POLICY PAPER

100

Strategies for Enhancing Soil Organic Carbon for Food Security and Climate Action

NATIONAL ACADEMY OF AGRICULTURAL SCIENCES, NEW DELHI

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Preface

Soil organic carbon (SOC) governs the native productive capacity of soils and regulates climate change and ecosystem services that are critical for sustainable growth of agricultural productivity and food supplies. Management practices influence soil carbon build-up and its subsequent sequestration. Intensive tillage accelerates decomposition and diminishes carbon content while integrated nutrient supply promotes its restoration and retention. Since India has a predominantly tropical agroecosystem, the scientific efforts hover around understanding SOC dynamics in terms of spatial and temporal distribution. Indian soils are low in carbon, hence the strategies on its restitution through the addition of organic manure, legume intercrops and conservation tillage must be central to the smart soil management practices. This becomes more important in view of the declining factor productivity and rising cost of inputs. India has pledged in the 2015 Paris Agreement to reduce greenhouse gas emission intensity by 33-35% of the 2005 level by 2030. For this, a carbon sink of 2.5-3 billion tonnes of CO_2 equivalent has to be created by 2030. Another action agreed upon in the Paris Agreement is to implement the '4 for 1000' initiative, which means raising the SOC level at a rate of 0.4% per annum in the top 1 m soil layer.

In view of the above, the NAAS organized a brainstorming session on *"Strategies for Enhancing Soil Organic Carbon for Food Security and Climate Action"* on August 21, 2020. The session was attended by representatives of the Indian Council of Agricultural Research, State Agricultural Universities, Ministry of Agriculture and Farmers Welfare, Ministry of Environment, Forest and Climate Change, CGIAR and UNDP. I trust and believe that the recommendations emerging from this session will be well received by the stakeholders, including the scientific community, farmers, and developmental organizations.

On behalf of the academy, I compliment Drs Ch Srinivasa Rao and Anil K. Singh for organizing this brainstorming session, and sincerely thank all the participants. I also thank Dr P.S. Birthal and Dr (Mrs) Malavika Dadlani for their editorial support in bringing the document to its present shape.

(Trilochan Mohapatra)
President
National Academy of Agricultural Sciences

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Strategies for Enhancing Soil Organic Carbon for Food Security and Climate Action

1. INTRODUCTION

Despite significant economic progress, a large population in the world still continues to live in abject poverty and suffers from undernutrition. In 2018, more than 820 million people suffered from hunger making it the biggest challenge of achieving the target of zero hunger (SDG 2) by 2030 (FAO, IFAD, UNICEF, WFP and WHO, 2019). Another worrying fact is that around 2 billion people experience moderate to severe food and nutritional insecurity.

The global agricultural production is estimated to increase by 60% by 2050 over 2005 (Alexandratos and Bruinsma, 2012). However, climate change and its extreme events, primarily driven by anthropogenic activities, are adversely affecting the agricultural productivity and natural resources. Climate-related disasters, namely, droughts, floods, and storms, account for 80% of all global disasters. During 2011-2016, large parts of the world were affected by severe droughts, leading to crisis-level food insecurity for 124 million people in 51 countries. Climate change can push another 122 million, mainly farmers, into extreme poverty by 2030 (IPCC, 2018). Agriculture absorbs 26% of the economic impact of climate disasters, rising to 83% for drought in developing countries (FAO, 2015).

One-third of the global soils are degraded, releasing 78 gigatons (Gt) of carbon-di-oxide into the atmosphere, which cost over 10% of the global GDP through lost biodiversity and ecosystem services (FAO 2019). The atmospheric concentration of greenhouse gas (GHGs) emissions has increased from 277 ppm in 1750 to 403.3 ppm in 2016 (WMO, 2016). Climate change, including its extreme events (i.e., floods, droughts, heatwaves, cyclones, storms and sea-level rise) already have a range of complex impacts, especially in environmentally fragile areas and ecosystems. Such environmental issues are mostly related to hunger, health, food consumption patterns, education, gender gaps, inequality and migration. Environmental problems, viz., land degradation and resource depletion (water, energy, food and biodiversity) are the major sources of conflict and migration (Gupta et al., 2016; UNCCD, 2017). Irregular rainfall patterns driven by climate change adversely affect crop yields (Mandal et al., 2008; Srinivasarao et al., 2012a, b). Thus, environmental protection and achieving sustainability of the production system are the major concerns (ILO, 2016). There is the prediction of a significant increase in the prices of staple food crops, and in the number of hungry people by 2050 (IFPRI, 2014). However, the questions confronting the global community are: Will the global food production be able to meet the food demand of the growing population? Can this demand be satisfied without impairing the natural resource ?

Soil organic carbon (SOC) influences three major functions, viz., land degradation neutrality, agricultural productivity and climate change adaptation and mitigation. Land degradation neutrality can be achieved by increasing water-holding capacity; faunal activity and soil aeration; improving soil structure; soil buffering capacity; and reducing soil erosion. Agricultural productivity can be increased by increasing nutrient cycling and improving soil-water-nutrient-crop relationships. Climate change adaptation can be achieved through increased water storage and nutrient-use efficiency, and mitigation by offsetting the greenhouse gases through the improvement of SOC. SOC also plays an essential role in maintaining soil and water quality, as well as plant nutrition and health. Therefore, maintaining and enhancing SOC in diverse ecosystems is critical for food security, land degradation neutrality and climate action.

1.1. Global strategies for SOC improvement

Soil organic carbon (SOC) content, being an energy source for soil biota, is a critical determinant of soil health, and has multiple functions in soil-water-environmental interactions. The physical, chemical and biological properties of soil contribute to overall soil health. In fact, soil health is directly dependent on SOC. Healthy soil is the key to higher crop yield and its resilience against drought. Hence, soil health management has occupied the central stage in the discussion on global food security and climate action (Lal et al., 2018, Srinivasarao et al. UNFCCC, 2020; Lal, 2020). Meeting the increasing demand for food, and achieving sustainable development goals (SDGs) are dependent on efficient management of land and water resources.

The importance of SOC at the United Nations Framework Convention on Climate Change (UNFCCC) is amply reflected by the concept of '4 per mille' SOC on global platforms: which implies increase in global soil organic carbon (SOC) stocks by 4 per 1000 (or 0.4%) per year as a basis for food security and compensation for global emissions of greenhouse gases (GHGs) by anthropogenic sources, conceptualized at the Conference of Parties (COP21), Paris, France. The report says '4 per mille' (Minasny et al., 2017) or even higher sequestration rates can be achieved under the best management practices. High C sequestration rates (up to 10 per mille) can be achieved for soils with low initial SOC stock, and in the first twenty years after the implementation of best management practices. Areas which have reached equilibrium will not be able to increase their sequestration further. The 4 per mille number was based on a blanket calculation of the whole global soil profile carbon stock, however, the potential to increase SOC is mostly on the managed agricultural lands. Considering 4 per mille in the top 1m of the global agricultural soils, SOC sequestration is between 2-3 Gt per year, and can effectively offset 20–35% of global anthropogenic greenhouse gas emissions. Overall, the strategy of improving SOC in diverse ecosystems is to move to land degradation neutrality (LDN), sustainable food production and climate action for reducing GHGs.

1.2. SOC and Indian agriculture

India supports 1.35 billion of the 7.70 billion global population on 2.4% of the land area and 4% of the water. Hence, there is tremendous pressure. The per capita land availability declined from 0.136 ha in 2006 to 0.118 ha in 2018 and the per capita water has reduced from 5177 m^3 in 1951 to 1486 m^3 by 2021. Indian soils are low in SOC in the top plow layer (0.2 meters). Several studies have estimated SOC in Indian soils (Bhattacharyya et al., 2008; Srinivasarao et al., 2009; Banger et al., 2015; Sreenivas et al., 2016). With an annual Carbon emission of about 566 million tons, the required Carbon sequestration rate for India would be about 23–28 per mille as against the global requirement of '4 per mille' (Katyal, 2020). Considering only a marginal increase in forest area (0.56% between 2017-2019) (Forest Survey of India Report, 2019) and available 120.72 million ha of degraded land (ICAR/NAAS, 2010), there is an immediate need for rehabilitation measures for improving SOC stock.

1.3. Lessons from long-term manurial experiments in India

Long-term experiments with balanced fertilization (NPK) and 5–10 Mg ha^{-1} year^{-1} of organic residues in cropped land have shown an increase in SOC content by 10–20% of the soil's initial value ensuring a carbon build-up rate of only 0.13 to 0.27 t C ha^{-1} year^{-1} under different rice-based cropping systems (Srinivasarao et al., 2012a). The average SOC sequestration rate in different rainfed production systems is in the range of 240-790 kg ha^{-1} year^{-1} with the application of 4-10 Mg ha^{-1} of FYM/crop residue/groundnut shell/green leaf manure (Srinivasarao et al., 2014). With these carbon sequestration rates of 0.024 to 0.089 Gt year^{-1} and about 25 Gt of SOC stock in India, it may be possible to contribute about 1–4 per mille SOC lost through C emission. Long-term experiments have clearly shown that to cause zero depletion and maintain the SOC level, at least 0.31 to 5.16 t C ha^{-1} year^{-1} is needed to be added to soils through crop residues or some other organic sources in different agro-ecological zones of the country. Promotion of pulses and legumes, diverting a part of fertilizer subsidy and efficient use of available crop residues (679 million t annually) and municipal solid wastes (64.8 million t annually) along with green manuring and suitable cropping systems may help improve or at least curb declining trends in SOC stock in Indian soils (Srinivasarao et al., 2020).

2. TECHNOLOGICAL OPTIONS FOR ENHANCING SOC AND ITS MULTIPLE FUNCTIONS

2.1. Land degradation neutrality (LDN)

Soil degradation is one of the major constraints threatening the food security of the country. Of the 328.7 million ha of total land, 36.70% (120.72 Mha) is degraded. Among the principal degradation processes, 60.27% (73.27 Mha) is affected by water erosion, 10.30% (12.40 Mha) by wind erosion, 14.50% (17.45 Mha) by chemical degradation, and 0.90% (1.07 Mha) by physical degradation (ICAR/NAAS, 2010). Soil erosion (water and wind erosion processes) and removal of surface soils (human activities) are the key reasons for the degradation. Accelerated soil erosion is considered to be the principal cause of a decline in the SOC pool. Poor and inappropriate management practices, as well as climate change, contribute to the physico-chemical and biological degradation of cultivable lands.

The major land-degradation components include desertification, salinization, acidification, soil erosion, deforestation, and sand-dune encroachment. Globally, approximately 40% of the agricultural land is severely degraded. Rain-fed agriculture is more frequently troubled by climate change with the temperature being the key factor in the decline of crop yields by hastened decomposition of soil organic matter (SOM). Approximately more than 5 billion tons of top soil is being eroded every year, while nearly 30% of the soil (about 1.6 billion tons) is lost in the sea through rivers. About 74 million tons of major nutrients are lost due to erosion, besides the already stored SOC. Thus, the country loses approximately 0.8, 1.8, and 26.3 million tons of N, P and K respectively. According to Space Application Centre (2016), land degradation is more in states like Telangana, Madhya Pradesh, Odisha, Jharkhand, Karnataka, Jammu & Kashmir, Gujarat, Maharashtra and Rajasthan. Most of the significant processes of land degradation in dry sub-humid and semi-arid regions are the water erosion and removal of vegetation, while in arid regions it is the wind erosion. As SOC is strongly associated with improved aggregation, its enrichment in the soil is considered to reduce the soil erosion process in vulnerable regions. Improving SOC in rainfed drylands and arid ecosystems is a serious challenge due to long fallow periods, soil erosion and rapid decomposition of existing SOC. However, various integrated nutrient management (INM) and better nutrient management (BNM) options under 6 long term manurial experiments (LTME) in different rainfed crops showed considerable improvements in SOC across soil types and ecosystems in India (Figure 1) (Srinivasarao, 2018). The challenge is to work out these critical levels and C saturation levels so that we can estimate the soil carbon saturation deficit to identify hot spots and realizable C sequestration potential; thus improving SOC is strongly linked with LDN strategies across the world. Soil health restoration by improving SOC and soil fertility is amply reflected in the regions where tank silt addition under Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGA) (Figure 2) (Srinivasarao, 2020).

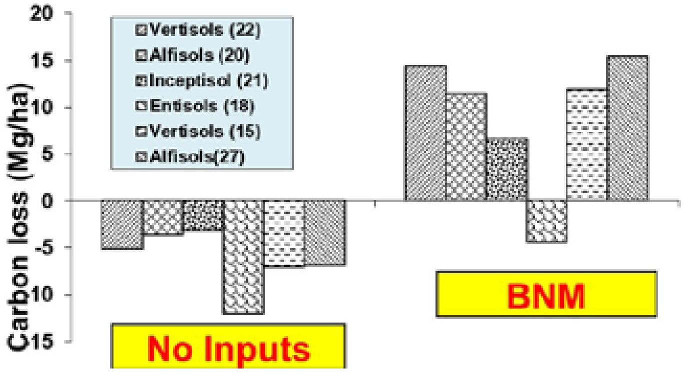

Figure 1. SOC maintenance with integrated nutrient management (INM) practices in rainfed agriculture systems (6 LTME)

Figure 2. Soil restoration with tank silt addition to the Alfisols (red soils) under MG NREGA (Lower-Tank Silt applied; Upper-No Tank Silt applied) in Telangana

2.2. Agricultural productivity

In regions with high inherent SOC content, for example in temperate regions, it may prove difficult to further increase their C levels, as these regions may have already reached equilibrium with current practices. Conversely, in India with low inherent SOC, it can also be difficult to increase the C content, as high temperature mediates the decomposition of organic matter added to the soil. Cropping management strategies that are based on exogenous C inputs (addition of compost or manure, or biochar sourced from elsewhere) also require additional energy, cost, and resources. There has also been an interest in composting municipal wastes for use as a soil amendment in urban agricultural areas for SOC sequestration and nutrient cycling. The application of straw or crop residues in soil that would otherwise be removed from the field or burnt, has a bigger opportunity for C sequestration. About 300 million tonnes of farm residues from field crops, vegetables, fruits, and flowers are burned in India; and recycling of these may add 120 million tons of organic matter to the soil directly. Application of additional inorganic fertilizers which enhances crop growth, particularly root biomass, and thus additional C sequestration, needs to consider the additional energy. *In situ* management strategies, such as stubble retention, reduced tillage and crop rotation are possible options that not only contribute to the existing soil carbon stocks but also enhance the short-term SOC. Another important option is to promote balanced nutrient application which promotes biomass production of shoot and root and thus provides an opportunity to recycle the organic matter into the soil (Figure 3). Conservation methods, such as the use of nitrogen-fixing legumes, in addition to no-till practices, increase carbon sequestration. Soil erosion reduction technologies in diverse ecosystems of India provide ample opportunity to reduce soil carbon and nutrient loss from farmland. Recycling eroded soil accumulated in farm or village tanks could also improve SOC. For example, the reported critical limit of SOC concentration in tropical soil is 1.1%, however, most cropping soils in tropical regions of India have SOC levels of 0.5% or lower. As per earlier reports, higher critical C input (2.47-3.47 Mg C yr^{-1}) is required in regions receiving a higher rainfall (>900mm) and double-cropping systems. An increase in SOC in the root zone may be possible not only just by increasing the addition of external C input (i.e., FYM, compost) but also by protecting, stabilizing and building up the existing C stocks in soils. Such SOC improvements in soil results in improving nutrient use efficiency (NUE) of added inputs and higher agronomic

Figure 3. Larger biomass availability for recycling into the soil with soil health card based balanced nutrient application in the cotton production system (NAIP Field Report)

productivity as reported in the long-term manurial experiments in India (Figure 4). Further, the availability and affordability of organic manure in large quantities by resource-constrained farmers in rainfed areas is an important consideration. The National Policy on Crop Residue Management provides a good platform to convert biomass into various SOC improving inputs in agriculture and food systems. The overall philosophy is to utilize crop residues for different uses in crop production. Once improved, the SOC contributes to improved food security of various crops as shown in Figure 5.

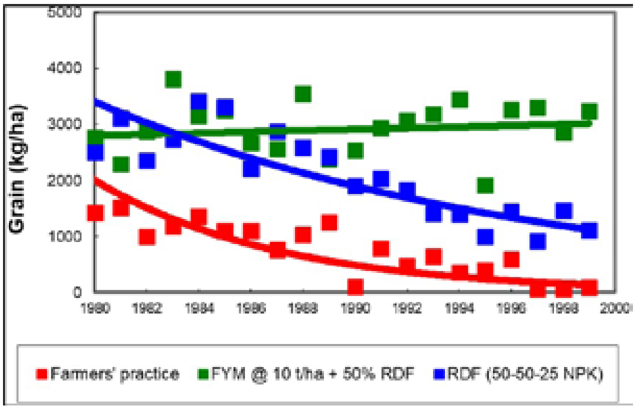

Figure 4. Sustaining the finger millet yield with organics + fertilizers at Bangalore (Alfisols with 750 mm rainfall) (based on Long Term Manurial Experiments Reports)

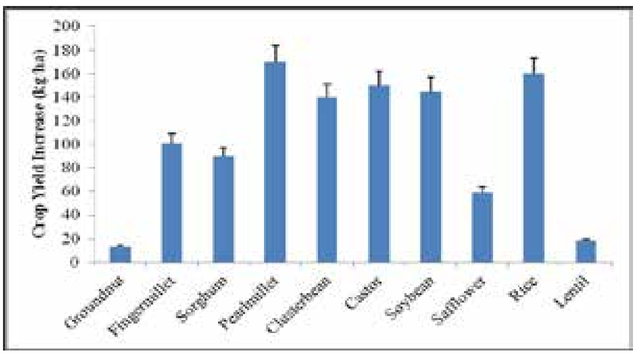

Figure 5. Increase in crop yield (kg /ha) for every Mg /ha increase in SOC stock in the root zone in different rain fed production systems (Srinivasarao et al., 2014)

3. 4 PER MILLE AND CLIMATE ACTION

The "4 per mille" is an ambitious global goal to promote good soil management practices that can help mitigate climate change. Agricultural areas hold about 600 Gt of C in their top 1m of soil. Increasing SOC stocks for all of these areas by 4 per mille (about 2.5 Gt C year^{-1}) can offset about 30% of global greenhouse gases emission. It should be more about the concept than any specific number. There is some scope to increase SOC. The challenge for farmers is to find a new generation of practices that will further improve soil health and increase soil carbon. Such technologies should also avoid offsetting effects for different greenhouse gases. Additionally, the initiative could be an opportunity to implement a sound and credible soil carbon auditing protocol for monitoring, reporting, and verifying SOC sequestration that can be fit into national GHGs inventory procedures. As a strategy for climate change mitigation, SOC sequestration needs to be implemented on a priority basis. It will buy us time over the next decade during which viable, effective, sequestration and low carbon technologies will become available. Progress in 4 per mille requires collaboration and communication between scientists, farmers, policymakers, and agri-business managers. Farmers primarily apply management practices to improve their soils C and can simultaneously contribute to the sequestering of C and mitigating climate change impacts. Scientific innovation should provide confidence for investment for SOC sequestration. Institutional regulations and policies that facilitate market-based approaches can take a step forward for the success of soil C 4 per mille. The multiple positive impacts of "4 per mille" are summarized in Figure 6 (Mandal and Choudhary, 2020).

Figure 6. The Impact of "4 per mille" SOC on UN Sustainable Development Goals

The increment in atmospheric carbon dioxide (CO_2) was 6.0 ± 0.2 Gt in 2016 (2.85 ± 0.09 ppm), well above the 2007-2016 average of 4.7 ± 0.1 Gt a year (Le Quéré et al., 2017). Such increments in CO_2 leading to an increase in atmospheric temperature are ultimately resulting in global warming. Unless GHG emissions are reduced radically, it would continue to pose the risk of pervasive effects of climate change leading to loss of agricultural productivity and food insecurity, economic slowdown and increased potentials for violent conflict (SIDA, 2018). The IPCC 1.5°C report stresses on the very limited time left to mankind to mitigate/curb GHGs emissions to the extent necessary in order to minimize average global warming to this level, thereby avoiding expensive adaptation costs that will otherwise be required (IPCC, 2018). Sequestration of atmospheric CO_2 into SOC will be an effective option to slow down the climate change impacts as the faster decomposition of SOC in agricultural soils is highlighting its harmful impacts on climate change and crop productivity. Soil carbon sequestration implies transferring atmospheric CO_2 into long-lived pools and stocking/storing it in soil for a longer period in order to mitigate/curb global warming and avoid extreme events of climate change so it is not immediately re-emitted. In a simple term, sequestration is storing of CO_2 in the soil through crop residues and other organic inputs; but it broadly means enhancing soil organic and inorganic carbon stocks through judicious management of existing resources, land use and recommended management practices. Storage of soil carbon helps to offset GHG emissions from fossil fuel combustion and other activities while improving soil quality and stability. Carbon sequestration in the soil system however depends on the balance between the residue C inputs and the rates of mineralization.

Accelerated soil erosion is considered to be the principal cause of a decline in the SOC pool. Poor and inappropriate management practices, as well as climate change impacts, share their greatest contribution towards physico-chemical and biological degradation of cultivable lands. In the world, approximately 40% of the agricultural land is severely degraded. Impact of climate change is destroying the SOC status of the terrestrial ecosystem, thereby, affecting the crop yields. Reclamation of such degraded lands has huge potential for C sequestration to counteract the climate change impacts. Maintaining and improving the SOC stocks is the most potent weapon to combat against soil degradation and ensuring sustainability in the agriculture system. Improving SOC stocks in different ecosystems contributes to food production (Srinivasarao et al., 2014; Lal, 2020). Soil-management practices that usually improve SOC include use of variety of organic amendments like FYM, vermicompost, oilcakes, poultry manure etc.; judicious fertilizer application; reduced/no-tillage for minimum soil disturbance and utilization of previous crop's residue and moisture; integrated nutrient management to minimize excess chemicals; use of biofertilizers; crop residue incorporation; rotation with high-residue/high biomass crops; application of biochar produced by heating crop residues or wood chips; intensive use of cover crops for frequent carbon addition; amelioration of degraded land with organic amendments; mulching with crop residue; switch from single cropping to inter-cropping, pasture cropping and agroforestry with trees/shrubs with crops; introducing pulse crops in cropping system to promote atmospheric N_2 fixation; eliminating summer fallow periods; avoiding residue burning; use of technology for soil carbon monitoring etc., are more or less effective for increasing C sequestration as revealed from studies conducted over the past two decades.

4. SOC SEQUESTRATION OPPORTUNITIES IN INDIA

Effective utilization of organic resources can enhance SOC in Indian soils. At present, about 150 million tons of crop residue is burned that can be potentially brought back to the soil resulting in 40 million tons of organic carbon. Green manure crops are grown on 8 to 15 million ha and produce 100 million tons of fresh biomass. Similarly, there is an ample opportunity for legume relay cropping in the rice fallows covering 15 million ha. Enhanced composting and FYM management can add considerable organic matter to the soils. Indigenous soil health practices like sheep and goat penning provide enough opportunity for SOC improvement in arid and semi-arid regions. Composting of water body based weeds in high rainfall regions as the North East Hill region, Kerala, and West Coast is an important strategy for SOC improvements. Agro-forestry promotion with price guarantee has a long way to go and contributes to SOC stocks in Indian soils. Conservation agriculture (CA) or resource conservation technologies in wide-spaced horticulture crops has a great potential for SOC stocks improvements. In these systems, the wide-spaced fruit crop area (almost 10 M ha) can be utilized. There is a potential of bringing major horticulture areas, for example, mango (2-3 m ha), citrus (1.0 m ha), apple (0.3 m ha), pomegranate (0.3 m ha), coconut (2.1 m ha), cashew (1.0 m ha) and areca nut

(0.5 m ha) under CA system (Srinivasarao 2018). According to Nath et al. (2018) adoption of Best Management Practices (BMPs) by the 120 farm holdings of small and marginal farmers, constituting more than 85% of total farming families can sequester 70-130 Tg CO_2 equivalent per annum. The carbon sequestration potential of various technological options is shown in (Table 1).

Table 1. SOC Sequestration/Restoration potential

Technological options	**Sequestration potential (tons C/ha/year)**
Croplands	0.10-0.20
Conservation tillage	0.05-0.10
Mulch farming (4-6 Mg/ha/year)	0.1-0.2
Compost (20 Mg/ha/year)	0.05-0.1
Elimination of bare fallow	0.1-0.2
Integrated nutrient management	0.1-0.2
Restoration of eroded soils	0.05-0.1
Restoration of salt effected soils	0.1-0.2
Agricultural intensification	0.1-0.3
Water conservation and management	0.05-0.1
Afforestation, grassland and pastures	0.05-0.1

Source: Lal et al. (2018)

5. AGENDA FOR SOC ENHANCEMENT IN INDIA

The options also exist to actively remove atmospheric CO_2, for instance, through afforestation and bioenergy, combined with carbon-capture-and-storage, direct-air-capture, enhanced weathering and increasing SOC (IPCC, 2018). New environmental governance challenges are emerging, such as the "4 per 1000/ 4 per mille" initiative launched by France on 1st December 2015 as a part of the Global Climate Action Plan (GCAA) adopted by the United Nations Framework Convention on Climate Change (UNFCCC) at the conference of the parties COP 22 as a follow-up of the COP 21 intends to enhance SOC and C sequestration by implementing proper agricultural practices adapted to local environment viz., agro-ecology, agro-forestry, CA practices or landscape management. The main aim of this initiative is to demonstrate that agriculture, and in particular, agricultural soils will play a pivotal role where land degradation, food security and climate change are concerned. In 2018, at COP 24, held in Poland, the soils advantage event as a part of the larger agriculture advantage 2.0 event series emphasized the importance of enhancing SOC stocks to meet food security and climate change mitigation goals. The topics related to improved soil carbon, soil health and soil fertility under grassland and cropland and integrated systems were presented at Subsidiary Body for Scientific and Technological Advice (SBSTA) 50th session in Bonn, Germany COP 25 in 2019 (Srinivasarao et al., 2019). The 2030 Agenda for Sustainable Development Goal (SDG) through its target 15.3, for example, promotes achieving a Land Degradation Neutral world, with SOC as one of the key indicators for monitoring.

India is committed to meet its national commitments made to the international community through the UNFCCC and the Paris Climate Change Agreement in 2015. Our Hon'ble Prime Minister Shri Narendra Modi received the "Champions of the Earth" Award in 2018 that recognizes the contribution to the field of environment protection (MoEFCC, 2018). Several ICAR Institutes and State Universities, besides National Remote Sensing Agency (NRSA), are also involved in monitoring and estimation of SOC stocks in different land categories. The national action plans through different policies and programs viz., National Project on Organic Farming (NPOF), National Mission on Sustainable Agriculture (NMSA), Soil Health Card (SHC) Scheme, National Adaptation Fund for Climate Change (NAFCC) and also some action plans under the National Action Plan on Climate Change (NAPCC). Policies that are concerned with agriculture and directed towards net GHG emission reduction should critically consider the total effect of all these adaptation plans and the comparative attractiveness of carbon sequestration versus other strategies. A multidimensional research agenda together with incentives and policies to stimulate sequestration activity is needed for food security and climate actions.

Region-specific priorities need to be included in various state and central government programmes and expansion of the technology implementation is essential on community participation (Table 2).

Table 2. Ecosystem specific technology priorities for SOC improvement in India

Agroecosystem	Technologies				
IGP	Residue recycling	CA	Agri-horticulture	Minimized soil-based brick industry	Reclamation of salt-affected soils
Rainfed	Cover crops	Local organics manures	Agro-Forestry	Tank silt and farm ponds	Rainfed horticulture and Intercrops
Eastern	Land reclamation	IFS	SSNM	Crop diversification	Organic Farming
NEH	Arial Seeding	Contouring	Zoom land rehabilitation	Riverbank stabilization	Relay cropping
Arid	Sand Dune stabilization	Agroforestry	IFS	Water management and Farm ponds	Legumes
Himalayan	Land covers	Agroforestry	Contouring	Perennial crops	Agri-horticulture
Central	Sustainable intensification	Legumes	Organic farming	Water erosion Reduction technologies	Intercrops
Island	Organic manures	Composting local organics	IFS	Seabank stabilization	Contouring

Note: IGP stands for the Indo-Gangetic Plains; and NEH for the North Eastern Hill regions; CA stands for Conservation Agriculture; IFS stands for Integrated Farming System; and SSNM stands for Site-specific nutrient management

6. RECOMMENDATIONS

6.1. Research & development

- Tracking and assessment of SOC changes in diverse ecosystems through scientific interventions for rapid, cost-effective and authentic monitoring.

- Assessment of the current status of agro-ecosystem based SOC enhancing strategies towards '4 per mille' soil targets.
- Setting up of a National level SOC monitoring network project involving multi-ministerial R & D institutions.
- Quantification of interaction effects of SOC with LDN, agriculture productivity and climate adaptation
- Identifying and inventorying locally available organic resources suitable for SOC enhancement.
- Promoting strategies for crop residue management including business models with a focus on zero residue burning
- Establishment of long term experiments covering diverse crop-fodder-grasslands-horticulture-agro-forestry based systems in different agro-ecosystem sub-regions.

6.2. Policies

- Develop SOC based policies and programs for sustaining soil quality, climate regulation and promote biodiversity conservation in line with UNFCCC/Paris agreement.
- Focus on convergence of multi-ministerial programs like NAPCC and SAPCC and the eight national missions of the central government.
- Promote farmer and/or community-centric Holistic Land Management (HLM) practices.
- Institutionalize Payment for Ecosystem Services (PES) to farmers for adopting SOC enhancement practices.
- Encourage production of quality organic fertilizer particularly (low-volume-high-nutrient products) with adequate subsidy support akin to chemical fertilizers.
- Encourage Private (Corporate/Industry)-Farmers involvement with a special emphasis on small & marginal farmers to incentivize regenerative agricultural practices for SOC enhancement.

6.3. Governance

- Conducting large-scale awareness programs against crop residue burning.
- Strengthening existing national and state-level programs by incorporating SOC enhancement interventions.
- Establish a national mission on carbon sequestration at the macro level and creating farmer's innovation and cross-learning platform for C sequestration at the micro-level.
- Promotion of legume cover-crops seed systems to encourage land cover, enrich soil carbon and nitrogen etc.

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