising approach to address these challenges. CSSM integrates practices designed to enhance soil carbon sequestration, optimise nutrient cycling, and improve water retention capacities while mitigating greenhouse gas emissions. These strategies are critical for ensuring the resilience of agricultural systems, particularly in the face of changing climate patterns that exacerbate soil degradation and reduce fertility (Veni et al., 2020). Moreover, they align with the global Sustainable Development Goals by fostering ecosystems that support biodiversity, carbon sequestration, and sustainable food production systems.

Adopting CSSM for shrink-swell soils involves practices such as the use of organic amendments, conservation tillage, cover cropping, and agroforestry. These interventions are designed to improve soil structure, reduce erosion, and enhance water use efficiency. For example, organic matter additions have been shown to mitigate the effects of shrink-swell cycles by stabilising soil aggregates and increasing porosity (Kok, 2024). Additionally, agroforestry systems contribute to microclimate regulation, protecting soils from extreme temperature variations that exacerbate soil swelling and shrinking (Dissanayaka et al., 2023).

Given the complexity of shrink-swell soils and the multifaceted nature of climate-smart interventions, research in this area focuses on site-specific strategies tailored to local environmental and socio-economic conditions. The integration of advanced soil monitoring technologies and predictive climate models further enhances the effectiveness of CSSM practices, ensuring their adaptability and sustainability (Konfo et al., 2024). These innovations underscore the importance of interdisciplinary approaches that combine agronomy, soil science, and climate modelling to develop resilient systems for managing shrink-swell soils. By adopting climate-smart soil management practices, we can address the dual goals of improving soil health and mitigating the adverse impacts of climate change on agricultural systems. This paper examines the current best practices and their implications for the sustainable management of shrink-swell soils, with a focus on long-term productivity and ecosystem resilience.

Soil Resource in India

Soil plays a central role in economic and social development by ensuring food, fodder, fibre, and renewable energy supplies to sustain human, animal and plant life. India is known as a land of paradox due to its diverse soils. Diversity in geographical formation, diverse climate, topography and relief. The total geographical area comprises 328.7 million hectares, with seven taxonomic soil orders. For sustainable development at the local, regional, and national levels, and efficient crop planning and technology transfer, the

entire country has been delineated into 20 agroecological regions (AERs) and 60 agroecological subregions (AESRs) based on bioclimate, soilscape, and length of growing period. The predominant soil orders in India are Inceptisol (39 %), Entisol (24 %), Alfisols (13 %) and Vertisols (9 %) as shown in Figure 1.

The Vertisols, Inceptisols, and their intergrades are mainly localised in Peninsular India and are shrink-swell soils, which occupy about 106 million hectares of land, constituting about 35% of the total geographical

area of the country. This group of soils is generally fertile, with high production potential under both rainfed and irrigated agriculture, and contributes significantly to increasing food production in the country. The shrink–swell soils are generally medium to very deep, usually calcareous, alkaline in nature, dark in colour with low chroma, clayey with high smectite clay minerals, low in organic matter with high CEC, base saturated and high shrink-swell potential with sticky and plastic consistency with poor drainage and low infiltration rate.

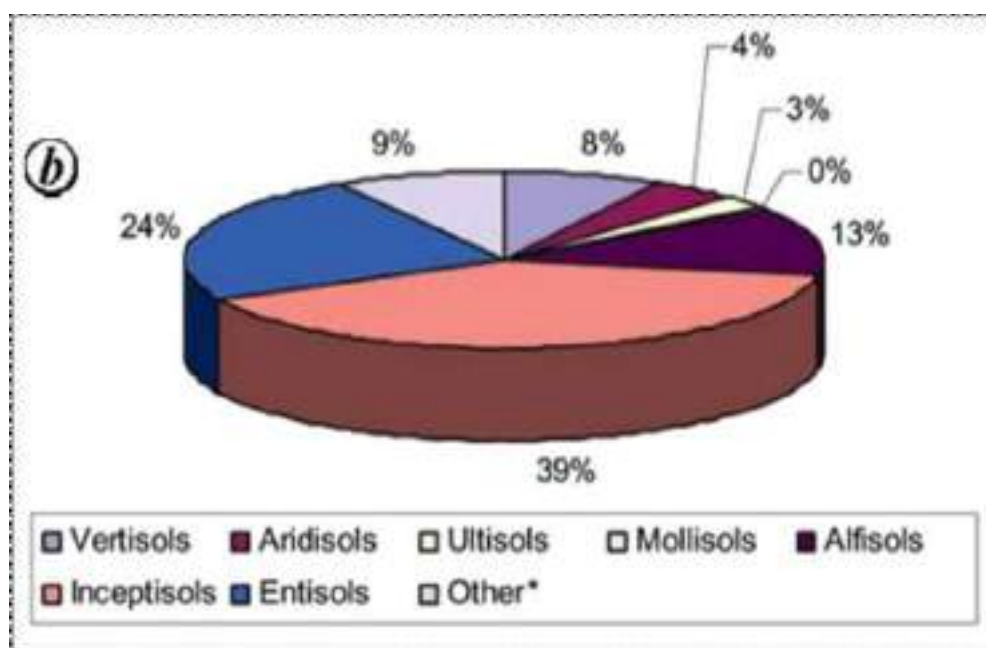


Fig. 1: Various soil orders and their extent in India (Source: Bhattacharyya et al., 2013)

Soil Health

Healthy soil is the basis for food production and sustainability, which has the capacity to minimise the yield gap through improved soil health. Seybold *et al.* (1999) defined soil health as the capacity of soil to function within ecosystem boundaries, sustaining biological productivity, maintaining environmental health, and promoting the health of plants and animals. Soil health refers to the biological, chemical, and physical features of soil that are essential to long-term, sustainable agricultural productivity with minimal environmental impact. Thus, soil health provides an overall picture of soil functionality. Although it cannot

be measured directly, soil health can be inferred by measuring specific soil properties (e.g. organic matter content) and by observing soil status (e.g. fertility).

Soil Health Status of Indian Soils

In the semiarid tropics, poor soil health leads to sub-optimal crop yields (1 to 1.5 t ha⁻¹) and lower economic return in spite of existing potential (2.5 to 7.0 t ha⁻¹). Indian agriculture has a net negative balance of nutrients, as every year there is a net deficit of about 10 million tonnes of nutrients added and extracted from the soil. Apart from major nutrients, the soils are now also showing a deficiency of secondary nutrients, such as

sulfur and multiple micronutrients. According to the DARE (2018), the soil fertility maps of India indicate that approximately 59% of soils are low in available nitrogen, 36% are medium, and only 5% are high. Similarly, about 49%, 45%, and 6% of soils are low, medium, and high, respectively, in available phosphorus. With respect to potassium, about 52% of soils are high, 39% of soils are medium, and only 9% of soils are low. All India Coordinated Research Project on 'micro and secondary nutrients and pollutant elements in soils and plants' reported nearly 49, 15, 6, 8, 11 and 33% samples were found to be deficient in available zinc, iron, manganese, copper, molybdenum and boron, respectively, across the country and hence all contribute towards poor soil health. (Shukla *et al.*, 2012).

Formation of SIC is the major reason for chemical degradation, resulting in poor soil quality. The soils of semiarid tropics are favoured for the formation of pedogenic calcium carbonate, accentuating inorganic carbon sequestration, which has a deleterious effect on soil quality since it affects soil pH, ESP and hydraulic properties. (Bhattacharyya 2021a & b).

Organic carbon is an index of good soil health, and application of organic manure helps in maintaining high organic carbon content of the soil. Shrink-swell soils have very low organic matter content. Therefore, without regular application of organic manures and recycling of crop residues, we cannot hope to maintain good soil health to sustain productivity and ensure high responses to fertilizers. For rejuvenating soil health, it is very essential to step forward to formulate a soil-centric programme, *viz.*, conservation of agriculture practices, INM and IPM, crop residue management, green manuring, cover crop and mulching, crop diversification with strong support of government policies.

Climate Change and Its Impact on Agricultural Productivity

The Inter-Governmental Panel on Climate Change (IPCC), in its 5th Assessment Report, has warned that the global climate has been changing and it will continue to change in future (Field and Barros,

2014). The scientific community has stated that due to climate change, global temperatures are expected to increase, which will significantly hamper agricultural productivity. The Food and Agriculture Organisation (FAO) (2018) report indicated a continuous rise in world hunger due to the impacts of climate change on agriculture.

The agricultural sector in India is climate-sensitive and highly vulnerable due to its monsoon climate, widespread poverty, and the dependence of about 58 per cent of its population on agriculture for their livelihood. Among the 119 countries, India ranked 100 and was classified in the “serious category” with a score of 31.4 in the 2017 Global Hunger Index (Von Grebmer *et al.* 2017). Therefore, nations must act sincerely to achieve the Sustainable Development Goals (SDGs) related to food security and improved nutrition.

Impact of Climate Change on Soil Health

Healthy soils are a natural source of essential plant nutrients and play a critical role in achieving higher agricultural productivity. Soils are formed by the complex interaction of many factors (*viz.*, climate, relief, parent material, and organisms) over time. However, the climate factor is the most significant element that influences soil formation, substantially impacting soil development and management regarding structure, stability, water retention, fertility status, and erosion (Karmarkar *et al.*, 2016). Higher temperature and weather extremes, *viz.*, extreme rainfall, drought conditions, frost situations, storms, and a rise in sea level, are the main predicted outcomes of climate change, which pose serious threats to the soil in terms of erosion, compaction, soil health and productivity (Lal, 2011). Higher CO₂, temperature, and rainfall significantly impact the diversity and distribution of microbes, as well as soil erosion, runoff, infiltration, and moisture storage, ultimately affecting soil health and fertility (Balasundram *et al.*, 2023). The expected consequences of climate change on various soil processes are listed in Figure 2.

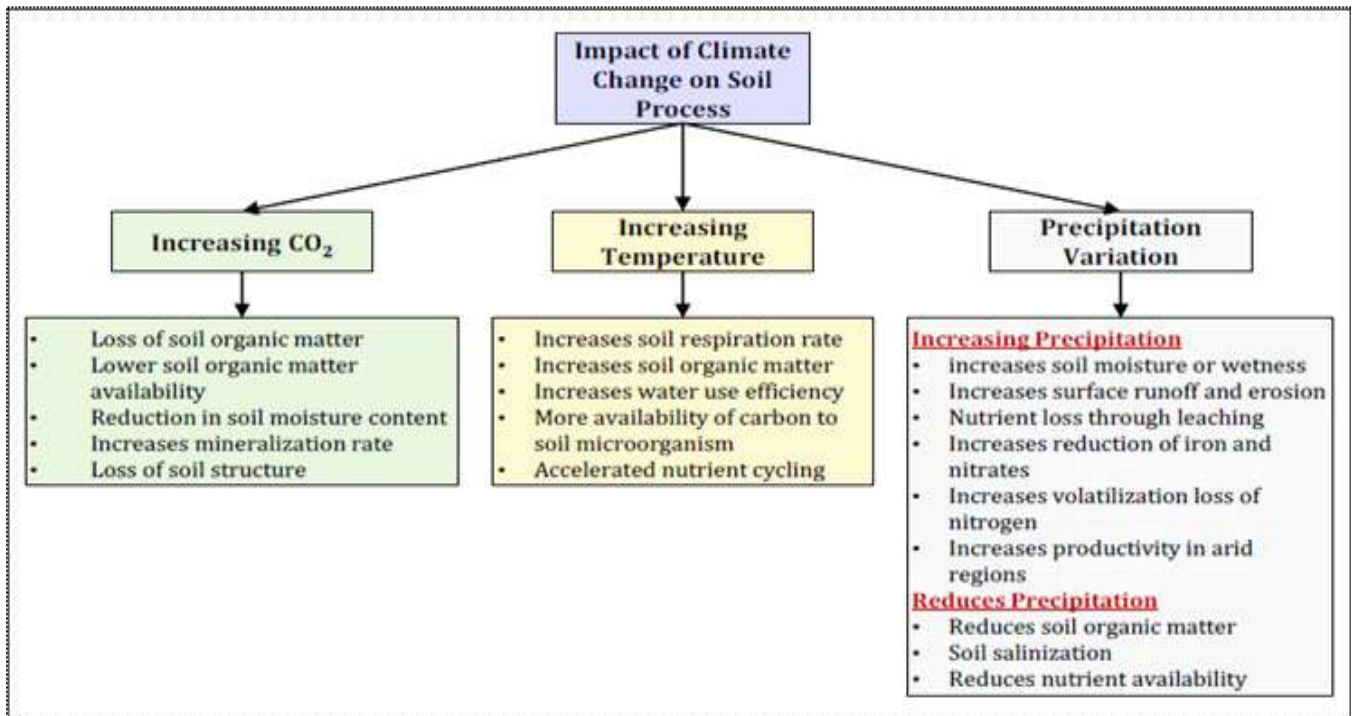


Fig. 2: The possible influence of climate change on soil activities (Source: Balasundram et al., 2023)

Climate change will also impact the soil, a vital component of the agricultural ecosystem. The amount and activity of soil organic carbon and microorganisms, therefore, influence soil productivity and nutrient cycling.

Climate Smart Soils for Climate Smart Agriculture

The vital share of success of climate-smart agriculture depends on a climate-smart soil management strategy, which is a smart approach for helping soil through enhanced carbon loading, curbing greenhouse gas emissions, and improving productivity under changing climatic conditions. Agricultural land contributes a major share (37% as N_2O and CH_4) of agricultural emissions. (Tubiello *et al.*, 2013) While land has contributed 25% of total global anthropogenic GHG emissions (Smith *et al.*, 2014).

Decreasing GHG emissions and sequestering carbon through improved soil management practices increases soil organic matter (SOM) content and tightens the nutrient cycle in the soil, thereby improving

fertility, productivity, and biodiversity, which in turn helps develop resistance capacity against the adverse effects of climate change (Rakshit *et al.*, 2021). The SOM acts as a sink for atmospheric carbon, which helps to improve soil structure as a stable aggregate, nutrient bio cycling, and also impacts the biological resilience of the agro-ecosystem. During decomposition of SOM, the multiplication of soil biota in the soil food web releases essential plant nutrients and also forms a clay humus complex by enhancing soil CEC.

The French Govt has suggested an increase in the carbon concentration of soil carbon in agricultural soil of 0.4% per year, in accordance with the Conference of the Parties to the UN Framework Convention on Climate Change (UNFCCC) negotiations in December 2015. This would lead to a 1.2 petagram (Pg) increase in carbon sink per year. (Paustian *et al.*, 2016). The native ecosystem usually supports much higher soil carbon stock than agricultural counterparts, and soil C loss ranged from 0.5 to greater than 2 t per year of carbon by following land conversion to crop land (West and Six, 2007).

Climate-smart agriculture (CSA) can be defined as a strategy for addressing the challenges of climate change and ensuring food security in the pursuit of achieving the SDGs (FAO, 2010). The CSA has three focal areas, viz., (1) agronomic and economic productivity, (2) adapting and building resilience to climate change, and (3) Climate change mitigation (Palombi and Sessa, 2013). The key concept related to

raising productivity is increasing food production sustainably from existing farmland while minimising pressure on the environment (Totin *et al.*, 2018).

There is a need to implement climate-smart management practices to enhance carbon sequestration and mitigate agricultural soil greenhouse gas (GHG) emissions. Figure 3 illustrates an integrated research support and implementation platform with appropriate climate-smart management practices.

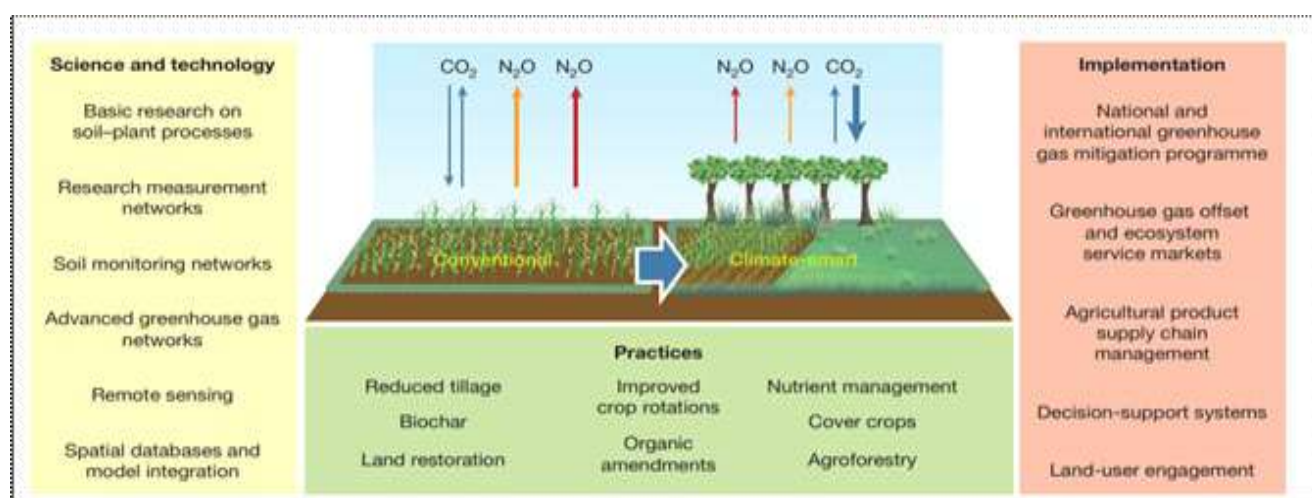


Fig. 3: Climate Smart Soil Management Strategy and Implementation platform (Source: Paustian *et al.*, 2016)

Management Strategies for Climate-Smart Soil

1. Conservation Agriculture

Conservation Agriculture (CA), an approach based on the principles of minimum soil disturbance, retention of crop residues, or any other soil surface cover combined with appropriate crop rotation has emerged as an important management strategy to bring favourable changes in soil properties which affect the delivery of ecosystem services including climate regulation through carbon sequestration and greenhouse gas emissions (Palm *et al.*, 2014). Zero tillage has been reported to increase soil organic carbon (SOC) by $270 \text{ kg ha}^{-1}\text{yr}^{-1}$ (Gangwar *et al.*, 2006) to as high as $501 \text{ kg ha}^{-1}\text{yr}^{-1}$ (Pandey *et al.*, 2012), whereas retention of crop residues has been reported to increase SOC by $90 \text{ kg ha}^{-1}\text{yr}^{-1}$ to $440 \text{ kg ha}^{-1}\text{yr}^{-1}$ (Nayak *et al.*, 2012). With these

considerations, a long-term experiment was established in 2006 to evaluate the effect of various combinations of tillage, crop establishment methods, and crop residue management on crop productivity, economic profitability, and SOC changes in rice–wheat under maize–wheat–green gram cropping system (Modak *et al.*, 2019). Their results indicated that conservation agriculture practices lead to 40% higher SOC sequestration in top layers. Deep soil layers accounted for 68 % of sequestered carbon. The SOC accumulation and sequestration rates were also enhanced significantly by conservation agricultural practices. SOC sequestered in aggregates significantly enhanced crop yields.

About 400 million tonnes of crop residue are produced in the country, which has the potential to supply about 7.3 million tonnes of NPK. Sugarcane crop is one of the major cash crops grown in India. Sugarcane can add huge quantities of biomass to the soil. After harvest of

the sugarcane, 8-10 t trash ha⁻¹ is generated. Burning of trash is a common practice in sugarcane-growing areas, leading to significant loss of precious organic matter and nitrogen loss through volatilisation. CSRS, Padegaon of MPKV, Rahuri, recommended technology for the sugarcane trash management. Application of 1 kg decomposing culture, 8 kg urea and 10 kg single super phosphate per ton of sugarcane trash with 10 t ha⁻¹ FYM is recommended to ratoon sugarcane for obtaining higher cane yield and maintaining soil fertility.

Reddy (2024) evaluated the impact of tillage, residue and nutrient management on soil organic carbon, biology and yield under a multi-ratooning sugarcane system in basaltic soils of semi-arid tropics. The results indicated that residue retention had a 17% higher total SOC, with 63%, 34%, and 15% higher labile, less labile, and non-labile C pools, respectively, than residue burning. The total SOC stock contribution of passive pools was 72-78 % higher than that of active pools. Reduced tillage coupled with residue retention and 50% RDF as basal and 50% through fertigation plots showed higher microbial and enzymatic activity and the highest net SOC enrichment of 5.23 Mg C ha⁻¹. In four seasons, a maximum average ratoon cane yield (153 t ha⁻¹) was obtained in reduced tillage with residue retention, whereas yields (137 t ha⁻¹) were reduced in the residue burning treatment; the corresponding values for conventional tillage were 113 and 95 t ha⁻¹, respectively.

The results of 32-year long-term tillage and nutrient management practices on *rabi* sorghum grown on Vertisols in Dry farming research station, Solapur revealed that the TOC in minimum tillage (Table 1) at harvest was found to be significantly highest (0.92 and 0.85%) at 15-30 and 30-45 cm soil depth over conventional tillage (0.81 and 0.75%) respectively. The higher TOC in LT and MT practices compared to CT might be due to fewer disturbances to the surface layer of the soil, which might have led to sequestration and greater conservation of organic carbon in the soil. The depth-wise C sequestration rate as influenced by tillage management practices under rainfed *rabi* sorghum was increased with an increase in soil depth. At all three depths, the medium tillage practice was found to have a significant C sequestration rate over conventional

tillage. A comparatively slow carbon sequestration rate was attributed to the disruption of soil aggregates, the incorporation of crop residue during tillage operations, and enhanced soil carbon mineralisation, resulting in increased aeration and drier conditions, which caused a reduction in soil carbon stock (Kalbhor, 2019). Tillage practices have a significant effect on SOC pools. Intensive cultivation enhances the oxidation rate and microbial activity through decomposition by increasing aeration and temperature, resulting in a significant loss of SOC from the surface layer (Purkayastha *et al.*, 2008).

2. Cover cropping and mulching

Planting cover crops during fallow periods or between cash crops helps in preventing erosion, compaction, improving soil fertility, reducing weed growth, promoting growth of beneficial soil organisms, enhancing carbon sequestration, and reducing the need for chemical fertilisers. Growing leguminous plants as a cover crop can help to increase carbon pools and reduce C and N loss from soil (Singh *et al.*, 1998). Tonitto *et al.* (2006) found that cover crops reduce nutrient losses, including nitrate that is otherwise converted to N₂O. Higashi *et al.* (2014) showed that cover cropping with conservation tillage (mainly no tillage) in sandy clay loam soil increased SOC concentration up to 22%. Growing of cover crops in sandy clay loam soil gives stability to soil aggregates, which in turn provides protection to SOC from mineralisation (Unger, 1997).

Mulch plays a vital role in moisture conservation, water infiltration, maintaining temperature and stabilising soil structure. Mulches modify the hydrothermal regime, recycle plant nutrients, promote crop development and increase yields. Kadam (2022) studied the effect of different crop residue mulching on soil temperature, soil moisture and nutrient availability in *rabi* sorghum under *rainfed* condition and found that the treatment having wheat straw mulch recorded significantly higher sorghum grain yield (23.8 q ha⁻¹) and stover yield (54.9 q ha⁻¹) as well as soil organic carbon content (7.2 g kg⁻¹) in rainfed *rabi* sorghum which was at par with pearl-millet straw mulch, Gliricidia tendrils mulch and sorghum straw mulch. The moisture

use efficiency ($4.34 \text{ kg ha}^{-1} \text{ mm}^{-1}$) was found significantly higher in the treatment having wheat straw mulch in *rainfed rabi* sorghum, followed by the use of pearl-millet straw mulch.

3. Agroforestry:

Agroforestry is very important as a carbon sequestration strategy because of the carbon storage

Table 1: Effect of tillage on depth wise distribution of total organic carbon and soil carbon sequestration rate in dryland *rabi* sorghum

Treatment	TOC (%)			Soil respiration rate ($\text{mg CO}_2\text{-C } 100 \text{ g}^{-1} \text{ of soil}$)			C seq. rate ($\text{kg ha}^{-1} \text{ yr}^{-1}$)		
	0-15 cm	15-30 cm	30-45 cm	0-15 cm	15-30 cm	30-45 cm	0-15 cm	15-30 cm	30-45 cm
LT	0.98	0.86	0.80	7.9	7.4	6.9	438.2	493.8	618.8
MT	1.00	0.92	0.85	8.6	8.0	7.5	535.1	690.9	749.9
CT	0.99	0.81	0.75	8.0	8.1	6.9	508.7	490.0	604.9
Mean	0.99	0.87	0.80	8.1	7.6	7.1	494.0	531.9	657.2
CD ($p=0.05$)	NS	0.02	0.02	0.33	0.41	0.32	46.0	44.8	24.1

Low Tillage (LT) - Seed drill sowing + light harrowing after sowing (SSDH),

Medium Tillage (MT) - One harrowing + SSDH + One hoeing

Conventional Tillage (CT) - Ploughing once in 3 years + One harrowing + Ridges and furrows+ One harrowing + SSDH + three hoeing.

potential in its multiple plant species and soil, and its applicability in agricultural lands and reforestation. Agroforestry can also indirectly benefit carbon sequestration by helping to decrease pressure on natural forests, which are the largest terrestrial carbon sinks. Forests play a major role in global terrestrial carbon cycling. On the one hand, forests, through photosynthesis, sequester carbon dioxide from the atmosphere and accumulate biomass (including trunks, branches, leaves and roots) as well as contributing to organic carbon in soils. Though forests account for only 38% of terrestrial lands on the earth, they store 893 Pg C or 45.70% of the terrestrial carbon stocks (Yoda, 1993). The ability of bamboo to sequester high amount of C per unit time can make the bamboo-based agroforestry system a possible prototype for Clean Development Mechanism (CDM) type projects.

Integrating trees with crops or livestock on the same piece of land helps in improving soil fertility, enhancing biodiversity, providing shade, and

sequestering carbon. A long-term field experiment on different species of bamboo was conducted by Gaikwad *et al.* (2022) at NARP, Dryland Sub-Centre (Agroforestry), Mahatma Phule Krishi Vidyapeeth, Rahuri. The results concluded that the highest soil carbon sequestration rate (Table 2) was found in the soil under the treatment of *Bambusa nutans* ($27.31 \text{ t C ha}^{-1} \text{ yr}^{-1}$), followed by treatments of *Bambusa tulda* ($25.75 \text{ t C ha}^{-1} \text{ yr}^{-1}$). Whereas, the carbon sequestration rate in different bamboo species varies from $11.95 - 27.31 \text{ t C ha}^{-1} \text{ yr}^{-1}$.

4. Crop Rotation and Diversification

Alternating different crops in a given field within a specific time can help in reducing soil erosion, nutrient depletion, breaking pest and disease cycles, improving soil structure, and nutrient cycling. Diversification can also enhance resilience to climate extremes. A farming system model encompassing crops, trees and livestock is the best option against climate change, recurrent

Table 2: Effect of different bamboo species on total carbon stock and carbon sequestration rate

Treatment	Total plant biomass carbon stock (t C ha ⁻¹)	Total soil carbon stock (t C ha ⁻¹)	Total carbon stock (Plant + soil) (t C ha ⁻¹)	Bamboo carbon sequestration rate (t C ha ⁻¹ year ⁻¹)
<i>D.brandisii</i>	16.46	19.50	35.96	17.98
<i>B.nutans</i>	27.83	26.79	54.62	27.31
<i>B.balcooa</i>	9.16	20.60	29.76	14.88
<i>D.strictus</i>	11.90	24.47	36.37	18.19
<i>B.tulda</i>	26.68	24.82	51.50	25.75
<i>B.bamboos</i>	8.57	15.34	23.91	11.95
<i>D.asper</i>	11.33	16.22	27.55	13.78
SEm±	0.22	0.10	--	--
CD @5%	0.67	0.29	--	--

Source: Gaikwad *et al.*, (2022)

droughts, loss of biodiversity and land degradation. Three farming system models were evaluated during 2008-09 and 2009-10 at MPKV, Rahuri, Maharashtra, to study their effect on the economic returns, water productivity, employment generation, energy balance and soil health improvement. The integrated farming system (IFS) involving field crops, horticulture, dairy, poultry and fishery proved promising and remunerative to the soybean–wheat cropping system with higher net returns, water productivity, employment generation and energy output. On-station and on-farm IFS models were found more remunerative than the on-station cropping sequence model, showing maximum net returns of Rs. 1,99,848, water productivity (Rs. 991 ha⁻¹cm⁻¹), employment generation (1,275 mandays ha⁻¹ yr⁻¹) and energy balance (4,11,949 MJ ha⁻¹), while the on-farm IFS model resulted Rs. 48,477, Rs. 406 ha⁻¹cm⁻¹, 657 mandays yr⁻¹ and 3,25,528 MJ ha⁻¹ values of these parameters, respectively (Surve *et al.*, 2021).

5. Organic Farming

Organic farming plays an essential role in the

improvement of soil physical, chemical, and biological processes, and the soil organic carbon (SOC) is one of the most important indicators of soil quality and health. It helps to enhance soil fertility and crop productivity. Therefore, maintaining or increasing SOM is critical. Soil is a component of the terrestrial carbon (C) cycle and can be either a source or a sink of atmospheric carbon dioxide. So, their judicious management has a significant potential for mitigation of CO₂ and other GHG emissions (Ghosh *et al.*, 2012).

The use of synthetic nutrients is banned on organic farms, so organic farmers must rely on naturally occurring fertilisers such as compost and manure for enhancing nutrient content in soils. The use of organic amendments has been shown to increase soil carbon sequestration, which may help to mitigate climate change by locking away carbon that could otherwise act as a greenhouse gas in the atmosphere. However, organic soil amendments can vary significantly in nutrient content, carbon-to-nitrogen ratios, and the timing of nutrient release, which has led to variability in the impacts of organic soil amendments on soil health.

6. Integrated Nutrient Management and Site-Specific Nutrient Management

Using organic sources of nutrients like compost, manure, biofertilisers, and incorporating them with inorganic fertilisers helps in maintaining soil fertility while reducing the environmental impact. Site-specific nutrient management (SSNM) results in higher use efficiency, higher productivity and profitability, besides

positive environmental benefits. A field experiment on a soil test-based targeted yield approach for balanced fertilisation of Bt cotton in Inceptisol was conducted at MPKV, Rahuri, from 2009-10 to 2013-14. Application of fertiliser nutrients as per 40 q ha⁻¹ yield target of Bt cotton along with 10 t FYM ha⁻¹ (Table 3) recorded the highest yield (42.62 q ha⁻¹), B:C ratio and maintained the soil fertility in Inceptisols (Kadlag *et al.*, 2016).

Table 3: Effect of fertilizer application to Bt cotton based on targeted approach on yield, economics, nutrient uptake and residual fertility status (pooled data of 5 years)

Treatments	Cotton Yield (q ha ⁻¹)	Nutrient Uptake (kg ha ⁻¹)			Residual soil fertility status				B:C ratio
		N	P	K	OC (%)	Av. Nutrient (kg ha ⁻¹)			
						N	P	K	
Absolute Control	20.86	77.06	30.66	45.01	0.58	166.4	15.0	485	1.86
GRDF	32.19	128.55	48.94	72.79	0.61	187.2	18.0	530	2.20
AST	31.45	121.82	45.45	70.59	0.59	188.1	17.7	521	2.62
STCR target 40 qha ⁻¹	38.49	153.72	56.79	83.34	0.59	186.3	19.0	562	2.68
STCRC target 40 q/ha+10 t/ha FYM	42.62	167.95	66.08	89.22	0.62	192.1	20.9	570	2.69
Only FYM	26.42	97.62	39.30	53.99	0.68	181.5	16.8	554	1.53
CD (p = 0.05)	2.17	17.02	6.28	8.64	0.035	8.88	1.36	54.74	

7. Soil and Water Conservation Measures

The problem of conserving soil and moisture is of great importance in extensive regions with low and uncertain rainfall. Agricultural land in the major part of the country suffers from erosion. Apart from reducing the yield through the loss of SOM and nutrients, erosion destroys the soil resources themselves every year. Agronomic practices for soil and water conservation help to intercept raindrops and reduce the splash effects, helping to obtain a better intake of water by the soil. The contour cultivation, mulches, dense growing crops, strip cropping and mixed cropping are some of the major practices for improving soil quality. The

impact of *in situ* water conservation measures on different crop yields in different locations of India was summarised by Srinivasarao *et al.* (2016) and given in Table 4. *In situ* water harvesting with simple technologies enables greater water infiltration, improves soil porosity, prolongs the availability of moisture to the crop and enables the crop to survive under variable rainfall conditions (Srinivasarao *et al.*, 2016).

8. Smart Irrigation Practices

Employing efficient irrigation methods such as drip or sprinkler irrigation reduces water wastage, maintains soil moisture, and supports sustainable

Table 4: Impact of *in situ* soil and water conservation measures on crop yields

Practice	Crop	District/Location	Yield improvement over farmers' practice (%)
Regions receiving <500mm rainfall			
Bunding & Levelling	Sorghum	Kutch	30
	Cotton	Kutch	61
	Sesame	Kutch	18
	Castor	Kutch	61
Conservation furrow	Soybean, Pearl millet	Ahmednagar	15
Land levelling	Paddy, cotton, cluster bean	Sirsa	11-33
Regions receiving 500–1000 mm rainfall			
Compartmental bunding	Rabi sorghum	Baramati	45
	Pearl millet	Agra	35
	Pearl millet	S K Nagar	26
Mulching	Okra	Jehenabad	51
	Chilli	Bengaluru	75
	Cotton	Rajkot	12
Conservation Furrow	Castor	Kurnool	8
	Cotton, pigeon pea	Nalgonda	5-8
	Cotton	Aurangabad	10
	Pigeon pea	Aurangabad	15
	Cotton	Rajkot	18
	Groundnut	Anantapur	8
	Soybean	Akola	17
	Soybean, Pigeon pea, Cotton	Parbhani	35-40
Trench cum bunding	Finger millet, maize, horse gram, groundnut	Davanagere	22–24
Bunding	Paddy	Jehanabad	45
	Soybean	Amravati	32
Land levelling	Paddy	Jehanabad	35
	Pearl Millet	Baramati	23
Sowing across slope	Soybean	Amravati	29
Ridge & Furrow	Cotton	Amravati	58
	Black gram, maize, pigeonpea, green gram, soybean, mustard	Morena	8-10
	Castor	Kurnool	18
	Maize, Soybean	Nandurbar	15
	Rabi Sorghum	Solapur	22
Regions receiving >1000 mm rainfall			
Ridge and furrow	Wheat, chick pea, lentil	Uttarkashi	50
	Cotton	Khammam	11
	Tomato	Cooch Behar	74
Mulching	Cucumber	Cooch Behar	10
	Mustard, Toria	East Sikkim	70-82
	Chilli	Khammam	12
	Turmeric, Ginger	East Singhbhum	12-15
	Potato, Tomato	Biswanath Chari	75
Hoeing & Weeding	Paddy, maize, pigeon pea, groundnut, sesame	Phulbani	16-22
Summer ploughing	Maize	BallawalSaun khri	14
Sowing across slope	Maize	BallawalSaun khri	
Set Furrows	Pearl millet, Pigeon Pea	Vijayapur	11-14

Source: Srinivasarao *et al.*, (2016)

agriculture. The MPKV, Rahuri has been contributing a lot in precision irrigation water management, including the development of mobile and web-based applications, IoT and sensor-based applications such as Phule irrigation scheduler (PIS), which is a mobile and web-based application. The Phule Jal mobile app is also developed for the estimation of evapotranspiration rate (ETR). Similarly, the mobile app (Spatial IWR) has also been developed for estimation of location-specific, real-time irrigation water requirement for different crops.

Kale *et al.* (2018) studied the effect of fertigation on yield and nutrient use efficiency of ratoon banana (*var.* Grand naine) cultivated in medium deep soils of Western Maharashtra. The study indicated that 80% recommended dose of water-soluble fertilizer (9:5:33) application through fertigation (18 fortnight splits) increased the ratoon banana crop yields (79.66 t ha⁻¹) with concomitant increase in their nutrient use efficiency (20.19 kg kg⁻¹).

9. Restoration of Degraded Land

a. Restoration of Eroded Soil

The application of tank silt in agricultural land is a traditional practice to improve crop growth. The tank sediment deposited over the years contains all the nutrients required for plant growth and can amend the very eroded soil when recycled, improving soil fertility (Padmaja *et al.*, 2003; Osman *et al.*, 2009). The addition of tank silt to cultivated land also enhances the physical properties, which results in good crop growth and higher yield (Vaidya and Dhawan, 2011). Most of the soils of Osmanabad district in Maharashtra State are very shallow in depth, poor in fertility and moisture-holding capacity and a study was carried out to understand the morphological, physical and chemical behaviour of these hybridised soils when amended with tank silt and its impact on the yield of the soybean crop. The field results showed that the maximum yield of soybean (31.44 q ha⁻¹) was recorded with 1500 m³ ha⁻¹ of silt application corresponding to 15 cm depth, which was threefold higher than that of no application (9.6 q ha⁻¹). Application of tank silt has increased yield by 47 per cent in *rabi* sorghum, and income increased by Rs.

10000/- per ha. It has improved soil fertility and moisture holding capacity as well as enhanced moisture use efficiency up to 50 per cent (Vaidya and Dhawan, 2015)

b. Salt-affected soil

Inorganic carbon in the soil of semi-arid tropics is one of the major reasons for chemical degradation, resulting in poor soil quality and modifying chemical and physical properties into less productive ones. The drier climate is the primary actor responsible for depletion of Ca²⁺ ions from soil solution due to the formation of CaCO₃ (Bhattacharyya, 2021a & b). This suggests that the source of Ca²⁺ for the formation of pedogenic carbonates is the soil exchange complex (Pal *et al.*, 2000), which leads to a concomitant increase in exchange Na, resulting in the formation of sodic soil. Most of the soil properties are influenced by soil modifiers. The positive modifiers are calcium zeolite and gypsum, whereas the negative modifiers are pedogenic carbonates and palygorskite minerals found in Indian soils, which may degrade the physical, chemical, and biological properties of the soil and thus retard crop growth and productivity (Bhattacharyya, 2021a).

The effect of irrigation-induced soil salinity and sodicity on the soil mineralogy of shrink-swell soils was studied by using random powder bulk soil mineralogy by using spray drying techniques, XRD, SEM and TEM studies. These mineralogical studies of fine clays of normal rainfed shrink-swell soils indicated that the predominance of smectite 99%, with a negligible quantity of kaolinite, whereas irrigation induced saline sodic soils showed association of pedogenic palygorskite (1-10 %) with smectite (88-99 %). Bulk soil mineralogy showed an association of pedogenic palygorskite (3-18 %) with smectite in saline sodic soils, which is absent in rainfed normal soils. These results indicated that a saline sodic pedo-environment favours the formation of pedogenic palygorskite (Hiller and Pharande, 2008).

c. Reclamation of Salt-Affected Soil

Soil salinity and soil alkalinity are the primary land degradation processes in agricultural lands, and both adversely affect the crop's yield. Injudicious and inefficient irrigation water management leads to

waterlogging and the development of soil salinity/alkalinity. Integrated soil management of such soils, including reclamation through subsurface drainage (SSD), the use of chemical amendments, salt leaching, improved agronomic practices, irrigation and nutrient management, alternate land uses, and the use of salt-tolerant varieties, has a profound effect on

productivity. Subsurface drainage and mole drainage help to improve physical and chemical properties. Subsurface drainage (SSD) with corrugated perforated pipe at 1.32 m depth and 25 m lateral spacing (Table 5) showed a significant decline in water table, an increase in drain discharge, and hydraulic conductivity after 3 years of installation in Vertisols (Rathod *et al.*, 2008).

Table 5: Effect of SSD on soil physical and chemical properties in Vertisol at ARS, K. Digraj

Soil properties	Hydraulic conductivity (m day^{-1})	Drain Discharge (L Day^{-1})	Water table (cm)	Soil pH	Soil EC (dS m^{-1})
Initial	0.0236	-	26.50	8.47	9.25
After 1 year	0.0297	5669.76	120.00	8.11	8.11
After 2 nd year	0.0421	8138.67	122.86	7.63	5.75
After 3 rd year	0.0575	9813.37	126.40	7.59	3.60

Source: Rathod *et al.*, (2008)

Results of RKVY Farmer First Project

The subsurface drainage (SSD) technology was demonstrated at 10 different locations on farmers' fields in the Sangli district of Maharashtra, specifically on

saline-sodic Vertisols. The soil pH, EC, and ESP were continuously decreased (Table 6), resulting in improved physical and chemical properties within three years.

Table 6: Effect of subsurface drainage (SSD) on soil properties in saline sodic Vertisols on farmers' field of Sangli district

Period	Soil properties		
	pH (1:2.5)	EC (dS m^{-1})	ESP
Before SSD	8.40	15.80	15.30
1 year after SSD	8.17	11.80	11.73
2 years after SSD	7.67	6.32	5.72
3 years after SSD	7.66	4.40	5.12

Results of Community-Based Subsurface Drainage Project

The Datta Co-operative Sugar Factory, Shirol, Dist. Kolhapur, Maharashtra, implemented community-based SSD technology on the 7000-acre area of the adjoining 19 villages of Shirol tehsil.

Development of subsurface drainage has increased the productivity (Table 7) of land appreciably to the tune of 96 per cent and has provided a source of regular income of Rs. 142533 ha^{-1} from sugarcane to resource-poor farmers. The B: C ratio of sugarcane production under irrigation induced soil degradation, analysed through the budgeting technique before drainage and after

installation of SSD, was 0.87 and 1.59, respectively. The increase in yield is due to a drastic decrease in soil salinity. The initial electric conductivity of the soils ranged between 7.20 and 28.00 dS m⁻¹, whereas the electric conductivity of the soils after one year of

installation of sub-surface drainage was in the range of 0.60 and 5.74 dS m⁻¹. The overall reduction in the soil electric conductivity was 95 per cent within one year after installation of sub-surface drainage technology (Patil, 2022).

Table 7: Impact of SSDS on yield of sugarcane on community based SSDS project, Tal. Shirol, Dist. Kolhapur, Maharashtra.

Sr. No.	Name of Farmer	Yield of sugarcane before SSD (t ha ⁻¹)	Yield of sugarcane after SSD (t ha ⁻¹)	Increase in yield (t ha ⁻¹)	Percent increase in yield
1.	Shri. MallapaAinapure	51.38	117.85	66.47	129.37
2.	Shri. RamgondaAinapure	84.35	122.88	38.53	45.68
3.	Shri. BaburaoMaraje	58.68	129.37	70.69	120.47
4.	Shri. BaburaoMaraje	73.98	139.44	65.46	88.48
	Average	67.10	127.39	60.29	96.00

Source: Patil, (2022)

Futuristic Farming: Precision Farming Tool for Climate Smart Agriculture

Precision Agriculture is a management strategy that gathers, processes, and analyses temporal, spatial, and individual data, combining it with other information to support management decisions based on estimated variability, thereby improving resource use efficiency, productivity, quality, profitability, and sustainability of agricultural production. It involves the precise management of resources, such as soil, water, fertilisers, seeds, and pesticides, using tools like GPS, satellite imagery, remote sensing, sensors, IoTs, and data analytics. Through these tools, precision agriculture can significantly contribute to combating climate change by reducing greenhouse gas emissions, preserving natural resources and promoting sustainable practices. The key components and methods are soil moisture resources, weather data, an automated irrigation system variable rate irrigation/ applicator, crop sensors, remote sensing imagery, irrigation scheduling software, and precision fertigation for nutrient management. The tools required for precision agriculture are GPS, GIS, remote sensing, grid soil sampling, variable rate applicator, soil

spectroscopy, information management, yield monitoring and mapping IoT, etc. (Lenka *et al.*, 2023). Some of the precision agriculture strategies for combating climate change include site-specific resource management for irrigation and nutrient management, precision seeding, weed management, etc. The primary goal is to enhance crop yield by minimising agricultural input wastage, energy consumption and environmental impact (Kumar *et al.*, 2021)

Indian Council of Agriculture research (ICAR) and National Agriculture Higher Education Project (NAHEP) sanctioned a World Bank-aided project entitled Centre for Advanced Agriculture. Science and Technology for Climate Smart Agriculture and Water Management to M.P.K.V., Rahuri to develop climate-smart technology on water management and strengthen the postgraduate and Doctoral level programmes and the Postgraduate diploma in the respective field. The various climate-smart solution was developed with advanced technologies such as the application of robotics, drones, IoTs, geoinformatics, and precision machineries for climate-smart precision and efficient farming activities. The outcome of this project is the development of different tools/systems viz., Auto Phule irrigation

Scheduler, Agriculture spraying and seeding drone, Smart weather stations, Phule soil moisture sensor-based irrigation scheduling system, Smart Phule irrigation scheduler and Phule Robo for spraying. Therefore, there is a need to create awareness among students, researchers and farmers about climate-smart precision agriculture technology and to identify the research studies to make these techniques available to small and marginal farmers for their effective use.

Conclusions

The vital share of the success of climate-smart agriculture depends on a climate-smart soil management strategy, which is a smart approach for keeping soil healthy and sustainable through enhanced carbon loading, thereby curbing greenhouse gas emissions and improving crop production under changing climatic conditions. Climate-smart soil is highly relevant for mitigating and building resilience in the agricultural system, while also increasing or sustaining production in a climate change scenario. Climate-smart soil management practices, such as conservation agriculture, the implementation of integrated farming systems, improving soil biodiversity, organic farming, reducing soil degradation processes, and precise water and nutrient management practices, should be adopted based on the farmer's economic condition and resource availability. The development of climate-smart, soil-water, and nutrient-efficient management technologies is the need of the hour for sustainable soil health. It is crucial to ensure this benefit; there should be good linkage between researchers, students, farmers and policymakers for achieving sustainable soil health and productivity.

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