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Plans and Policies for Soil Organic Carbon Management in Agriculture

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Preface

The carbon (C) problem and its impact on climate have been attracting attention for many decades. The last few decades have seen tremendous changes in agriculture and the world's food chain. New and modern agriculture techniques result in more depletion of C from the soil and cause a remarkable increase in C concentration in the atmosphere. Increased demand for food and energy is the two main anthropogenic factors affecting soil organic carbon (SOC) status in a climate change era. While global trade in agricultural commodities has increased interconnectivity among food resources in developed and developing countries, it has also contributed to and exacerbated the challenges related to malnutrition, food security, environmental degradation, and large-scale soil sustainability, making it harder to achieve the targets of Sustainable Development Goals (SDGs) of eliminating poverty and hunger. Different technologies, programs, and policies should be adopted for enhancing SOC in the soil of various agroecosystems. Soil C levels have reduced over decades of conversion of pristine ecosystems into agricultural landscapes, which now offers the opportunity to store C from the air into the soil. C stabilization into agricultural soils is a novel research approach and offers a promising reduction in atmospheric carbon dioxide (CO_2) levels. This book brings together all aspects of plans and policies for SOC management in agriculture, with a special focus on the diversity of management practices of soil in agricultural systems. The book offers broad ideas of new plans and policies for improving SOC in the agricultural production system. It will be suitable for teachers, researchers, policymakers, and undergraduate and graduate students of soil science, microbiology, agronomy, ecology, and environmental sciences.

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Ram Swaroop Meena is an Agronomist working in the Department of Agronomy, Institute of Agricultural Sciences, Banaras Hindu University (BHU), Varanasi, India. Dr. Meena has been awarded the Raman Research Fellowship by the Ministry of Education, Government of India. He has completed his postdoctoral research on soil carbon sequestration under Padma Shri Prof. Rattan Lal, World Food Prize *Laureate*, Columbus, USA. Dr. Meena has completed 10 externally funded projects including, MHRD, ICAR, DST, etc. and published more than 130 international research and review papers in peer-reviewed reputed journals and has H-index of 52 and citations over 8000 with a total impact factor is 268.35. He has published 4 books at the national level and another 20 books (Springer) at the international level and contributed to the books with 15 chapters at the national and 70 at the international levels.

Cherukumalli Srinivasa Rao acquired his Ph.D. in Soil Science and Agricultural Chemistry from IARI, New Delhi, and postdoctoral (Fellow) from Tel-Aviv University, Tel-Aviv, Israel. Dr. Rao worked in ICAR system in different capacities from Scientist to Director. Currently, he is serving as Director, ICAR-National Academy of Agricultural Research Management, Hyderabad since 2017. He also served the International Crop Research Institute for Semi-Arid Tropics (ICRISAT), Patancheru, Hyderabad for 2 years. He is the recipient of 40 national and international awards which include the Rafi Ahmed Kidwai Award for Outstanding Research in Agricultural Sciences, 2019.

Dr. Rao is the Fellow of the National Academy of Sciences, National Academy of Agricultural Sciences; and Member of various National and International Committees globally. Dr. Rao is specialized in Soil Carbon Sequestration, Carbon Balance, Dryland Production Systems, and Climate Policy. Dr. Rao is credited with 317 Research Papers, 49 Books authored/edited, 12 copyrights, and 17 Policy/Strategy/Status Papers. He visited more than 15 countries for scientific meetings.

Arvind Kumar a renowned educationist and researcher has been appointed two terms as a Vice Chancellor of RLBCAU, Jhansi. Prior to this assignment, Prof. Kumar worked as Deputy Director General (Education), ICAR, New Delhi from 2009 to 2014, held the additional charge of Deputy Director General (Fisheries), ICAR, New Delhi about 5 months and was the Director of Directorate of Rapeseed-Mustard Research (DRMR), Bharatpur from 2002 to 2009. Under his dynamic leadership, Education Division, ICAR took several initiatives and made policies for the improvement of agriculture education in India. Dr. Kumar has been awarded with Dr. Rajendra Prasad Purushkar (1991–93) by ICAR for the book on Crop Geography of India (In Hindi), Fellow of the Indian Society of Agronomy (1996), Fellow of the Indian Society of Oilseed Research, Fellow of the Society of Extension Education (2009), and Fellow of the National Academy of Agricultural Sciences (2012). President of the Indian Society of Agronomy (2011 and 2012) and the Society of Rapeseed Mustard Research since its inception (2008).

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Reforming the Soil Organic Carbon Management Plans and Policies in India

Ram Swaroop Meena, Sandeep Kumar, Cherukumalli Srinivasa Rao, Arvind Kumar, and Rattan Lal

Abstract

The importance of soil health and balanced fertilizer application based on soil test results must be taken into account in various agricultural community programmes and initiatives. In India, a programme on soil health management, integrated nutrient management and organic farming has been launched to improve soil carbon (C) management by incorporating and integrating multiple strategies, techniques and resources. In this respect, organic carbon (OC) stored in agriculture is one of the imperative strategies that enhance soil C content, maintain soil health and quality, mitigate climate change, conserve biodiversity and ultimately sustain the entire food system, although, to implement these technologies, policies, economic analysis and scientific as well as financial support are required especially for resource-constraint smallholders of developing countries. The SOC content in the upper layer of Indian cultivated soils is estimated to be 0.2% or less,

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which is well below the critical threshold level of 1.5% needed for healthy soil. The goal of this chapter is to provide understanding on sufficient food supply while also coping with changing climates, improving SOC, reducing losses and developing techniques to improve the soil C pool in rural soil. These policies for C management and restoration need to be tailored to the local situations, because the livelihood of millions of people across the country directly depends on how SOC pools are maintained using sustainable land management practices and policies. Hence, effective policy implementation relies on several factors that are well coordinated with socio-economic and natural characteristics and may be supported by good governance and stakeholder engagement.

Keywords

Agriculture · Plans · Policies · Soil organic carbon

Abbreviations

AMF	Arbuscular mycorrhizal fungi
ARDF	Agricultural Research and Development Fund
BMPs	Best management practices
C	Carbon
CA	Conservation agriculture
CBD	Convention on Biological Diversity
CBO	Community-based organizations
CDP	Crop Diversification Programme
CoP	Conference of Parties
FAO	Food and Agriculture Organization
GEF	Global Environment Facility
GEFSOC	Global Environment Facility Soil Organic Carbon
GoI	Government of India
GSP	Global Soil Partnership
ICAR	Indian Council of Agricultural Research
IFAD	International Fund for Agricultural Development
IGP	Indo-Gangetic Plains
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
KJWA	Koronivia Joint Work on Agriculture
LDNW	Land-degradation neutral world
NAMA	Nationally appropriate mitigation action
NAP	National action plans
NARS	National Agricultural Research Systems
NEHR	North-Eastern Himalayan Region
NFSM	National Food Security Mission

NGOs	Non-governmental organizations
NHM	National Horticulture Mission
NICRA	National Innovations in Climate Resilient Agriculture
NMSA	National Mission for Sustainable Agriculture
NSC	National Seed Corporation
NT	No-till
OC	Organic carbon
PES	Payment of ecosystem services
R & D	Research and development
REDD	Reducing emissions from deforestation and forest degradation
RKVY	Rashtriya Krishi Vikas Yojana
RWSs	Rice-wheat systems
SCOs	Civil society organizations
SLM	Sustainable land management
SMN	Soil monitoring network
SOC	Soil organic carbon
SSC	State Seed Corporations
TMC	Technology Mission on Cotton
TMIDHNER	Technology Mission for the Integrated Development of Horticulture in the North-Eastern Region
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNCED	United Nations Conference on Environment and Development
UNFCCC	United Nations Framework Convention on Climate Change
WOCAT	World Overview of Conservation Approaches and Technologies

1 Introduction

Despite India being the leading country in agricultural production, no specific strategy planning has been done so far regarding soil carbon (C) sequestration at ground level. A large section of farmers is unaware about the importance of soil organic carbon (SOC) sequestration and its role in improvement in food, nutrition, environmental and economic conditions of the country IUCN (2018). Arable soils generally have low SOC concentrations in the root zone, ranging from 1 to 10 g kg^{-1} (Manna et al. 2003), and often considerably lower. The croplands of Indo-Gangetic Plains (IGP) have a SOC pool of 8.5–15.2 Mg C ha^{-1} at 40 cm deep and 12.4–22.6 Mg C ha^{-1} at 1 m depth (Singh et al. 2011). Low SOC concentrations and pools in the root zone are partly responsible for low crop productivity and wide yield differences (Lal 2015). Crop diversity, maintaining consistent vegetative ground cover, introducing carbonaceous substances, lowering insecticides/pesticides/herbicides and minimizing tillage, among other strategies, should be used to restore soil health. Soil conservation and restoration may directly contribute to climate change resistance, making them crucial for humanity's food, water and energy. Over the previous three decades, the Government of India (GoI) has made a significant investment in preventing soil health degradation and regulating soil fertility.

There is no separate organization dealing with the research on soil C sequestration, further intensifying the challenges to politicians, researchers, policymakers and extension workers. Hence, there is a need to establish plans for soil C restoration along with designing financial policies to promote C management practices across different agroecological regions, landscapes and cultural contexts to the farmers (Meena et al. 2021). The objective of this chapter is to ensure enough food supply and cope with changing climate and improved SOC, decrease losses and develop strategies to enhance the soil C pool in country soil.

Government should take initiatives by reducing subsidies on C-exhaustive inputs such as chemical fertilizers and heavy tillage machinery to minimize their use. Incentives should be given to promote activities which enrich soil C such as planting trees/shrubs in the agroforestry system or transforming tillage practices from conventional to no-till (NT) that ensure a positive impact on soil C build-up (Meena et al. 2021). A successful policy should restore C-exhausted lands including the direct benefit of farmers and ensure their active participation in training and demonstration, and make easy availability of tools for C sequestration. For soil C enrichment, a Californian scheme, i.e. the 'Healthy Soils Initiative', is a good example to encourage farmers' participation in the C management system. Similarly, the government should also promote farmers' education, motivation, knowledge-sharing among farmers, rewards and monetary support to the farmers and land managers to promote efficient soil C sequestration activities. For example, in order to restore SOC in agroecosystems, three important priorities need to be addressed:

1. An overview of the case and a plan of action, for instance, including countries like Australia, Canada, Ethiopia, Bhutan, Uruguay and others who have already included soil in their national agenda.
2. A detailed business plan that brings together public and private investors to increase finance levels and improve soil C management.
3. A strategy to provide financial support for producers and managers of the land to restore soil C through the adoption of best management practices (BMPs).

To generate a holistic approach for developing an action plan in India, there needs to establish a better linkage among scientists, policymakers, farmers and land managers for designing efficient policies by utilizing the available technical and scientific resources to restore the SOC pool in national soil and terrestrial ecosystems. Six crucial steps to be followed in this series (Meena et al. 2022) include:

1. Determining regional and national trends of SOC loss.
2. Assessing how the adoption of BMPs can prevent SOC loss in major soils of key ecological regions.

3. Evaluating economics of SOC from a productivity and environmental perspective.
4. Designating and implementing policies that promote soil C sequestration.
5. Developing standards and indices for promoting C sequestration practices.
6. Formulating policies for the practical execution of recognized strategies.

Government policy and legislation support are needed to strengthen the local natural resources (i.e. soil) through different types of sustainable land management (SLM) practices (e.g. agroforestry, conservation agriculture, range management, etc.) and to maintain or increase SOC stock and soil biodiversity. From the perspective of policies for raising soil C stock, there are still huge gaps in policy creation and execution in the domain of land use and management in India which may include the lack of national action plans or their implementation.

2 Fertilizer Policy and Nutrient Management

Nutrient management is a prime concern for agricultural productivity and soil health. The supply of required nutrients, according to crop and soil status, is essential to make the balance of the soil system as well as to enhance agricultural production. The availability of fertilizer for agricultural use requires the production of the needed amount of fertilizer, regulated markets and distribution of inputs and fertilizer policies in the country. In this perspective, GoI has implemented some programmes and policies which encourage the balanced and judicious application of agrochemicals based on soil test attributes. This is also supported by financial grants and assistance through collaborative approaches among different states by facilitating subsidy, training, capacity building and demonstration practices to aware the farming communities towards balance fertilizer use UN (2012). In 1991–1992, GoI initiated the balanced and integrated use of fertilizers in the farmer's field from a sustainability point of view. This includes the nutrient management that comprises various key components in planning as follows:

1. Enhance the soil testing facilities across the country.
2. Promote the use of compost using biodegradable soil waste products of the city.
3. Increase farmers' training for upscaling the knowledge and skills.

The importance of soil health and balanced fertilizer application according to the soil test must be given due consideration in the various programmes and initiatives among the farming community. GoI has implemented several outreach activities to sensitize farming communities about the issues of fertilizer use and management. In this perspective, various soil health programmes are broadcasted on national TV platforms regarding demonstration of various success stories among farmers, farmers' clubs, celebrations of national soil health day, national soil health mission, etc. to enhance awareness about the need for sustainable management of soil resources UN (2012).

The balanced and integrated use of fertilizers programmes was continued till 2000 and was later amalgamated into the Macro Management of Agriculture Schemes. Further, under the National Mission for Sustainable Agriculture (*NMSA*), the programme on soil health management and integrated nutrient management and organic farming are initiated for effective soil nutrient management by adopting various conservation practices and techniques and incorporation and integration of various resources in India (Chaudhari 2018).

3 Conservation Agriculture

Conservation agriculture (CA) is a well-known approach based on the interrelated principles of minimal mechanical soil disturbance, permanent soil cover with living or dead plant material and crop diversification through intercropping or rotation. It helps to enhance and boost yield potential in addition to decreasing risks of land degradation, protecting the environment and withholding challenges associated with climate change. With the extensive agricultural practices, it is the need of the hour to adopt this practice to a larger extent, especially in a rice-wheat-based cropping system. Hence, planners and institutional leaders should come up with different policies and plans to transform the existing tillage, cropping system and agricultural practices into system-based CA by providing incentives and encouraging farmers to adopt such a system that will increase the soil C pool. It can be achieved by providing a regulatory standard framework, strengthening research and development, developing training programmes, implementing legislation and providing incentives and payback programmes. With the adoption of CA, there is a direct enhancement in SOC concentration which in turn improves soil fertility and C stock. Thus, GoI must standardize and promote the adoption of CA through organizing various programmes and creating awareness among farmers. As in some cases of Africa and Europe, it has been observed that farmers plough the soil after taking their crops as they are well aware of the fact that the decomposition of organic matter upon ploughing will enrich the soil with nutrients and reduce the cost of fertilizer input. Henceforth, a policy framework is required for farmers/landowners to ensure the continuous addition of biomass-C into the soil. Policies should encourage and enable the unification and validation of CA protocol in a practical form so that farmers can get monetary assistance for providing certain ecosystem services. Likewise, the farmers should also get financial and technical aid from GoI for implementing the CA system to reduce the risks of soil erosion and SOC loss. Such plans/policies inspire the producers to transform their existing crop management systems into CA-based systems.

CA adoption at a broader level is primarily driven by an increase in crop yield, reduction in unit cost, decrease in dependence on livestock, reduction in labour requirements, increased availability of CA machineries, access to credit, donor funding and government support on incentives, taxes and interest rates. This indicates the role of all public sector, private sector and civil society organizations (SCOs) as all sectors have their own strengths and they should try their best collective efforts to fill the gap in CA adoption on a larger scale. In this regard, the public sector needs to invest more in research and capacity building, infrastructure improvement, reforming and consolidating land tenure systems through strengthening institutional support and formulation and implementation of policies for subsidies, tax relief, credit and insurance. Likewise, the private sector can ensure their active involvement in research and development (R & D) and their cost sharing, machinery development, the formulation of farmer's friendly business model, custom hiring services and establishment of viable value chain like contract farming, whereas SCOs should organize smallholder's collective actions and the establishment of linkage of R & D programmes and link farmers with the delivery of seeds, machineries, fertilizers, credit, market and other inputs. So, there is an urgent need for movement for advancing CA-based technologies at regional and national levels by involving all parties in the agri-value chain. CA policies should be integrated into a coherent national policy for the sustainability of the agricultural ecosystem. In order to accelerate mainstreaming of CA-based technologies, it is necessary to develop national and regional networks of different stakeholders. Different target groups such as professionals, policy advisors and financial institutions ought to be sensitized to CA for improving policy advocacy and capacity building. The training modules should be targeted at specific audiences, such as farmers, extension specialists or service providers. The specific researchable, developmental and policy issues are described by NAAS (2018).

3.1 Development-Related Issues for Implementing Conservation Agriculture

The principal actions that need to be undertaken for the implementation of CA technologies in rice-wheat systems (RWSs) are as follows:

1. Providing funds for laser-assisted land levelling to cover a significant area by promoting custom services and as possible as many cultivated areas could be brought under CA-based crop management practices.
2. Promoting direct seeding of basmati rice and other rice-based systems.
3. Supporting single-window services for NT planting of wheat and sugarcane, with residue retention and minimizing residue burning using double-disk planters and turbo happy seeders.
4. Delineating the problematic areas by surveying the water quality of tube wells. Accordingly, fertilizer application in the cropping system should be advocated based on the groundwater quality, residue retention, tillage and crop establishment methods, crops and cultivar selection.
5. Advancing technologies including remote sensing and GIS tools must be used to map problematic soils.
6. Adopting dual-purpose wheat in connection with programmes intended to improve livestock productivity, and such wheat must be grown in areas where diaries are located such as peri-urban areas.

7. Enhancing crop diversification to decrease area under rice cultivation to reduce pressure on the declining water table by growing alternate crops such as maize, pigeon pea, soybean, etc.
8. Providing quality prototypes of tillage machinery (i.e. multipurpose turbo happy seeder, multi-crop planter, multi-crop double disk planter) for promoting CA.
9. Establishing system-based technical advisories for farmers and help in use of modern information and technology communication.
10. Creating facilities for government officials to link the existing database to the Unique Farmer Identity for soil testing and other government schemes and programmes.
11. Encouraging farmers to purchase improved CA machineries and other equipment by facilitating and subsidizing.
12. Strengthening human resources by capacity building and improving communication with extension agents and farmers across agroecological regions and promoting farmer interactions through farmer schools, exposure visits, travelling seminars, etc.
13. Facilitating strong public-private partnership for knowledge sharing on inputs, markets, weather, etc.
14. Creating long-term research platform trials and farmer participation trials.
15. Farmer participatory seed systems and seed cooperatives for quality seed.

3.2 Researchable Issues

Priority researchable issues include the following:

1. Establishing long-term basic and strategic research platform in diverse ecologies and production systems to track C sequestration, GHG emissions and resource use efficiencies and link them to adaptive research modules for out-scaling of potential technologies.
2. Developing, refining and adapting components technologies specifically tailored to the CA requirements under various production environments and conditions.
3. Describing prevailing location-specific CA-based crop management technologies matched to diverse agroecologies, production systems and socio-economics of smallholder farmers.
4. Assessing farmer's efforts for practising CA and the corresponding ecosystem benefits should be strengthened to ensure enticements to farmers for ecosystem services.
5. Analysing and documenting the potential contribution of CA in improvement in factor productivity in the production system.
6. Conducting long-term studies to determine potential environmental and economic benefits of CA on crop residue incorporation in soil.
7. Refocusing crop breeding programmes to tailor cultivars that meet the needs of different systems and enhance the adaptability of CA at a larger scale.

8. Designing and developing CA machinery with special emphasis on small and marginal farmers.
9. Expanding R & D to include more crops and agroecologies with a special focus on smallholder farming.
10. Identifying and documenting limitations for upscaling CA technologies.
11. Identifying potential areas for adoption of CA practices.
12. Integrating CA with salinity-alkalinity research.

3.3 Policy Issues

Pertinent policy issues to be addressed are as follows:

1. Reviving the rice-wheat consortium so that it can provide a neutral forum for policymakers, researchers, private sector representatives, R & D managers, non-governmental organizations, Consortium of International Agricultural Research (CGIAR) institutions and farmers to assess local and national needs, exchange information and define priorities for the deployment of CA with special emphasis on resource-constraint farmers.
2. Prioritizing and ensuring efficient use of allocated resources. National systems have made significant investments, for instance in India, National Innovations in Climate Resilient Agriculture (NICRA), Rashtriya Krishi Vikas Yojana (RKVY), *National Food Security Mission* (NFSM), National Agricultural Innovation Project (NAIP), a national initiative on CA and Indian Council of Agricultural Research (ICAR) institutions are working in this line. It is vital for such schemes to be integrated and complementary, as well as monitored and evaluated (M & E) for mid-course corrections and greater impacts at the field level.
3. Ensuring widespread dissemination and adoption of CA technologies by farmers, the R & D of an active feedback-based farming system, including specialized crop insurance, appropriate incentives and institutional and policy support, is essential.
4. Integrating CA technologies with existing government programmes and mapping government initiatives to technology traits.
5. Designing new CA-based programmes in synergy with government mega programmes.
6. Strengthening institutions to build a strong linkage between CA technologies with international treaties and programmes, for example, C credit to benefit smallholder farmers.
7. Creating an environment favourable for the private sector for investment in CA.
8. Developing a mechanism to enhance capacity building for different groups on CA such as the inclusion of CA in the course curriculum at the graduate level and masters and PhD degrees on CA in SAUs.
9. Developing efficient and reliable mechanisms of documenting CA databases in the region to enable researchers and policymakers to pursue further actions.

10. Establishing mechanism for providing financial assistance to CA farmers, including remuneration for C credits.
11. Providing CA machinery with all the necessary spare parts of standard quality, after-sale services and operating manuals, which are currently lacking.
12. Creating agro service centres for resource-poor small landholders to provide CA-based machineries and services.

4 Policies for Promotion of Crop Diversification

Crop diversification is the production of different variety of crops from the same area to diversify agricultural commodities and bring down the climate-changing adverse effects of multiple biotic and abiotic stresses, intensified due to practicing of monoculture. To promote crop diversification, various government policies and programmes have been initiated. Considering the significance of crop diversification in resource conservation and economic development, the major government initiative was the launching of the 'Technology Mission for the Integrated Development of Horticulture in the North-Eastern Region' (TMIDHNER) to strengthen research, production, extension, post-harvest management, processing, marketing and exports-related activities in North-Eastern Himalayan Region (NEHR) (FAO 2001). Another scheme in this direction was the National Agriculture Insurance Scheme (NAIS) which promoted the cultivation of food crops, oilseeds and other commercial and horticulture crops. In addition to these, other government programmes such as the National Horticulture Mission (NHM), Technology Mission on Cotton (TMC), provision of capital subsidy for construction/modernization/expansion of cold storages and storages for horticultural produce, creation of watershed development fund for the development of rainfed areas, infrastructure support for horticultural development with emphasis on post-harvest management, strengthening agricultural marketing, Seed Bank Scheme, Cooperative Sector Reforms, etc. greatly help to promote crop diversification with enhancing the production and productivity of the crops (FAO 2001; Alur and Maheswar 2021).

After analysing the negative impacts of rice-wheat cultivation on soil health and ecological conditions, the government is now seeking new horizons through crop diversification that is remunerative and soil health in a sustainable manner. For instance, in Punjab, Haryana and Western Uttar Pradesh provenience of India, maize, oilseeds, pulses, millets, fruits and vegetables are being encouraged as a substitute for the continued rice-wheat system. Punjab government launched a 'multi-year contract farming' scheme in 2002 to promote crop diversification to protect natural resources including soil health. Taking forward this, in 2005–2006, the Punjab government established Agricultural Diversification Fund (ADF) to improve the soil ecosystem under the existing RWS. Under this fund, a sum of Rs. 50.56 crores (~US$6.85 million) was released in 2006–2007 by the state government to strengthen the agricultural infrastructure and diversification of RWS. Further, to support it, the Punjab government also established Agricultural Research and Development Fund (ARDF) through the release of additional

Rs. 10 crores (~US$1.35 million) in 2005–2006 for the screening of alternative crops and their improved management practices (Meena et al. 2021). After that, from 2013 to 2014, a sub-scheme, i.e. the Crop Diversification Programme (CDP), has been being implemented under (RKVY) in green-revolution states, i.e. Punjab, Haryana and Western Uttar Pradesh, to diversify exhaustive RWS to other alternate crops such as maize, pulses (in particular, pigeon pea), oilseeds (soybean and mustard, in particular) and agroforestry to revive the soil fertility and water table level (Mukherjee 2015). In 2020, under this programme, Punjab Agriculture Department has successfully achieved 0.5 M ha areas under alternate crops through Crop Diversification Pilot Scheme. Still, it needs to extend similar in other states to enhance crop and soil productivity.

But the efforts made so far in this direction are not enough as most small and marginal farmers practise crop diversification under resource deficiency conditions, but to a greater extent, it needs good infrastructure, and financial support with better market linkages. Hence, direct policy intervention is needed for refining rural infrastructure, supporting price, farmer training for alternate crop cultivation, technological interventions, increasing access to institutional credit and endorsing research and innovation for the development of inexpensive plant nutrients, rainwater conservation, surface irrigation development, etc. (Mukherjee 2015; Meena et al. 2021). To implement an alternative cropping system, some policies should be followed such as those (Rakshit et al. 2021):

1. Adoption of district/block approach: based on the soil and water-related problem facing selected districts should opt for suitable alternate crop-based diversification.
2. Creation of infrastructure: to promote crop diversification, quality seed should be provided through establishing seed hubs in addition to the farm machinery banks or custom-hire centres and storage facilities also to avail crop-wise requisite machinery at a subsidized rate. As in the rice-wheat prominent belt of Punjab and Haryana states of India, to encourage the cultivation of maize, pigeon pea, soybean and mustard, special attention should be given to producing and supplying quality seeds timely for that the National Seed Corporation (NSC) and State Seed Corporations (SSC) need to engage more actively in their quality seed production.
3. Establishment of processing industries and facilitation of new value chain: to sell farmer’s produce at good prices, there is a need for identification of seed production sites and to create a proper market through adopting viable value chain addition of their produce. Hence, establishing processing industries for diversified crops will create a market in addition to substantial job opportunities and earnings for the farmers. Government-Industry Summits need to focus on the possibilities to encourage private/corporate investment in the establishment of such industries across the country. Other initiatives under Skill India with support from Mudra Bank will also enable the establishment of rural entrepreneurship in different areas.

4. Cross-subsidization of alternate cropping system in lieu of ecological benefits: to switch the existing cropping system, the government should avail additional subsidies or incentives to encourage farmers to adopt more environmental and soil-friendly cropping systems such as cereals + pulses. Such steps will save water, energy, ecology and health in addition to broadening crop distribution and hence will cause a lesser dent in government's overall spending. Besides, by transferring price differentials directly to farmers through the DBT scheme, farmers will have a good effect on promoting alternate crops at the field level.
5. Crop insurance for alternate crops: the crop insurance policy should be revised for crops like maize, pigeon pea, soybean and mustard based on the existing potential of their cultivars, not based on the yield alone.
6. Funding for research and out-scaling projects of diversification: though crop diversification efforts have been made for a long time, it has gained limited success. This indicates there is a need to intensify the diversification efforts through policy-driven measures. Government funding in research on potential crops needs to be amplified to meet the changed scenario. Conducting the large-scale demonstration of different cropping systems will also play an integral role in this regard.

Besides, all these policy recommendations, the following measures should also be adopted for diversification and sustainability:

1. Developing a viable cold chain system specifically for corn and perishable vegetables.
2. Facilitating contract farming through the advancement of industries for seed, feed, poultry, oil, dal, etc.
3. Facilitating export by establishing export zone for soybean, pigeon pea, mustard, maize, etc.
4. Funding to industries that grow alternative crops for the protection of natural resources.
5. Imposition of safeguard duty on soybean imports, similar to that applied to oil palm in India.
6. Rebates on transport for diversifying crops from the production area to the industrial site.
7. Reducing or banning subsidies on groundwater pumping.
8. Tax rebates for industries buying diversified crops.

5 Interventions for the Soil C Stabilization

5.1 Biochar: Role in C Stabilization

Biochar, as opposed to other organic substances that usually mineralize less than 30 years, is less liable to weathering process and microbial decomposition and thus helps to stabilize soil cover decades while preventing soil degradation, and enhancing production sustainability (Datta and Meena 2021). Biochar is known to be the most desirable CO_2 because of its modulative porosity, texture and low cost, which makes it a great choice as a C-stabilizing material. It is obvious that soil C is categorized as labile (half-life 1–20 years) and stable (half-life 20–100 years). Of these, stable C stock is more resistant to the mineralization process and thus contributes to maintaining the C stock in soil for a long time, as biochar is made of paralysed organic materials 20–80% of stable C, which is not released into the atmosphere in the form of CO_2 and is retained in soil longer (Meena and Kumar 2022). Biochar contains the majority of fused aromatic C and hydrocarbons consisting of polycyclic aromatic compounds, compared to other organic matter resistant to rapid mineralization and having aromatic C compounds (e.g. lignin). In soils, biochar application increases a fluorescent substance similar to humic acid and reduces co-localization of aromatic C and polysaccharides C. At the same time, during carbonization, hydroxyl and hydrogen atoms are broken down simultaneously, which stabilizes biochar C, making it more resistant to decomposition. These changes, along with the reduction of C metabolism (a lesser rate of respiration), are apparent to be crucial to soil C stabilization amended with biochar.

Although despite all these, the C-stabilizing properties of biochar in terms of the content of stable polycyclic aromatic C fraction depend on several factors including feedstock type, paralysing temperature and soil conditions to which biochar is applied. The stable polycyclic aromatic C friction determines the resistance to mineralization and duration of C stability in soil. Biochar formed stable polyaromatic C at 600–700 °C at 80% of total organic C. That's why biochar production at higher temperatures (525–650 °C) was reported to have very less C mineralization at the advanced stage of incubation (8–16 months). After biochar application, the reduced mineralization rate coupled with increased cation exchange capacity and soil pH shows a positive relationship between high cation exchange capacity and C stabilization. Along with these, biochar application in weathered soil containing higher native SOM concentration leads to more stabilization of applied C and resultant decreased soil loss from erosion and transport, compared to clayey soil with low SOM content.

5.2 Soil Microbial Consortia for the C Stabilization

The soil ecosystem is a highly complex system with a multitude of interactions among soil resources (Meena et al. 2020), and there is an urgent need to develop plans and policies for C stabilization (Fig. 1). The activities of soil microbes increase soil porosity, soil aggregation, water retention and infiltration leading to the development of suitable soil conditions for other organisms like mosses, lichens and herbaceous and perennial plants, which in turn increases the soil C storage and sequestration potential. Microalgae are photosynthetic organisms which play a significant role in C sequestration as there is potential to sequester around 50% of C in the cell dry mass of microalgae. Through quantitative stable isotope probing (*qSIP*), C persistence traits of microbial strain genomes can be analysed to establish

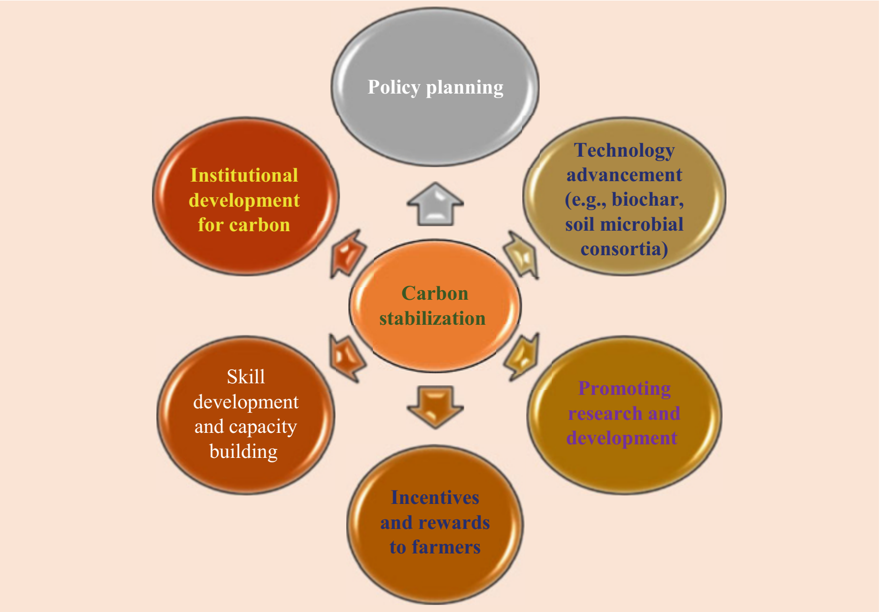

Fig. 1 Roadmap for achieving greater carbon stabilization in soil

robust mechanistic linkages between C cycling and soil microbial community (Meena and Lal 2018). The utilization of 'omics' techniques also will help to decipher the biological activities undertaken in the soil micro-niche for C sequestration.

Among the fungi, arbuscular mycorrhizal fungi (AMF) in symbiotic association with crop roots play a key role in C stabilization. It has been reported that the AMF of the division Glomeromycota transfers essential nutrients to plants which in turn dispense about 20% of the fixed C in soil. Glomalin belongs to this division and is a recalcitrant, insoluble and hydrophobic glycoprotein which is resistant to degradation. It creates a 'lattice-like waxy layer' that makes soil particles, sand, organic matter, clay and silt sticky allowing complicated aggregation processes in the soil to begin. As we all know, soil aggregation and aggregate stability are inextricably tied to C stabilization. As a result, soil aggregate stabilization increases the importance of glomalin since it shields the interior part of carbonaceous compounds from degradation. The decomposition of organic materials contained in soil aggregates is slowed. Glomalin creates a hydrophobic coating on hyphae that holds soil aggregates together, resulting in physical C stability. Alternatively, glomalin is believed to slow down the natural dissolution of soil aggregates. Furthermore, the fact that when C is sequestered into glomalin, it becomes a part of the refractory and hardly decomposable fraction of the soil C pool enhances the stability of soil C stock. It is essential to mention that C in glomalin is stable because its turnover can take several years depending on the environment. Glomalin-like proteins have a stubby structure that facilitates SOM sequestration. According to Wang et al. (2019), glomalin-related soil protein contributes to SOC build-up by holding and extending C soil stock turnover through recalcitrant composition.

Glomalin can store more than 5% of soil C and nitrogen, protecting Caseous components from breakdown and offering resistance to wind and water erosion (Meena and Lal 2018). It was established that glomalin, which makes up the majority of organic matter, stores 27% of soil C. Glomalin accounts for almost one-third of the global C pool, and is the main source of soil N and an important store of other elements in SOM that can be extracted. Hence, glomalin is effective in preserving soil C pools, forming aggregates and expanding organic content. In today's world, when degraded and nutrient-depleted soil could become a sink for an excessive quantity of CO_2, this increased soil C storage could help to prevent global climate change. In this way, AMF populations in the soil must be stimulated to invest C in the production of glomalin, resulting in increased glomalin stock, and subsequently C stabilization. It's also crucial to understand the role of soil microbes in CO_2 capturing and C locking-up within soil aggregates, as well as how to keep it stable for a long period. In addition, it is vital to place a focus on developing research proposals, programmes and policies to better understand the role of in situ microbes in soil C sequestration and stabilization.

5.3 Possibilities and Action Plans for C Stabilization

To meet the emission reduction target of the government and C budget, preventing measures for emissions and exploring new ways of enhancing/maintaining existing soil C stock are needed to follow. For this, a strong evidence base must be established to develop effective policies and measures to protect soil C flux. To protect and increase soil C, a better understanding of trends of soil C levels and cost-effective techniques has to be made. In addition, we must explore the potential benefits of new technologies, for example, biochar. In this way, we need to do everything we can to protect existing soil C stock. Also, our future actions need to be centred on the need to protect our existing C stores and ensure that all future policy development about soils is guided by this understanding. To support this, we must develop a comprehensive strategy for protecting our soil (DEFRA 2009).

6 Policy Recommendations for Enhancing SOC Stock

The 23rd Conference of the Parties (COP 23) to the United Nations Framework Convention on Climate Change (UNFCCC) established the Koronivia Joint Work on Agriculture (KJWA) including the soil as an important component in agriculture under the UNFCCC framework through the project 'Improved soil C, soil health and soil fertility under grassland and cropland as well as integrated systems, including water management'. KJWA develops a framework to implement different actions for C sequestration in soil by considering the inherent capacity of soils to store C and the existent gap in the majorly of soil for SOC capacity (FAO and ITPS 2015). As per the IPCC report, the enhanced SOC content is one of the cost-effective approaches to combat land degradation, desertification and food security in changing climate scenarios (IPCC 2019). Through supporting the implementation of RECSOIL (Re-carbonization of Global Soils) programme started under the Global Soil Partnership (GSP) which promotes SOC-centred sustainable soil management. RECSOIL aims to prevent the activities that make the further loss of SOC from C-rich soils and promote the practices that increase SOC stocks with enhanced farmer's income and soil productivity to contribute to improved food security and nutrition by mitigating climate change.

Appropriate policies for natural resource conservation and land tenure should focus on national land planning, market-oriented instruments and legal frameworks (i.e. control, access and ownership). The problem of poor land productivity has been aggravated by the local market distortions and the adoption of an inappropriate constitutional and regulatory environment in prospective locations for good land management. There is a lack of coordination and communication in the execution of the best management action plan at the field level due to a lack of coherence between land-use policies, market drives and formal institutional frameworks.

The institutions that are meant to deal with land concerns are weak in constitutional frameworks, particularly regarding SOC. In most national administrations, the value of SOC is mostly veiled inside other related subjects, and it is not given the priority it deserves. Traditional institutions and land rights are also not mentioned explicitly. In some places of the world, investment in land rehabilitation programmes is limited. International organizations should be able to channel funding to national governments so that the SOC conservation agenda can be implemented at the federal level. To enforce compliance with soil and SOC conservation at the national scale, suitable policies should focus particularly on land planning, legal structures and regulatory mechanisms coupled with efficient incentive structures.

Better coordination is required between policymakers and scientific society at regional, national and international levels through clear and simple messages. Environmental problems need to be addressed by formulating effective policies and their implementation (action) at the end level for getting desirable results (Table 1).

In this line, policy imperative (SOC accrual and maintenance), policy profile and discourse (increasing public awareness), policy rationale (societal and economic advantages) and policy support (programmes and services) are imperative to reform at the local, national and international levels for raising SOC and soil health. *Policy imperative* must include the formulation of SOC restoration programmes taking into account farmers' socio-economic conditions, resource availability and production potential of the field at a local level, whereas at the national level, land planning, constitutional framework, regulatory systems and monitory inducements should all be focused to encourage soil protection and health improvement. Soil C enhancement must be included in the policy arena by correlating its role in current issues of food security, climate change and sustainable livelihood. In *policy profile and discourse*, at the local level, a suitable discourse must be adopted that focuses on

Table 1 Components of a policy process to improve soil organic carbon status (Wesemael et al. 2015)

	Section	Regional level	National level	International level
Policy agenda	Policy imperative	Agroecological alternative	Integrate SOC into coherent national soil protection laws, NAPs and NAMAs	Conservation + sustainable use of biodiversity (CBD)
		Sustainable soil and land management		Climate adaptation + mitigation (UNFCCC, LDNW, UNCCD)
		Boosting productivity		
		Prevent soil degradation		
	Policy profile and discourse	Adapt to local sociocultural context	Value of SOC	Include SOC in mainstreaming of sustainable development plans
		Education	Regional patterns	Hyperbole
	Policy rationale	Devise a plan for long-term livelihoods	Several advantages	Maintaining SOC for future generations
		Reduced risk	Minimized expenses on erosion control	Reduce fragility of populations
	Policy support	Field-scale SOC models (cool farm, comet VR)	National incentives and PES	Coordination SMNs
		Demonstrate BMPs at the local level (WOCAT)	Simulation modelling tools GEFSOC	Develop soil evaluation research
		Smartphones	Soil monitoring networks	Climate adaptation and environmental funds
			Google maps	
Action	Advocates and institutions	NGOs, CBOs and other farmers' organizations	Cross-compliance ministries, focal points, NARS	Global conventions and partnerships, international NGOs, IFAD, UN, World Bank, GEF, FAO
	Governance	Agricultural extension	C footprint	CoP, GSP, IPBES, IPCC
		Conservation districts	Soil certification	
		Local producers/	Markets and labelling	

(continued)

Table 1 (continued)

	Section	Regional level	National level	International level
		watershed committees	Agricultural plan and sectors	
			NAMAs	

BMPs Best management practices, *GSP* Global Soil Partnership, *SMN* soil monitoring network, *GEFSOC* Global Environment Facility Soil Organic Carbon, *CoP* Conference of Parties, *GEF* Global Environment Facility, *CBO* community-based organizations, *CBD* Convention on Biological Diversity, *FAO* Food and Agriculture Organization, *IFAD* International Fund for Agricultural Development, *IPCC* Intergovernmental Panel on Climate Change, *NAPs* national action plans, *NARS* National Agricultural Research Systems, *NGOs* non-governmental organizations, *IPBES* Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, *LDNW* land-degradation neutral world, *UNFCCC* United Nations Framework Convention on Climate Change, *PES* payment of ecosystem services, *UN* United Nations, *NAMA* nationally appropriate mitigation action, *WOCAT* World Overview of Conservation Approaches and Technologies, *UNCCD* United Nations Convention to Combat Desertification

farmers' holistic perceptions of soil fertility and their economical access to resources. At the national level, public training programmes and events should be implemented by conveying a clear message of soil as a heritage and the role of SOM in improved soil health. Internationally, the focus should be on proper coordination and communication among various agencies, for example, all of the harmed efforts to promote awareness by various hotspots should be grouped with a unified group (i.e. GSP), and media should be addressed and expanded with a novel solution, and the establishment of international agenda to encourage and accelerate the implementation of all preceding ideas. To maintain a healthy environment for coming generations, an economic valuation of soil C should be based on a methodology to enumerate soil capital, and especially the significance of SOC under *policy rationale*. *Policy support* should be given for the development of programmes that bring together information on cropping systems and practices in developing countries and increase local capacity to employ tools and methodologies. Also there is a need to harmonize SMNs at the national level so that they can be compared and include the elements required to produce SOC estimates, besides facilitating easy data interexchange where national or regional restrictions exist. In this way, along with the right policy support, proper *advisories and institutional support* are crucial. In this series, in spite of the use of SOC indicators for several benefits, we need to move beyond by linking SOC indicators with food security, climate change, biodiversity and sustainable livelihood. Good *governance* must integrate the relevancy and values of SOC in all stages of decision-making and action through strong international organizations such as UNCCD, United Nations Conference on Environment and Development (UNCED), NAPs, NAMAs and institutions at all levels (NARS, NGOs). Initiatives to emphasize SOC must be backed up by mechanisms that give precisely targeted incentives/subsidies as well as punishments for non-compliance.

In order to capture climatically considerable amounts of C in soils, financial shortfalls exist, particularly in underdeveloped nations, though, if resources are available, they must still be supported by the establishment of institutions and mechanisms that will enable such investments to be made. This is especially important in nations with unstable governments and weak legislative and fiscal systems, including those in tropical and subtropical regions, where the need for increased yield and associated soil C build-up is highest. Such organizations abound in North America, Europe and Australia, but these territories have not yet trapped climatically substantial amounts of C (Amelung et al. 2020).

SOC has yet to be substantially incorporated into market-based policy for two major reasons (Amelung et al. 2020):

1. PES such as sequestering C in soil is typically explicit because the benefits are hard to quantify and standardize, necessitating arbitration between global recipients and regional and local service providers.
2. Individual farmers are more concerned with crop productivity gain than with C sequestration. As a result, additional incentives for land managers to encapsulate extra SOC are required, such as finding productivity improvements, improved market access or investment rewards on C holdings (Vermeulen et al. 2019).

Changes in management systems to improve SOC are estimated to cost from \$3 to \$130 per tonne of CO_2 (Tang et al. 2016). They are determined by soil-specific management changes and the potential to enhance SOC in a particular region, i.e. these values differ significantly at regional dimensions. Financial support to adopt management improvements that withhold more C, however, has a track record of success, whether imposed by the private or public sectors (or both), as in Australia (Vermeulen et al. 2019). Market-based payments, taxes and subsidies for C or cap-and-trade systems are all possible rewards, with the best option relying on local or national governance, societal values and operational cost (Mooney et al. 2007). All of these possibilities should be examined further to see if they can result in massive SOC sequestration.

For the wider acceptance of soil C-promoting measures, normative beliefs, along with behavioural and psychological aspects, must be emphasized (Kurkalova et al. 2006). Because of these ambiguities and complexities, a regional, and especially a national, soil management approach for C sequestration is a ‘wicked policy issue’, with several viable paths (Levin et al. 2012). Being a wicked problem, this can be addressed only with a coherent policy measure. In this scenario, it’s critical to develop solutions that link soil C confiscation and GHG emission reductions to environmental eminence, food security, climate change and biological diversity. This linkage of C sequestration in soil with food security and poverty alleviation programmes, soil health and REDD (reducing emissions from deforestation and forest degradation) and biodiversity will further accelerate the policy’s development and implementation. The strategies that can be found will most likely be varied and gradual. There won’t be a single global ‘silver bullet’, but instead a wide array of small, disparate and ideally interconnected ‘silver buckshot’ initiatives.

Various scientific studies support that maintaining or increasing the SOC stocks in potential regions significantly contributes to improvement in soil health. In support of local and nation-specific schemes and plans for SOC sequestration, we

Table 2 R & D is crucial to support the global implementation of C sequestration agendas and to further advance the plans and policies

Area of focus for R & D	New study areas
1. A broad set of policies and bottom-up initiatives to increase the adoption of C sequestering practices, including farmer incentives, societal standards and actions 2. C sequestering farming systems: Full life-cycle GHG accounting 3. Comprehensive soil information systems for various parts of the world, including yield gap analyses and status of soil degradation 4. Detailed maps of soil C sequestration potential at the regional and national levels 5. Realistic forecasts of regional and local yield growth per tonne of sequestered C 6. Sustaining the sequestration of C with additional fertilizers in degraded land 7. Taking into account organic material transfers that may result in the release of C stored elsewhere	1. Assessing C sequestration of different agroecosystems on a priori 2. Closing gaps in terrestrial soil C models, such as by adding erosion or inorganic C fate, as well as peatland C dynamics in natural and drained states 3. Documentation of C sequestration success stories for various soils and climate zones, including ecological services and societal benefits monitoring 4. Estimates of soil C sequestration in different regions based on quantitative data 5. Harmonized, easy analytical techniques for assessing legacy-driven C losses and C sequestration potentials before their occurrence 6. Identifying optional methods for storing additional C in the subsoil

suggest focusing on seven key points of R & D with additional six new study areas to assist forward the objective of global soil C improvement plans (Table 2).

7 Need for Laws/Acts (E.G. Land Degradation/Conservation Law)

A clear delineation of land intended for agriculture and protection against urbanization and other non-agricultural uses is a must. Hence, it is a must to have 'Rights-of-Soil' or 'Rights-of-Nature'. Also, there should be a national soil protection policy and provision of payment for ecosystem services for farmers in India. For the last three decades, the need for policies and laws for soil conservation and land degradation has been felt at the global level to manage and control soil and land degradation. Such laws and policies contribute to sustainable land management and protection of agricultural land use. The laws must encompass the provisions of ecological, land use and constitutional planning, which control land degradation by regulating the type and extent of land use Land and Soil Policy (2019). Currently, the governmental policies and legislation are focused on land utilization instead of soil conservation; hence, they are absorbed in price support schemes, land settlement and developmental schemes in place of ecological services, though a variety of schemes, programmes, policies and legislations are required at regional, national and international levels for the management of land degradation and to safeguard the future sustainable use of land.

The laws of soil reforms regulate the different environmental protection laws in addition to other laws related to land, water, forest, wildlife and natural flora-fauna resource with a guarantee to provide healthy soil to the people. Such laws aim to develop an ecologically balanced social and economic system by protecting soil through managed and proper utilization of natural resources to safeguard it from any adverse ecological effects The Economic Times (2020). Under such laws, there are provisions to regulate state and local rights including citizens' obligations on soil protection specifying the optimum level of using natural resources. These laws also enable ecological training and education in public and stipulate state environmental guidelines and principles providing environmental assessment through developing databases and conducting research and financing.

Although, in a few countries, some laws and policies exist focusing on different environmental reforms through imparting national, social, cultural and economic plans and policies. For instance, in the USA, under the Soil Conservation Act (1935) and the Standard Soil Conservation District Law (1937), most of the state and local resource conservation laws evolved. These laws target various areas such as prevention and control of land degradation, groundwater protection, water quality management, rangeland management, protection of wetlands, prime farmland, wildlife habitat and regulating farm input products. The state resource conservation laws implement different conservation policies and soil conservation programmes and allocate funds, providing technical and educational assistance. Later in the 1980s, a major new environmental reform programme was undertaken in New Zealand, which leads to the development of the Resource Management Act in 1991 (RMA). Under RMA several provisions were included integrating environmental protection and conservation with a proper resource management regime of effectively defining land uses and preventing practices which potentially accelerate soil or land degradation. One of the major goals of RMA was to develop the Sustainable Land Management Strategies for New Zealand. UNCCD (2016) focusing on control of soil erosion, land degradation, sedimentation of river systems, soil compaction and urban run-off. It establishes a national land care trust and prepares guidelines for best management practices including advisory services, research and other regulations. Later in 1990, the Government of Mongolia commenced a major environmental law reform together with the law of the land, wildlife, protected areas, water, forest and native flora resources. Shortly after, in 1994, the Chinese Legislative Yuan first initiated the Soil and Water Conservation Law to preserve soil and water resources to prevent soil erosion and landslides, rehabilitate land and endorse the coherent and suitable usage of land with the application of agronomic and engineering technologies. Under this law, the zones for soil and water conservation have been designated over major river basins, reservoirs, watersheds and coastal areas to preserve the natural ecosystem.

UNCED in 1992 shows interest to prepare a global soil instrument under which all countries possess common principal policies, essential guidelines and rules for the sustainable management of soil facilitating institutional linkages between treaties UNCCD (2016). The key role of this global instrument was to design specific objectives, fundamental principles and common rights for development, consumption patterns and general obligations of all the states related to the conservation of soil. Through this instrument, the legal framework would be imparted to support soil and land degradation control, by creating fundamental principles to guide all states, organizations and individuals. It will set a common foundation at a global level upon which future laws targeting soil and land conservation might be developed.

8 Plans for Measurement, Mapping, Monitoring and Reporting on C Stock: Current Progress and Future Perspectives

The huge global land area is degrading continuously due to various biotic perturbations and mismanagement besides the natural process and hazards. These disturbances lead to the removal of a significant amount of SOC (25–50%) from the soil environment. The degradation of soil and associated services are more pronounced in the tropical region of the world, especially in developing nations. The source and sink of soil C and its assessment followed by monitoring and mapping are key building blocks for the management of soil resources judiciously. The scientific orientation regarding the SOC reserves and changes due to abiotic and abiotic forces within the ecosystems needs to be properly designed. Further, technological implications can be a good solution for balancing the C through C capture practices (Fig. 2). The SOC and stock varied as per the climatic and edaphic features of the locality and inflow and outflow of the soil C. Soil is an important ecosystem holding an enormous terrestrial C pool and opportunities to C-capture in the long fixed pool. The C balance in the soil depends upon the input and output of C in the soil ecosystem (Policy Brief 2019).

The awareness and facts regarding the land and soil resource are the building blocks for sustainable soil management. Farmers are directly engaged in soil

Fig. 2 Sustainable soil and environmental management

management; therefore, proper knowledge, information and training must be dissimilated among these communities to manage the soil sustainably and profitably. Further, common government intervention is implemented within the national plan of action and management of particular resources with effective regulations. The effective regulations of soil and land management needed a sufficient scientific database for evaluating and designing the critical limit and compliance of soil monitoring. The soil management practice regulation includes intricate institutional, organizational, technical and policy challenges. The effective and strict policies needed well-organized soil monitoring systems and their link between land management and soils. The desired output from the existing and future policies cannot be obtained without basic information on different aspects of soil systems. Therefore, regular assessment, monitoring and reporting of variation in soil systems at local, regional and national scales are essential. These all are essential for moving towards an operationalized system of land and soil resource management.

9 Conclusion

As an outcome, given the importance of soil C, this chapter focuses largely on efficient soil management and C restoration techniques and policies in agricultural soils, which will aid the country's resilience to climate change and soil degradation. To make the country and the globe a better place, it will also promote the 'Sustainable Development Goals. The government or an organization may invest to stabilize the SOC stock with the following conditions, viz. (i) higher resource use efficiency, (ii) promotion of the C farming, (iii) enhancement in C stability, (iv) financial assistance to C offsets and (v) government subsidies and financial incentives for C management.

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Technologies, Programs, and Policies for Enhancing Soil Organic Carbon in Rainfed Dryland Ecosystems of India

Ch. Srinivasa Rao, S. Rakesh, G. Ranjith Kumar, Kiran Pilli, R. Manasa, Samaresh Sahoo, Sumanta Kundu, J. V. N. S. Prasad, G. Pratibha, and G. Narayana Swamy

Abstract

The majority of the Indian farming community depended on rainfed agriculture; most of them are small and marginal farmers. Thus, to sustain food production and meet the requirements of an ever-growing population, there is a great necessity of concentrating rainfed regions for enhanced productivity without jeopardizing soil and water resources. Sixty-three percent of the area is prone to some degree of desertification in dryland ecosystems. About 67% of the Indian soils are deficient in soil organic carbon (SOC); specifically, soils of arid hot ecosystems are low in SOC stock as compared to those of semiarid, subhumid, and coastal environments. Increasing SOC stocks in dryland helps in mitigating the increasing atmospheric carbon dioxide (CO_2) concentration, besides improving the soil quality attributes such as stability of aggregates, soil fertility, nutrient cycling, etc. By changing the land-use pattern following sustainable ways such as through introducing higher biomass-producing crops, shrubs, and tree species coupled with soil management technologies in the existing system, the annual carbon (C) sequestration rate could be increased by 20–75 g C m^{-2}, and SOC may reach a new equilibrium in the interior several years. Therefore, this chapter aims on the productivity constraints and soil health issues of drylands, present status of SOC, and key reasons for its depletion in Indian soils and a technological approach to achieve the improved profile SOC stocks in dryland areas. This chapter also provides the way forward to have policy and implementation

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pathways to enhance the C sequestration programs at local, regional, and national scale in Indian rainfed dryland ecosystems.

Keywords

Crop residues · Drought · Land degradation · Soil carbon stock · Soil health

Abbreviations

AMF	Arbuscular mycorrhizal fungi
C	Carbon
CA	Conservation agriculture
CASI	Conservation Agriculture-based Sustainable Intensification
CC	Cover crops
CH_4	Methane
CO_2	Carbon dioxide
CT	Conventional tillage
DAP	Diammonium phosphate
FAO	Food and Agriculture Organization
FCO	Foreign and Commonwealth Office
FYM	Farmyard manure
$g\ Cm^{-2}$	Grams per square centimeter
$g\ Kg^{-1}$	Gram per kilogram
GHGs	Greenhouse gases
GHI	Global Hunger Index
GOI	Government of India
ICAR	Indian Council of Agricultural Research
IFFCO	Indian Farmers Fertiliser Cooperative Limited
INM	Integrated nutrient management
IPNI	International Plant Nutrition Institute
IUCN	International Union for the Conservation of Nature
$kg\ ha^{-1}$	Kilogram per hectare
LDN	Land degradation neutrality
$Mg\ C\ ha^{-1}$	Mega gram of carbon per hectare
$Mg\ ha^{-1}$	Mega gram per hectare
MGNREGA	Mahatma Gandhi National Rural Employment Guarantee Act
Mha	Million hectare
MNRE	Ministry of New and Renewable Energy
MOP	Muriate of potash
MT	Metric ton
Mt	Million tons
N_2	Atmospheric nitrogen
N_2O	Nitrous oxide
NAPCC	National Action Plan on Climate Change

NBMMP	National Biogas and Manure Management Programme
NCU	Neem-coated urea
NMSA	National Mission for Sustainable Agriculture
NPMCR	National Policy for Management of Crop Residue
NT	No-till
NUE	Nutrient use efficiency
OC	Organic carbon
Pg C y^{-1}	Pentagrams of carbon per year
Pg	Pentagrams
POM	Particulate organic matter
RDF	Recommended dose of fertilizer
RMPs	Recommended management practices
SAT	Semiarid tropics
SCD	Surface charge density
SDGs	Sustainable Development Goals
SHC	Soil Health Card
SIC	Soil inorganic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
Sq. km	Square kilometer
SSNM	Site-specific nutrient management
t ha^{-1}	Ton per hectare
TC	Total carbon
Tg C y^{-1}	Teragrams of carbon per year
TOC	Total organic carbon
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WHC	Water-holding capacity
WHO	World Health Organization
ZT	Zero tillage

1 Introduction

India is a subtropical country comprising of 15 agroclimatic zones, which are majorly depending on the southwest monsoon. Out of 140 Mha net-sown area, nearly 70 Mha are under rainfed condition. Most of the rainfed/dryland farmers are resource-poor small and marginal; but their share for the food production is almost 60% of the total food grain (Agriculture Census 2015–16). Rainfed areas in the country support nearly 40% of the country's population and 60% of livestock with the production of 90% of millets, 80% of pulses and oilseeds, 60% of cotton, etc. (Srinivasarao et al. 2015). Among all the existing issues, food crisis remains the most unsolvable problem around the globe until date as the human population growth is at an alarming rate. In developing countries, estimates show that 780 million people were undernourished (https://www.actionagainsthunger.org/global-poverty-hunger-facts). As per the FAO, every year roughly 1/3rd (around 1.3 billion tons) of the produced food gets wasted. Globally, food losses per year are 30% for cereals; 40–50% for root crops, fruits, and vegetables; and 35% for seafoods (Boliko 2019) which represents the waste of resources such as land, water, seeds, fertilizers, etc. used for the food production purpose in an unsustainable manner. According to the UN India, there are nearly 195 million undernourished people in India, which is a quarter of the world's hunger burden. In addition, roughly 43% of children in India are chronically undernourished. India ranks 71 out of 113 major countries in Food Security Index 2020. The frequency of household food insecurity is relatively high in some developed countries, ranging from 8 to 20% of the population (Pollard and Booth 2019). As per the GHI (Global Hunger Index) 2021, India ranks 101 out of 116 countries, which is a serious threat to nation's food security. Burgeoning population and food demand pressurize the lands for excess food production that are ultimately exploiting the existing natural resources (soil and water). Consequently, the rainfed arable lands in arid, semiarid, and subhumid areas are being extensively degraded.

To overcome the present food insecurity crisis, all the World Health Organization (WHO) members have adopted the United Nations' 17 Sustainable Development Goals (SDGs) in 2015, which include achieving zero hunger or zero undernourished population by 2030. Various agriculture and allied sectors such as field crops, horticulture, livestock, fishery, and poultry are strongly associated with several United Nations SDGs and more importantly zero hunger, nutrition, and climate action, and others. SDG 6 focuses on water and sanitation; SDG 11 on sustainable cities; SDG 12 on reducing the pressure on natural resources; and SDG 13 on climate change, and SDG 15 is linked to SDG 2 on food security. It is utmost challenge to ensure the food and nutritional security in spite of managing the existing resources without harming its regular functions. Agriculture in resource-scarce regions is the crucial component for achieving the SDGs, established to provide the framework to shape the policies and actions to ensure the prosperity for all human beings on the planet.

However, several critical challenges for the nation's food security such as climate change-induced droughts, cyclones, heat waves, irregular rainfall patters, etc. coincided with non-judicious management of natural resources which are degrading the soil productivity and affecting the overall crop yields and environmental quality specifically in drylands, consequently impacting the income of small and marginal farmers. To meet all the nutritional needs of the growing population, the country will have to produce additional food grains annually and increase the production of livestock, fish, and horticultural products. As per the estimations, by 2030, India needs to produce 304 million tons (Mt) of food grains; 96 Mt of fruits; 175 Mt of vegetables; 21 Mt of meat, eggs, and fish; and 170 Mt of milk (Srinivasarao et al. 2015), and by 2050, the production must be enhanced by 65% to meet the requirement of ever-growing population. This has to be achieved in the face of shrinking arable land and farm size, low productivity, growing regional disparities in productivity, and depletion of the natural resource base. Soil organic carbon (SOC) helps in maintaining the physicochemical and biological properties of the soil that ultimately helps in producing more biomass and food besides minimizing climate change to attain SDG goals (Rakesh et al. 2022). Sustainable management of SOC specifically in rainfed areas is critical to sustain the food security and soil fertility without impairing the environmental quality. However, large-scale programs and policies play a critical role in enhancing SOC in the dryland areas of India. Therefore, it is a need of the hour for the humankind to realize the mistakes done since decades and transform the current agriculture system to sustainable production system using present innovative technologies in order to ensure the global food security and environmental safety.

2 Productivity Constraints

In India, around 51% of the total cultivated area is under dryland/rainfed farming, which contributes about 44% of the total food production (80% of cereals, 50% of maize, 88% of soybean, and 65% of pigeon peas and chickpea, among other crops) and is playing a crucial role in safeguarding country's food security. These lands encounter several constraints that are limiting the crop productivity at a greater extent. Agriculture is facing constant challenges with a growing population (Rakesh et al. 2019); changing of climate is further affecting the key ecosystem functions which in turn results in stagnating agricultural productions. Rainfed areas are naturally fragile and vulnerable to climate change and largely inhabited by the poor farmers. However, at the same time, rainfed areas can bolster the nutrition security through millets, pulses, and oilseeds. Frequent droughts, soil degradation, low investment capacity, poor market linkages, etc. are the crucial challenges, which are leading to low productivity, which accentuates hunger, unemployment, and poverty in rainfed agriculture. Among all those, rainfall is a key factor that determines the crop productivity in dryland farming and becomes a serious challenge for attaining sustainability of rainfed ecosystems in India due to increased frequency of droughts (Srinivasarao et al. 2020a). Drought affects the overall food security of the nation (Srinivasarao et al. 2017a). This leads to other environmental issues such as land degradation and depletion of resources such as water, energy, food, and biodiversity which are the major sources of conflict, security issues, and migration. Intermittent and prolonged droughts are among the major causes of yield reduction in most of the dryland crops. Rainfed areas in India experience 3–4 drought years in every 10-year period (AICRPAM 2009–2010). Moisture stress is an important factor in determining the crop yields of drylands. Major soil types of rainfed agroecological regions of India are comprised of alfisols, vertisols and vertic subgroups, oxisols, inceptisols, entisols, aridisols, etc. and exhibit variations in moisture holding capacity (Srinivasarao et al. 2017a). Most of the crops in rainfed regions receive least attention of farmers toward application of manures and fertilizers. The fertilizer consumption in different rainfed states of India is presented in Fig. 1.

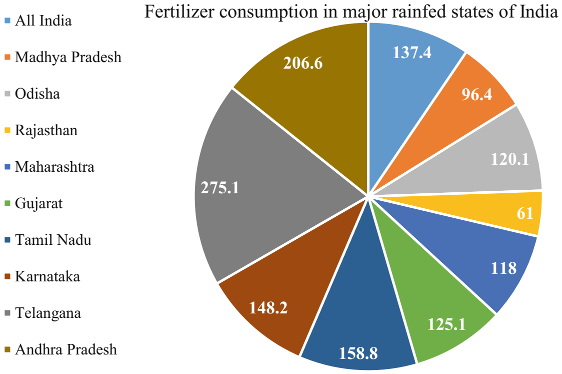

Fig. 1 Fertilizer consumption ($N + P_2O_5 + K_2O$) (tons) in major rainfed states of India (2020–21) (Data from Fertilizer Statistics 2020–21)

Consequently, nutrient deficiencies are emerging as the most important constraints in achieving the required yield targets. Thus, productivity of rainfed crops has remained low. Although it has been amply demonstrated that soils in rainfed regions are multi-nutrient deficient, balanced use of these inputs in rainfed crops is rarely achieved. Most of the dryland soils are deficient in nitrogen and phosphorus (other elements such as N, P, K, S, Mg, Zn, and B), but some regions have extremely low soil organic carbon status as low as 0.15%. Therefore, the untapped potential of Indian rainfed agriculture was massive (Chaturvedi and Ali 2002). Harnessing the full potential of rainfed drylands will contribute significantly to meeting India's rising food and nutrition necessities. In the context of increasing resource limitations (energy, water, land, and finances among others) and higher carbon footprint, these gains are realized in a sustainable, ecological, economic, and socially equitable manner. Severe incidence of pests and diseases is also a reason for the yield losses in rainfed crops. Due to uncertainties, there is lag in technology adaption in the dryland farming systems. Further, poor crop management due to untimely sowing and lack of intercultural operations like weeding, irrigation, and optimum plant density result in poor crop yields. Judicious crop management can substantially enhance productivity and improve agronomic and economic returns (Srinivasarao et al. 2013).

3 Soil Health Issues in Rainfed Dryland Ecosystem

Maintenance of soil health is the key to sustainable high productivity, good water and air quality, and healthy human and animal population. In dryland areas soil organic carbon depletion and loss of plant available nutrients are the major threats to the soil productivity and land degradation (Srinivasarao et al. 2009a, b, 2012a, b, c, d, 2021a). According to the FAO (2000), drylands are classified climatically as arid, semiarid, and dry subhumid regions. The dryland soils generally have low level of organic matter, alkaline to slightly acidic soil reaction in surface, accumulation of salts or lime or gypsum, coarse to medium texture, and low biological activity (Arnon 1992). Dryland soils are highly susceptible to wind and water erosion due to soil moisture deficit. It is estimated that wind erosion alone causes annual soil loss ranging from 10 to 50 t ha^{-1}. High evaporation and limited or no leaching causes salinity in dryland regions. In drylands, land use for cropping is problematic due to scarcity of irrigation water source and uneven rainfall during cropping season. In tropical regions, low-input farming system has adverse influence on soil organic carbon (SOC) through depletion of nutrient status, no turning of crop residues, and low productivity. In the semiarid and arid regions, low quantity of crop residue is rapidly oxidized due to high temperature and allowing humification. The soil organic matter content decreases with increase in temperature and decrease in rainfall owing to the sensitivity of organic matter breakdown to climate. Usually the soils of tropical environment contain less than 1% organic carbon, whereas temperate environments contain 2–4% (Virmani et al. 1991). Further, erosion of topsoil also contributes to low organic matter content of soils in dry areas. Characterization of 21 soil profiles under 8 rainfed production systems of India showed that soil was low in organic carbon (<0.5%) and lesser organic carbon stocks (Srinivasarao et al. 2009c). Most of the soils have extremely low SOC, ranging from 8 to 10 g kg^{-1}. Low additions of chemical fertilizers and organic amendments cause depletion of SOC (Lal 2004a, b). Besides the dryland soils are highly degraded, low in soil organic, and multi-nutrient deficient. Emergence of K, S, Mg, Zn, and B deficiency is one of the major constraints of crop production in arid and semiarid regions of the country (Srinivasarao 2011; Srinivasarao et al. 2006; 2008a; 2009a, b; 2011a; 2012a). Non-precise application of faulty methods in agriculture causes nutrient leaching, volatilization, and gaseous emissions leading to poor soil fertility and deterioration of soil quality. Poor soil fertility and quality are the key reasons for low nutrient use efficiency of P (15–20%), N (30–50%), Zn (2–5%), Fe, and Cu (1–2%). Micronutrient use efficiency is extremely low, i.e., about 1–5%. Falling nutrient use efficiency is one of the serious consents in rainfed agriculture. Synchrony of water and nutrient availability is critical for higher nutrient use efficiency in dry crops. However, depletion of SOC is often associated with declining use efficiency of added nutrients.

4 SOC Status of India and Rainfed Drylands

The soil organic carbon is the biggest carbon pool in the terrestrial biosphere. It is estimated that 3.667 tons of CO_2 is emitted from 1 ton of soil organic matter (Meena et al. 2016). The average concentration of soil organic carbon ranged from 0.30% to 1.05% in top 30 cm profile soil and accounts around 10% of the SOC stocks (140–170 Pg) in agriculture ecosystem and active fragments of terrestrial farmlands (Datta et al. 2017a). India is having 329 Mha of total geographical area, out of which 162 Mha is arable land, 69 Mha of forest and woodland, 11 Mha of permanent pasture, 8 Mha of permanent crops, and 58 Mha of other land use. The SOC pool in soil profile is estimated to be 21 Pg at 30 cm depth and 63 Pg at 150 cm depth. In most of cultivated soils, the SOC is less than 5 g kg^{-1} in comparison with uncultivated soils, i.e., 15–20 g kg^{-1} (Lal 2015a). About 67% of the Indian soils are deficient in SOC; specifically, soils of arid hot ecosystems are low in SOC stock as compared to those of semiarid, subhumid, and coastal environments. The carbon sequestration potential in Indian soils is estimated at 7–10, 5–7, 6–7, and 22–26 Tg C y^{-1} for restoration of degraded soils and ecosystems, erosion control, adoption of recommended management practices (RMPs) on agricultural soils, and secondary carbonates, respectively. Thus, in India the total C sequestration potential is 39–49 (44 ± 5) Tg C y^{-1} (Lal 2015b).

In general, SOC content in soil is directly proportional to clay content of soil and rainfall, whereas it is inversely proportional to the annual temperature. In most of the soils, SOC content is low because of intensive cultivation over the centuries, low farm input, crop residue burning, or removal and use of dung for fuel or other purposes. Because of the low clay contents, there is low SOC in the coarse-textured soils of southern India, alluvial soils of Indo-Gangetic plains, and arid zones of northwestern India (Dhir et al. 1991).

In India the southwest monsoon is blocked by very tall Western Ghats mountain range to reach Deccan Plateau, so the region receives very little rainfall (World Wildlife Fund 2001). This region consists states like Karnataka, Tamil Nadu, and Andhra Pradesh, which covers about 12% area of the country. The dominant soils in these states contribute 10% of soil organic carbon, 18% of soil inorganic carbon (SIC), and 13% of total carbon (TC) (Srinivasarao et al. 2020a). In India nearly 45% area is occupied by deccan plateau and covers the semiarid tropics (SAT) of the Indian subcontinent. The semiarid tropics of India are dominated with black soils (*vertisols* and some *entisols*) along with red soils (*entisols* and *alfisols*). The carbon storage capacity of soils depends on the quality of soil substrate and its surface charge density (SCD). Soil organic carbon has a direct effect on surface charge density and the ratio of external or internal exchange sites. The smectite and kaolinite clay minerals reserve large amount of carbon, which might be due to high surface charge density, large areal coverage, as well as greater carbon sequestration potential of these soils (38% SOC, 43% SIC, and 39% TC) (Srinivasarao et al. 2020a). The SOC content in most of South Asian soils ranged from 0.1% to 0.5%. In different regions of India, the SOC concentration significantly decreased after the intensive cultivation (1960s) as compared to the uncultivated soils prior to the 1960s in top 20 cm soil horizon (Lal 2013).

The soils in dryland areas have a great carbon sequestration potential, if appropriate management and land-use policies are followed (Marks et al. 2009). The increase of SOC stocks in dryland not only has the mitigating potential of increase in atmospheric CO_2 concentration but can also improve soil quality attributes such as stability of aggregates, soil fertility, nutrient cycling, etc. (Rakesh et al. 2020a). The decline in SOC needs to be counteracted by retention of crop residues on soil. Crop residue burning or removal from soil surface results in decrease in soil organic matter, reduced soil biological activities, incapacitate soil structure, disrupted water infiltration, and retention and release for plant growth (Karlen and Rice 2015). In the regions of semiarid and arid, soils are highly weathered, and some fertilization is needed to avoid the depletion of soil nutrients (Bationo and Ntare 2000). In the dryland areas, lack of sufficient moisture during crop growth influences crop productivity, SOC dynamics, soil microbial activity, and crop diversity (Skopp et al. 1990).

SOC stocks reduce due to intensive cultivation, climatic and edaphic characteristics, and farming practices without caring for the sustainability of the system. The soils of India in upper 40 cm soil horizons depleted SOC pool from <1.0 g kg^{-1} to 10–15 Mg C ha^{-1} (Lal 2015a). The soil C stock decreased at the rate of 0.1–1.0% per year due to prolonged intensive cultivation (Lal 2013). In global soils, intensive cultivation experienced a loss of 40 Pg carbon with an average rate of about 1.6 Pg C y^{-1} (Verma et al. 2015). High amount of C loss occurs mainly in soils prone to erosion, salinization, and nutrient diminution than the un-degraded soils with a range varying from 10 to 30 Mg C ha^{-1} (Lal 2013). The carbon loss from soil around the globe is estimated to be 78 ± 12 Pg (Lal 2004a; Buragohain et al. 2017).

The carbon depletion is associated with several factors such as disruption in soil aggregation, decomposition of SOM, accelerated aeration, alteration in plant productivity, biomass production, and soil biological properties (Datta et al. 2017b). Intensive cultivation results in deterioration of soil aggregates which leads to increased C loss and consecutive decrement in retention of new C addition (Six et al. 2000) and less addition of C materials to the soil (Solomon et al. 2007). The amount of C added by the crop plants to soils is highly susceptible to microbial decomposition than the woody plant C biomass, which remains in field (Meena et al. 2017).

Low SOC pool in India is adversely affected by decline in soil quality and soil degradation causing reduction in biomass productivity and low crop residue and root retention to the soil. There is a severe problem of desertification in dryland areas where 63% of area is prone to some degree of desertification (Lal 2015a). There is a severe and rapid depletion of SOC due to accelerated soil erosion. The fractions of soil organic carbon are preferentially removed by surface runoff and wind erosion. The eroded fractions are concentrated in the proximity of surface soil and have low density. Consequently, eroded sediments are enriched with SOC pool compared with the field soil with an enrichment ratio of 1.5–5.0 (Lal 1999). The fate of eroded sediments is governed by a series of complex and interacting processes, and a considerable SOC part is mineralized leading to the release of CO_2 under aerobic conditions and CH_4 under anaerobic environments. It is assumed that about 20% of eroded soil organic carbon is mineralized (Lal 1995).

In view of all the discussed facts, current intensive agriculture is greatly in need of sustainable intensification to protect the SOC loss. The annual C sequestration rate could be increased by 20–75 g Cm^{-2} by changing the land-use pattern through the adoption of SOC-enhancing technologies such as introducing higher biomass-producing crops, shrubs, and tree species in the existing system, so that the SOC may reach a new equilibrium in the interior several years (Kakraliya et al. 2018).

5 SOC-Enhancing Technologies

5.1 Crop Residue Recycling

Quality soil with greater amounts of SOC boosts the crop productivity (Rakesh et al. 2020b; Juttu et al. 2021). Crop residues act as a primary contributor to elemental carbon in soil, and it incorporates a large number of soil nutrients that helps for higher crop production. Soil organic matter (SOM) can be efficiently improved by the incorporation of crop residues such as stubbles, stem, leaves, husks, etc. which also play a decisive role in improving soil quality (controlling various soil physical, chemical, and biological functions) and sequestering soil carbon (Kumar and Goh 1999) as well as addressing several environmental issues. Various benefits of crop residue incorporation in soil fertility maintenance are illustrated in Fig. 2.

Residue incorporation changes the labile pool of SOC (Wang et al. 2004). Retention of sun hemp residues on soil surface significantly enhanced the SOC by 0.92% compared to control plots (no residue incorporation) (Wang et al. 2004). Plots which received legume stubbles contained 60% more SOC compared to control plots where no stubbles were incorporated. Legume-based residue incorporation ensures the production of huge biomass that confirms the net gains of carbon stocks in

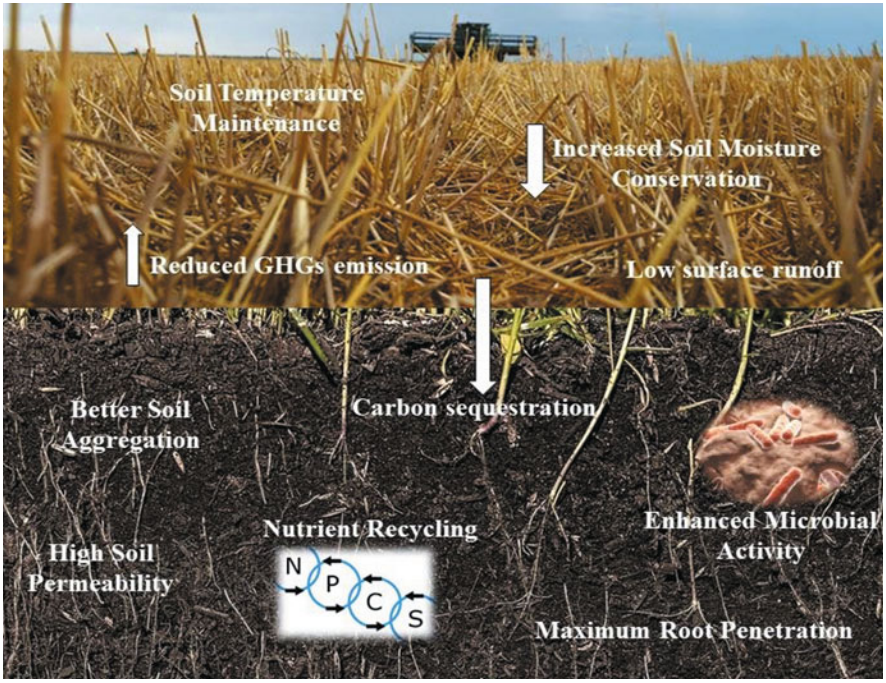

Fig. 2 Benefits of crop residue recycling in soil fertility maintenance

comparison with cereals, which produce less biomass (Tiemann et al. 2015). Alternatively, crop residues can also be used to make a biochar (by-product of the pyrolysis: biowaste is heated at 400–600 °C temperature in the absence of oxygen) (Sinha et al. 2021). Agricultural wastes such as poultry litter, waste wood, manure, plant material, bagasse, etc. are used in making biochar, which then becomes a great source of carbon. There are numerous benefits of application of biochar in soil, which improves soil water retention, provides better soil structure, enhances crop productivity and also reduces the greenhouse gas emissions. Recently, biochar is gaining importance, as it has a great potential for long-term C storage (Zhang et al. 2012).

In India, about 500 Mt of crop residues is produced every year as per the report of the Ministry of New and Renewable Energy (NPMCR 2020). It is always considered as a waste material in terms of their economic importance. Domestic sector consumes a big share and also an industrial sector. Apart from those, a huge portion of residues is left in the field. In some places, it is also burnt in the field itself. On-site burning of crop residues produces a huge amount of greenhouse gases (GHGs), i.e., majorly methane (CH_4) and nitrous oxide (N_2O) gases that harm the soil quality by depleting SOC (Sinha et al. 2021) and environment. Utilization of these residues as a nutrient source in the field brings a remarkable change in agricultural productivity and soil fertility.

5.2 Conservation Agriculture-Based System Intensification

Intensive tillage operations and non-judicious management of plant nutrients deplete the C pools and interrupt their dynamics (Bhattacharyya et al. 2012; Rakesh et al. 2020c). Continuous cultivation of agricultural lands using similar tillage implementation adversely affects the crop productivity specifically in semiarid regions (Sahoo et al. 2020a). Conservation agriculture-based sustainable intensification (CASI) or zero-tillage (ZT) technology involved with three basic principles, i.e., minimum soil disturbance, diversified cropping systems, and crop residue retention, may hold the key to address the C losses (Wright and Hons 2005). Also, ZT has been widely identified as an effective practice to increase soil aggregation and C sequestration compared to conventional tillage (CT) (Sahoo et al. 2020b). A successful management of crop residues as an in situ management is an integral part in a conservation agriculture (CA)-based system intensification (Jat et al. 2019). ZT or CA system has significantly enhanced the overall concentration of total organic carbon (TOC) at the upper two soil depths (0–5 and 5–10 cm) among all the sites (Fig. 3) studied in two different districts of West Bengal (Rakesh et al. 2020d). He also observed that TOC in rice-maize cropping system where residue biomass left on soil surface was maximum compared to rice-wheat under ZT management. Excessive addition of carbon substrate naturally improves the TOC in soil. An incubation study/C mineralization study conducted to compare the effect of ZT and CT also revealed that a %

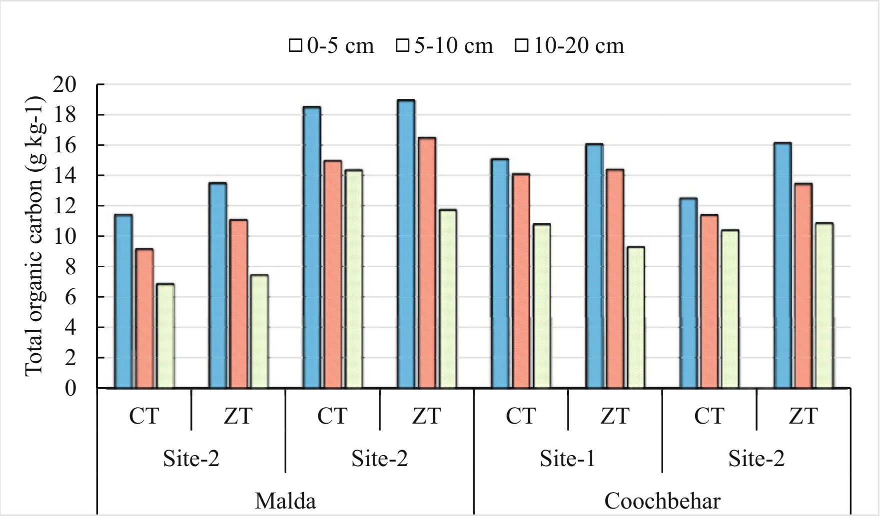

Fig. 3 Conservation agriculture/zero tillage (ZT) improved the total organic carbon over conventional tillage (CT) at different soil depths (Source from Rakesh et al. 2020d)

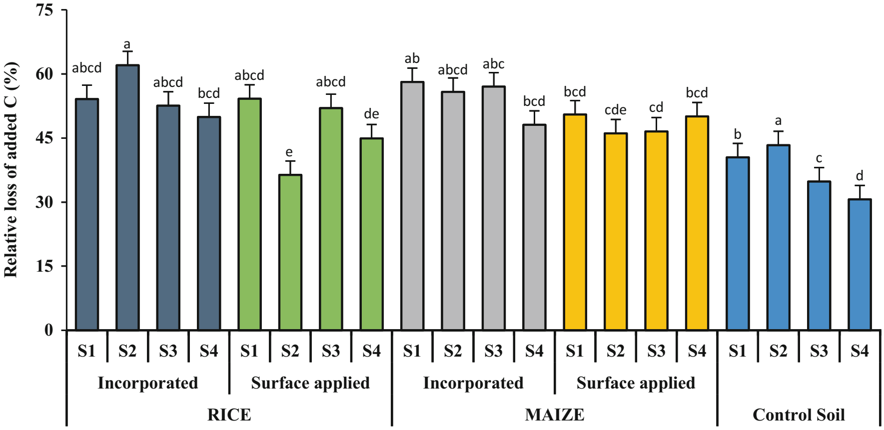

Fig. 4 Percent C lost from the residue incorporated and surface-applied treatments (Source from Rakesh et al. 2021)

C lost was minimum in the treatments where rice and maize residues were applied on soil surface compared to incorporation (Fig. 4).

Leaving the crop residue on the soil surface significantly minimizes the carbon footprints that helps in attaining sustainability from an environmental perspective (Rakesh et al. 2021). Potential benefits of ZT on SOC in farmers' fields of Eastern-Gangetic plains of India are shown by Sinha et al. (2019).

5.3 Cover Crops

Cover crops (CC) are well known for atmospheric-nitrogen (N_2) fixation that improves N recycling in the soil-plant system (Garcia-Gonzalez et al. 2018). It replaces bare fallows in crop rotations and is terminated before the subsequent main crop. Integrating CC into crop rotations highly benefits the soil by enhancing the soil C sequestration and organic matter (Poeplau and Don 2015). Incorporation of the roots and stubbles of leguminous cover crops grown for short periods helps in maintaining the high levels of SOM in some soils (Meena et al. 2020). Incorporation of short duration legume cover crops at the stage of flowering would enhance the soil organic matter that ultimately improves the nutrient cycling besides protecting the soil from erosion (Srinivasarao et al. 2017b). Inclusion of cover crops like pulses and legumes in the cropping systems under conservation agriculture, i.e., zero-tillage management, maintains the soil biophysical property and protects the soils from water and wind erosion (Ravisankar et al. 2020). Presence of plant cover and roots in soil profile aids in provision of improving SOC and soil aggregation and reducing bulk density (Abu-Hamdeh et al. 2006). Because of soil aggregation improvement, SOC slowly builds up through the improvement of particulate organic matter (POM) (Six et al. 2004). POM is a fresh organic material which comes from the larger C input, which is combined, contributed by crop residues and belowground root biomass (root decomposition, exudation, or deposition) in case of CC (Leung et al. 2015). Additionally, soil biological factors such as arbuscular mycorrhizal fungi (AMF) and microbial population and its activity would be efficiently promoted by CC, which have a large effect on soil aggregation (Kabir and Koide 2002). Adoption of CC substantially improved the SOC at the topmost soil layer (0–5 cm) during the experimental period as compared to the fallow plots after 2010 (Garcia-Gonzalez et al. 2018).

5.4 Integrated Nutrient Management

Integrated nutrient management (INM), whereby both organic manures/amendments and inorganic chemical fertilizers are combined, is an efficient technique for attaining sustainability in crop production (Ghosh et al. 2021). The SOC pool is significantly affected by land-use management practices including tillage (Dalal et al. 2011), crop residue management, fertilizer application, manure addition (Ding et al. 2014), etc. INM is one of the best strategies that would help in restoring the depleted SOC while improving the degraded soils and crop yields.

Percent increase in SOC stock over inorganic or recommended dose of fertilizer (RDF) treatment under various INM treatment combinations in different cropping systems has been illustrated in Table 1. From this study, it was noticed that INM practice in pearl-millet cropping significantly improved the profile SOC stock by 110–112% over the 100% inorganic treatment. Also, the INM in pearl millet-cluster bean-castor, groundnut, finger millet, and post monsoon sorghum crops enhanced

Table 1 Profile SOC stock and % increase over inorganic treatment under different INM treatment combinations

Crop/cropping system	INM treatment combination	Profile SOC Stock (Mg ha^{-1})	% SOC stock increased over inorganic/RDF treatment	References
Pearl millet-cluster bean-castor	50 percent RDN (F) + 50 percent RDN (FYM)	25.5	32	Srinivasarao et al. (2011b)
Groundnut	50% RDF + 4 Mg ha^{-1} FYM 50% RDF + 4 Mg ha^{-1} GNS	45.9 47.2	43 47	Srinivasarao et al. (2012e)
Finger millet	FYM 10 Mg ha^{-1} + 100% NPK FYM 10 Mg ha^{-1} + 50% NPK	85.7 81.6	22 16	Srinivasarao et al. (2012b)
Post monsoon sorghum	25 kg N (FYM) + 25 kg N (urea) 25 kg N (CR) + 25 kg N (urea)	62.6 65.8	16 22	Srinivasarao et al. (2012a)
Groundnut-finger millet	FYM + 50% NPK FYM + 100% NPK	72.9 73.0	9.6 9.7	Srinivasarao et al. (2012d)
Soybean-safflower	6 Mg FYM_N_{20} P_{13} ha^{-1} 5 Mg CR_N_{20} P_{13} ha^{-1}	69.9 68.7	7.2 6	Srinivasarao et al. (2012f)
Rice-lentil	50% organic (FYM) + 50% RDF	24.0	3.5	Srinivasarao et al. (2012c)
Groundnut	50% RDF + 6 Mg ha^{-1} compost (farmyard manure (FYM) + bio-fertilizers (BF))	71.6	8.4	Srinivasarao et al. (2020b)
Pearl millet	50% N-fertilizer +50% N-crop residue 50% N-fertilizer +50% N-FYM	44.2 44.6	110.4 112.3	Srinivasarao et al. (2021b)

Values in the parenthesis are profile SOC stock in the inorganic treatment the profile SOC stock by 32%, 43–47%, 16–22%, and 16–22%, respectively, against the inorganic treatment.

5.5 Tank Silt

"Tank silt" is a topsoil eroded with high intensive rains which contains fine soil particles (silt + clay) and organic materials that accumulated in farm or village tanks. It is a rich source of nutrients and SOC. The tank silt collected from some tanks of eight districts of Andhra Pradesh (Srinivasarao et al. 2011d) showed the nutrient content (range) as organic carbon (%) from 0.4 to 2.0; mineral nitrogen (mg kg^{-1}) from 200 to 1400; available P (mg kg^{-1}) from 8.0 to 35.2; available K (mg kg^{-1}) from 400 to 600; available S (mg kg^{-1}) from 12 to 50; available Zn (mg kg^{-1}) from 0.7 to 2.2; and available B (mg kg^{-1}) from 0.3 to 1.0. Being rich in soil organic carbon (SOC) and other nutrients, its application in rainfed agriculture can enhance water-holding capacity (WHC).

Several studies have demonstrated that application of tank silt in farmlands improves soil fertility (Obi Reddy et al. 2017) that helps in achieving higher crop productivity (Indoria et al. 2018) by increasing soil water-holding capacity (Deshmukh et al. 2019), organic carbon, and available nutrient status (Patil et al. 2017). Tank silt application improved the organic carbon from 0.30 to 0.38% (Bhanavase et al. 2011).

5.6 Balanced Nutrition

Fertilization of agricultural soils is the mandatory practice for achieving desirable crop yields. But the inappropriate practice always results in destruction of soil quality (Srinivasarao et al. 2020c) that ultimately causes soil degradation and loss of soil organic matter. Balanced fertilization/nutrition is the supplement of plant nutrients in the right proportion, in the right method, and at the right time for a specific crop and agroclimatic situation, which improve soil health and nutrient use efficiency (Srinivasarao et al. 2008b). Government of India launched Soil Health Card (SHC) in 2015 to ensure the farmland's nutrient status and decide the recommended dose of fertilizers to reduce the burden on agriculture soils. The International Plant Nutrition Institute (IPNI) has also developed a software called "Nutrient Expert" for determining the existing soil fertility status and estimate the remained nutrition supplement on a crop-specific basis. Implementation of site-specific nutrient management (SSNM) package (tested the individual fields for nutrient deficiencies and recommended the particular nutrient requirement of the crop) in eight clusters of Telangana and Andhra Pradesh resulted that it increased the yield by 25% in major rainfed crops in comparison with farmers' practices (Srinivasarao et al. 2011d). These methodologies help in minimizing the usage of chemicals in farming that ultimately results in reducing the cost of inputs, increasing productivity, improving nutrient use efficiency, and protecting the soil fertility.

Combining these techniques with carbon biomass addition in the form of manures and crop residues or with any other organic amendments would be effective in enhancing the SOC status of the soils. Long-term combined application of manure and inorganic fertilizers significantly increased the C sequestration rates and crop yield sustainability as compared to the inorganic fertilization (Srinivasarao et al. 2020b). Sequestration of carbon could be enhanced by the application of different nutrient fertilizers that yields high C biomass, manure application, or incorporation of crop residue (Cai et al. 2015). It has a greater and positive impact on crop yields. Long-term organic fertilization shows that each Mg of OC in the soil layer ($0 - 15$ cm) increased wheat productivity by $15 - 33$ kg ha^{-1} (Benbi and Chand 2007).

5.7 Use of Novel Materials

Nano-fertilizers which are nano-sized particles contain macro- and micronutrients that deliver nutrients to the plant in control mode. It is a great alternate for high crop production and soil restoration. Nano-fertilizers increase the nutrient use efficiency (NUE) and decrease the nutrient leaching to groundwater that helps in protecting the soil quality and environment by avoiding the chemical interference to soil microbial growth (Bose 2020). *Customized fertilizers* are the plant-specific nutrient package formulated scientifically based on the research findings. It is an effective nutrient formulation to supply multi-nutrients to the crop growth that helps in drastic reduction of external inputs. Due to its site and crop-specific formulations, the overall soil health can be effectively maintained. *Slow-release fertilizers* such as urea formaldehyde, neem-coated urea, sulfur-coated urea, etc. can release plant nutrients in small, steady amount over a period of time. These are generally eco-friendly fertilizers because of their nature of releasing nutrients slowly that avoids the loss of nutrients to the soil/environment. *Calcium bentonite* helps in improving nutrient holding capacity of the soil and also provides a better home for soil microorganisms. *Zeolite* is a crystalline made up of aluminum, silicon, and oxygen that acts as an amendment, attracts water molecules, protects soil from surface runoff, improves nutrient uptake, and reduces N losses through nitrification, leaching, and volatilization. In addition to this, *hydrogels* (hydrophilic polymers) can hold a large amount of water specifically suitable for the dryland soils. Both of these are called as a commercial absorbent.

5.8 Soil Restoration by Degradation Minimization

Soil is a nonrenewable resource, and extremely vulnerable to degradation that depends on complex interactions and factors and causes. Loss of SOC pool is driven by erosion, acidification, salinization, elemental imbalance, etc. through physico-chemical, biological, and ecological degradation leading to decline in soil quality (Fig. 5).

Fig. 5 Various soil degradation types and their impact on soil quality

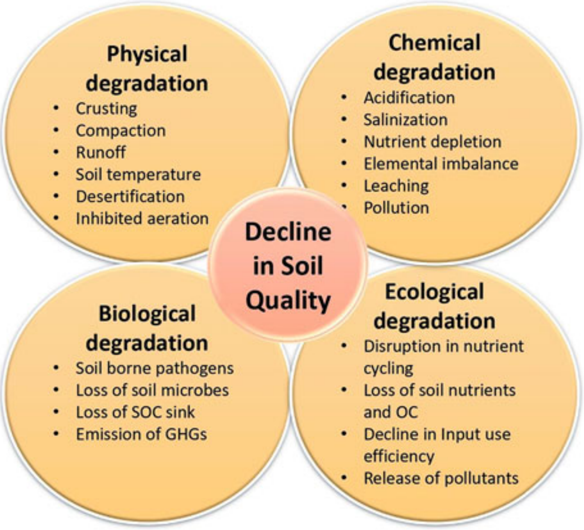

Table 2 Management options to correct the different soil degradation types

Degradation type	Management
Salinity/alkalinity/sodicity	Gypsum application for high alkali soils; leaching process for reducing salinity; tolerant tree species cultivation; green manuring; tolerant crop species
Soil acidity	Lime application, organic matter addition, plantation cropping, fruit cropping, agroforestry, etc.
Water erosion	Conservation agriculture, agroforestry, mulch-cum manuring, contour farming, contour bunding, bench terracing, contour trenches, half-moon terracing, strip cropping, mulching, cover crops, rainwater conservation, and farm ponds, silt traps in farm ponds, relay cropping, intercrops, tank silt recycling, etc.
Wind erosion	Afforestation, high density planting, agroforestry, planting of trees in borders of agricultural lands to act as shelterbelts; mulching, strip cropping, grassing, etc.
Soil fertility depletion	Introduction of legumes in mono-cropping, mulching, green manuring, conservation agriculture, crop residue recycling, judicious use of chemical fertilizers, combined application of fertilizers with organic amendments-INM, animal manures, SSNM, biochar and biofertilizers and legume cover crops

This can only be minimized through the adoption of recommended management practices. The major degradation types and their management practices are illustrated in Table 2. Increasing SOC pool in soil system through different techniques helps in improving soil structure, enhancing soil fertility, and enhancing microbial activity and species diversity of soil biota. This improvement in soil health ultimately helps in reducing the risks of soil degradation (physical, chemical, biological, and ecological) while improving the environment. Enhancing the SOC pool to above the critical level (10–15 g kg^{-1}) is highly required to set in motion the restorative trends (Lal 2015a). India joined the global commitment "Bonn Challenge" and pledged a total of 21 Mha to be restored by 2030 (13 Mha by 2020 and an additional 8 Mha by 2030). At COP14, Hon'ble Prime Minister, Shri Narendra Modi announced, "*India would raise its ambition of the total area that would be restored from its land degradation status, from 21 million hectares to 26 million hectares between now and 2030.*" This mainly focuses on restoring land productivity and ecosystem services of 26 million hectares of most degraded and vulnerable land by adopting a landscape restoration approach.

5.9 Mulch-Cum Manuring

Mulching has been considered as an effective practice for conserving soil health specifically under rainfed condition. In rainfed regions, soil moisture protection and reducing the C losses are great challenges. The in situ moisture conservation measures, such as mulch farming and crop residue management (Chakraborty et al. 2010) techniques, substantially increase the soil moisture availability and improve the overall crop yields (Kahlon and Lal 2014). Crop residues of rainfed crops such as cotton, castor, pigeon pea, maize, etc., left on the surface and a legume residue can be utilized as a mulch-cum manure that contributes to improved crop productivity and soil fertility. Decomposition of mulches leads to addition of nutrients and organic carbon to the soil. Recycling the residues of soybean as a mulch or incorporating into the soil along with an appropriate rate of chemical fertilizer can increase the SOC stock (Srinivasarao et al. 2012e). Mulching of maize stubble improved the SOC content by 1.9% (Choudhary 2015). Residue mulch application under no-till (NT) management enhanced the soil carbon concentrations by 1.26–1.50% (Kahlon et al. 2013). Apart from enhancing SOC, mulch increases reduce evaporation losses, insulate soil against extreme heat and cold by moderating soil temperature, reduce soil compaction, and control the wind and water erosion (Kahlon and Lal 2014).

5.10 Green Manuring

Incorporation of green manure biomass into the soil helps in the accumulation of organic matter and recycling of plant available nutrients (Ansari et al. 2022). Especially leguminous green manure is recognized to be a promising nutrient source that improves soil nutrient accumulation (Ansari et al. 2021). Because of its lowest C:N ratio than cereal crops, it promotes a faster mineralization of nitrogen (Ansari et al. 2022) which significantly increases enzymatic activities (urease and dehydrogenase) in the soil (Surucu et al. 2014). Green manuring/green leaf manuring improves soil biological health and enhances soil moisture storage, which helps in coping with intermittent droughts (Srinivasarao et al. 2020c). There are two types of green manuring: (1) in situ green manuring, growing green manure crops inside the

Table 3 Effect of different green manuring on depth-wise TOC stocks (Data from Ansari et al. 2022)

	TOC stocks (Mg ha^{-1})		
Treatments	0–15 cm	15–30 cm	30–45 cm
No green manuring	19.0	15.4	13.1
Green gram green manuring	21.4	17.2	14.1
Cowpea green manuring	23.4	18.5	15.1
Sesbania green manuring	24.6	19.2	15.1
LSD ($p < 0.05$)	1.06	0.88	0.69

farmland and incorporating it in the same land, and (2) ex situ green manuring, addition of green leaves brought from other places and incorporating it into the soil for manuring.

Growing short duration legume crops such as horse gram, green gram, cowpea, etc. and incorporating into the soil at flowering stage would add a huge amount of organic matter to the soil that helps in increasing crop yields. Horse gram incorporation in rainfed sorghum-sunflower and sunflower-sorghum rotations during rainy season demonstrated the restoration of degraded soils and improved crop yields in semiarid regions (Venkateswarlu et al. 2007). Green manure crops such as *green gram*, *cowpea*, and *sesbania* used for in situ manuring for five consecutive years helped in enhancing TOC stocks significantly ($p < 0.05$) compared to non-green manured soils (Table 3) (Ansari et al. 2022). Forest tree crops such as *Gliricidia* spp., *Pongamia glabra*, *Cassia fistula*, *Calotropis gigantea*, *Delonix regia*, *Azadirachta indica*, etc. can be utilized for green leaf manuring. Gliricidia used as a green leaf manure aided in supplementing both macro- and micronutrients (Srinivasarao et al. 2011c, d).

5.11 Coastal Soil Restoration

An anthropogenic activity in coastal zones has a significant effect on SOC. Reclamation/restoration of coastal soils aids in provision of balancing global carbon cycle. Earlier researches shown that SOC in coastal wetlands may be mineralized quickly due to reclamation, thus influencing the global carbon budget and balance (Cui et al. 2012) with positive feedback to global climate change (Gnanamoorthy et al. 2019). Rapid desalination and dealkalization of coastal wetlands aided in converting to farmlands that greatly increased the soil C and N sequestration (Yang et al. 2019). SOC can thus increase significantly over a long time period after coastal reclamation. Natural and restored mangrove forests in southeast coast of India have a great potential for carbon sequestration (Gnanamoorthy et al. 2019). High SOC stock and higher burial rates were found in mangrove areas than in restored areas. He also concluded that the conservation of intact mangroves is highly essential than either natural or restored mangroves. High rates of sedimentation in mangroves promote the accumulation of organic compounds in soils through an aerial and underground biomass production (Donato et al. 2011). However, the mangrove cover in India has come down from 6000 km^2 during the 1960s to 4740 km^2 during 2015; thus, restoration work is still needed to improve the ecosystem services and mitigate the impact of climate change. Depletion of SOC in salt-affected soils has created a C sink capacity that can be realized through restoration by adopting efficient management practices. Thus, manuring, crop residue management, agroforestry, pasture crops, crop rotations, and growing tree plantations in coastal lands potentially increase the C sequestration.

5.12 Composting

Composts are bulky in nature, for example, farmyard manure, vermicompost, kitchen waste composts, sheep manure, poultry litter, bio-enriched composts, market waste compost, and night soils (urban composts). Such bulky manures are rich in carbon, and application of these composts to cultivating lands helps in restoring the SOC. Srinivasarao et al. (2013) observed that cultivation of crops without input of farmyard manure (FYM) results in decrement of biomass production (especially the root biomass) and its return into the soil; this is responsible for decline in soil organic matter. Organic manures substantially increase the SOC content that proliferates the soil microbial activity which ultimately results in retaining soil moisture and nutrients besides imparting drought tolerance during dry spells (Srinivasarao et al. 2020b). An action plan of 4 per milli/4 per thousand concept initiated in COP21, Paris, to increasing organic C stock in top 30 cm by 0.4%/year also suggested to support the farmers to locally generate organic manures for regular field use as the SOC buildup is also an important measure of reaching goal of LDN.

6 Programs and Policies

Government of India has initiated several policies and programs for promoting the buildup of soil organic carbon, which facilitated the farmers to improve their land fertility status through some innovative technologies.

6.1 National Mission for Sustainable Agriculture

National Mission for Sustainable Agriculture (NMSA) is one of the eight Missions outlined under National Action Plan on Climate Change (NAPCC) which has been formulated for increasing agricultural production specifically in dry regions focusing on synergizing resource conservation, integrated farming, soil health management, and water use efficiency. So far, the land area covered under the integrated farming system approach (agroforestry, livestock, horticulture, water harvesting, and vermicompost unit creation) in the rainfed area development, NMSA has achieved

9501 hectares of land in India over the target of 89,793 (NMSA official site, 2021–2022 data: https://nmsa.dac.gov.in/RptActivityAchievement.aspx).

6.2 Mahatma Gandhi National Rural Employment Guarantee Act

Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) scheme was launched by Govt. of India during 2005 for improving the livelihood of rural community in India. This act focused on improving the soil fertility and biodiversity, soil erosion control, reclamation of degraded soils, carbon sequestration, ground water recharge, and rain water harvesting. Recently, with the water conservation under MGNREGA, about 210 farm ponds were executed, and 54 check dams were developed, due to which about 580 dried bore wells got recharged in the drylands of Andhra Pradesh. In Gujarat, around 55 dryland farmers (who have about 2 acres land) take advantage of irrigation after the renovation of ponds.

6.3 Soil Health Mission

Soil Health Card (SHC) scheme was launched by Govt. of India in February 2015 (80) which displays soil health indicators and associated with vivid terms to a SHC to analyze the soil sample in authentic soil laboratory and determines the crops that can be cultivated in the particular soil. Based on the soil test results, the SHC will give information on practices needed to improve the soil fertility. SHC scheme in India issued 34 lakhs in 2015 until July. This scheme is the leading program for the agricultural sector in India by distributing 10.48 crores of Soil Health Cards by December 2018. Among the states, AP has taken lead in distribution of the Soil Health Cards to farmers. Other states like Punjab, Uttar Pradesh, Telangana, Chhattisgarh, and Odisha also distribute SHC. Two states, Punjab and Tamil Nadu, have collected the maximum amount of soil samples for testing during the kharif seasons, but Tamil Nadu has not distributed the cards yet. Kerala, Haryana, Arunachal Pradesh, Sikkim, Mizoram, Goa, Gujarat, Tamil Nadu, West Bengal, and Uttarakhand are the states in which farmers have not been issued a single card as against the target set for 2015–16. SHC scheme is a revolutionary scheme, which was initiated for farmers. GOI with agriculture department has also launched a soil health card agriculture portal (www.soilhealth.dac.gov.in) in which farmers need to register, along with details of soil sample and test lab reports.

6.4 Crop Residue Management Program

In order to prevent crop residue burning, in 2014, the Ministry of Agriculture developed a National Policy for Management of Crop Residue (NPMCR). This scheme helped to promote technologies for utilizing crop residues, provide machineries for farming practices and satellite-based technologies to monitor crop residue management, etc.

6.5 Customized Fertilizers

Government Policy Interventions Considering the recommendation of Task Force, Government of India (GOI) has created separate category of fertilizers named as “customized fertilizers.” It was included in the Gazette in 2006 under clause 20 B of FCO 1985. Later customized fertilizer policy guidelines were issued in 2008 by the GOI. In India, there are about 36 customized formulations approved by the FCO (Majumdar and Prakash 2018).

6.6 National Biogas and Manure Management Program

National Biogas and Manure Management Program (NBMMP) promoted the setting up of family-type biogas plants in rural and semi-urban/households. It uses organic substances like cattle dung; biomass from farms, gardens, kitchen wastes, and night soil wastes; etc. The final by-product, i.e., slurry produced from biogas plants, can be utilized as organic bio-manure for enhancing crop yield and maintaining soil health. The Ministry of New and Renewable Energy (MNRE) has set up about 65,180 biogas plants during the year 2017–18 that fixed an annual target of setting under the NBMMP. In India, so far, about 49.6 lakh household size biogas plants have been installed under the scheme NBMMP.

6.7 Paris Agreement and GHGs

India is committed to the UNFCCC and the Paris Climate Change Agreement as our Hon’ble Prime Minister Shri Narendra Modi received the Champions of the Earth award in 2018 that recognizes contribution to the field of environment protection (MoEFCC 2018). This agreement aimed to deal with climate change with a low GHG emission and climate-resilient pathway. Alongside, this will create an additional “carbon sink” of 2.5–3 billion tons of CO_2 equivalent through additional forest and tree cover by 2030. Several ICAR institutes and state universities besides NRSA in India are also involved in monitoring and estimation of SOC stocks in different land categories.

6.8 Neem-Coated Urea Scheme

Neem-coated urea (NCU) is a slow-release fertilizer – nitrogen – for optimum plant growth. This helps in judicious use N fertilizers/reduced its application and increases the crop yield besides improving the soil health. Indian government shifted to 100% neem-coated urea (by implementing NCU scheme in 2015) and reducing the weight of urea bag (from 50 kg to 45 kg) to improve nitrogen use efficiency (NUE) and reduce urea consumption. The Minister stated that the cost of MOP, DAP, and NPK reduced by Rs 5000/MT, Rs 2500/MT, and Rs 1000/MT, respectively, by the P & K fertilizer companies; it will encourage the farmers to use more P & K fertilizers which helps in balanced use of fertilizers.

6.9 Rehabilitation of Degraded Land Targets and Land Degradation Neutrality

The International Union for the Conservation of Nature (IUCN) and the Government of Germany had launched the Bonn Challenge in 2011 for a global effort to restore 150 Mha of deforested and degraded land by 2020 and 350 Mha by 2030. India has joined this global commitment and pledged 21 Mha to be restored by 2030 for achieving land degradation neutrality (LDN). At COP14, the Hon'ble Prime Minister, Shri Narendra Modi announced, "India would raise its ambition of the total area that would be restored from its land degradation status, from 21 million hectares to 26 million hectares between now and 2030." India has, therefore, committed to restore 26 million hectares of degraded lands and achieving land degradation neutrality (LDN) by 2030.

6.10 Nano-Fertilizers

Union Minister for Chemicals and Fertilizers Shri D.V. Sadananda Gowda said that by 2023 India will be self-reliant in the production of fertilizers under "Atma Nirbhar Bharat" program. He also said that nano-fertilizers are a game changer, are 25–30% cheaper, and result in 18–36% higher agricultural produce and maintains the soil health. The IFFCO has distributed the nano-fertilizers freely to 12,000 farmers and agriculture universities across the country.

6.11 Net Zero Emissions

Realizing the effects of climate change on environment and food production and governance aspect to become more resilient, Hon'ble Prime Minister Shri Narendra Modi announced in COP-26 that India will achieve net zero emissions by 2070. Union Environment Minister Bhupender Yadav also said that India is taking a serious note of environmental, social, and governance aspects to become more resilient.

7 Conclusion

In Indian soils, the soil C stock in the upper 40 cm soil horizon is depleted at the rate of 0.1–1.0% per year due to prolonged intensive cultivation. Additionally, climate change and other key factors are further worsening the status of cultivating lands specifically in dry regions of India. Rainfed farming areas in tropical and subtropical regions are generally poor in soil fertility status because of several constraints and limitations such as low/irregular rainfall patterns, high temperature and oxidation, poor land management practices, etc. In rainfed agriculture, among all extreme events, temperature is being one of the key factors for destroying soil organic matter that declines the crop yields and productivity of lands at a greater extent. Usually the soils of tropical environment contain less than 1% organic carbon, whereas temperate environments contain 2–4%. Almost about 63% of area is prone to some degree of desertification in dryland areas. Thus, managing SOC in dryland has become a biggest challenge for the agriculture community as the profile SOC stocks are always considered as a potent weapon to combat against soil degradation and ensuring sustainability in agriculture system. Soil management practices that aid in provision of adding high C biomass inputs (green manuring, cover crops, crop residue recycling) or balanced plant nutrient input/output for sustaining the SOC levels (INM, balanced nutrition, tank silt, composting) or for protecting/improving the residual profile SOC stocks (conservation agriculture, soil restoration by degradation minimization, coastal soil restoration, mulch-cum manuring) specifically in dryland situations help in achieving the land degradation neutrality (LDN) and Sustainable Development Goals (SDGs) in India. Yet, the collaboration of stakeholders such as government, nongovernment organizations, researchers, and local farmer's societies is pivotal for framing the site-specific programs and coordinating policies of integrating soil carbon with national climate commitments in order to promote/implement the SOC management technologies at both local and national scales.

8 Way Forward

- Creating awareness among farmers regarding the soil fertility depletion, its correction, and the importance of SOC in crop production is critical.
- Identification of key performance indicators such as increase in SOC, soil cover buildup, productivity gains, etc. to confirm the land restoration level is needed.
- Remapping for the assessment of the actual SOC-depleted areas for the year 2021–22 is crucial for planning and decision-making.
- Development of rehabilitation policy programs at microlevel to promote soil management practices that are a net sink for atmospheric C.
- Convergence of interdepartmental collaborations and inter-ministries with a group of secretaries for monitoring the various government schemes.
- Encourage the community participation in taking care of their own land under the supervision/guidance of scientific community, development agencies, and appropriate policies to achieve land restoration at national scale.

- Encouragement of integrated and holistic land management practices with public support helps to sustain SOC sequestration rates.
- Establishing national mission on SOC sequestration at macro level and creating farmer's innovation and cross learning platform for SOC sequestration at microlevel.

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Traditional Land Use Systems' Potential as the Framework for Soil Organic Carbon Plans and Policies

Erhan Akça, Takanori Nagano, Takashi Kume, Claudio Zucca,
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Abstract

Carbon's regulatory role in life dynamics has been acknowledged over the past 20 years all over the world. Humans, on the other hand, have known for thousands of years, albeit not conceptually, the impact of carbon in life on the quality of the soil necessary for the production of food, clothing, and shelter materials, and have attempted to maintain their land fertile, whether via beneficial or harmful management. While some societies burned trees to create more fertile agricultural fields, others built stone terraces to keep the soil from being washed away by erosion. Civilizations have collapsed as well, such as Mesopotamia, due to poor irrigation practices accelerated by climatic changes. Countries had to take action against accelerated land degradation, loss of biodiversity, and

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desertification, as well as climate change, in the past five decades, with a deeper context, after the 1970s, due to excessive natural resource exploitation in the nineteenth century. As a result, they have developed international and national policies to seek to prevent and eliminate these threats. Countries prioritized adaptation and mitigation activities since prevention efforts on these problems did not generate sufficient benefits. Unfortunately, the traditional wisdom of society and today's socioeconomic reality cannot be claimed to be taken into consideration when adopting these procedures. While many national activity plans involve the transition to agro-ecological agriculture in a region, the budget and training that will be provided for this are not well defined. These programs are frequently ineffectual, as demonstrated by the fact that almost 1 billion people are starving and 25% of the world's land has been degraded. It is widely acknowledged that organic carbon must be managed effectively in attempt to face the global threats of climate change, land degradation, and biodiversity loss, and in this study, traditional knowledge and current policies were reviewed on a global scale as much as possible, with compatibilities and contradictions tried to be revealed. The intention is that traditional knowledge, which has accumulated and proven itself over thousands of years by overcoming challenges, will take an active role in national and international policies.

Keywords

Organic carbon · Traditional knowledge · Climate change · Biodiversity loss · Land degradation

Abbreviations

BC	Before Christ
BCE	Before Common Era
BP	Before Present
CDM	Clean Development Mechanism
CTU	Can Tho University
EC	European Council
GHGs	Greenhouse gasses
JIRCAS	Japan International Research Center for Agricultural Sciences
SDG	Sustainable Development Goals
SOC	Soil organic carbon
$t\ C\ ha^{-1}$	Ton carbon per hectare
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification

1 Introduction

This study does not claim to address the impact of traditional land uses on all continents, as well as the land use policy of each country, on soil organic carbon. However, if such a study had been conducted, it would have filled a significant information gap. However, the remarkable traditional land use and present policy on each continent have been reviewed to the greatest extent possible, and the compatibility, conflicts, and gaps between tradition and laws have been attempted to be exposed to the best of its ability.

All living organisms of the planet Earth are made from carbon. So, it would not be inappropriate to argue that carbon management is the foundation of survival. Humans modify carbon dynamics through transforming the form of carbon directly or indirectly, albeit this is not on the same scale as natural processes. While the first agricultural techniques in history to increase biomass and animal husbandry were human systems that produced healthy carbon, energy consumption can be thought of as human systems that convert carbon into harmful forms for the environment. Humans did not face global carbon-related threats until the eighteenth century because the production of useful carbon was much greater than the production of harmful carbon. However, it's worth noting that civilizations have fallen apart in the past as a result of excessive irrigation, which resulted in salinization in Mesopotamia, and the sacrifice of trees for grain in Central America, which depleted soil nutrition. No human-caused environmental event in history, however, has been as catastrophic as the eighteenth century and beyond. The increased use of fossil fuels after the eighteenth century, the acceleration of global population growth in the nineteenth century, the intensive use of agricultural chemicals to meet growing population demand in the twentieth century, and the resulting overconsumption of natural resources have resulted in the fact that the predominant carbon today is harmful carbon. People have been forced to take precautions as the carbon balance has shifted in favor of harmful carbon.

Air, soil, water, and biodiversity, which are components of the environment and affect the carbon cycle, are assets that cross borders. For this reason, sustainable carbon management requires cooperation between regions and countries. The actions against environmental issues began with the Stockholm Declaration in 1972 and continued with the Rio Summit's 21st Agenda in 1992, the Rio + 20 Sustainable Development Goals, and the 2030 Sustainable Development Goals (SDGs) adopted in 2015 as threats to life increased. The ultimate goal of all of these processes is to eliminate environmental and socioeconomic threats to the Earth's future through international cooperation.

Countries have begun to establish their own environmental policies within the framework of UN-led environmental policies. Unfortunately, regional and especially local realities were often not taken into account when creating these policies. National policies are shaped in the form of a kind of translation of the UN's policies on a global scale. As a result, although these policies are aimed at protecting the environment, they have often not achieved the desired goal or even attracted a negative reaction from the local population.

Mitchell (1989) discovered that until the 1990s, environmental protection policies were carried out by nominated civil workers in the state and that these policies remained far away from public realities. According to DeLeon (1994), in environmental policies, politicians frequently take environmental elements as the main goal and keep them away from the public, which is the true goal, as an impediment to success. Barr (2012), who considered it difficult to attain the objectives of environmental policies, underlined society's unwillingness to generate behavioral changes. After the protection/prevention project conducted in Central Anatolia under a semi-arid continental climate, which was threatened with desertification as a result of overgrazing and land processing in the 1960s, Akça et al. (2016b) observed that the annual number of plant species in natural pasture increased from 7 to 130. This success, however, had only been achieved because the local people were completely relocated from the protected area and the area was barbed-wired (Akça et al. 2016a; b). Due to a desertification conservation scheme, farmers have moved to cities and away from farmland. Farmers were allowed to resume farming in Karapınar when the threat of desertification was removed, and the use of irrigation water from deepwater sources in the early 2000s resulted in the formation of more than 330 sinkholes in the region (Akça et al. 2012; Orhan et al. 2021).

The failure of environmental policies cannot be attributed to a few factors. Laitos and Okulski (2017) have excellently described a multitude of reasons in their book entitled *Why Environmental Policies Fail*. Although Laitos and Okulski (2017) claimed that a variety of variables contribute to the failure of environmental policies, they identified the primary issue as policies that do not thoroughly account how people interact with nature.

People genuinely managed the environment in a mutually sustainable fashion until the eighteenth century. They've also established some sort of sustainable land use in all of the world's geographies and climates. The 1950s, on the other hand, mark the breaking point in the balance. The demand to improve people's quality of life is the critical component for the pressure on natural resources after the 1950s throughout the world (Novotny 1999; Ehrlich et al. 2001; Dearing et al. 2012; Salvia et al. 2019). With the rise in local environmental awareness in the 2000s, governments have been pushed to formulate their environmental policies on a regional rather than global scale. Kostka (2014) stated that Chinese politicians have recently prioritized shifting away from polluting growth to sustainable and efficient resource use. Local ecological knowledge gives guidance information for environmental policies, according to Iniesta-Arandia et al. (2015) in their interesting article. Drought-resistant plant selection was identified by Kapur et al. (2019) as an environmentally benign production technique in ancient Mediterranean land use heritage, and authors suggested a new production town system based on specific crop-soil ecosystems for policymakers. Zucca et al. (2010) manifested locals' participation in sustainable land management in a harsh environment of Morocco with limited water and soil resources.

Sato et al. (2018) highlighted several examples of sustainable land management based on local ecological or technical knowledge. But, the current environmental policies for soil organic carbon management in agriculture are still mainly based on global initiatives rather than local knowledge. With good and failed samples from each continent, this chapter intends to provide information on how much local knowledge is involved in carbon policies in agriculture, and set a source of information for policymakers to review their policies, because environmental projects that are not governed/supported by local residents inevitably fail and have the potential to produce conflict not only within the carbon framework but also between decision makers and the community at large.

2 Local Knowledge on Carbon Management

Carbon is a prevalent intersecting element as both a solution and a source of today's worldwide environmental issues. Carbon is an element that, when retained in organic or inorganic form as bicarbonate (HCO_3) and calcite ($CaCO_3$) in terrestrial and marine life, does not create challenges, even contributes to the production of biomass, and also sustains life by preventing a reduction in pH in the seas (Mook and Koene 1975; Akça et al. 2010; Raymond and Hamilton 2018; Büyük et al. 2020). International and national institutions have developed a variety of approaches and concepts for mitigating, adapting, protecting, or combating global challenges of climate change, desertification, and land degradation. The following are the definitions of circular and bioeconomy, which are now being advocated to alleviate environmental problems. The European Union defines a circular economy as a production and consumption paradigm that encourages people to share, lease, reuse, repair, refurbish, and recycle existing materials and products for as long as feasible, suggesting that the product's life cycle can be extended in this way (European Parliament 2021). The definition of circular economy was initially provided in Boulding's study in 1966 (Boulding 1966); it was only when it was recognized as a policy by the European Union that it achieved global prominence. Many people interpret the European Parliament's circular economy term as an industrial definition; one of the simplest definitions was provided by Geisendorf and Pietrulla (2018) as the restoration of resources, which leads to the carbon cycle being a component of the circular economy. For thousands of years, harvest leftovers have been recycled as organic fertilizer in agriculture (Gotass 1956). The usage of animal manure in archaeological sites extends back to 5000 years ago, according to Wilkinson (1982). These ancient uses are the indicator of the circular economy which recycles carbon in an environmentally friendly manner.

The following definition is the most widely accepted one for bioeconomy introduced by the European Union (European Council 2015), who has approved it as a policy: the sustainable production of renewable resources from various ecosystems and their conversion into food, feed, fiber bio-based products, and bioenergy, as well as related goods for public use. According to Aguilar et al. (2019), the bioeconomic approach should be adopted or embedded by society in order to be successful. Even if we merely look at historical agricultural land uses, we can see that bioeconomy has already positioned itself as a public approach. According to Gajula and Reddy (2021), bioeconomy is the primary economic activity of the ancient world because practically all of the past cultures' economies were based on agriculture.

Before the widespread use of chemical fertilizers in the mid-1950s, societies had just two agricultural production alternatives: The first was to provide organic additions such as barnyard manure, pruning, and harvesting leftovers to the soil to keep it the land fertile, or the second was to abandon the soil with reduced production and relocate more fertile forest or grazing regions for agriculture. This type of land use has various names such as shifting cultivation, bush-fallow agriculture, swidden cultivation, or slash-and-burn cultivation (Raman 2001). We in this section primarily focus on practices that lead to land degradation before evaluating good/successful ones. The reason for this is to show what kind of regulations these misconducts imposed in the past which were a kind of carbon policy action plans of today.

The second practice, i.e., slash-and-burn, was quite common in several parts of the world particularly with sloping topography or mountainous regions alike Bolivian Amazons, Laos, Guatemala, and India (Stab and Arce 2000; Raman 2001; Rumpel et al. 2006; Williams et al. 2007; Vashum and Jayakumar 2016; Dussol et al. 2021). In modern Estonia, the term *buschland*, originated from the local Baltic German dialect, was used to describe the land that had been used for regular combustion approximately every 20 years burning (Tomson et al. 2016). In India the word *jhum* is used for defining this practice, while ladang is the word in Indonesia and in the Philippines, it was kaingin (Myllyntaus et al. 2002). According to recent studies, swidden agriculture is not a poor practice in and of itself (Saito et al. 2006). However, most of the time, this practice did not take into account the land's resilience, climate, or vegetation capacity. Hereby, it has been recognized that this method frequently results in conflicts, wars, and even the extinction of civilizations, as was the case with the Mayans. Anselmetti et al. (2007) calculated an annual soil loss of 1000 t km^2 year^{-1} during initial land clearance of forest by ancient Mayans at 700 BCE. Although it is unlikely to evaluate the impact of ancient cultures' slash-and-burn technique on organic matter, research undertaken now can provide some insight to the magnitude of loss as it can be seen Kotto-Same et al.'s (1997) study which manifested a soil carbon loss from 308 t C ha^{-1} to 88 t C ha^{-1} during converting forestland to cultivated land in Cameroon.

It can be stated that problems such as migration and turmoil arise in societies that apply management aimed at obtaining new agriculture rather than improving the soil, whereas communities that understand agriculture and manage soil health by incorporating what the soil produces increase their well-being. Singh et al. (2018) stated that ancient agricultural practice of straw burning causes several health and environment problems due to emission of various harmful gasses during burning in India and is prohibited by the government. While agricultural activities that harm the environment are intended to be prohibited by legislation, like in India (Singh et al. 2018), Europe (Nikolov 2011), and other parts of the world, environmentally beneficial traditional agricultural activities are not adequately supported. Due to insufficient support, farmers producing within the framework of ecological agriculture are shifting to today's intensive agriculture, which is supposed to yield high incomes. Marini et al. (2011) observed that traditional agriculture in the Italian

Alpine mountains has given way to modern agriculture, which is said to be more profitable. They propose preserving this heritage by compensating farmers for the production of organic fertilizers and the careful management of steep meadows.

In the following part, agricultural cases from around the world in favor of soil organic carbon are described, and the impact of traditional agricultural producers on soil carbon dynamics is assessed by examining how many of these techniques are included in national agricultural policies.

2.1 Traditional Land Use and Carbon Policy in North and Central America

Agriculture in North and Central America does not date back as old as to the settlement/s on the Tigris, Euphrates, Nile, Indus, and Yellow Rivers, but North and Central natives have a heritage of impressive agricultural production systems (Hurt 2002). Traditional techniques of agriculture and land use in Central and North America, although considered primitive as Wilken (1990) said, have supplied society's food, clothing, and housing needs for thousands of years as early as 4000 years BCE (Fig. 1).

One of the interesting facts of North and Central American agriculture, according to some, is that women, in particular, are active in agriculture and have the potential to generate varieties (Hurt 2002) that adapt to the natural conditions in where they

Fig. 1 The ancient agricultural locations of North America

Fig. 2 The Dust Bowl in 1932 (From Wikimedia Commons, the free media repository)

reside. However, because North American societies were primarily hunters and gatherers, agricultural activities were not as prevalent as in Central America. Immigrants from Europe initiated the transition to intensive agriculture in North America in the sixteenth century (Wessel 1976). In this case, it can be said that in the sixteenth century, traditional methods of natives in North America began to be abandoned by cultivating fields with European culture (Duerden and Kuhn 1998). When deciding how to utilize resources based on local traditional technical knowledge, not only economic interests but also social reality are taken into account (Freeman 1992). For example, when values such as who, how, and when the resource will be used in the community are also evaluated, it can be concluded that local technical knowledge enables more sustainable use of natural resources than today's money-oriented perspective. However, there are some who question if local socially collective decisions have a positive impact on the environment against the research of Fertig (1970). Archaeological studies in North America, according to Peacock (1998), reveal that indigenous peoples are having a negative impact on the environment.

The land use in North and Central America was significantly changed in the sixteenth century. With the arrival of European immigration in the sixteenth century, the expansion of agricultural areas in North and Central America began to endanger natural areas, resulting in increased erosion and a decline in biodiversity (Turner and Butzer 1992). Improper land use, which began in the sixteenth century, peaked in the capitalist era of the nineteenth century, as symbolized by the well-known Dust Bowl (Worster 2004) (Fig. 2). The cause of the Dust Bowl was the drought that prevailed in the 1930s (Cook et al. 2009); however, intensive cultivation led to loss of soil structure and organic carbon which both decreased soils' resistance to erosion. Cook et al. (2009) manifested that throughout the 1920s, cultivation spread into the central

Great Plains which resulted in shifting to drought-sensitive wheat at the expense of drought-resistant species of grazelands.

The Soil Conservation Service, the Agricultural Stabilization and Conservation Service, and the Cooperative Extension Service were founded in the United States after the 1930s to assist improve soil management (Hess and Holechek 1995). Despite these institutions, however, some ineffective policies that neglected local realities and social structure in favor of a centralist approach failed to mitigate land degradation. Hess and Holechek (1995) identified improper policies as providing support for lands that exceed their carrying capacity economically and ecologically, as well as insufficient techniques and training. But the reality might be that the primarily profit-oriented demands of local producers in the management of these lands may have been a factor for the programs' failure at the time.

Today, no one can say that land degradation has been eliminated because it is well known that pollution in Mexico and United States, erosion in the United States and Central America, and deforestation induced by agriculture in Central America still continue (Kanter 2018; Bebbington et al. 2018; Taghizadeh-Mehrjardi et al. 2019; Olivares et al. 2020). All these are the drivers of low organic soil development (Olson and Gennadiev 2020) and a great economic burden; as calculated by Thaler et al. (2021) only in the corn belt of the United States annual loss attributed to A-horizon erosion is $2.8 billion. Most people are skeptical when it is stated that Canada's annual soil loss ranges between 60 and 117 million tons per year, identical to the steppes of Asia, but this is a truth; even 2.2 million hectares of the country have a salinity problem (Çilek et al. 2020). Indigenous peoples' land use rights in Canada were enhanced after 1973, and approximately three million ha land is controlled by indigenous people Rodon (2018). However, land degradation is an issue for Canada because indigenous people have significant vulnerabilities such as place dislocation due to land expropriation, relocation, and landscape fragmentation (Ford et al. 2020). So, owning land is not the solution for sustainable land management for communities. Furthermore, these constraints presented a threat to the survival of indigenous knowledge systems.

Surprisingly, despite all of the concerns with land degradation, the United States, Canada, and Mexico do not have national action plans against degradation or Land Degradation Neutrality targets submitted to the UNCCD. As a result, when the sources were examined to see how much local technical knowledge influences the country's policies, it was determined that the outcome was not as pleasant as Mcgregor (2021) stated. Eckert et al. (2020) cited failures to implement best practices, inadequate funding, knowledge incompatibilities, and colonial effects as grounds for indigenous knowledge's poor impact on environmental policies in North America.

Consequently, in North and Central America, the desire for maximum profit from resources, whether native or later, people of foreign origin, causes soils to degrade, and as a result, soil organic carbon dynamics cannot reach the target level despite various policies, even going backwards.

2.2 Traditional Land Use and Carbon Policy in South America

According to de Moraes et al. (2017), South America nests 10% of global soil organic carbon. Although the organic carbon content of soils in South America's natural vegetation is high, it is hard to deny the same for soils used in modern agriculture. Except for natural fires and local groups clearing small areas for their own survival, South America's forests and grasslands were not endangered by humans until the eighteenth century. The first notable forest loss occurred between the eighteenth and nineteenth centuries. It has been documented that lumbering for mining operations had a significant impact in those times (Armesto et al. 2010). Matricardi et al. (2020) calculated that the Brazilian Amazon lost 337,427 km^2 of forest between 1992 and 2014, which is more than Italy's 301,000 km^2 territory. Therefore, forest massacre is the shift from traditional land management to money-oriented land management, which is accused of being centered solely on land exploitation until the early twentieth century (Fig. 3).

The decline in organic carbon in agricultural soils can be attributed to the recent introduction of cash crops and the state subsidies offered for their cultivation. And, for the last three decades, in South America, recent subsidies for ethanol crops like wheat, corn, potatoes, beet, sugarcane, and cassava, as well as biodiesel commodities like palm oil, soybean, rapeseed (canola), and sunflower (Gerasimchuk et al. 2012), impose a lot of pressure on soils because these plants require lots of fertilizer, irrigation, and pest management. In their excellent review, Bennett et al. (2018) suggested that during the mid-twentieth century development history rural agricultural policies and government support for fashionable crops dramatically changed local people's land use strategies in tropical forests.

Soil organic carbon is negatively affected by aggregate breakup and evaporation of soil moisture caused by intensive agriculture, along with removing all of the biomass from the land (Zinn et al. 2005).

The pampas are South America's second carbon pool after forests (Fig. 4). Pampas have had a very limited history of cultivation. The majority of Argentina's pampa was native grassland until the early twentieth century, when land use changed to livestock husbandry and farming. The shift in land use at the period prompted economic progress and well-being in Argentina (Bedano et al. 2016). However, the ostensible improvement in people's well-being has come at the expense of soil carbon losses. It is calculated that the organic carbon content of the soil in the Pampas region reaches 100 t C ha^{-1} which is quite higher than cultivated soils' 86 t C ha^{-1} of pampas (Berhongaray and Alvarez 2013). Bedano et al. (2016) reviewed that the recent government initiative for no-till agriculture of soybean cultivation in pampas, said to be better for the environment and called a "no-tillage package," caused high soil bulk density and above 82% soil carbon losses.

In the Pampas, high-profit soybean farming has reduced not only the natural plant diversity of the pampas but also the diversity of agricultural crops (Manuel-Navarrete et al. 2009). Similar to pampas, cerrados (woodland savanna) in Brazil which has the richest plant biodiversity among all savannas of the world (Klink and Machado 2005) are threatened by policies that support cultivated crop production.

1984

2020

Fig. 3 The land cover change in Escondido (Brazil) from 1984 to 2020

Brazil has turned the cerrado into a soy-producing zone at the expense of protecting the Amazon forests with the Soy Moratorium Plan (Heilmayr et al. 2020) which has resulted in a substantial percentage of organic matter decrease in cerrado soils. Before the soy moratorium, Bustamante et al. (2006) determined the average soil organic carbon level of cerrado soils to be 100–174 t C ha^{-1} per 1 m, while the yearly organic carbon level loss of soy-farmed cerrado soils was 0.1 t C ha^{-1} year^{-1} (Batlle-Bayer et al. 2010). Furthermore, Bonini et al. (2018) argued that soy farming

Fig. 4 The Argentinean Pampas (Royalty free, Pixabay)

has depleted nearly all of the organic carbon in the topsoil of cerrado with a total loss of 130.5 t C ha^{-1}.

The Andes Mountains (Fig. 5), with their abundant and high-quality natural resources, hold a tremendous diversity of ecosystem, implying that even a modest degradation in this richness will have a severe impact on South America, and subsequently the rest of the globe, in a chain reaction. Unfortunately, the same misconceptions that prevail in the Amazon forests and pampas also exist in the Andes. The primary reason for this is that indigenous peoples who have struggled to survive in the harsh conditions of the Andes highlands for millennia have recently turned to agricultural production in order to increase revenue, which has had a severe impact on soil quality (Blackmore et al. 2021). However, only 40 years ago, Godoy (1984) claimed that the Andes Mountains had essentially little ecological damage. The reasons, according to the researcher, are that the people who process the land in the region engage in agriculture in harmony with nature and the village council has been proven to avoid overexploitation of natural resources. Interestingly, the same researcher brought up the fact that rising agricultural activity is beginning to jeopardize Bolivia's ecology, which was tragically justified when looking at current findings. According to Balthazar et al. (2015), agricultural activities and the conversion of natural grasslands to pine forests resulted in a 16% decline in ecosystem service in the Andes during a 50-year period.

The response to current land use and pressures on forests, pampas, cerrados, and mountainous regions in South America is soil organic carbon losses. These land use changes are the result of policy outcomes until recently in South America that have emphasized economic concerns over environmental issues, either directly (as in the instance of the Soy Moratorium) or indirectly (as in the case of cash crop subsidies for ethanol production). However, it has been seen that development plans that overlook ecosystem realities and local people's traditional land use culture in order to stimulate the economy in South America sometimes led to losses in soil organic carbon. Increased wealth from oil plantations, soybean fields, and extensive animal

Fig. 5 The Andes Mountain belt

husbandry have masked the public's response to environmental deterioration in the short term, leading to a deepening of the social and environmental problems. In most locations, migrations of individuals who could leave their villages to migrate to these intense agricultural areas, the loss of natural systems, and pollution caused by excessive agriculture coupled with climate change are now almost irreversible. However, in recent years, the ambition to build an environmental policy that reflects the demands of the public has grown in popularity, with Chile being the most notable example which was shown by Berasaluce et al. (2021) that 79% of Chilean citizens support an ecological constitution in a survey conducted in May 2021. Of course, a policy that is based on public demands and prioritizes environmental concerns over monetary worries has a strong chance of succeeding. There are national action plans in South America to address desertification, which will have a positive, if not direct, impact on soil organic carbon because these activities intend for sustainable land use (UNCCD 2022). When these plans are reviewed, however, it is commonly noted that a specific area will be reforested, a particular region will be conserved, or natural vegetation will be cultivated, and there are very few activities that highlight traditional land use that have been verified to be sustainable.

2.3 Traditional Land Use and Carbon Policy in Africa

As the continent Africa encompasses various contrasts in terms of environment, social structure, and economy, it provides an opportunity to see and evaluate successes and failures in these aspects concurrently. Natural processes indeed are extremely effective in shaping resources on the African continent; for example, it is known that 3000 years ago, the rainforests of central Africa turned into savannas due to climate change (Bayon et al. 2012); however, it is a painful fact when human influence particularly agricultural activities causes problems that extend to desertification, which is far more severe than natural processes (Vågen et al. 2016).

Agriculture has far deeper socioeconomic linkages with Africa than with other continents, as it employs 43.8% of the continent's workforce. Considering agricultural activities have long been Africa's primary source of income, the African people have developed traditional land use traditions that safeguard the long-term sustainability of natural resources. For example, the Maasai people have been using small fires on a field scale in savannas for a long time to prevent massive, catastrophic late-season fires by allowing these fires throughout the dry season (Butz 2009).

When most people think of Africa, they think of feminine and tough living conditions, and what's more this picture is frequently joined by a savanna without plants. But archaeological studies revealed quite rich food production in several parts of the continent (van der Veen 1999). Actually, land use history of Africa which directly affects soil organic carbon can be classified into three stages. Stage 1 can be called the wise land use phase, also known as the first land use period, began around 9000 years ago and lasted until the mid-1950s, despite a significant collapse in the nineteenth century. Agricultural activities discovered in archaeological findings during these periods have shown that Africans do not totally disapprove of food, even in the most challenging of conditions 7000 years before present (van der Veen 1999) (Fig. 6). Marshall et al. (2018) even claimed that since roaming herders repeatedly hosted the animals of livestock-farming groups in the same place 3000 years ago, the hosting sites have become agriculturally productive spots fed by feces containing rich savanna grass.

The claim of enrichment of grasslands of Marshall et al. (2018) was initially suggested by the discovery of 120 taxa of plants during an 8000-year-old early Neolithic survey at Nabya Playa, Egypt (Wasylikowa and Dahlberg 1999).

Africa's smart land management, which extends back 9000 years ago, was almost abandoned after the 1950s, as it was in many other regions of the world, and replaced with a capitalist strategy to fully exploit the land. This period from the 1950s to the early 2000s can be named epoch of degradation which is Stage 2 (Eswaran et al. 2001; Dimobe et al. 2015; Mani et al. 2021). During this time, the growing population and unplanned encroachment of woody plants, overgrazing, land rights, and the expansion of agricultural regions to increase income threatened the organic carbon in the soils (Tamene et al. 2019).

Increasing awareness for food safety, security, and ecosystem sustainability has led to the formation of many initiatives and actions in Africa throughout the current

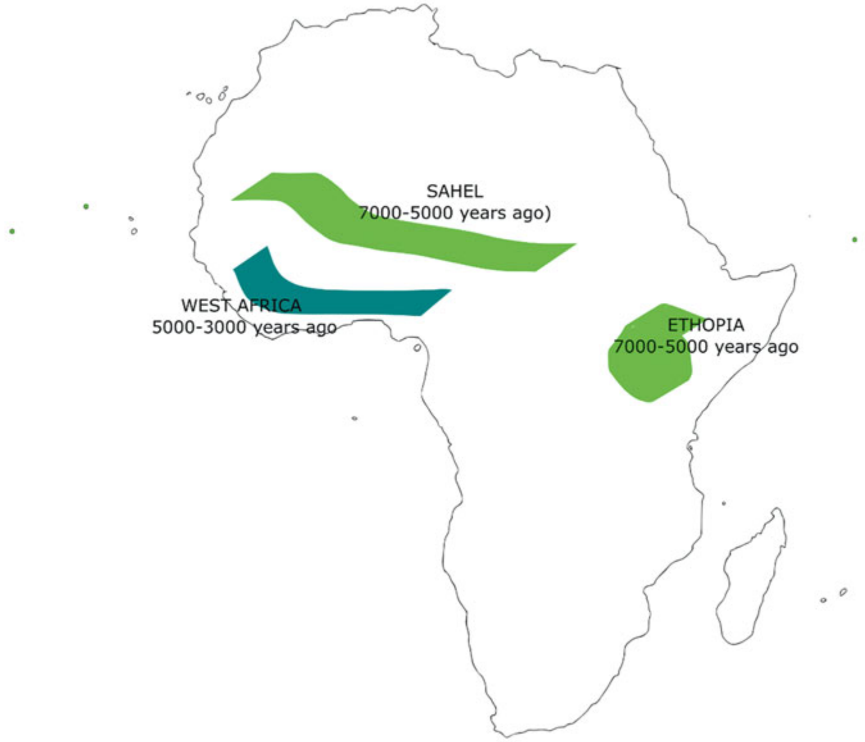

Fig. 6 Africa's first agricultural production communities' location

third stage, which encompasses the last two decades. Countries developed national action plans to avoid land degradation using LDN and SLM approaches, both of which aim to increase soil organic carbon while also focusing on socioeconomic development for societal well-being (Gnacadja and Wiese 2016; Mataga 2021). When the countries' SLM policies are examined, it is stated that substantial progress would be implemented. South Africa, for example, has planned rehabilitation and sustainable management in a total area of 17,193,874 hectares in natural and agricultural fields through 2030, but has not specified traditional land management in these plans (Environmental Affairs 2018) (Fig. 7). Benin can also be used as an example. It was expected to invest US$5.8 billion by 2030 on development, improvement, and adaptation strategies as a result of land degradation totaling US $490 million, or 8% of the country's GNP. Traditional land usage, on the other hand, was not considered in the country's action plan (Global Mechanism 2018). Farmers in Benin, on the other hand, choose termite dirt mounds as a farming region based on thousands of years of experience (Fairhead and Scoones 2005). These dirt mounds, according to farmers, indicate the presence of the goddess of fertility. In reality, the farmers' choice of this aerated, high-organic-matter environment is a strong sign of their foresight.

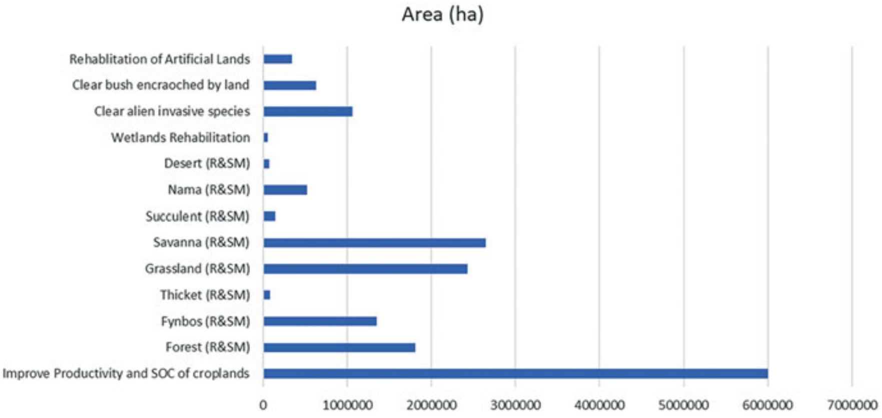

Fig. 7 The Land Degradation Neutrality plans of South Africa targeting 2030

Thus, a common language that especially politicians can grasp and appreciate the local's traditional management systems is vital for Africa's traditional land use systems to survive and succeed.

2.4 Traditional Land Use and Carbon Policy in Asia

It is difficult to debate carbon policy, local technological knowledge, and people's demands for the entire Asia continent in this subsection, but it has endeavored to provide a general view by sharing experiences from some unique points. It's impossible to define Asia in a few pages with its 44,390,958 km^2 of land and a population of more than 4 billion people.

Rice is a major staple crop in south and southeastern Asia. Rice is cultivated during rainy seasons with use of rainwater alone or with supplementary irrigation. Inundation in the early stages of growth is important because it gives an advantage in competing with weeds. Cultivation fields should be leveled and flooded by surrounding the perimeter of the farmland. It is important to reduce permeability of the core soil under the cultivated soil. Securing water sources for supplementary irrigation was another important point in the history of agricultural land reclamation in Asia. In lowland river floodplains, it is easy to secure water because the height difference between the water source and paddy field is small, and there are many clay-rich soils suitable for water retention in the fields. It was also possible to reclaim paddy fields in the upper reaches of rivers where water was easily accessible from small streams. In the mountains, there are cases where rice fields were reclaimed along the ridges by creating waterways along the contour lines to supply water taken from mountain streams.

Satoyama is a Japanese term for landscapes that comprise a mosaic of different ecosystem types including secondary forests, agricultural lands, irrigation ponds, and grasslands, along with human settlements (Kumar 2012). It is estimated that

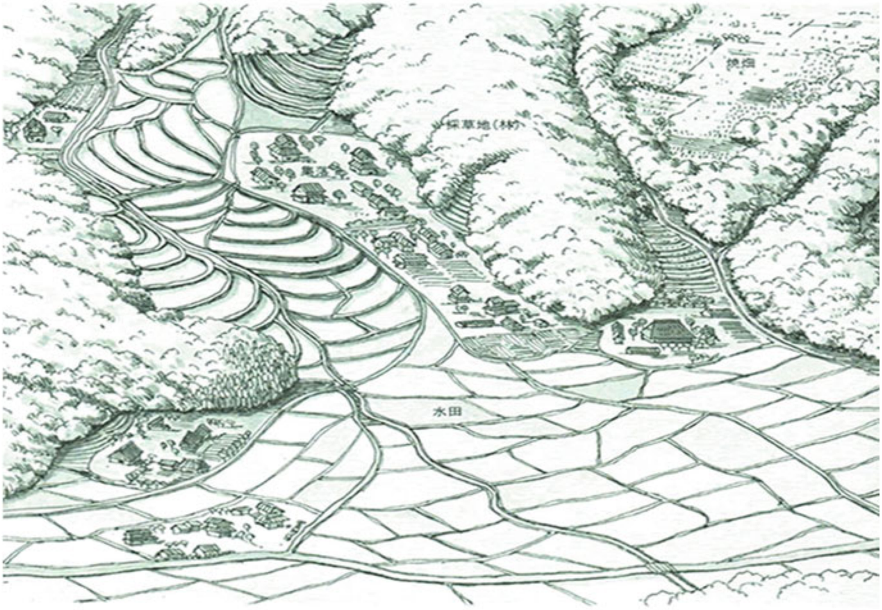

Fig. 8 Typical *Satoyama* landscape in Japan (Agriculture Reclamation Information Center 2005)

Satoyama comprises more than 40% of Japanese land area (Ministry of the Environment, Japan 2001). Similar landscapes are also seen in the Korean Peninsula and in the southern parts of China.

In Japanese agricultural villages, areas which had long sunshine hours were turned to paddy fields. Houses were situated at the foot of mountains where access to small streams or shallow groundwater was secure. Kitchen gardens were created close to the houses. Grasslands and secondary forests were fertilizer sources around these cultivated lands. Forests far from villages were used for hunting and logging. When the mountains were deep, slash-and-burn fields were distributed in an excursion near the outer edge. Lands with different usage patterns were interconnected components that were indispensable for the continuation of life and production for basically self-sufficient rural villages. Figure 8 illustrates a typical *Satoyama* landscape.

Fertilizer was already used in China in the second century BCE. The uses were mentioned in literature such as *Lüshi Chunqiu* and *Shī Jīng*. The use of green manure is mentioned in *Qí mín yào shù* (532–549). In *nóng shū* (1154), mixing rice bran, straw, and tree leaves with enteruia for fermentation (composting) is mentioned. In mountainous parts of Asia, slash-and-burn agriculture was widely practiced. The effect of ash must have been recognized. In Japan, slash-and-burn was practiced until the use of compost was introduced from China in the ninth century (Nakano 2009).

Traditional fertilizer for rice cultivation in Japan was young leaves and shoots cut from coppice forest (*Satoyama*) before transplantation of rice. They were called *Karishiki*, *Katsuchiki*, *Kororo*, *Yamamekari*, and *Kokusa*, which were tilled in soil fresh. Large amount of summer hay was also harvested and put in stables to ultimately make compost. Hay was also dried to form stocks for forage. For these purposes secondary forests considerably larger than agricultural fields were necessary.

Toward the end of the twelfth century, the use of enteruia was widespread in Japan. Agricultural fields increased rapidly in the fifteenth to seventeenth century, and the access to organic matter from *Satoyama* became increasingly difficult, enhancing the use of enteruia. In the Edo period, enteruia in cities were purchased by farmers in the surroundings. This practice continued until the arrival of chemical fertilizers in the twentieth century.

In Asia, home gardens exist alongside rice paddies as an important land use. Home gardens are called *Yashikirin* in Japan, VAC in Vietnam, and *Pekarangan* in Indonesia and are biological production systems with a sustainable material cycle function, built on traditional knowledge. *Yashikirin* is also an important system that forms ecovillages, such as *Satoyama* in Japan. Home gardens are historically important landscape components in Asia, but in a few cases, they are directly linked to carbon policy per se. However, home gardens have a variety of functions, including carbon fixation. As they also have high potential to be incorporated into carbon policy in the future, here we would like to share knowledge about home gardens as a traditional form of land use, focusing on the aspects of material cycles such as carbon and nitrogen.

The carbon storage capacity of home gardens is said to be high. The amount of carbon dioxide stored in old trees in *fukugi* (*Garcinia subelliptica*) home gardens in Okinawa, which was established about 300 years ago during the Ryukyu Kingdom period, was investigated. The results showed that the total amount of carbon stored in 23,518 *fukugi* trees in the home gardens of 10 villages was 6089 tons. This is equivalent to the carbon storage of about 20.9 ha of cedar (*Cryptomeria japonica*) plantation forests of 40 years old (Chen and Kusajima 2021).

In the Sendai Plain coastal area of Miyagi Prefecture, Japan, home gardens called Igune form a landscape unique to this region, where “I” means residence and *gune* means partition. Igune was originally home gardens built around a house to protect it from the seasonal winds blowing down from the Ou Mountains (Ujiie et al. 2013). Some articles from newspapers reported Igune has mitigated the damage caused by the tsunami that followed the Great East Japan Earthquake which occurred 11th March 2011 (Si et al. 2013). Igune is an important component of the landscape, not only for its function as a carbon fixation and biological production system but also for its ability to protect houses from the harsh natural environment and earthquakes.

Home gardens in Vietnam are a traditional complex agricultural system based on organic resource recycling, known as VAC. Here, V stands for *Vuon* (garden), A for *Ao* (pond), and C for *Chuong* (livestock pen). VAC system combines rice cultivation, fruit tree cultivation, aquaculture, and animal husbandry, and uses rice straw and rice waste for raising livestock and fish, and livestock manure for fertilizing rice paddies and fruit trees. Material circulation takes place in the form of reusing agricultural by-products. VAC system farmers, who are mainly rice farmers, are specifically referred to as RVAC farmers. VAC systems are found throughout Vietnam, but the largest number of studies has been conducted in the Mekong Delta. In the VAC system in the Mekong Delta, rice cultivation is positioned as a stable, land-dependent source of income, livestock farming and fruit trees are the productive sectors with high returns, and aquaculture is a cost- and labor-saving means of securing protein for private consumption (Ohira et al. 2005).

According to the IPCC's Fourth Assessment Report (IPCC 2007), agriculture and forestry account for about 31% of global greenhouse gas (GHG) emissions. In Southeast Asian countries, the share has improved, with 98% in Laos, 93% in Cambodia, 69% in Myanmar, and 53% in Vietnam. Sources of GHG emissions from agriculture include rice cultivation, agricultural soil, and gastrointestinal fermentation and manure management of ruminant livestock. In addition, deforestation and peatland development in forestry are sources of GHGs. Therefore, proper management of agricultural lands and forests is needed to fix GHGs in soil and biomass.

Therefore, Japan International Research Center for Agricultural Sciences (JIRCAS), Can Tho University (CTU), and Can Tho City jointly form a Clean Development Mechanism (CDM) project in the Mekong Delta to install household-scale biogas generators in approximately 1000 farm households, including those with VAC systems, to reduce GHG emissions by 1200 tons annually, and then registered the project with the UN CDM Executive Board in August 2012. In the VAC system, pig farming is the main livestock production to support household income. Therefore, biogas generated by anaerobic fermentation of pig manure was used to reduce GHG emissions by replacing cooking fuels (LPG and firewood). They also estimated the emission reductions if biogas was also used as fuel for preparing pig feed. The study results showed that up to 1.8 t CO_2 $year^{-1}$ per household could be reduced (Izumi et al. 2014). Furthermore, JIRCAS and CTU introduced a water-saving irrigation technology called alternate wetting and drying (AWD) for paddy rice cultivation. They reported that the results suggested the possibility of reducing methane emissions per cropping season by about 30% (more than 1 t CO_2 ha^{-1}) compared to constantly waterlogged conditions.

Home gardens called *Pekarangan* are widely distributed in rural Indonesia. *Pekarangan* is the core of the agricultural production system in Indonesia, together with rice cultivation in rice paddies, as well as VAC. There, a wide variety of plant mixtures are cultivated, including fruit trees such as banana, coconut palm, pineapple, and papaya, as well as herbaceous crops such as sugarcane, taro, yams, and corn, and appreciation crops. According to Kubota et al. (1992), *Pekarangan* states that although various styles exist, structurally they can be divided into the following four categories: (1) those in which the entire garden is dominated by a variety of useful plants, including fruit trees, (2) those in which only a portion of the garden is limited to a few plant species and the rest is a mixture of various plants, (3) those in which the entire garden is limited mainly to a few types of fruit trees or vegetables, and

Table 1 Total GHG emission from farmland in Japan, 2019 (MAFF 2021)

N_2O	Farmland	558	19.7%
	Waste management of livestock	369	
CH_4	Rice	1195	46.2%
	Waste management of livestock	233	
	Ruminant emission	756	
CO_2	Combustion	1570	34.1%

(4) those in which monoculture type where only specific crops are planted throughout the garden.

Pekarangan varies in style, ranging from those with a significant subsistence function to those with a significant economic function. *Pekarangan* is a space that has been artificially created and transformed to replace forests that are disappearing, and has been shaped by the historical evolution of the relationship between humans and plant use. It has also been shown to have the function of maintaining biodiversity (Kubota et al. 1992).

The home gardens in Asia are very valuable from both historical and cultural perspectives. They also have high potential to be utilized in close relation with carbon policy in terms of material circulation and carbon fixation. However, they are not economically superior to large-scale agricultural operations, and it is also true that some home gardens are becoming difficult to maintain due to the time and effort required for upkeep and management. In the future, a framework will be needed to find new value in the home gardens and to maintain and form ecovillages as a historical and cultural product of the region.

In 2019, Japan emitted 1.21 Gt CO_2 Eq. of GHG. Agriculture, forestry, and fisheries account for about 4% of the total emission. Japanese agriculture emits 47.4 Mt CO_2 Eq. of GHG as of 2019 (MAFF 2021). Table 1 summarizes origins of the emission.

CH_4 emission and N_2O emission from farmland were 12.0 and 5.6 Mt CO_2 Eq., respectively, and in these two in total amount to 37.0% of total emission. Sequestration at farm and grasslands was 1.8 Mt CO_2 Eq., very small compared to emission. The Japanese government aims to increase sequestration to 8.5 Mt CO_2 Eq., by increasing the rate of organic agriculture. In Japan, no-till is not common because paddy accounts for 54% of total farmland (4.34 Mha, 2022) and because cultivation of GM crops is prohibited; thus, use of herbicide is relatively low. The Ministry of Agriculture Forestry and Fisheries has been monitoring soil carbon stock in 3028 points in farmland and 375 points in grasslands. Another monitoring is carried out in 310 points in farmland and 30 points in grassland with continuous compost input (15 t/ha). Based on agricultural soil study since the 1950s, it has been revealed that sole use of chemical fertilizer would decrease soil carbon stock, whereas application of compost or green manure at a rate of 15 t/ha can sequester 1.4–6.3 t CO_2 /ha depending on soil type as shown in Table 2 (MAFF 2012).

India has a significant potential for terrestrial/soil carbon sequestration due to its enormous geographical area and diversified ecoregions. On the other side, for contemporary land uses in India, Lal (2019) cited excessive tillage, the removal of

Table 2 Carbon sequestration rate at fields with continued compost input (15 t year ha) (MAFF 2012)

Soil type	Sequestration (kg C/year/ha)	Sequestration (kg CO_2/year/ha)
Andosols	400	1400
Brown forest soil	600	2400
Yellow soil	700	2600
Gray lowland soil	1700	6300

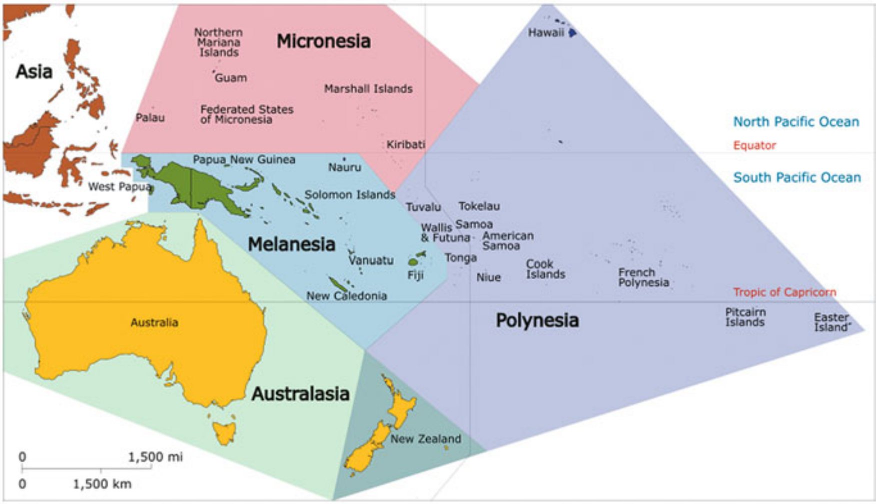

Fig. 9 The regions of Oceania

plant residues, and the inability to replenish nutrients removed from the soil as causes for the estimated 21-billion-ton organic carbon in Indian soil for the entire country being low. Srinivasarao et al. (2014) showed that the organic carbon of Indian soils, particularly in dry and semiarid regions, is low and that each unit of organic carbon applied to the field increases yield significantly in peanut, millet, sorghum, soybean, and rice. The lowest organic matter input range required to prevent organic matter loss in Indian soils was determined to be 1.1–3.5 t C ha^{-1} by the same researchers. The cause for the variation in values, according to experts, is proportional to soil type and production pattern.

2.5 Traditional Land Use and Carbon Policy in Oceania

Oceania, unlike other continents, is home to a diverse range of geographies, as it is a region made up of thousands of islands surrounded by seas and oceans, including Australasia, Melanesia, Micronesia, and Polynesia (Fig. 9). The fact that the sea, rather than the land, is the primary source of livelihood in this region has, in some ways, prevented overuse of the soils as mentioned for Papua New Guinea where it is among the 15 countries in the world with the highest SOC (Beillouin et al. 2022). Biodiversity has increased as a result of the abandonment of most of the islands, as well as livelihood from the sea, both of which have contributed to the region's soil carbon content improving (Weiser and Lapofsky 2009). Although Mauerhofer et al. (2018) claim that abandoning lands results in a decline in biodiversity rather than an increase, studies in Oceania demonstrate that abandonment boosts biodiversity (Beilin et al. 2014). The abandonment of European agricultural methods, in particular, has resulted in a positive improvement in soil SOC content. According to Queiroz et al. (2014), the initiation of European farming methods in Oceania in the eighteenth century frequently resulted in habitat loss and degradation.

Sutton (1996) manifested that prior to the colonization of Australia, aboriginal land use was quite robust and resistant to climatic conditions. Sutton (1996) supported this viewpoint with Evans' (1992) description of *birrjilka* in aboriginal oral laws of land use with the concepts of time-occasion way-manner-pace, law-way-custom, and morals-way of living, and event is a sign of wisdom. Oceania's natural resources were wisely managed by native peoples without being under pressure until the eighteenth century, due to the continent's absence of a dense population at any point in its history.

The difficulties that we are seeing today, which are contributing to a decline in soil organic matter, are mostly due to the land use strategies of the eighteenth century immigrants. Khanna et al. (2019) stated that Australia's woodlands contain a large amount of aboveground carbon, which boosts soil organic carbon. Clearing native vegetation for agricultural purposes, on the other hand, increases carbon dioxide emissions and restricts soil carbon enrichment.

The Native Title Act of Australia, passed in 1993, granted aboriginals the right to use their land in accordance with their customs. On the other hand, there is currently limited information about the effect of native land use methods on parameters that signifies the health of the soil ecosystem, such as soil organic carbon. According to Craig (2000), although natives are given the legal right to use the land, they face difficulties in administering it due to the incompatibility of non-native legislation and policy with traditional methods. Craig (2000) demonstrated the inconsistency between historical use and current rules in the Tumut-Brungle Area Agreement, which authorizes mining near Adelong (NSW).

In Micronesia, annual and perennial agroforestry in traditional gardens enables local people to ensure food security by producing in marginal areas (Manner 1993). Moreover, Kauffman et al. (2011) revealed that ecosystem carbon increased from 479 t C ha^{-1} at sea level to 1.068 t C ha^{-1} inland in natural mangrove forests in Micronesia. To give an example, although not in Oceania, policies allowing deforestation in Cambodia have been shown to result in total ecosystem carbon reductions of up to 60% (480 t C ha^{-1}) (Sharma et al. 2020). As a result, policymakers in Oceania should be especially sensitive to policies aimed at protecting traditional methods, rather than profit-driven development policies constituted by public pressure on politicians. However, because the environmental threats in Oceania are caused by climate change rather than people, as stated in Tuvalu's National Action

Plan to Combat Land Degradation and Drought (NAP of Tuvalu 2006), directing policies toward climate adaptation will contribute to the development of more effective solutions.

2.6 Traditional Land Use and Carbon Policy in Europe

The European continent is a geographical area inhabited by people of many ethnicities, with an almost arctic environment on one side (North) and a dry Mediterranean climate on the other (South). Although Europe is one of the world's leading regions in terms of scientific consciousness of the public on environmental issues, it cannot be claimed that there are no challenges threatening soils and thus soil organic carbon in Europe (Lugato et al. 2018). The following targets in the Green Deal program (EC 2019), which aims to alleviate Europe's soil and agricultural issues until 2030, highlight the seriousness of the continent's environmental problems. Montanarella and Panagos (2021) describe Green Deal agriculture and soil targets as a 50% reduction in pesticides, a 50% decrease in excess nutrient content, and a 20% in fertilizer use while increasing organic farming by 25% and land protected areas by 30%, as well as restoring wetlands and halting land degradation. It is discussed from a socioeconomic and technological perspective that the land degradation problems in Europe continue to worsen despite the financial assistance provided for many years. While some experts ascribe the causes of this problem to improper land use and abandonment of lands (Bajocco et al. 2012), others point to the difficulty to effectively plan cultivation due to a lack of data on how much land has been entirely degraded (Briassoulis 2019).

The history of land use in Europe is marked by dramatic shifts. In the Neolithic (ca. 8000 years BP) due to low population density and pristine natural resources, shifting agriculture with slash-and-burn was established as an unbiased approach to nourish soils and prepare land for cultivation (Rösch and Wick 2019). In the Late Neolithic, the slash-and-burn mode of food production caused natural forests in Lake Constance (Germany) to change almost entirely to shrubs and coppiced woodland, according to Rösch (2013). However, deforestation has continued in Europe throughout history, not just during the Neolithic, as Kaplan et al. (2017) has proven through his pollen study.

Before the imperial culture, city-states used the land without excessive pressure for their own purposes in pre-Roman times, whereas empires began to use what the land produced more intensely not just where it produced but also to keep the imperial economy alive. The basis for this conclusion is that Gilgen et al. (2019) discovered in his research that the growth in agricultural waste and wood burning, as well as the change in aerosols, corresponded with the Roman period. Aside from Gilgen's work, Ascoli and Bovio's (2013) finding that numerous fires were used to fertilize fields, develop or renew pastures, manage pests, or hunt in Greco-Roman times confirmed our theory that the imperial land use concept triggered soil degradation.

The incorporation of natural trees into the environment by scientists and researchers in Medieval Europe is evidence of awareness, according to Nijnik

Fig. 10 The terraced olive field on the Mediterranean coast of Turkey (Authors archive)

et al. (2009). It may be claimed that the age of the industrial revolution in the eighteenth century and the two world wars that followed was when the degradation of the soil and biomass, the earth's organic carbon source, was truly endangered in Europe (Møller 1986; Blaikie and Brookfield 2016).

Although deforestation, excessive exploitation of natural resources, and catastrophic wars have all had a negative impact on the carbon cycle throughout Europe's history, European people have created methods that ensure the quality of the soil while carrying out very successful production. Despite its sloping, shallow soils, and arid climatic conditions, Europe's Mediterranean coastline, for example, have been environments where olive, carob, fig, and viticulture have been successfully carried out for thousands of years (Akça et al. 2020) (Fig. 10).

Mercuri et al. (2019) found that people have been living in silvo-pastoral and mixed plant pattern agriculture for thousands of years without harming nature within the context of multifunctional land use in their research of ancient land uses in six archaeological sites in Italy, Greece, Turkey, and Spain. However, the European population is no longer the low-density population of the past, and their individual resource consumption is higher than that of most other continents. Low-intensity production amid ancient terraced gardens, extensive pastures, and picturesque countryside, as a result, falls far short of matching demand. Aside from that, it has been witnessed on various occasions as farmers insist on land use methods that they believe are traditional, resulting in soil deterioration. For example, Faulkner et al. (2003) and Sastre et al. (2017) determined that the farmers' persistence for tilling olives for weed combatting in Spain caused significant erosion.

Europe has some of the highest agricultural subsidies in the world, and many farmers rely on them to supplement their income, putting pressure on politicians. Although there are laws in place to preserve traditional land use methods and supporting ecosystem services, issues with implementation and monitoring the consequences of application have deemed the policies ineffective (Simoncini et al. 2019).

Prior to the Ukraine-Russia conflict in February 2022, the European Union set targets for 2050 that would positively affect soil organic carbon within the scope of the Green Deal, but the vulnerability of food security as a result of the conflict, as well as the resurgence of fossil fuels such as coal for energy, made meeting these targets unlikely. This has been an unpleasant example that highlights the high vulnerability of policies, regardless of how precisely they are addressed.

3 Global Land Use Policy and Organic Carbon

After the 1992 Rio Summit, the world clearly realized that land degradation and desertification, as well as climate change, would be life-threatening by another definition, which would result in the extinction of biodiversity. Climate, soil, water, and biodiversity, all components of the environment, are cross-border assets. As a sense, collaboration across regions and countries is required for sustainable environmental management. Since the 1970s, when population pressure began to threaten practically all components of the environment, the UN has mobilized international diplomacy to take steps and make recommendations under this topic. The process began with the Stockholm Declaration in 1972 and continued with the Rio Summit's 21st Agenda in 1992, the Rio + 20 Sustainable Development Goals, and the 2030 Sustainable Development Goals (SDGs) adopted in 2015 as risks escalated. The ultimate goal of all of these procedures is to eradicate environmental and socioeconomic threats to the world's future through international cooperation.

Carbon, the focus of this chapter, is one of the environmental quality indicators. It is not possible to cover the complete process of global carbon policies here as it is beyond the scope of this chapter. However, because the UN Sustainable Development Goals are the policies of most countries, it is vital to call attention to Target 15.3, which directly affects carbon, among the 17 targets of the UN. The United Nations Convention to Combat Desertification (UNCCD) is the body in charge of preventing desertification and restoring degraded land, which is Goal 15 of the UN 2030 Sustainable Development Goals. Data on this indicator are generated by UNCCD through its national reporting and evaluation procedure, which began in 2018 and is repeated every 4 years thereafter. 15.3.1 "The ratio of degraded land to total land area" is the purpose indicator. Countries establish policies based on country facts in order to achieve this. Therefore, the primary goal is to achieve sustainable agriculture. Sustainable agriculture can be roughly classified into four categories. Countries develop policies under the following headings in order to achieve this:

A. Creating and preserving healthy soil.
B. Managing water wisely.
C. Minimizing air, water, soil, and environmental pollution.
D. Preventing and mitigating climate change.
E. Preserving biodiversity.

Fig. 11 Stone terraces for water harvesting in an almond farm in Turkey

There is no law or support in most countries that directly supports soil carbon increase. Researchers suggest that if the aforementioned objectives are met, soil carbon stores will often improve. Although establishment costs for soil conservation techniques are not very expensive, farmers are not willing to allocate budget for these. For example, a farmer agreed to stone terrace construction if the construction expense is met by governmental funding (30 cm × 30 cm × 400 cm) in an almond farm in Turkey. The stone terrace cost US$1300 ha which was ¼ of the farmers' total income (Fig. 11).

The "4 per 1000" initiative was announced at the COP21 summit in Paris to slow rising CO2 levels in the atmosphere (http://4p1000.org). The goal of this program is to boost worldwide agricultural soil organic carbon (SOC) stocks by 0.4% every year. In fact, because there is no single recipe for increasing soil organic carbon, the cost of doing so is unclear. New investments will not enhance soil carbon in a humid and rainy environment if there is no excessive demand on the soil, such as expanding up agricultural fields, because the soils are already saturated with organic carbon. Arid zones, on the other hand, are the contrary. The increase of soil organic carbon in these areas is reliant on fertilizer and water, putting carbon increase an incredibly expensive goal. Van Groenigen et al. (2017) calculated that 100 Tg/year nitrogen is required to achieve 4 per 1000 globally, and for that today's global nitrogen production should be raised by around 75%. In a nutshell, achieving this goal is impossible.

4 Conclusion

There are thousands of studies focused on achieving global sustainable agriculture goals which directly or indirectly affect soil organic carbon. Despite slight variations, sustainable agriculture is being tried under a variety of names, including ecological agriculture, good agriculture, carbon farming, organic agriculture, permaculture, climate-friendly agriculture, and smart agriculture (close to 50,000 resources are listed on the Scopus search page). All of these systems are based on working with nature rather than against it, and production is handled according to ecological principles. On the other side, there are many who criticize (Avery 2007) sustainable agriculture and traditional land use (such as olive cultivation on terraces), which are intended to increase soil organic carbon. Critics of sustainable agriculture contend that, in addition to greater labor expenses, its proposed methods result in lower crop yields and wider agricultural expansion to meet farmers' higher revenue demands. Sustainable farming methods, it is claimed, will not be able to feed the world's population, which is predicted to exceed 8 billion by 2030. For this reason, it is very difficult to fulfill the demands of the people, even if they are environmentally friendly, in today's volatile world, which we experienced during the Covid-19 process. So far, failure to consult local technical knowledge or local people in the policies developed to achieve the sustainable land use techniques outlined above precludes policies from succeeding in reality. As a result, unproven agricultural practices in every geographical location of the world, as well as items to be used in policies to raise soil organic carbon, should not be advised, even if they are advertised as "sustainable agriculture," because poor outcomes may divert the producer's attention away from sustainable agriculture techniques.

5 Future Prospective

It is not enough to have the approval of the local population for policies to function, especially when it comes to environmental regulations, because the facts envisioned by environmental policies will be used and realized by the local population. However, many environmental regulations, particularly those relating to sustainable land management, are unable to succeed, not only in developing countries but also in developed countries. According to studies, 70% of Europe's lands have lost their ability to fulfill their ecological roles (Veerman et al. 2020). The issue of soil organic carbon, on the other hand, necessitates a great deal of effort because policies and investments in organic carbon may not show up right once, and it might be difficult to explain what it is for to the common citizen. It is critical to design and distribute regulations that take into consideration local people's proven and mainly carbon-friendly land uses, with the exception of the time in the last 70 years when the natural resource has been used solely for profit by landowners. In truth, the solution is right in front of us. Sustainable land management and carbon-friendly policies can be found in gardens with olives and vineyards, terraces that harvest water and hold the soil, front-of-house gardens with dozens of plants, free livestock farming that moves around according to plant density in the pasture, and farms managed by women and men. If politicians pay close attention to these gains that have been occurring for thousands of years, listen to local knowledge, and implement policies with local input, environmental policies will become concepts that are not only accepted, but embraced by the public.

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Enhancing Soil Organic Carbon Sequestration in Agriculture: Plans and Policies

G. K. Dinesh, M. Sinduja, B. Priyanka, V. Sathya, S. Karthika, Ram Swaroop Meena, and Shiv Prasad

Abstract

Soil organic carbon (SOC) is a vital factor that positively affects soil fertility, agricultural production, and food security. However, current farming practices, intensive tillage, increasing global warming, and climate change have created a risk of losses of SOC, affecting food supply. Therefore, various management strategies to build soil carbon accumulation and sequestration have been continuously adopted. Net soil carbon sequestration on agricultural lands has the potential to offset 4% of yearly worldwide human-induced greenhouse gas emissions for the remainder of the century, making a significant contribution to reaching the Paris Agreement's emissions reduction objectives. It is also pledged to adopt various plans and policies for building SOC in agriculture. By 2030, a carbon sink of 2.5–3 billion tons of CO_2 equivalent must be created. A package like this would contain restrictions to limit soil carbon loss and encourage sustainable development and "win-win" solutions to current issues and many other climate change risks.

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Keywords

Soil organic carbon · C sequestration · Carbon policy · Carbon management

Abbreviations

C	Carbon
CDM	Clean Development Mechanism
CER	Certified emission reduction
CO_2	Carbon dioxide
CSA	Climate-smart agriculture
EU	European Union
FAO	Food and Agriculture Organization
GHG	Greenhouse gas
GIS	Geographic information system
Gt	Gigatons
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature and Natural Resources
LCA	Life cycle analysis
M ha	Million hectare
Mg	Megagrams
N	Nitrogen
NAPCC	National Mission for Sustainable Agriculture
NASS	National Academy of Agricultural Sciences
NMSA	National Mission on Sustainable Agriculture
NPOF	National Project on Organic Farming
Pg	Petagrams
PKVY	Paramparagat Krishi Vikas Yojana
SHM	Soil Health Management Scheme
SOC	Soil organic carbon
SOM	Soil organic matter
UNCCD	United Nations Convention to Combat Desertification
ZBNF	Zero-budget natural farming

1 Introduction

Soil organic carbon (SOC) is one of the essential factors which plays a significant role in the functions of soil and ecological services. SOC improves physicochemical properties of soil, particularly infiltration, water-holding capacity, and nutrient mineralization, and boosts microbial and enzymatic activity (Panda and Biswal 2018). Though the soil is primarying for carbon as it sequesters the carbon in the soil biomass, its evolution due to microbial decomposition contributes a considerable amount of carbon dioxide to the atmosphere (Frey et al. 2014). Thus, it has a dynamic role in the biogeochemical cycling of carbon and gains importance in climate change (Mehra et al. 2018). Furthermore, soil health mainly depends on the soil's organic matter content and biological activity, whereas both factors mostly rely on the soil's organic carbon (Turmel et al. 2015). Hence, it is essential to consider soil organic carbon in all the plans and policies related to soil health management.

A lot of research is continuously focused on the elucidation of soil organic carbon pool and its dynamics in soil. However, the role of soil in the mitigation of GHG emissions and climate change is still in the dark, and hence this aspect is lacking in the framework of soil health (Paustian et al. 2019). However, global countries have taken several initiatives toward soil health improvement via national or international frameworks, policy-making, and providing incentives/subsidies. Still, it is a long way to go to achieve progress in soil health, the evaluation of soil organic matter/organic carbon, the assessment of the adoption of technologies for soil health improvement, and the outcome at the field level. Hence, we need to integrate soil health with climate-smart agricultural practices (Roper et al. 2017; Bünemann et al. 2018; Stewart et al. 2018). Moreover, soil health assessment and the climate change perspective may increase its monetary value and gather political attention.

In India, many initiatives such as the National Mission on Sustainable Agriculture (NMSA), Paramparagat Krishi Vikas Yojana (PKVY), Soil Health Card Scheme, National Project on Organic Farming (NPOF), Soil Health Management (SHM) Scheme, etc. have been taken to manage soil health. Furthermore, raising interest toward climate-resilient agriculture and contribution of soil organic carbon for mitigation of climate change attracts the global countries toward soil health management through different initiatives such as the “4p1000” initiative, Recarbonization of Soil (RECSOIL), Global Assessment of SOC sequestration potential (GSOCseq) program, Save Organics in Soil (SOS), etc. These initiatives will ensure sustainable development through productive, climate-resilient, and more economical agriculture. This chapter aims to highlight the potential role of SOC, enhancing SOC sequestration in agriculture; gaps in research and practical policy and various plans and policies for SOC management in agriculture and allied sectors are also comprehensively discussed.

2 Potential Role of Soil Organic Carbon

SOC is one of the vital factors in the global carbon cycle (Nieder et al. 2018). Hence, the status of SOC should be maintained in equilibrium and to be enhanced in the low carbon-containing soil. Soil organic carbon plays a significant role in various ecosystem services, such as maintaining soil fertility, biodiversity, and food security (Bengtsson et al. 2019). SOC can play an influential role in climate change adaptation and mitigation and combat desertification, land degradation, and food insecurity.

2.1 Soil Organic Carbon in Climate Change Adaptation and Mitigation

Even though the changes in temperature and precipitation due to climate change are small, their impact on soil fertility is more pronounced. It affects soil processes and soil properties by changing soil macro- and microclimate. There are agricultural practices to adapt to climate change impacts. Several options such as zero-tillage, crop residue incorporation, fallow lands, diversified crop production, changing the pattern of irrigation and fertilization, and various agronomic practices are available to minimize the adverse impacts of climate change (Jat et al. 2016). In addition, there are different farming practices such as conservative agriculture, restoration of soil nutrients, and soil conservation strategies to enhance soil carbon stocks and encourage soil functional stability (Abbas et al. 2020).

Improving the SOC content is essential to maintain soil quality and mitigate the impacts of climate change. Therefore, monitoring SOC content is crucial for policymaking, and it ensures the improvement of SOC at the farm level to enable incentives (Minasny et al. 2017). Additionally, the adaptations had beneficial impacts on grain and biomass production soil functions. It also enhanced the soil's carbon sequestration potential, filtration, transformation, and recycling capacity. However, the impact of climate change on the biological activity and properties of the soil is not still appropriately elaborated. Therefore, the adaptation decisions in agriculture that could mitigate climate change would be impassible if farmers instigated properly (Aryal et al. 2020). Various physicochemical factors affecting the SOC are mentioned in Table 1.

2.2 Soil Organic Carbon in Combating Land Degradation and Desertification

Due to intensive agriculture and urbanization, more than 70% of forest area in the world has been degraded in terms of SOC depletion. Tropical forests are critical since the area decreased at a 5.5 million ha yearly rate. Globally, one-fourth of land has been degraded, and it is predicted that by 2050, only below 10% of the earth's

Table 1 Biophysicochemical factors affecting SOC and influencing yield

Important factors	Effects of SOC
Biophysical, chemical	
Physical	Clay/carbonate
Parent material	Alkalinity, soil structures, precipitation
Climate	Temperature
Vegetation	Natural vegetation, peat/bogs
Anthropogenic	
Land management	Tillage system, irrigation, cropping system, fertilization
Land exploitation pollution	Sealing, mining, waste disposal, pollutant emission

land will be conserved without any impacts due to human activities (Arneth et al. 2021). The extensive land degradation will severely impact the soil organic carbon, which is mainly formed due to the decomposition of biomaterials. Soil organic carbon is essential and provides the biosphere of the Earth via food production, employment generation, poverty reduction, biodiversity maintenance, and, more importantly, one of the giant sinks for carbon after oceans (Laban et al. 2018). Thus, a slight change in soil organic carbon will affect sustainability, either quantitatively or qualitatively.

A global target is fixed in the Bonn Challenge launched by Germany and IUCN to restore 150 Mha of degraded land by 2020 and 350 Mha of land by 2030. The committee on science and technology formed by the UNCCD has issued a report on realizing the carbon benefits of sustainable land management practices. This report provides guidelines for estimating soil organic carbon in the context of "land degradation neutrality planning and monitoring" in COP 14 of UNCCD held in New Delhi. The report highlights the crucial role of SOC in the prevention of land degradation and desertification. Land Degradation Neutrality (LDN) is the optimum quantity and quality of land resources required for the ecosystem's practical functions and services and improved food security (Cowie et al. 2018). It should be remained unchanged or increased both temporally and spatially. It epitomizes the pattern of that change in the policies and practices of land management. It is an exceptional strategy to offer the expected land degradation and the restoration of degraded lands. It deliberately deals with land-use planning in conservation, sustainable management, and restoration of lands. Soil organic carbon was taken as one of the indicators of LDN. Generally, the LDN has been indicated by land cover changes and land productivity dynamics (net primary productivity). SOC is the basic indicator of soil health, and it also has multiple roles in land management. It is also related to missions of Rio conventions which mainly played a critical factor in selecting appropriate management options for land in a sustainable way to achieve LDN (Akhtar et al. 2017). Management of SOC is essential for enhancing the quality of soil and yield of crops and decreasing soil loss. Sequestering carbon improvements improve soil health and crop productivity, steadily maintain carbon cycling, and positively affect agriculture production (Ramesh et al. 2019). Due to the variety of roles and functions of SOC and its essentiality in land management, SOC has been considering one of the three indicators of Land Degradation Neutrality (LDN). Hence, predicting and monitoring the chain that occurs in SOC are crucial for achieving LDN targets.

2.3 Soil Organic Carbon and Global Food Security

SOC plays a significant role in enhancing food security for the global population. More than 3/4 of the world's population faces insufficient nutrient supply, which leads to malnutrition or hidden hunger. However, problems associated with soil, such as erosion, salinity, acidity, depletion of SOC, etc., are the major threats to food security. Among all the factors, soil organic carbon has special attention regarding food security. Improving the SOC content in soils of temperate and tropical regions is challenging. External application of carbon-containing inputs such as compost, manure, biochar, etc. is also considered the management strategy for SOC enhancement (Tiefenbacher et al. 2021). On-farm management methods such as incorporating crop residues, stubble retention, less or zero-tillage, and rotation of crops are the possible options for enhancing short-term SOC. Protecting, stabilizing, and building up the existing C stocks in soils through a balanced nutrient application, conservative agriculture, etc. improves nutrient use efficiency and increases productivity.

The National Policy on Crop Residue Management effectively converts biomass into SOC, improving agriculture and food systems inputs. The improved SOC will contribute to enhancing the food security of different crops. However, it is estimated that 116 Gt of soil organic carbon has been lost from the time when agriculture began. There are a few crucial problems associated with soil properties and ecosystem services due to the depletion of SOC. Generally, low SOC soil is described by its low content of nutrients, high rate of soil erosion and compaction, etc.

Furthermore, it contains common soil microbes, low water infiltration, retention capacities, etc. These soils can be restored through recarbonization practices such as adding organic inputs, reducing SOC loss by no-tillage, etc. These management practices will enhance food security through more fertile soils and climate-resilient agricultural practices (Rao et al. 2016). Many research proved that the enhancement of SOC would increase yield and agricultural productivity. Improvement in food products due to an increase in SOC stocks would be a prime advantage for small farmers. In addition, it may serve as a tool to overcome the hesitancy of farmers to change their regular farming practices.

3 Enhancing Soil Organic Carbon Sequestration in Agriculture

SOC-oriented farming system, adaptation of zero-tillage practices, organic farming, appropriate manure management, zero-budget natural farming, agroforestry, and soil erosion control practices are good options for SOC sequestration and promote soil fertility by promoting soil fertility, increasing the amount of soil organic matter in the soil. Many options for enhancing SOC sequestration in agriculture are shown in Fig. 1.

3.1 Carbon Farming

Carbon farming aims to increase carbon sequestration in soil and plants and create a net carbon loss from the atmosphere. Some practices, such as reduced tillage, longer-rooted crops, and organic matter, encourage the captured carbon to remain in the soil and become carbon neutral (Marks 2019). In addition, improving yield and soil management can reverse net CO_2 emissions into the atmosphere. Indeed, increasing

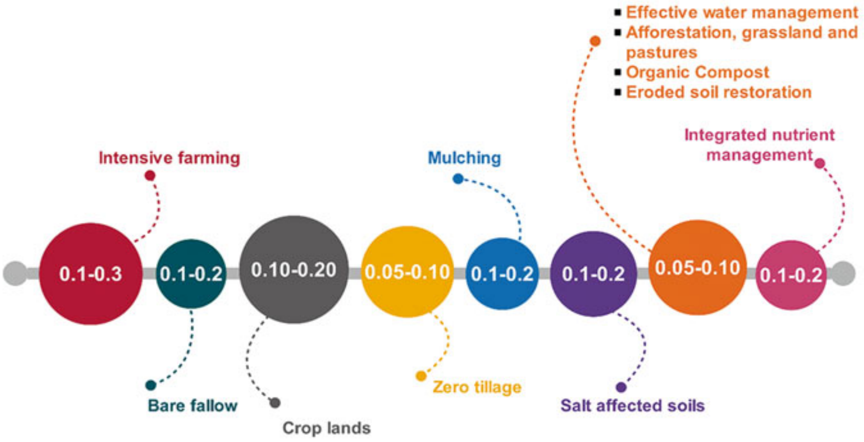

Fig. 1 SOC sequestration potential of various technological options (tons C/ha/year) (Data source: Lal et al. 2018; NAAS 2021)

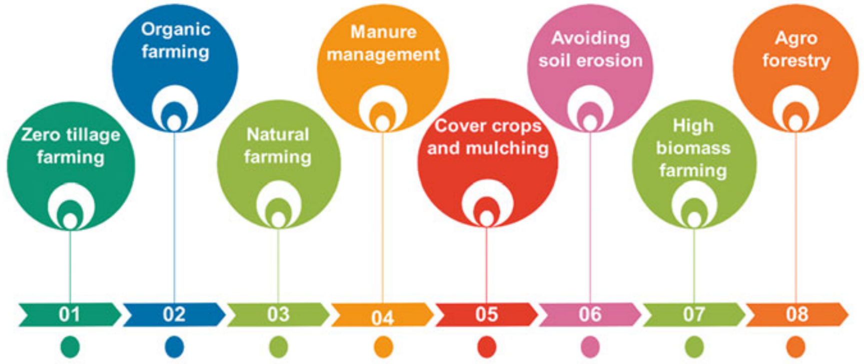

Fig. 2 Options for enhancing SOC sequestration in agriculture

the soil's capacity to absorb and store significant quantities of atmospheric carbon in a stable form provides a realistic and immediate answer to some of humanity's most severe issues, i.e., global warming and climate change. Many options for enhancing SOC sequestration in agriculture are shown in Fig. 2.

Natural ecosystems are depleted in conversion to agroecosystems due to reduced biomass C return, increased losses of SOC due to erosion and leaching, and significant variations in temperature and moisture regime. Carbon accumulated in the soil is 2–4 times that of the atmosphere and 4 times that of plants (Hussain et al. 2021). The organic carbon stock of various physiographic regions of India is mentioned in Table 2.

Table 2 Soil OC stock – physiographic region of India

S. no	Physiographic regions	Organic carbon	Pollutant	Medium	Vegetation
			0–30 cm	0–150 cm	
1.	Northern Mountains	0.40–2.75	7.89	18.31	Dry temperature, coniferous forest, moist temperature
2.	The Great Plains	0.40–2.8	3.28	10.53	Tropical mixed deciduous forest
3.	Peninsular plateau	0.3–3.40	3.62	10.11	Tropical dry deciduous thorn forest
4.	Peninsular India	0.04–2.31	3.64	13.34	Mixed deciduous thorn forest
5.	Plains of the islands and coastal plains	0.28–1.70	2.24	10.90	Littoral and swamps

Source: Modified from Bhattacharyya et al. (2000), Mandal and Sharda (2011)

Table 3 Land and soil management practices and their effect on SOC

Practice	Effect of SOC	Positive environmental effects	Carbon stock (Mg C ha^{-1} $year^{-1}$)	References
No-tillage	Reduced carbon level	Erosion control reduced fuel consumption	0.07–0.33	Robertson et al. (2000), Arrouays et al. (2002)
Addition of organic amendment (compost, manure)	Increase carbon input	Increase soil respiration	0.05–0.15	Arrouays et al. (2002)
Use of cover crops	Reduced/ increased carbon loss	Increase soil respiration	0.15–0.25	Arrouays et al. (2002)
Crop rotation	Increase on inputs	Increased soil respiration	0.05–0.25	Lal (2004)

Source: Modified from Komatsuzaki and Ohta (2007)

The technical potential of C sequestration in cropland soil is 0.4–1.2 Pg C (Lal 2015). However, land-use changes such as agricultural output have resulted in considerable soil carbon (C) losses. Therefore, constantly increasing the C stock of farming soils is suggested to counterbalance or decrease the warming impact of C emissions (Luo et al. 2010). Various soil and land management practices that impact SOC are mentioned in Table 3.

Techniques include zero-tillage farming, organic farming, natural farming, manure management, cover crops, mulching, soil erosion, high biomass farming, and agroforestry systems (Mattila et al. 2022). Ecosystem-based options for carbon sequestration in India are mentioned in Table 4.

Table 4 Ecosystem-based options for carbon sequestration in India

Agroecosystem	Cropping management				Land and water management	
Himalayan	Agroforestry	Land covers/ mulching	Agri-horticultural system	Perennial crops	Contouring	–
North-Eastern Hill regions	Arial seeding	Relay cropping system	–	–	Zoom land rehabilitation/ riverbank stabilization	Contouring
Indo-Gangetic Plains	Zero-tillage	Utilization of crop residue	Agri-horticultural system	–	Salt-affected soil reclamation	Minimized soil-based brick industry
Eastern	Integrated farming system	Organic farming	Site-specific nutrient management	Crop diversification	Reclamation of deteriorated lands	–
Central	Sustainable intensification	Organic farming	Intercropping	Crop diversification with legumes	Reducing water erosion	–
Rainfed	Agroforestry	Organic manuring	Rainfed horticulture and intercrops	Cover crops/live mulching	Pond and tank restoration and desilting	–
Arid	Integrated farming system	Agroforestry	Water management by farm ponds	Crop diversification with legumes	Dune stabilization	–
Island	Integrated farming system	Organic manures	Composting local organics		Contouring	Seabank stabilization

Source: Modified from NAAS (2021)

3.2 Organic Farming

Organic farming is thought to promote soil fertility by increasing the amount of soil organic matter (SOM) in the soil. As a result, the sequestration of carbon dioxide from the atmosphere would significantly benefit agriculture and the allied system. According to the study's findings, soil carbon content (SOC) grew by 2.2% each year after practicing organic farming systems (Leifeld et al. 2013). The organic farming system enhances soil C growth compared to traditional agriculture (Gattinger et al. 2012). Soils under this system had higher C stocks than soils under conventional farming. In addition, they found that organic farming got more external (manure, slurry, compost) C inputs (1.20 Mg C ha^{-1} per year) than CF (0.29 Mg C ha^{-1} per year). High and frequent external organic inputs have been linked to higher soil C concentrations in the organic farming system (Leifeld et al. 2013).

Many studies have examined the environmental benefits of organic farming, including improved soil quality, decreased nutrient production, and lower energy consumption (Pimentel and Burgess 2014). However, the findings vary by farm activities (Sharma et al. 2021). For example, organic farming emits more ammonia, nitrogen, and N_2O per unit product than conventional farming (Clark and Tilman 2017). In addition, organic farming conducted using dairy and pig farm manure had typically higher GHG per unit area than traditional farming (Cederberg et al. 2013). However, it improves the soil carbon from the external organic outputs and has a lower carbon footprint than conventional farming (Adewale et al. 2018).

3.3 Natural Farming

Natural farming has been advocated as a more eco-friendly and zero-budget system in India, since it has four major components, i.e., *jeevamrutham*, *beejamrutham*, *acchadana* (mulching), and *whapasa* (soil aeration), which has been claimed to boost microbial activity, increase soil carbon, provide nitrogen through green mulching, and increase the availability of existing topsoil nitrogen (Smith et al. 2020). Comparative life cycle analysis (LCA) indicated that zero-budget natural farming ZBNF systems consume 50–60% less water and 45–70% less energy and produce 55–85% fewer greenhouse gases (Rose et al. 2021). However, it should be highlighted that the LCA sample size was small and did not consider soil carbon sequestration. Hence, ZBNF had a research gap on carbon sequestration; more scientific studies need to be done for policy options.

Permaculture is a natural farming technique, a modified Masanobu Fukuoka natural farming (Fukuoka 1985; Krebs and Bach 2018). Organic manuring is an essential principle in permaculture, but unfortunately, farm cattle and animals are believed to emit more GHG than tractors. Contrasting the above view, some findings show that cattle plowing uses less energy than tractors (Spugnoli and Dainelli 2013; Krebs and Bach 2018). The excessive use of animal manure causes environmental issues such as eutrophication of groundwater and freshwater, heavy metal deposition in soil, ammonia emissions, and greenhouse gas emissions (Jongbloed and Lenis 1998; Bolan et al. 2010). Recent research shows that soil organic matter and carbon storage are improved by organic manure (Bolan et al. 2010; Maillard and Angers 2014). Hence, permaculture with less organic inputs is a good option for soil carbon sequestration.

3.4 Manure Management

Appropriate manure management is an important option to improve the carbon sequestration in the soil. Several long-term European trials have proven that organic manures sequester more SOC than chemical fertilizers (Smith et al. 1997; Powlson et al. 2013). Long-term usage of manure increased the SOC pool at the 0–30 cm depth by 10% in Denmark, 22% in Germany (90 years), 100% in Rothamsted, UK (over 144 years) (Jenkinson 1990), and 44% in Sweden (more than 31 decades) (Powlson et al. 2013). The yearly growth in manure nitrogen production leaped from 21.4 Tg N year in 1860 to 131.0 Tg N year in 2014 (Zhang et al. 2017). Cattle produced 44% of total manure nitrogen output in 2014, followed by goats, sheep, swine, and chickens. Application of manure nitrogen to farmland amounts to less than one-fifth of total production (Gross and Glaser 2021).

Organic manure degrades quickly as it is rich in nitrogen content and has a low C: N ratio. Hence, manure may also enhance soil carbon levels due to its high carbon concentration. Many research examined the influence of manure application on SOC stocks; few studies reported increases in carbon, while others found relatively minor or negative impacts on SOC stocks (Gross and Glaser 2021). Due to manure application, studies are needed to understand parameters that govern the degree of change in SOC stocks. According to the recent findings by Gross and Glaser (2021), the increasing impact of manure on carbon is complex and variable. Soil texture, SOC content, and tillage intensity should also be considered to increase carbon content. More long-term SOC field data must be studied to understand carbon dynamics better, and new comprehensive approaches in carbon dynamics assessment methodologies are also needed.

3.5 Cover Crops and Mulching

Growing cover crops and mulching practices have advantages over other management methods that enhance soil organic carbon (SOC) and crop yields. Around the world, farmers, scientists, and policymakers are interested in the potential contribution of cover crops to soil carbon sequestration (Lal 2015). Though research on the regional, national, and international impacts of cover crops on carbon sequestration is widely made (Franzluebbers 2010; Poeplau and Don 2015; Ruis and Blanco-Canqui 2017), the policy-making and implementation for cover crops and mulching is lacking (Tellin and Myers 2018). The influence of cover crop green manuring on SOC stocks, on the other hand, is often underestimated. SOC stock changes occur due to an imbalance between carbon inputs, mainly in dead plant material or manure, and outputs, primarily due to decomposition, leaching, and erosion (Poeplau and Don 2015). In addition, global food consumption increases due to the growing worldwide population and rising affluence in emerging nations, limiting the amount of farmland converted to natural vegetation or grassland (Tilman et al. 2011). As a result, effective strategies such as cover crops and mulching for raising SOC stocks while maintaining high agricultural output are essential.

3.6 Avoiding Soil Erosion

Agricultural soils are prone to erosion due to removing most vegetation by conventional tillage. Erosion is a selective process that preferentially removes the light organic fraction (1.8 Mg/m^3) (Malhi et al. 1994). As a result, the SOC pool is impacted (Lal 2019). Total C moved by erosion is estimated to be 4.0–6.0 Pg/year, assuming a 10% delivery ratio and a 2–3% SOC content (Du et al. 2019). Traditional tillage methods, such as deep plowing, harm agricultural soils and contribute to global land degradation (Bai et al. 2008). According to the World Resources Institute, 60–90 Pg of soil organic carbon (SOC) was lost worldwide in the preceding decades due to excessive and continuous tillage methods.

Furthermore, since 1750, misusing agricultural technology has led to a 66–90 Pg C loss in soil carbon stores, while deforestation has contributed to a 22% loss (Lal 1999). As a result, conserving natural resources and ensuring food security while reducing environmental impact are critical to alleviating the issues associated with land degradation. In addition, the degradation of biomass and soil C stock has been a significant source of CO_2 emissions (Hussain et al. 2021). Hence, ecologically appropriate strategies may reduce C emissions and sequester them in soil and biota.

3.7 High Biomass Farming

The idea of carbon sinks, credits, and trading boomed the interest in herbaceous bunch-type grasses and woody perennials which can be used as energy crops and feedstock for biofuels. Biomass and biofuel crops generate vast quantities of biomass, have great energy potential, and grow on all types of soils. C sequestration rates range from 0.6 to 3.0 Mg C ha^{-1} year^{-1} for bioenergy crops grown in deteriorated soils and 1631 Tg per year globally from 757 M ha of land. It has a vast carbon offsetting potential, 1 kg through biomass and 0.6 kg through fossil fuel reduction. Plants like *Panicum virgatum* L., *Pennisetum purpureum* Schum., *Populus Salix*, and *Prosopis* are among the most crucial short-rotation woody perennials used for biomass farming (Lemus and Lal 2005). Carbon sinks alone cannot reduce GHG emissions; a significant decrease in fossil fuel usage is required. This is an essential part of a prospective society's reaction to a GHG emission reduction strategy.

3.8 Agroforestry

Agroforestry includes many carbon-trapping practices like agrisilviculture systems that can help mitigate climate change. However, soil type determines the efficacy of soil C sequestration in the agroforestry system. Crop leftovers and tree litter restore vast amounts of organic C to the soil in sustainable agroforestry systems. Those inputs may help stabilize soil organic matter (SOM), slow biomass degradation, and improve SOC stocks (Oelbermann et al. 2004; De Stefano and Jacobson 2018). The meta-analysis notably shows that agroforestry systems and shelterbelts are effective strategies to raise SOC stocks in top- and subsoils, especially in subtropical climates (Hübner et al. 2021). From another meta-analysis study, SOC stocks decreased by 26% and 24% when land use changed from forest to agroforestry at 0–15 and 0–30 cm, respectively. Changing from agriculture to agroforestry increased SOC stock by 26, 40, and 34% at 0–15, 15–30, and 100 cm. Agroforestry boosted SOC by 25% at 0–30 cm but decreased 23% at 0–60 cm (De Stefano and Jacobson 2018). If the land use evolved from simpler systems like agriculture to agroforestry, SOC stocks would rise. Hence, agroforestry is an effective technique to sequester the soil's organic carbon.

4 Gaps in Research for an Effective Policy

According to Pathak et al. (2014), many research gaps need to address and promote:

1. Agricultural residue management practices and business models that minimize residue burning and improve SOC.
2. Local organic resources for SOC enhancement identification and inventorying.
3. Determination of long-term trials with crop-fodder-grassland-agroforestry systems in various agroclimatic regions.
4. Creating a national SOC monitoring network with multi-ministerial R & D institutes.
5. Quick, cost-effective, and practical monitoring of GHG emissions and SOC changes in various ecosystems.
6. Developing regional GHG emission-mitigation and SOC simulation models using remote sensing and GIS tools.
7. Developing low C and N technologies and evaluating their GHG reduction potential.
8. Developing methods for reducing cattle GHG emissions via improved feeding and waste management (Pathak et al. 2014; NAAS 2021).

Pathak et al. (2014) also indicated important points in policy-making that need to address:

1. Linking fertilizer, water, and other agri-input subsidies to GHG reduction and establishing the notion of "green budgeting" at the state-federal levels.

2. Adopting adaptation technology with mitigation advantages in national and state climate action programs.
3. Encourage farmer and community-based holistic land management.
4. Developing novel payment for ecosystem services and mitigation assistance for smallholder farmers.
5. Ensuring soil quality, regulating climate, and conserving biodiversity are SOC-based policies and initiatives.
6. Focus on combining multi-ministerial projects like NAPCC and SAPCC.
7. Subsidize the development of excellent organic fertilizer (low-volume, high nutritional products) with chemical fertilizers.
8. Motivate private (corporate/industry) farmers to engage in regenerative farming methods for SOC improvement and awareness and capacity development on management practices in GHG reduction and carbon sequestration.

5 Policy Options in Soil Carbon Management

Policies can help to define the goals and provide guidance about how to achieve the objectives of soil carbon management through various options. For example, according to the World Bank, 2012 farmers need to be encouraged to increase carbon sequestration. Policies and measures that promote sequestration of carbon include, as shown in Fig. 3, (i) boosting the adoption and investment more in climate-smart agriculture, (ii) multinational global cooperation agreements, (iii) incentives and payment of ecosystem services, (iv) motivating public-private participation in carbon management, (v) long-term policy building based on scientific evidence, and (vi) emission reduction, mitigation, and adaptation planning.

Boosting the adoption and investing more in climate-smart agriculture is very important in the current scenario. Climate-smart agriculture (CSA) is climate-friendly agriculture that includes practices that enhance SOC sequestration, reduce GHG emissions, improve crop yields and nutrient use efficiencies, and promote climate resilience. It helps to strengthen capacities to implement a climate-friendly agricultural policy (Magaudda et al. 2020). National policies, strategies, and investment plans should be changed to recent developments and trends in carbon policy and management. It is possible that better guidance and training for farmers on land management may result in more carbon sequestration and more environmentally friendly agricultural policy-making (Kløve et al. 2017).

A multinational global cooperation agreement is crucial for policies and measures that promote carbon sequestration. The IPCC encourages carbon sequestration through international global cooperation agreements, where food security and climate change adaptation and mitigation are significant concerns. Agricultural adaptation and mitigation must be adequate for long-term policy-making about carbon sequestration. This will lead to a greater understanding of the role of agriculture in ongoing global climate talks.

Incentives and payment of ecosystem services must be part of policies that promote carbon sequestration. The worldwide government and institutions need to

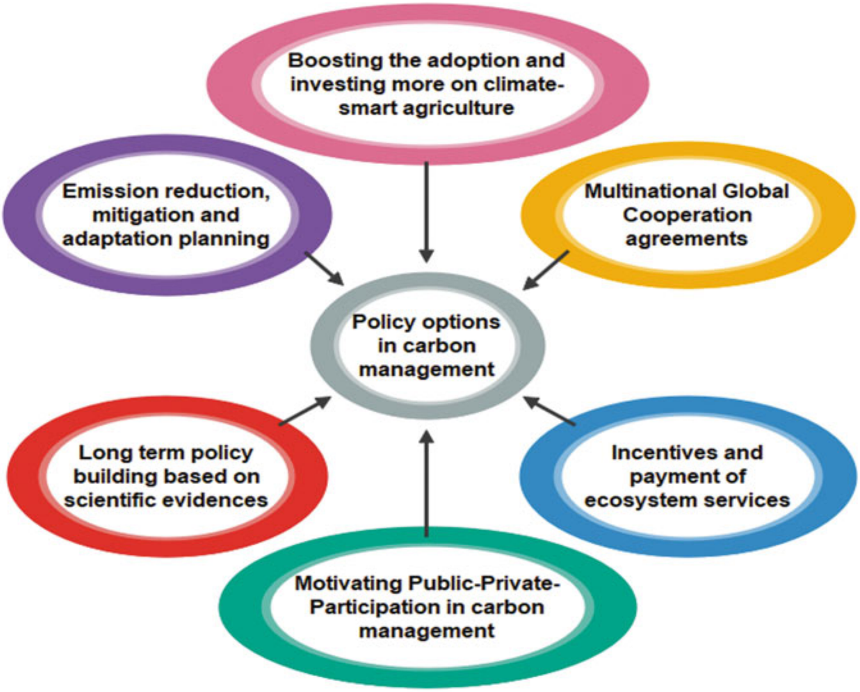

Fig. 3 Policies and measures that promote sequestration of carbon

increase funds and develop the financing mechanism for farmers who act early to mitigate carbon and adopt carbon management practices (Stringer et al. 2012). Better agricultural practices will require public, private, and corpus funds. Combining climate finance with food security is one of the most promising ways to fund climate-smart agriculture. Payments for ecosystem services (PES) might help farmers embrace conservation agriculture, natural farming, and chemical-free organic farming, requiring specialized equipment and significant upfront investments (Devi et al. 2017; Kumar et al. 2019). In addition, PES for early-stage agroforestry producers may profit from carbon financing (Idol et al. 2011).

Motivating public-private participation in carbon management is very important given changing climate scenarios. Its adaptation can help to avoid many climate change-related future problems (IPCC 2014). This platform can include developing social and ecological infrastructure, policies, process technology, and resource management in planning carbon management through agriculture (Lebel et al. 2007). Currently, government commitment and financial investment are the only carbon management source. So, the private sector's commitment to climate-friendly agriculture is critical to sound policy-making. A public subsidy may entice private investment in R & D, tree planting, and seed and seedling production. Incentives from commercial and financial service providers should encourage farmers to employ sustainable land management to overcome the constraints above. Public policy and public-private partnerships may stimulate private investments such as agriculture finance and insurance bundling and alternative risk management like index-based weather insurance or weather derivatives.

Long-term strong policy building based on scientific evidence can play a significant role in carbon management and climate change mitigation plan from a long-term perspective (Moss et al. 2010). Greenhouse gas emission reduction and adaptation of mitigation strategies must be effectively supported by institutions, governance, innovation, and investments in environmentally friendly technology, infrastructure, and sustainable livelihoods. Innovative infrastructure and technologies and assets in low-carbon and carbon-neutral energy technology, which are environmentally friendly, may help decrease greenhouse gas (GHG) emissions and increase climate change resilience (IPCC 2014).

6 International Plans and Policies Frameworks for Soil Organic Carbon Management

The United Nations Framework Convention on Climate Change (UNFCCC) came into effect on 21 March 1994. The convention aims to prevent harmful human meddling in the climate system (Gao et al. 2017). The Convention on Biological Diversity (CBD) also plays a vital role in biodiversity conservation, particularly active soil biodiversity that drives the dynamic equilibrium of SOC under unchanged land use. Midgley et al. (2010) demonstrated that high C levels corresponded to a high biodiversity system in tropical latitudes. Organic matter decomposition, nutrient cycling, soil structure development, and climate regulation are essential activities and services performed by the soil biota (Dominati et al. 2010; Pulleman et al. 2012).

The United Nations Convention to Combat Desertification (UNCCD) plays a vital role in sustainable land management (Kutter 2015). Globally, arid, semiarid, and dryland areas are prone to loss of organic C due to severe erosion. Consequently, SOC content in drylands (usually smaller than 1%) is recognized as a parameter reflecting degradation and desertification trends. However, despite the importance of SOC in monitoring and assessing desertification, current policy analyses have paid little attention to this measure. Incorporating SOC as a meaningful indicator into the UNCCD's regular reporting system will undoubtedly increase soils' prominence in the convention's negotiation process and synergize with the CBD and UNFCCC (Lorenz et al. 2019). The potential for such synergies has already been well recognized within the Millennium Ecosystem Assessment (2005). In addition, the UNCCD is working on preventing desertification/land degradation and mitigating the effects of such losses toward achieving environmental sustainability and tackling land degradation (Ma and Zhao 1994; Prăvălie 2021).

The FAO's Global Soil Partnership (GSP) was created in 2012 to promote sustainable soil management (SSM) and improve soil governance to ensure healthy and productive soils. Besides these supporting and provisioning ecosystem services for food security and improved nutrition, climate change adaptation and mitigation and long-term development must be addressed (Rodríguez Eugenio 2021). GSP has five pillars which are directly or indirectly associated with SOC management and combat climate and sustainability:

1. Promote protection, conservation, and management of long-term soil productivity.
2. Promote soil education, extension, and policy.
3. Promote soil research and identify gaps, priorities, and synergies with environmental and social initiatives.
4. Furthermore increase the availability of information and data quality on the soil by collecting, validating, monitoring, and integrating with other disciplines.
5. Harmonization of methods, measurements, and indicators for the sustainable management and protection of soil resources.

SOC is a cross-cutting issue entering many different EU policy frameworks. The EU promotes practices that favor maintaining or even increasing SOM levels (Sočo and Kalembkiewicz 2009). However, in many regions of the EU, the soil is irreversibly eroded or has a low organic matter content. The EU's agriculture, energy, transportation, and cohesion policy changes provide the opportunity to build the framework and the necessary incentives to achieve this goal. In addition, EU policies consider their direct and indirect effects on land use targeted to reach no net land taken by 2050. That would help reduce soil erosion and enhance soil organic matter buildup (Montanarella and Panagos 2021).

The IPCC provides scientific assessments on climate change, its implications, and potential future risks and adopts adaptation and mitigation options (Junk et al. 2013). According to the IPCC, markets will effectively stimulate carbon sequestration only if the monetary worth of carbon stocks and sinks is recognized and paid. Some developing countries see the need for carbon offsets to facilitate cash inflows to finance conservation and other efforts (McAfee 2016). The tradable emissions permit is a new instrument that has the potential to have a significant impact on carbon sequestration (Kauppi and Sedjo 2018).

Companies with surplus emissions permits can sell them to companies that need more. As a result, total emissions are no longer accessible but come at a cost to the company. Therefore, firms with surplus permits can either sell them or sacrifice the potential to get paid – this is known as an opportunity cost. As a result of this method, the market can reallocate emission permits, hence emissions, to the users who get the best return on the licenses, allocating carbon emissions permits to the most efficient users (Bayer and Aklin 2020).

Under the Kyoto Protocol, the CDM is a project-based GHG offset method. The scheme intends to help Annex-I nations (those with binding emission reduction objectives) lower global GHG emissions more cost-effectively by letting them invest in offset projects in non-Annex I countries (low- and middle-income countries without binding targets). The CDM, as the world's most important regulatory project-based mechanism, allows high-income countries' public and private sectors to buy carbon credits from low- and middle-income countries' offset projects (Ba et al. 2018).

The CDM enables nations to satisfy a portion of their Kyoto obligations by funding carbon emission reduction projects in low- and middle-income countries. Because lower-income countries have lower energy efficiencies, cheaper labor costs, weaker regulatory requirements, and less advanced technologies, such projects are arguably more cost-effective than projects executed in higher-income countries (Steel and Harris 2020). The CDM is also intended to benefit the host country's long-term development. CDM projects provide emissions credits known as certified emission reductions (CERs), which can be purchased and exchanged (Boyd et al. 2009). Visit the Paris Agreement website for more international carbon trading under the current climate policy system.

The Clean Development Mechanism (CDM), as specified in Article 12 of the Protocol, allows a nation with a Kyoto Protocol (Annex B Party) emission-reduction or emission-limitation commitment to implement an emission-reduction project in developing countries. These projects can yield saleable certified emission reduction (CER) credits, one ton of CO_2 equivalent. Many consider the mechanism to be a game-changer. It is the world's first worldwide environmental investment and credit system, offering CERs, a standardized emissions offset mechanism. A CDM project activity could include, for example, a solar panel-powered rural electrification project or the construction of more energy-efficient boilers. The method promotes sustainable development and emissions reductions while allowing industrialized countries considerable flexibility in meeting their emission reduction or limitation commitments.

7 India Plans and Policies Frameworks for Soil Organic Carbon Management in Agriculture

In India, various plans and policy frameworks have been initiated to manage SOC in agriculture and climate change-related issues (Liu et al. 2016). The National Mission for Sustainable Agriculture (NAPCC) India intends to help agriculture adapt to climate change by developing climate-resilient crops, expanding weather insurance mechanisms, changing agricultural practices, and emphasizing waste management and recycling to use it as an organic carbon source. Many policies and legal framework plans for soil organic carbon conservation, land planning, and other regulatory measures that efficiently comply with soil and organic carbon improvement at the national level have been initiated.

In order to meet India's commitments under the UNFCCC and Paris Climate Change Agreement in 2015, various ICAR institutes and universities are involved in estimating and monitoring the soil organic carbon stocks in widespread diverse landscapes. India is also involved in bringing different plans and policies, including the National Mission on Sustainable Agriculture (NMSA), National Project on Organic Farming (NPOF), National Adaptation Fund for Climate Change (NAFCC), National Action Plan on Climate Change (NAPCC), etc., for the concern toward carbon sequestration through soil management practices. In addition, many multi-ministerial policies encourage the farmers to implement SOC-based sustainable procedures and enhance the farm managing ability toward climate regulation (Smith et al. 2008; Fulton and Benjamin 2011).

The Government of India emphasizes the thrust on adopting climate-smart agriculture, especially on conservation agriculture principles. Nowadays, this is popularizing among the farmers as an act to coincide with extreme weather events. Adaptation, mitigation, and productivity are the pillars of climate-smart agriculture. Crop diversification, residue retention, water management, nutrient management, zero-tillage, and information and communication tools (ICTS) are considered management practices under climate-smart agriculture to achieve greater sustainability. Climate-smart agriculture-based practices are all done because the soil will be the potential sequester and sink of atmospheric carbon dioxide in the form of soil organic carbon (Pathak et al. 2014). Studies found that this conservation agriculture sequester nearly 24–40 MT of carbon per year. Therefore, the total soil quality would also improve. Some techniques like zero-tillage direct-seeded rice (DSR) and alternate cropping increased SOC stocks. The negative impacts could be decreased by improving these agricultural practices, especially the soil's biological activities and soil properties (Bhattacharyya et al. 2015). Soil quality can be studied by the disobedience and liability indices which provide information about the stable carbon in the soil. Climate-smart agriculture practices were found to elevate the overall sustainability of the earth.

According to the National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), soil in India has 20–25 Gt of organic carbon. The primary cause of soil organic carbon declining pool is accelerated soil erosion (Gama-Rodrigues 2011). The recurrent droughts also result in a decline in biomass production and a decrease in the organic carbon content in the soil, leading to land degradation, especially in the northwestern region of India. It was also found that the carbon sink capacity has been reduced (Jat et al. 2019). The practice of conservation tillage, majorly in western Indian regions, enhances the development of soil organic carbon. However, various features in the Indian conditions may not apply these strategies in all areas. In order to elevate the sequestration of carbon, submission on agroforestry systems under the National Mission on Sustainable Agriculture (NMSA) emphasized enlarging the tree cover area, thus enriching the soil organic carbon. This enhances the proper risk management toward climate resilience (van Wesemael et al. 2011). Presently, this mission is being implemented in 20 states and 2 union territories.

The National Policy on crop Residue Management is working to elevate SOC by making crop residues available and converting biomass into a source of SOC to enhance crop growth, ultimately resulting in enhanced carbon sequestration (Monfreda et al. 2008). Other management under in situ strategies like zero-tillage, nitrogen-fixing legumes, and crop rotation helps increase existing carbon stocks in the soil. The national program of sequestering carbon was recently initiated, including:

1. National Mission for Green India: As forests sequester billion tons of carbon as soil organic carbon stock and biomass and thus act as effective carbon sinks, thereby enhancing the ecosystem services.
2. National Mission for Sustainable Agriculture: The Indian Ministry of Agriculture has channelized the need-based knowledge to boost productivity in farm practices. This paved the way for land-use planning and regional soil and water databases. It also allowed the biotechnological approaches of sequestering carbon, drought resilience, and increased crop productivity.

The application of farmyard manure and organic manure usage potentially enhances the SOC (Lal 2019). Significant policies and technological options such as agriculture intensification, mulch farming, and composting lead to increased organic carbon stocks in soil (van Wesemael et al. 2011). According to COP 21–22 report, agroecology, agroforestry, conservation agriculture practices, and landscape management can play an essential role in achieving India's SOC management and carbon sequestration goal. The Soil Health Card program provides information to farmers about soil nutrient status and recommends dosages of nutrients. The Paramparagat Krishi Vikas Yojana is a centrally sponsored scheme in the NEH region to facilitate organic farming produce, which enhances SOC and increases soil sustainability (Aayog 2020). Agriculture-related policies are directed toward reducing net GHG emissions. Carbon sequestration strategies need multidimensional research and policies to inspire carbon sequestration (Soussana et al. 2019). Area-specific priorities need to be comprised of various state and central government programs, and the technology implementation is vital to public contribution. A country like India with a tropical agroecosystem should make scientific efforts to understand the dynamics of SOC both spatially and temporally (Deffner et al. 2020).

For the quick, inexpensive, and authentic monitoring of the changes in the status of SOC in diverse ecosystems, we may require scientific interventions:

1. Monitoring SOC at the national level.
2. Measuring the interaction of SOC and productivity of agriculture.
3. Identification of resources, which can be effectively utilized for SOC improvement.
4. Promotion of crop residue management, with zero burning of residues.
5. Through long-term experiments on SOC in various agroecosystems, crop diversification, and cropping systems.
6. Development of SOC-based programs and policies for sustainable soil quality and regulation of climate change.
7. Linking of multi-department programs toward sustainable SOC enhancement.
8. Promotion of holistic land management approaches with farmer/community participation.
9. Providing incentives to farmers for the ecosystem services, particularly SOC management practices.
10. Encouraging the production of quality organic manure with appropriate subsidy support instead of chemical fertilizers.

11. Promoting corporate-farmer partnership with particular attention to SOC improvement with incentives.
12. Conducting SOC management awareness programs on a large scale against burning crop residues.
13. Strengthening existing programs at the state and national level by incorporating SOC improvement interventions
14. Establishing the national mission on carbon sequestration at the farmer's level and scientists' levels
15. Promoting legume-based cover crops to improve land cover, soil carbon, nitrogen, etc.

8 Future Scope and Perspectives

Soil is a dynamic system that provides several ecosystem services like water quality, crop productivity, biogeochemical cycles, and climate change impacts. Soil health is connected with sustainable agricultural practices since soil biota and its activity are the crucial components of soil health. Soil organic carbon (SOC) administers the inherent productivity of soils. It controls climate change and ecosystem services that are significant for a sustainable enhancement of crop productivity and supply of food. India has enormous potential for carbon sequestration in sustainable agriculture and productivity. However, inappropriate practices or management leads to the acceleration of greenhouse gas emissions into the atmosphere, affecting climate change. Intensive agriculture and improper management of natural resources affect soil health and food quality and worsen other environmental issues. In several states (e.g., Punjab Haryana, Uttar Pradesh, Madhya Pradesh, West Bengal, Tamil Nadu), SOC has declined ~0.2–0.4%. So, it is time to focus on restoring the SOC pool through appropriate land-use and farming practices, soil conservation, sustainable food production, and environmental security. The government has taken a few initiatives to enhance C sequestration by launching different schemes in agriculture and various other allied sectors. But on practical aspects, much more attention and motivation from the farmers are still required to successfully implement these plans and policies to fulfill the required target of soil C restoration.

9 Conclusion

Soil organic carbon management primarily focused on meeting India's particular food grain production objectives in the agricultural research and development paradigm. Policy options in soil organic management provide a new paradigm for food security, agricultural research, and development. The need for a paradigm change has become imperative in light of the pervasive issues of resource degradation that have followed earlier attempts to increase output while paying little attention to the integrity of natural resources. In order to achieve continuous productivity increase, it is necessary to integrate concerns about productivity, resource conservation, soil quality, and environmental considerations. Scientists will need a much-increased ability to approach challenges to formulate long-term plans and policies, collaborate closely with farmers and other stakeholders, and significantly improve knowledge and information-sharing processes. Considering the importance of SOC, focused practical plans and policies in agriculture will eventually make the country more secure against climate change and soil sickness. It will also support the aims of Sustainable Development Goals for a better country and the planet in general.

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Plans and Policies for Soil Carbon Storage

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Abstract

Soil carbon is vital for long-term ecosystem sustainability. Capturing of carbon in soil is cost- and time-effective strategies for reverting the process of soil degradation. Increasing carbon content in the soil, through good agricultural practices, results in enhancement of soil microbial biodiversity, soil quality, and soil water retention. Indian soils are universally deficient in soil organic carbon however has got good potential for soil carbon sequestration. Important strategies of soil C sequestration includes restoration of degraded soils and adoption of recommended management practices of agricultural and forestry soils. India should develop time-bound strategy for improving carbon storage in agricultural soils taking into account of antecedent/existing soil carbon content, soil texture, and climate (rainfall and temperature) of the region. Management interventions like balanced fertilization, INM, conservation agriculture, residue incorporation, crop rotations, and biochar application should be formulated to attain the desired goal under the given time frame. It is also imperative to formulate policy and procedure that should be auditable and verifiable with respect to baseline conditions and the additional benefits from adopting best management practices.

Keywords

Soil carbon · Land use · Conservation agriculture · Biochar · INM · Policy

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Abbreviation

CA	Conservation agriculture
CO_2	Carbon dioxide
FYM	Farmyard manure
GHGs	Greenhouse gases
INM	Integrated nutrient management
N_2O	Nitrous oxide
SOC	Soil organic carbon

1 Introduction

Long-term ecosystem sustainability depends on healthy and productive soils (Blum 2005), which is essential for supporting ecological, economic, and social management goals (MEA 2005; Comerford et al. 2013; Adhikari and Hartemink 2016; Baer and Birgé 2018; Grilli et al. 2021). Soil organic carbon (SOC) is recognized as one of the most important indicators to evaluate land degradation (Lorenz et al. 2019) and soil quality (Bünemann et al. 2018). Soil carbon sequestration is the process of capturing CO_2 from atmosphere via photosynthesis and ultimately storing into the soil. SOC is directly linked with nutrient storage, soil structure, water retention, aeration, plant health and productivity, and microbial biomass and activity (Wander 2004; Comerford et al. 2013; Murphy 2015; Adhikari and Hartemink 2016). Soil loss coupled with SOC loss is one of the most important environmental issues, which, along with climate change, threatens globally ecosystem sustainability and food security (Cherlet et al. 2018). Lal (2015a, b) opined that the maintenance of SOC concentration in the range of 1.1–1.5% is important to reduce soil and environmental degradation risks.

Increasing carbon content in the soil, through good agricultural practices, produced numerous ancillary benefits such as enhancement of soil microbial biodiversity, soil quality, and soil water retention and ultimately productivity. Restoration of soil organic matter through good agricultural practice that can further seize the process of land degradation and can improve soil quality through improved soil organisms and related ecological processes. Also through better nutrient cycling and soil water retention, practices that stabilize carbon will also help in enhancement in food production and optimizing the use of synthetic chemical fertilizers, thereby minimizing emissions of greenhouse gases from agricultural land. Capturing of carbon in soil is thus very cost- and time-effective strategy (FAO 2008). It also creates a valuable win-win approach through mitigation (CO_2 removal) and adaptation, both enhanced resilience to climate variability in agroecosystem. Under climate change scenarios in colder regions of the world, increased temperature may increase soil organic matter mineralization and CO_2 emission from soils (FAO 2008).

Adoption of good agricultural practices will lessen the effects of global warming by permanent soil cover.

Intensive tillage operations in conventional agriculture coupled with burning of residues and imbalanced fertilizer application resulted in declining crop productivity and soil health. Soil could be a source or sink for atmospheric carbon dioxide (CO_2), depending on how it is managed. Due to rapid increase in CO_2 concentration in air, now more focus is given on soil to act as a possible sink for atmospheric CO_2. Now it is well documented that increased carbon content of soil is the most effective strategy for climate change adaptation and mitigation and to land degradation and food insecurity (IPCC 2019). Soils encompass the largest pool of actively cycling carbon in terrestrial ecosystems and store 1500–2400 Gt C (to a depth of 1 m) (Jobbagy and Jackson 2000; Ciais et al. 2013; Stockmann et al. 2013), in various organic forms ranging from fresh plant litters to well-decomposed humified material and inorganic carbon or carbonate carbon. Worldwide about 1500 Pg carbon is stored in first 30 cm of soil (Batjes 1996); for India it is only 9 Pg (Bhattacharyya et al. 2000). Indian soils are deficit of SOC, and, ranging from 0.1 to 1% and majorly less than 0.5%, its impact on soil physical, chemical, and biological properties is of great significance. Bhattacharyya et al. (2009) computed order wise soil total carbon stock to the depth of 1.5 m. According to them, Indian soils classified under Inceptisols and Entisols contribute about 20% and 8.5% of the total carbon stock, respectively. Vertisols are extensive in the central and southern part of India and contribute about 23% of the total carbon stock, whereas arid soils belonging to arid ecosystem contribute 24% of the total carbon stock mainly because of large area occupied by them. Most of Alfisols occur in subhumid to humid regions of the country and contribute about 22% of the total carbon stocks (Bhattacharyya et al. 2009). The low SOC concentration in Indian soil is attributed to extractive practices of nutrient mining because of low or imbalanced fertilizer use, removal of crop residue for fodder or household fuel, and soil degradation. In general, SOC may reach a near steady state after several centuries (500–1000 years). However, depletion of soil organic carbon to the tune of 23–59% of original value was found under cultivated fields (Jenny and Raychaudhuri 1960). The agricultural soils of northwest India exclusive of the Himalayas have lost about 50–66% of their original organic carbon content.

Soil organic matter fractions with functional significance in the turnover of soil organic carbon have been identified in the last few decades. Among all, soil microbial biomass C and water-soluble C fractions are the most dynamic in nature, which have very short turnover times. Slow pool or particulate organic carbon is generally used as an indicator of soil quality. Organo-mineral fractions of specific particle size (<0.053 mm) can lead to development of stable microaggregates, which is having a slower turnover time. Crop diversification coupled with good agronomic practices substantially improved C storage in semiarid regions of India. The experience gained from long-term fertilizer experiment established that NPK and NPK + FYM maintained or improved SOC pools over initial value. Application of balanced fertilization or integrated approach significantly improved labile portion of soil organic carbon such as particulate organic carbon, water-soluble carbon and hydrolysable carbohydrates, and soil microbial biomass C and N. Agroforestry, agro-horticulture, and agro-silviculture are alternate land-use systems, which is more remunerative for SOC restoration as compared to sole cropping system. It was observed that northeast hill states of India, where all the above three land-use systems are existed, reduced considerably soil erosion and SOC loss. Also, change in land use from agriculture to agro-horticulture resulted in a significant increase in SOC, soil biological activities, and fertility status. One way to increase the amount of crop residue carbon added to soils is through the use of cover crop which besides adding carbon to the soil helps to decrease erosion and suppress of diseases and nematode population. Multiple cropping with two or more crops in a year can result in increased SOC contents due to the addition of large amount of aboveground as well as belowground biomass in soil. This is further enhanced the by inclusion of green manuring crops. Also, minimum tillage coupled with good soil cover (at least 30% crop residue cover) and crop diversification not only helps to check runoff and soil erosion but also improves soil aggregation and infiltration and enhances carbon sequestration in the long run. Conservation agriculture can improve and make more efficient use of natural resources through integrated management of available soil, water, and biological resources combined with external inputs. It contributes to environmental conservation as well as to enhanced and sustained agricultural production. SOC-centered sustainable soil management practices not only mitigate GHGs emissions but also provide multiple benefits such as enhancing food security and farm income, reducing poverty and malnutrition, and providing essential ecosystem services. Recarbonization of our soils could be a feasible solution to decarbonize our atmosphere.

2 Carbon Sequestration Potential of Indian Soil

The terrestrial ecosystems contain nearly 3170 GT of carbon. Out of this, about 2500 GT is found in soil (Lal 2008). Hypothetically, carbon in soil is divided in three distinct pools: active, slow, and recalcitrant. Each pool is having different mean residence time in soil and typically varies from few days to 1000 of years. The allocation of carbon in each pool dictates capacity of soil to supply nutrients. Pristine soil carbon stock under natural vegetation may be used as a reference site for determining carbon sequestration potential of adjacent land use. Also it gives an idea about the influence of land use on soil carbon loss. Lal (2004) estimated carbon sequestration potential of Indian soils to the tune of 39–49 (44 ± 5) Tg C/year with the assumption of conversion of degraded land to restorative land use. Majority of agricultural soils contain soil carbon less than 5 g/kg compared to 15–20 g/kg in uncultivated soils. Low SOC content is attributed to intensive tillage operation, burning and removal of crop residue and other biosolids, and mining of soil fertility. About 6 Tg C/year is lost due accelerated soil erosion due to water. Afforestation of degraded sites coupled with mechanical measures is the main strategies for restoration of wasteland. About 7–10 Tg C/year could be stored through restoration of degraded soil, whereas 5–7 Tg C/year could be captured by erosion control.

Similarly, 6–7 Tg C/year could be sequestered by adoption of good agricultural practices and 22–26 Tg C/year through secondary carbonates.

3 Soil Carbon Loss in Context of Land Degradation

About 60% of degraded land in India is either unirrigated farmland or forest land. The burgeoning population is increasing the pressures on soil resources. Deforestation is another evil that causes significant decrease in the area under natural forests. Under existing climatic scenario such as the rising of temperature and shrinking of annual rainfall in many parts of the country, there is a great risk for tropical soils of the Indian subcontinent. It may cause further reduction in soil quality especially in terms of decrease in soil organic carbon. To combat such a situation, the restoration of organic carbon using best management practices along with improvement in the forest and grasslands should form the strategic perspectives to sustain the health of Indian soils. According to an estimate, the SOC stock is 21 and 63 billion tonnes in 30 and 150 cm soil depth, respectively (Lal 2004). To arrest the rising global temperature below 2°C in this century and to prevent further rise in temperature, 192 countries ratified the COP 21 in Paris in 2015. Sequestration of carbon present in air to soils is the best way out to achieve the COP 21 objectives (Minasny et al. 2017). The additional advantages of carbon sequestration such as favorable changes on soil physical, chemical, and biological properties will help in increasing the world food grain production (Lal 2015b). As per FAO (2015), grasslands cover less than nearly 50% of the land surface area. About 70% of agriculture land lies mostly in arid and semiarid regions of Africa, Asia, and America. These regions have very low primary productivity in comparison to world average production (Abdalla et al. 2016). Although these regions store only about 10% of the global SOC stocks, it is nearly half of that is sequestered in forests worldwide (FAO 2015). SOC in grassland is very sensitive to land-use management practices. Research across the landscapes has indicated depletion of SOC stocks in grassland soils due to their mismanagement. There exists a large discrepancy in the management of grasslands with respect to soil organic carbon. An analysis of 235 study sites in 18 countries concluded that controlled grazing with high density of grazers was the best practice increase SOC by 21% (Phukubye et al. 2022). Also, burning of grasslands decreased SOC by 9.3% in most of studies. Controlled low grazing helps improve the SOC. Different climatic conditions also decide the SOC management in grasslands. Burning in moist to humid climates decreases SOC by 10.9%, while it is comparatively low (1.7%) under arid to semiarid conditions. Exclusion of grazing was found advantageous grasslands of arid and semiarid regions. Also policy planners have been suggested to recommend rotational grazing instead of open grazing for sustainable management of the pasture lands to prevent further degradation and decrease in SOC. Besides, Conant et al. (2017) recommended best grassland management practices such as low stocking rates, exclusion of grazing livestock, and planned rotational grazing-enhanced SOC stocks. There are mixed report on effect of burning on SOC. In some investigation burning of grasslands has improved SOC in subtropical humid

South Africa, while other studies in Spain (Granged et al. 2011) and Brazil (Nardoto and Bustamante 2003) observed 35% and 13% decline for another site in Brazil. Another intensive meta-analysis of 628 soil profiles showed that decreasing quality of grasslands resulted in on average 9% decline in SOC (Dlamini et al. 2016). Also decrease in SOC is associated with rise in frequency of grazing due to net loss of vegetation and poor root development of grasses (Abdalla et al. 2016).

4 Land-Use Impact on Soil Carbon Storage

Soil carbon dynamics changes with change in land-use system. It is crucial to understand effect of land-use change on carbon sequestration for making best management strategies to improve soil carbon buildup. Converting a forest land to agriculture land causes a loss in SOC by about 20–50% (Don et al. 2011). Soil carbon decreases by 59% even when land use is changed to agriculture from grassland. However, the soil carbon stock improves from agriculture to forest or grassland by 53% and 19% (Guo and Gifford 2002). Land-use change is a major factor that disrupts carbon input output balance in any ecoregion. Intensive agriculture leads to a significant loss of soil carbon and soil quality as well. Afforestation provides a sustainable alternative for decreasing CO_2 from atmosphere. Although, several investigations have highlighted the contribution of afforestation in addressing the changes in carbon in different regions, there is meager on SOC changes with afforestation (Neal et al. 1999).

5 Microbial Diversity and Soil Carbon Storage

Shift in land use causes changes in biodiversity along with a significant effect on ecosystem functions and services on a large time scale especially with respect to SOC storage. (Poeplau et al. 2011). Resistant fractions of soil organic carbon compounds in soil and physical protection of SOC are considered the predominant mechanisms of SOC sequestration for enhancing carbon buildup. Recent theories project the significant role of microbes for development of soil organic matter (Lange et al. 2015). In general, SOC stock is a function of above- and belowground biomass production, organic secretions from plant roots, and their subsequent mineralization by microbes. The increase in carbon storage with plant diversity reflects higher biomass production or prolonged persistence of plant-derived organic materials due to slower decomposition. No single mechanism of soil carbon sequestration can be considered for all soils and production systems. The underlying mechanisms could be many. Higher plant residue inputs might either increase the rate of mineralization and subsequently lower the metabolic efficiency or even increase the mineralization of native soil carbon. In opposite, higher amounts of plant residue inputs could enhance carbon buildup due to increased microbial necromass accumulation over time.

6 Biochar: A New Resource for Soil Carbon Buildup

Carbon sequestration is the process that involves carbon capture from atmosphere and its storage on long-term basis in soil, vegetation, or hydrosphere. Soil carbon sequestration is storage of carbon in to soil on centurial or millennium basis. It enhances microbial activities, improves soil health, and helps mitigate or defer global warming. In fact, carbon is also captured naturally from the atmosphere through various processes such as biological, chemical, or physical. Besides, there are many artificial processes that can produce similar effects. Organic carbon derived through photosynthesis is recycled through microbes in the carbon cycle. Pyrolysis of this photosynthetically generated biomass makes it relatively inert as it is not easily acted upon by microbes. Biochar is the product of slow pyrolysis of biomass generally between temperatures 300 and 500°C. It has high carbon content generally above 60%. Biochar preparation is thus a potential method for long-term soil carbon storage. It has been estimated that biochar can remain stable in soil for hundreds to thousands of years (Preston and Schmidt 2006). The half-life of biochar has been found to vary from 100 to 10,000 of years. However, its properties are not constant and vary significantly depending on type of feed stock and conditions of pyrolysis. Along with the carbon sequestration, the biochar can be applied to soils for enhancing crop productivity and soil health. Thus, biochar has invited interest among the scientific community for long-term storage of carbon in soils and to some extent as a source of nutrient reservoir. Globally, the biochar production has been reported to be between 50 and 270 Tg year^{-1} (Kuhlbusch 1998; Suman et al. 1997). Biochar improves the water and nutrient holding capacity of soil and is being used as manures across the countries. Biochar holds plant nutrients and supply to crops when they need them. Among the indirect effects, it decreases leaching loss of nutrients and provides them to plants slowly and reduces the need for fertilizers, which ultimately minimizes cost of manufacture and transport, especially for nitrogenous fertilizers. Though humus has similar ability to sequester carbon for long time, it requires years to form humus. However, biochar is made faster through pyrolysis. In India, about 313.62 million tons are surplus out of total residue of 435.98 million tons every year. These residues are either partially utilized or remain unutilized due to various constraints (Murali et al. 2010). These may be utilized for making biochar to sequester carbon directly into soil for years together as it does not degrade in soil fast. Its half-life is around 1500 years. An incubation study on microbial decomposition of rice residue biochar revealed that CO_2 emission was reduced by 30–40% at 50 and 100% field capacity of the soil. It also improved the soil physical and chemical properties and microbial community structure (Biederman and Harpole 2013; Rousk et al. 2010). Some of constituents of biochar such as minerals, volatile organic compounds, and free radicals (Spokas et al. 2011) can sometime affect microbial community structure (Ahmad et al. 2016; Mackie et al. 2015; Rutigliano et al. 2014) and modify the soil enzyme activity (Paz-Ferreiro et al. 2014). Biochar also has its influence on soil microbial biomass, bacteria/fungi ratio, and soil enzyme activity.

7 Agronomic Measures for Soil Carbon Storage

Non-judicious agriculture management practices for crop production have resulted in decline of soil carbon and crop productivity throughout the world, although healthy soil always helped to fight against combating the global warming due to having high organic matter, which is always helpful in higher carbon dioxide sequestration into the soil. Globally, it is estimated that 1417 pg of soil C is stored in first upper 100 cm soil layer, whereas about 456 pg soil C is stored in above- and belowground biomass and other dead organic matter (Hiederer and Kochyl 2012). Soil C sequestration involves the capture of CO_2 from atmosphere by plants and stored in soil via addition of soil organic matter (SOM). In common, carbon stays live in wide range of forms, majorly as vegetation, soil organic matter, atmospheric CO_2, and dissolved in sea water. In general, the SOC distribution and storage in soil depend on natural as well as human-induced factors. For example, the high rate of carbon storage in soils when decomposition rates are very slow and productivity is very high is most commonly found in tropical rainforest areas. Similarly, the low carbon storage was found in deserts and cropland areas due to low carbon input rate and high rate of SOM decomposition due to removal of organic matter in the form of crop harvest (Johnston et al. 2009). Agro-techniques/agronomic management practices (tillage, crop rotations, fertilizers, and crop residue) for crop production are also equally responsible for SOC storage/losses in soil. Besides, climatic conditions and bioclimatic factors also influenced the soil carbon storage. Several researchers have reported that adoption of zero-tillage operations, following diversified crop rotations and application of organic sources of nutrients, can be the best option to enhance the carbon storage (Smith et al. 2008: Paustian et al. 2016). In general, soil has a great potential to carbon sequestration as soil works both as sources and sinks of carbon; however, it is determined by the availability of carbon input intensity and its agronomic managements (Zomer et al. 2017). Almost 30% of total greenhouse emissions from agriculture are largely responsible due to faulty agricultural activities that resulted in the decline of carbon content in soil. In general, agro-techniques can be helpful in the lowering of the emission of greenhouse gases (GHGs), if best agronomic management testacies are to be followed under the intensive agricultural production system, and then soils would act as a sink for carbon storage/sequestration.

Agronomic measures that can be useful in for soil carbon storage include conservation agriculture (CA), zero tillage/minimum tillage, diversified environment-friendly cropping systems, legume/cover crops, crop residue management either though retention or incorporation, minimization of soil and water runoff through mulching, integrated nutrient management (suitable combination of integration of organic and inorganic manures combinations), application of soil organic amendment for improving soil fertility and promotion of agroforestry, etc. which are the major agro-technologies that can be supportive in soil carbon storage for healthy soils. These agro-techniques can be useful in lessening of different GHGs and temperatures, minimizing the biotic and abiotic stresses for higher crop productivity and improving soil health. Similarly, crop diversification is also an important aspect

Table 1 Rates of carbon storage varied under different management practices and land use

Land-use systems	Carbon sequestration rate (Mg C ha^{-1} $year^{-1}$)
Afforestation	0.60
Conversion to pasture	0.50
Use of organic amendments	0.50
Zero-tillage farming	0.30
Residue incorporation	0.35
Crop rotation	0.20

Data sources: Minasny et al. (2017)

that can contribute to carbon sequestration through variety of modified cropping system and their root biomass. In common, application of agro-techniques in CA stored soil carbon 1.8 Mg CO_2 $hectare^{-1}$ $year^{-1}$ (FAO 2008). The rates of carbon sequestration varied under different management practices and land uses (Table 1) although their management practices depend on several factors like climatic conditions and locations (Paustian et al. 2016).

8 Soil Carbon Dynamics Under the Practice of Conservation Agriculture

In order to attain the goal of C sequestration, it is important that content of stable pool of SOM should increase. In conservation agriculture, zero tillage, crop residue incorporation/retention, and diversified crop rotation are the agro-techniques that may increase carbon content in soil. The key mechanisms carbon storage in soil with following of zero-tillage farming are increase in soil aggregates especially microaggregates and deep placement of carbon contents. The minimization of tillage operations will impact the maintenance of the carbon in unrecompensed crop residue and enhance soil carbon storage. The burning or removal of crop biomass after harvest of the economic produce leads to decline SOC especially under conventional till farming.

West and Post (2002a) while analyzing the global dataset on C sequestration rates reported that a multiplication factor of 1.16 and 1.07 may be used for computation of enhanced soil carbon stock under no tillage and rotation complexity, respectively. Another study by Chivenge et al. (2007) concluded that for developing best CA practices to improve SOC contents and long-term agroecosystem sustainability, priority should be the maintenance of C inputs (e.g., residue retention) but should focus on the reduction of SOC decomposition (e.g., through reduced tillage) in fine-textured soils. Conventional tillage practices for cultivation of agricultural crops led to decrease in SOC form 30–50% (Schlesinger 1985; Sharma et al. 2000). Consequently, increasing the emission of GHGs and enhancing the atmospheric temperature over the years affected the ecosystem services, brought unexpected changes in climatic events, and then influenced the crop productivity and soil health. Further, the impact of climate change is considered to attain a level where irreversible changes are expected in the functioning of the planet Earth. Therefore, we reduce emissions of greenhouse gases from the atmosphere in long-lived pools, so that it cannot be re-emitted into the atmosphere (Kundu et al. 2013). Hence, conservation is one of the best options for crop cultivation to increase the carbon storage in soil while minimizing the GHGs emission (Meena et al. 2016) due to reduced fuel consumption and improved the soil properties (physical, chemical, and biological) (Lal 2003). Besides, it holds higher amount of leftover crop biomass (crop residue) on soil surface which led to increase in SOC level on soil surface layer as compared to conventional tillage (Drury et al. 1999; Huchinson et al. 2007), though tillage practices may be varying upon the soil type, crop management practices, and accessibility of agro-techniques. However, the relationship between tillage operations and soil constitution and SOM dynamics is crucial for the soil carbon storage/sequestration ability of agricultural soils. Long-term 67 field studies showed that on average change in soil carbon sequestration from conventional till farming to zero-tillage farming can sequester 57 ± 14 g cm^{-2} year^{-1} and highest carbon sequestration was attained after 5–10 years of conversion period (West and Post 2002b). For improving carbon storage, the primary concern is reducing the emission of GHGs from sources of point, viz., fertilizer use, volatilization rate, denitrification, and crop residue burning, and in secondary the adoption of standardized agro-techniques in combination with the carbon can sequester at desired level of carbon (Kushwah et al. 2014). Furthermore, a report indicated that the following of zero-tillage farming can sequester about 25 Gt carbon in the next 50 years, which can be beneficial for carbon storage in soil (Pakala and Socolow 2004).

9 Integrated Nutrient Management for Carbon Buildup

The application of chemical fertilizer is the primary cause of GHG emission mostly nitrous oxide (N_2O) emissions, and use of fertilizers and organic manures contributed to agriculture at 0.68 and 1.8 Gt CO_2 emission every year, respectively (Tubiello et al. 2013). Besides, it is an established fact that nonscientific adoption of chemical fertilizer has led to negative impacts in soil health and impaired the environment quality, as it is a key source of N_2O emissions (Adegbeye et al. 2020). Therefore, integrated nutrient management (INM) strategy should be able to minimize the GHGs emission while enhancing soil carbon storage and sustaining soil biodiversity (Meena et al. 2019). Soil C buildup is imperative for soil health and higher crop biomass as it tailored various soil functions and ecosystem services. Also carbon sequestration/storage has been proposed, a plan and policy to mitigate the potential impact of carbon dioxide on climate (Deluz et al. 2020). CO_2 emission reduction measures and sequestration of atmospheric CO_2 together are called negative emissions technologies (NETs). Soil may play important in the accumulation or storage of atmospheric carbon through its sequestration as soil is considered as the most feasible NET as it can store high amount of CO_2 without any specific technology requirement (EASACl 2018). Several researchers have reported that use of inorganic fertilizers in combination of organic manures can boost soil carbon storage and sustain the soil productivity over the years (Manna et al. 2005; Purakayastha et al. 2008; Jha et al. 2014; Meena et al. 2019; Meena et al. 2021) as inclusion of organic manures in nutrient management strategies sustains active and slow release pools of soil carbon (Gami et al. 2009; Shahid et al. 2013). A good planning on integrated nutrient management strategy and fertilizer (NPK) policy program helps sequester atmospheric CO_2 into soil organic carbon through improved crop growth which consequently increases the soil organic matter by improving soil carbon storage (Purakayastha et al. 2008). As fertilizer is necessary for higher crop productivity (Verma et al. 2012) and combined use of crop residue and nutrients, particularly nitrogen boosts the carbon sequestration up to 21.3–32.5% (Windeatt et al. 2014). However, the carbon stock or carbon sequestration rate is mainly depending on supply of carbon inputs in the form of leftover root biomass and amount of organic manures along with fertilization. Hence, INM strategy (integration of soil test based fertilizers along with organic manures) is a promising technology for reducing emission of CO_2 while increasing the carbon storage in soil (Meena et al. 2021).

10 Soil Carbon Dynamics Under Organic Agriculture

The adoption of organic farming is a well-recognized tactic to improve the soil organic carbon storage. An estimate that the world's mean carbon sequestration potential of organic agriculture is nearly 0.9–2.4 Gt CO_2 year^{-1} is corresponding to mean sequestration potential of about 200–400 kg C ha^{-1} year^{-1} for all croplands (Niggli and Fliebbach 2009). However, carbon storage depends on the constancy between quantity and quality of carbon inputs and rates of mineralization in soil. There is an urgent need for the development of specific protocols to enhance carbon storage. Optimal levels of SOC and nitrogen can be managed through adoption of balanced fertilization along with diversified crop rotations (Purakayastha et al. 2008). Adoption of higher quantity of organic manures had also positive impact on soil carbon storage, which might have higher belowground biomass (root biomass) due to better plant growth and high soil nutrient status and help sequester atmospheric CO_2 into SOC by increased plant biomass. Hence, it is well established that organic manure is a good source of organic matter contributed immensely increasing soil carbon storage. Increment in soil carbon storage through adopting carbon favoring management practices has great potential to mitigate the emission of GHGs. Adoption of organic agriculture is paramount for sustaining soil health and is a prime source of carbon which affects the soil carbon concentration in different crops and cropping systems (Stewart et al. 2007). Previous researchers (Purakayastha et al. 2008; Moharana et al. 2012; Meena et al. 2019) also reported that use of organic manures along with NPK increased carbon sequestration in rice-wheat system; however, inclusion of green manure crops in organic system sequestrated more carbon in maize-wheat system (Kukal et al. 2009). Besides, use of biochar (carbon-rich product) has positive impacts on soil health through carbon sequestration; it increased the crop yield and strengthened the cation exchange capacity, nutrient capacity of soil, and moisture capacity of soil, increasing the soil organic matter and promoting the plant growth (Wei et al. 2020). The research finding suggests that biochar sequesters about 50% of the carbon available within the biomass feedstock depending on the availability of feedstocks (Lehmann et al. 2006).

Continuous application of nitrogenous fertilizer alone resulted in decline in SOC as evident from long-term fertilizer experiments which are being practiced over 50 years in under cropping system and soil types in different agroecological regions of India, whereas balanced application of NPK either maintained or enhanced SOC over the starting value. Continuous application of farmyard manure (FYM) along with NPK resulted in significant improvement in SOC as well as crop productivity. The improvement in SOC and crop productivity is mainly attributed to the greater input of carbon in the form of belowground biomass and external carbon input. Here, nutrient supply was far greater than the demand, which is important for improving net primary productivity and maintenance of SOC at desirable state. Hence, it could be concluded that balanced fertilization and integrated nutrient management practices are an important strategy for minimizing CO_2 concentration in atmosphere by stabilizing carbon in soil.

It is also evident that alternate strategies like agri-silviculture, agri-horticulture, and afforestation of degraded and wasteland were found to be more efficient for SOC stabilization in comparison to sole cropping. These systems were found very effective not only for improvement in SOC content but also for reducing soil loss (Lal 2008). Agronomic practices like conservation agriculture, residue incorporation, and organic farming and INM approach were found beneficial for restoration of soil carbon as well as reduction in soil loss.

11 Future Strategies on Soil Carbon Storage

Each soil has an upper limit of soil carbon stabilization. This upper limit of carbon is referred as soil carbon saturation or the protective capacity of soil. The difference of stabilization deficit may be used as a priority tool for land-use evaluation for soil carbon sequestration. It is generally observed that carbon stabilization would be greater in samples with larger saturation deficit and soil carbon sequestration rate decreased as the soil carbon content increased. Therefore, the planners, policy makers, and administrators should take into account the current status of soil carbon in stabilized pool and the capacity of soils to stabilize carbon. It is well proved that once a soil attains its upper limit of carbon, then chances in improvement in soil carbon would be meager with addition carbon input. Stabilization of decomposable SOC can be obtained by complexation to mineral and organic soil surfaces, entrapment within soil aggregates, and accrual to soil pores inaccessible to decomposers and extracellular enzymes. Soil structure is one of the most important factors that control and indicate the SOC sequestration in soil. Modification in soil physico-chemical environment for proliferation of fungi is another viable strategy for soil carbon stabilization. Some of the best management practices include changing the quality of plant C inputs, long duration crop species, no-till system, neutral soil pH and good amounts of exchangeable base cations (particularly calcium), proper drainage, and erosion control.

12 Conclusions

Carbon level in soil is the result of interaction of several ecosystem variables, of which photosynthesis, respiration, and decomposition are most important. Soil temperature and soil moisture are the key factors which affect ecosystem variables. Anthropogenic activities determine whether the soil will act as a source or sink of carbon dioxide. Loss of SOC stocks due to anthropogenic activities and land degradation has created a soil carbon deficit that provides an opportunity to store carbon in soil through several land management approaches.

- The steady state of soil carbon would only change when carbon input from photosynthesis will be more than the soil carbon losses (respiration). In majority of soils of India, the carbon content is in steady-state condition due to long-term practice of repetitive management interventions.
- India should develop time-bound strategy for improving carbon storage in agricultural soils taking into account antecedent/existing soil carbon content, soil texture, and climate (rainfall and temperature) of the region.
- The next step is to define or compute the attainable carbon content of soils of different region utilizing the knowledge gained from long-term fertilizer experiments running across different agroecological regions of the country. For example, attainable carbon content of coarse texture soils of Punjab should be kept not more than 0.50–0.75% (oxidizable carbon concentration) because of soil and climatic limitations, whereas fine-textured soils of central India can have carbon concentration to the extent of 1.2–1.5% owing to high clay and moderate rainfall conditions.
- Subsequently, attainable deficit of soil carbon stock of different agricultural soils should be mapped, and priority intervention should be given to those soils which are having higher carbon deficit.
- Based upon the attainable carbon deficit map of country, management interventions (balanced fertilization, INM, conservation agriculture, residue incorporation, crop rotations, biochar application) should be formulated to attain the desired goal under the given time frame.
- Well-calibrated carbon models (RothC, APSIM, Century) may be used to know the exact time frame for attaining the desired carbon stocks.
- Effort should be made to offset the process of land degradation by changing the land-use pattern from agriculture to agri-silviculture.
- Next step is regular monitoring of soil carbon stock using state-of-the-art technology for precise determination of changes in soil carbon stock.
- Exploring new methods to accelerate market development for carbon farming.

- Policy and procedure should be framed for auditable and verifiable accounts of the baseline conditions and the additional benefits from adopting best management practices.

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Soil Organic Carbon Sequestration in Rice-Based Cropping Systems: Estimation, Accounting and Valuation

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Abstract

Crop management practices largely govern the complex process of carbon (C) sequestration in agricultural soils. In rice-based systems, small alterations in cultivation practices can lead to increased soil organic carbon (SOC) contents in soil and reduced GHG emissions, thereby complementing the C sequestration. Due to enormous complexity of C sequestration process, monitoring soil C changes could be costly and extremely variable in C stocks on micro- and macro-scales. To assess the soil C change, the factors driving the driving soil C dynamics are accounted, and models are developed. However, it is worth notable that these modelling and measurement efforts are relatively new considering the history of C dynamics. It will be challenging to settle on annual-to-decadal target rates for rebuilding soil C based on the available modelling and measurement tools. Overall, change in soil C fraction is reported in many studies with choice of agronomic management practices in rice-based cropping systems. The combined application of inorganic fertilizers and organic manures seems to be the best option to increase rice yields while improving soil C accumulation. An attempt has been made in this chapter to compile and analyse all the available information

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related to the soil C sequestration potential of rice-based cropping system, particularly rice-wheat and rice-rice cropping system, in addition to the mechanism, measurement and valuation of C.

Keywords

Soil organic carbon · Agronomic management practices · Rice-based cropping system · Carbon sequestration measurement

Abbreviations

BD	Bulk density
C	Carbon
CDM	Clean Development Mechanism
SOC	Soil organic carbon

1 Introduction

Soil is the greatest carbon (C) reservoir, accounting for more than 80% of total C in the terrestrial biosphere. The transfer of C from the soil to the atmosphere is a continual process that is heavily impacted by various factors. Soil organic carbon (SOC) sequestration invariably refers to the process of restoration of SOC pool, through conversion of atmospheric CO_2 through the process of photosynthesis and humification. It can be increased by enhancing the soil C stocks through sustainable land management. Some of the agronomic management practices, viz. diversifying the cropping system by crop rotations, choice of crop establishment method, fallow period management, fertilizer and water management, have the potential to either reduce or increase soil C stocks (Baker et al. 2007). Increased C losses would arise if stored C is released into the atmosphere due to temperature-induced breakdown (Bradford et al. 2016). A reduced C loss is induced by a relative increase in the amount of contributed and/or plant-derived C over decomposition (Kallenbach et al. 2016; Paustian et al. 2016). The response is based on two factors: breakdown and soil C addition. Increasing the soil C stock has many advantages which are strongly tied to soil nutrient status, soil fertility, soil aeration, etc. In tropical soil, temperature-induced breakdown leads to decline in SOC levels; however, complete exhaustion of SOC in soil is not possible in nature. In general, a steady state is maintained in the SOC levels of cultivated soils which is referred to as a lower equilibrium limit (Buyanovsky et al. 1998). In an erosion-free environment, the fluctuation in SOC level depends on the management practice. Crop cultivation leads to SOC stabilization at the lower equilibrium level, but addition of organic inputs in addition to fertilizer applications tend to shift the equilibrium towards the upper limit (Nayak et al. 2012a). Extensive adoption of improved crop management practices is recommended with an aim to maintain or increase SOC levels, thereby improving soil fertility and mitigating climate change (Lessmann et al. 2021). The most recent scientific discussions accept that timely intervention is needed to rebuild SOC for sustainability.

Rice is staple in South and East Asian countries, and it also represents a fairly large fraction of global agriculture. It is established that transplanted rice have higher soil organic C storage. Organic C accumulation is faster owing to slower organic matter decomposition in low and shallow lowlands due to anaerobic/reduced condition created by flooding (Watanabe 1984). Microbial activity is slowed down under flooded conditions resulting in declined decomposition rate. However, the potential of C sequestration in rice-based cropping systems is not well recognized. In rice-based systems small interventions in cultivation practices could result in substantially modified SOC contents (Zhu et al. 2014). Heavy tillage operations and intensive agriculture with flawed nutrient management in rice ecosystems are mainly responsible for depletion of SOC pools. Ratnayake et al. (2017) reported significant reduction or no increase in the soil C stocks in rice-based cropping systems. Alternatively, Nayak et al. (2012b) reported potential of C sequestration in rice-based cropping system with appropriate residue retention and nutrient management.

In this chapter, an attempt has been made to compile and analyse all the available information related to the soil C sequestration potential of rice-based cropping system, particularly rice-wheat and rice-rice cropping system, in addition to the mechanism, estimation and valuation of C.

2 Potential of C Sequestration and Emission Reduction in Rice Soils

C sequestration potential varies from region to region even under the same type of management, due to difference in climate, soils, cropping systems and available technologies. Extensive efforts have been made to identify the agronomic management practices for soil C sequestration and emission reduction in rice soils. Table 1 lists several agricultural management practices and their role in either increasing C inputs to soils or reducing C losses from soils.

Long-term studies (Table 2) have shown that agricultural practices involving improved fertilizer management, application of manures, crop residue retention, crop diversification, green and brown manuring, optimum tillage, rationalized irrigation and agro-waste recycling enhance C storage. These agricultural practices are highly sustainable and help in mitigating climate change through C sequestration on one hand and reduction of GHGs emissions on the other.

It has been pointed out that a combination these practices may be required to effectively sequester C rather than depending on one particular practice. Higher C input through cropping system and soil management practices is likely to maintain the higher SOC level in soil (Mandal et al. 2007). For the past 15 years, calculated potential of SOC sequestration under different ecoregions in different cropping systems with diverse soil management options has been reported in India and abroad

Table 1 Agricultural management practices that can increase organic carbon storage and promote a net removal of CO_2 from the atmosphere

Management practice	Increased C inputs	Reduced C losses
Improved crop rotations and increased crop residues	√	
Cover crops and green manuring	√	
Manure and compost addition	√	
Improved grazing land management	√	
Improved crop rotation with legumes	√	√
Addition of biochar to croplands	√	√
No tillage and other conservation tillage		√
Rewetting peat and muck soils (organic soils)		√
Balanced fertilization		√

Modified: Paustian (2014)

Table 2 Agricultural practices for soil carbon sequestration in rice-based cropping systems reported in India

Technology	Cropping system	Region	References
Green manuring	Rice-wheat	North-west India	Aulakh et al. (2001)
	Rice-wheat	North and Eastern India	Nayak et al. (2012b)
	Rice-rice	Tropical India	Singh et al. (1991)
	Rice-rice	Tropical India	Kumar and Goh (1999)
Mulch farming/conservation tillage	Rice-wheat	North-west India	Aulakh et al. (2001)
INM	Rice-rice	Northern India	Dinesh et al. (1998)
	Rice-wheat	North-west India	Yadav et al. (2000a)
	Rice-wheat	Northern India	Singh and Dwivedi (1996)
Residue incorporation in rice with barley straw	Rice-barley	Tropical dryland	Kushwaha et al. (2001)
Residue incorporation in rice with wheat straw	Rice-wheat	North and Eastern India	Nayak et al. (2012b)
Restoration of sodic land	Rice-wheat	Central India	Nayak et al. (2008)
Addition of FYM	Rice-rice	Eastern India	Mohanty et al. (2013)
	Rice-rice	Eastern India	Shahid et al. (2017)
	Rice-wheat	North and Eastern India	Nayak et al. (2012b)

(Table 3). Globally, 40 to 80 billion tonnes of C is estimated to be sequestered in agricultural soils over a period of 100 years (Cole et al. 1997) with appropriate management practices. In India, the total potential of C sequestration is 12.7 Tg C year^{-1} to 16.5 Tg C year^{-1} which includes about 8.5 Tg C year^{-1} from restored soils

Table 3 Effects of agronomic management techniques on percent increase in SOC content over RMP

Agronomic management	Cropping system	Average increase in SOC content over control (%)	Place	References
Residue incorporation	Rice-rice	10	Iksan City, South Korea	Ku et al. (2019)
	Rice-wheat	20	Ludhiana, India	Singh et al. (1994)
		18	Kanpur, India	Tiwari et al. (1998)
		34	Sabour, India	Yadav et al. (2000a); Singh et al. (2019)
		14	Kalyani, India	Majumder et al. (2008)
Manure application to both the rice crops	Rice-rice-fallow	28	Dhaka, Bangladesh	Naher et al. (2020)
Green manure incorporation before rice planting	Rice-wheat	16	Ludhiana, India	Singh et al. (1994)
		11	Kanpur, India	Yadav et al. (2000b)
		32	Sabour, India	Yadav et al. (2000a), Singh et al. (2019)
FYM addition to both the rice crops	Rice-rice	80	Assam, India	Gogoi et al. (2021)
		18	Cuttack, India	Mohanty et al. (2013)
		11	Cuttack, India	Shahid et al. (2017)
	Rice-wheat	14	Kalyani, India	Majumder et al. (2008)
		33	Ludhiana, India	Singh et al. (1994)
		15	Kanpur, India	Tiwari et al. (1998)
		38	Sabour, India	Yadav et al. 2000b
Biochar addition to both the rice crops	Rice-rice	169	Cuttack, India	Munda et al. (2018)
Plastic mulching in ridge and furrow system of planting in rice	Rice-fallow	86	Sichuan Province, China	Zhang et al. (2013)
Double zero tillage, i.e. zero-tillage DSR followed by zero-tillage wheat	Rice-wheat	23	Chitwan, Nepal	Paudel et al. (2014)

and 6 Tg C year^{-1} to 7 Tg C year^{-1} from advanced agronomic management practices (Lal 2004).

2.1 Potential of SOC Sequestration in Rice-Rice Cropping System

Stagnation in rice productivity in rice-rice cropping systems has been an outcome of extensive use of inorganic fertilizers. Moreover, the rice-rice system has become associated with reduced fertility and overall decline in soil health. In fact, reports from long-term fertilizer experiments throughout the world suggest deterioration in physical, chemical and biological soil attributes for crop production with continuous application of inorganic fertilizer in rice-rice system (Basak et al. 2016). Globally, cultivation of double rice over the years have led to the destruction of soil structure, as a result of which stability of soil aggregates have been disturbed and the C content of soils have declined. Relatively lower magnitude of depletions in SOC is reported in areas with continuous submergence (8–9 months in a year) of soils under rice-rice system. Higher SOC concentration in lowland rice soils is generally observed compared to upland soil. Swarup (1998) reported substantial increase of about 60% in SOC concentration over a period of 20 years with INM in rice-rice cropping system. Possible explanation for lower SOC depletion may be lower inherent C concentration in the studied soil.

Studies suggest that sole application of FYM and combination with FYM and 100% NPK both increased C content in soils significantly. This can be explained in relation to increased biomass of crops (root biomass and root exudates) with complementary and sometimes additive effect of organic and inorganic fertilizers. An increase in SOC stock was reported by Majumder et al. (2008) and Chaudhary et al. (2017) and attributed it to the combined application of fertilizers and FYM. Similarly, Srinivasarao et al. (2012) reported increased SOC stock with sole application of FYM. At a long-term study at Cuttack, India, SOC concentration and stocks had increased substantially with combined application of chemical fertilizers and manure as compared to untreated control in rice-rice cropping system (Shahid et al. 2017; Mohanty et al. 2013). The SOC stock of surface soil increased in all treatments as compared to the initial value recorded 41 years ago. The differences in the SOC stock were non-significant in the greater depths of soil profile. It was also established from the study that crop residue in the form of rice roots and stubbles is sufficient to counter the C loss through decomposition of organic matter. C sequestration potential can further be improved with combined application of chemical fertilizers and manure.

2.2 Potential of SOC Sequestration in Rice–Wheat Cropping System

A perceived threat to rice-wheat cropping system is the reduction in SOC stock and the associated reduction in nutrient supplying capacity of soil. Long-term studies in

India showed a decline in SOC content in treatments without addition of organic input (Ladha et al. 2003). From the same studies, it is reported that applications of FYM before rice in a rice wheat rotation resulted in SOC build-up and higher grain production. Rice crop residues (agro-wastes) are burnt on field in huge quantities particularly in North-west India. The burnt agro-wastes (19.6 million tonnes of straw of rice and wheat) in India are equivalent to 3.85 million tonnes of SOC, 59,000 tonnes of nitrogen, 2000 tonnes of phosphorous and 34,000 tonnes of potassium. The agro-wastes could be one of the alternatives to improve the SOC stocks in addition to supplementation of plant nutrients. The combined use of organic input (residue from rice or wheat) and inorganic fertilizer in rice-wheat systems may work complementarily and increase the crop yield and SOC build-up.

Studies in Indo-Gangetic Plains (IGP) suggest that the application of chemical fertilizers over a period of 23–26 years in cereal-cereal (rice-wheat) cropping systems has positively influenced the SOC of surface soil. However, a decrease of 2 and 35% of SOC concentration was reported with no fertilizer application in middle and lower IGP, respectively, whereas at trans- and upper IGP, it has more or less maintained the SOC level (Nayak et al. 2012b). Because of low SOC concentration initially, trans- and upper IGP could maintain their SOC level with no fertilizer application despite a declining yield trend. The higher stubble and root biomass in response to fertilizer application in turn results in higher yield. The SOC increased in surface soil along the IGP except at lower IGP where initial SOC value was comparatively higher than others. Most of the reports from long-term experiments suggested that optimum application of inorganic fertilizers helped in increasing SOC stocks (Purakayastha et al. 2008) or maintaining the SOIC stocks (Biswas and Benbi 1997). Brar et al. (2013) even reported C sequestration in rice-wheat system without any external organic input. Some other reports suggest that substitution of part of fertilizers through FYM or crop residue or green manure has also enhanced the SOC considerably. The combination of organic and inorganic sources improves the organic C content of soil over that achieved with fertilizers alone, due to the additive effect of organic and inorganic sources and their interaction thereof (Nayak et al. 2012a). Similarly, SOC build-up in response to cropping system management, addition of manures with chemical fertilizers and incorporation of paddy stubbles and green manures have been widely reported from long-term studies (Yadav et al. 2000b).

In many of long-term experiments on rice-wheat system conducted in diverse agro-climatic zones of India, application of 50% of N through FYM along with 50% recommended dose of NPK in rice and application of 100% recommended dose of NPK in wheat-sequestered 0.39, 0.50, 0.51 and 0.62 Mg C ha^{-1} $year^{-1}$ over untreated plots, respectively, at Ludhiana (Trans-Gangetic Plains), Kanpur (Upper Gangetic Plains), Sabour (Middle Gangetic Plains) and Kalyani (Lower Gangetic Plains), (Table 3). In China, Hao et al. (2008) reported that combined input of chemical fertilizers and manures sequestered C in soils. Nayak et al. (2012b) reported a very wide range of C sequestration (0.08 to 0.98 t ha^{-1} $year^{-1}$) in IGP with different organic inputs (FYM, crop residue, green manure) along with NPK in rice-wheat system, which are similar reports from other studies (Causarano et al.

2008; Kundu et al. 2007). A C stock budgeting was reported by Bronson et al. (1998) from different agroecosystems of Asia. It was reported that increase in C stock in soil is possible even in tropical lowlands, even though very high temperatures prevail in tropical region round the year. They opined that C mineralization was relatively slow due to anaerobiosis. Addition of large quantities of organic C from photosynthetic algal communities in the rice-based ecosystems is also responsible for slow mineralization of C. Similarly, it was also observed that clayey soils have more potential to sequester C than sandy and silty soils in the lowland tropics, due to mineral coating on SOC giving a physical protection (Matus et al. 2008). It also explains the reason for higher SOC sequestration rate at lower IGP which is characterized by higher soil clay content.

Overall, the SOC enrichment (C sequestration) in soil with organic input is largely established; however, the extent of SOC enrichment is dependent on many other factors such as cropping systems and choice of crop management practices.

3 Estimation of SOC Sequestration

The variations in the SOC sequestration arise even under same management practices because of various factors, viz. soil and climate type, cropping system, etc. Under such scenario, estimations of soil C sequestration are being made using measurement and monitoring technologies, to remunerate the C sequestration achieved, through so-called moving baselines. Various analytical tools to assess C sequestration/storage have been developed and available in the existing literature (Paustian et al. 2019; Falloon and Smith 2000; Gulde et al. 2008; van Wesemael et al. 2019; Wiesmeier et al. 2019). The measurement standards and procedures for soil C sequestration are still evolving. Rapid and cost-effective measurements of soil C concentration on a large scale, i.e. at the landscape and regional level, and on a vertical scale at profile level are being tested for making recommendations (Lobsey and Viscarra 2016; Ramifehiarivo et al. 2017). New technologies like eddy covariance flux towers are being used to estimate C sequestration at the ecosystem level (Nayak et al. 2019). For accurate estimation of SOC, some of the pre-estimation parameters need to be considered along with the suitable methods of SOC estimation.

3.1 Critical Pre-estimation Parameters for Accurate Assessment of SOC

Establishing the Baseline

As mentioned earlier in the chapter, the SOC sequestration varies with choice of management practice in a particular agricultural system, and it is influenced by soil type and climatic factors. Many of the earlier researchers have calculated and reported C sequestration on the basis of difference in SOC in the treated plot and non-treated plot while considering the non-treated as the baseline without considering the SOC stock before treatment implementation (Shahid et al. 2017). Some researchers believe that this may give erroneous information (Nayak et al. 2019) because both the treated as well as non-treated plots are losing SOC, though at a different rate. Hence, initial SOC level must be taken into account before imposing the treatment so that a boundary line is fixed to correctly assess the SOC change, be it steady state, retention, loss or gain of SOC (Olson 2013).

Fixing a Timeline

Fixing a timeline is necessary for measuring the SOC sequestration as SOC changes take place very slowly which support a higher inconsistency at spatial scale and inconsistently lower instance of variability at a temporal scale. Detecting the SOC in terms of absolute quantity compared to real initial value is difficult. Sometimes, it is argued that less than 20 years is a very short time to establish equilibrium in SOC in soil with high clay content. Similarly, in soils exposed to convention management practices, loss of SOC continues for 50–100 years (Sanderman and Baldock 2010). Therefore, Kumar et al. (2012) suggested that spatial variability and rate of SOC change are the key factors for correct assessment of SOC sequestration. In light of the above discussion, long-term field experiments lasting many years or decades are recommended for assessing SOC sequestration within various agroecosystems and crop management options.

Determination of the Frequency of Measurement

Soil C stocks are relatively stable in undisturbed soil; nevertheless, any disturbance to topsoil causes SOC stocks to be lost. SOC is lost when grasslands and forests are converted to other uses that involve soil disturbance. Apart from land-use change, management methods, particularly in cropping systems and grasslands, can have a considerable impact on SOC stocks. The frequency with which soil C stocks are measured varies, depending on the land use and soil management system in practice. The frequency has implications for the method used to prepare a C inventory as well as expenses and can range from once a year for land-use change operations to once every 5 years for long-term projects.

Sampling Method

The method for sample collection should be based on the objective (i.e. short- or long-term storage change). Several methods are being used traditionally, viz. digging open pits, core sampling with a punch core, core drill method, etc. However, sampling method should be chosen on the basis of objective of the study. For example, augers should be used to take undisturbed cores, however, in a soil with coarse roots, auger sampling should be replaced with rotary core device (Rau et al. 2011). Comparison studies are suggested to make a reasonable decision on choice of sampling. Methodologies that combine soil pit and auger sampling techniques under different soil, topography and cropping system should be tested and compared for more comprehensive information related to choice of sampling method.

Bulk Density Corrections

The calculation of SOC stock at a given depth is done with the help of SOC concentration, bulk density (BD) and soil depth. Any error in the measurement of BD across the depth of sampling in treated and non-treated plots would magnify the bias and may result in complete wrong information on SOC stock. So, in order to reduce the error, corrections in the BD should be made before calculation of SOC concentration.

3.2 Measurement Techniques

There are numerous methods for estimating SOC, ranging from simple laboratory techniques to a more complicated diffuse reflectance spectroscopy. The examples are (1) Walkley and Black method or wet digestion or titrimetric determination, (2) colorimetry, (3) direct estimation of organic matter by loss-on-ignition, (4) CHN analyser, (5) diffuse reflectance spectroscopy and (6) modelling.

Wet digestion or titrimetric determination is the most popular approach utilized in the field, and it is also a cost-effective procedure. Despite its high accuracy, the C, hydrogen and nitrogen (CHN) analyser is rarely utilized in field investigations due to its high cost. Diffused reflectance spectroscopy is also costly, and it has yet to be widely adopted in the field. The availability of models and data to represent local situations limits modelling. The remote sensing method can only be utilized for large projects, and it still requires modelling and validation using data from other sources. It is necessary to enhance the accuracy and affordability of soil C collection and measuring methodology in order to monitor C changes in the soil and biotic pool. SOC stocks are calculated using two variables: SOC concentration and bulk density.

Wet oxidation Walkley and Black (1934) or dry combustion is the most used method for determining SOC concentration (Wang and Anderson 1998). The amount of organic C in most samples is known to be underestimated by the wet oxidation method; hence a correction factor must be applied. The adjustment factor's magnitude is known to vary by soil type. Despite the availability of more reliable procedures, the Walkley-Black method is still employed in some laboratories, particularly in India. Over the last 10 years, significant work has been made in refining, improving, and adapting the approach for measuring and monitoring soil C sequestration at field and regional scales. It is currently possible to monitor changes in soil C as tiny as 1 Mg C ha^{-1} or estimate them using simple or elaborate simulation models (Paustian et al. 1997; Smith et al. 2007). More accurate measurements will be more widely accepted if measurement errors are addressed and the measurement procedure is unbiased. When monitoring C sink operations, "uncertainties, transparency in reporting, and verifiability" should all be taken into account, according to Article 3.4 of the Kyoto Protocol (Smith 2004). In situ measurements can be done using laser-induced breakdown spectroscopy (Cremers et al. 2001), inelastic neutron scattering (Wielopolski et al. 2000) and diffuse reflectance IR spectroscopy (Christy et al. 2006).

On some dynamic and geographically relevant basis, measurement and monitoring procedures employing current or new methodologies must be integrated to field-level and regional scales using computer simulation and remote sensing (Paustian et al. 1997; Smith et al. 2007). When monitoring C sink for trading purposes, uncertainty in measurement, transparency in reporting and verifiability should be taken into account. Due to various pools and tiny incremental changes expected, monitoring soil C changes at the project level could be costly and extremely variable in C stocks on micro- and macroscales. SOC change could be estimated in one of three ways: (1) using SOC stock change values for specific practices reported in the literature based on research studies, (2) using process-based models of SOC dynamics, parameterized from experimental data and (3) using a combination of baseline measurements to assess the vulnerability of SOC pools and modelling informed by baseline measurements and understanding of the factors driving soil C dynamics. It is worth notable that these modelling and measurement efforts are relatively new considering the history of C dynamics. It will be challenging to settle on annual-to-decadal target rates for rebuilding SOC based on the available modelling and measurement tools.

4 Policy for Protection of SOC Sequestration

4.1 Economic and Political Will for SOC Sequestration

In the developing countries, the policymakers are not forthcoming to incentivize C sequestration measures because of permanence issues of SOC stocks, difficulty in quantifying contribution of C sequestration towards yield increase and other co-benefits. In the developing countries, the need for yield increase is prioritized over soil C sequestration. It is agreed that the most effective way to accumulate SOC is to increase C inputs, which implies that high organic C levels can be maintained with improved management and C input, irrespective of climate, soil type and cropping system. However, it is still difficult to quantify the contribution sequestered C towards improvement in crop yields, which makes it difficult to convince the policymakers for incentivizing the technologies related to enhancement of C sequestration. It is even more tedious to quantify the value of co benefits, viz. improvement in soil biodiversity, reduction in pollution, erosion reduction or other societal benefits. These co-benefits also vary spatially and temporally. Presently, SOC is not taken into account in market-based policy, primarily for two reasons: (1) expenses for ecosystem services (ES), as ES are difficult to measure and till now not standardized, and (2) the priority of farmers is higher crop production and not the C sequestration. Thus, new incentives for farmers to sequester extra SOC are required. Amelung et al. (2020) proposed establishment of seven-point soil information system for proper implementation of C sequestration policies:

1. Soil information systems for many parts of the world, including yield gap analyses and soil deterioration status.

2. Realistic forecasts of local and regional yield growth per tonne of sequestered C.
3. Requirement of additional fertilizer for long-term C sequestration.
4. Accounting for greenhouse gas emissions throughout the life cycle of C sequestering farming systems.
5. Regional and national maps showing soil C sequestration potential.
6. Accounting for organic material shift that may minimize stored C elsewhere.
7. Farmers' incentives, social standards and initiatives to scale up adoption of C sequestering practices.

Policies should evaluate both direct and indirect advantages, as well as local skills for long-term site-specific soil management. These activities are expected to be more effective throughout the world, tackling the common job of SOC sequestration on a scale and at a level that is appropriate for the difficult problem of land management.

Clean Development Mechanism

The unwise exploitation of soil organic matter can be devastating if not conserved and protected. It is the need of the hour to make regulation policies for conservation and protection of soil organic matter/SOC. Proper valuation should be done for protection of SOC as commodity, so that SOC can be traded like any other agricultural commodity. Valuation in terms of C credits is one such international attempt to sequester C and arrest the growth of GHGs emissions.

The Clean Development Mechanism (CDM) is one of the Kyoto Protocol's Flexible Mechanisms, as stated in Article 12. The rationale of the CDM is to promote cleaner environment by implantation of energy efficient projects which help in reduction in emission. The CDM is one of the Protocol's "project-based" mechanisms, in which commodities and services are created and catered with reduced emissions. The CDM is sometimes referred to as production-based mechanism as the CDM project produces an emission cut and it is subtracted against a hypothetical baseline of emissions. The baseline emissions are the hypothetical emissions that are predicted to occur in under conventional production system without CDM intervention.

The logic behind the implementation of these projects in developing countries only is mainly the substantially lesser expenditure incurred on emissions cut compared to developed countries. Such as, according to Sathaye et al. (2001), environmental regulation in developing countries is often lower than in developed countries. As a result, it is often assumed that developing nations have more capacity to cut their emissions than industrialized countries. The CDM was intended to meet two objectives:

1. To help non-Annex I parties (the developed nations) in contributing to the UNFCCC's ultimate goal.
2. To help Annex I countries in meeting their quantifiable emission restriction and reduction obligations (GHG emission ceilings).

Article 3.4 of Kyoto Protocol recognizes agricultural land as a potential C source that should be included in the UNFCCC Parties' regular emission inventories. The Protocol, on the other hand, makes no provision for national credits for C sequestration in agricultural soils. Afforestation and reforestation projects will be eligible for CDM credits throughout the Kyoto Protocol's first 5-year commitment period (2008–2012). Other sink activities will be ineligible, such as forest protection and soil C sequestration. Nonetheless, soil C sequestration may be eligible for CDM credits in future commitment periods (Gupta and Ringius 2001).

Baseline, Permanence and Leakage Related to CDM

In the absence of the CDM project, one of the major criteria is to create a baseline, which includes C emission by sources or decrease by sinks. The baseline might be the most expected land usage at the start of the project. The amount of sequestration that happens as a result of project execution above and beyond the estimated sequestration that would occur if the project was not completed is referred to as additionally.

It is generally suggested that over a period of time, schemes for soil C reaccumulation would be needed. This again raises the question of whether C stocks can actually be permanent. It is well understood that below-ground C is relatively more protected than above-ground C, i.e. plant biomass. So, forests might be felled at a later point to add to the below-ground C; however, agriculture is unlikely to be converted back to forests in emerging nations like India. Neither is it likely that farmers who benefit economically from conservation agriculture will go back to conventional agriculture. Therefore, question of permanence of soil C sequestration remains unanswered.

By minimizing leakage issues, some forms of contracts can assist to limit the probability of C sequestration reversal (Marland et al. 2001; Ellis 2001). The word "leakage" describes a situation in which a project accidentally moves an unwanted activity from one location to another, such as a forest conservation project that reduces deforestation inside the project area but promotes deforestation elsewhere. However, because soil C sequestration techniques are often more desirable than other land-use systems, they are less likely to have leakage consequences.

4.2 Costs and Valuation of C

Tonne of C dioxide equivalent, or $tCO2^e$, is used to calculate and express C trading. The intricacies of the method for determining costs and valuation are still being negotiated many years after the Kyoto Protocol was signed. In general, the polluting entity must pay for inputs that are directly related to pollution, such as gasoline costs. There are arguments in favour of accounting for all social costs (human health impacts from global warming), which will not only account for all expenses but also affect the polluting entity's decisions and actions. To assess the societal cost, value assessments on the significance of future climate impacts are required (Smith et al. 2001). Because not all commodities and services have a market price, valuations can be challenging. Inferring pricing for "non-market" products and services is possible. These appraisals, for example, of human health impacts or ecosystem impacts, are still being developed (Smith et al. 2001). There is an increasing recognition that possible good effects of climate change in some areas, such as tourism, do not compensate for negative effects in other areas, such as lower food production (Smith et al. 2001). The fundamental benefit of economic analysis in this field is that it enables for a thorough and uniform treatment of climate change implications. It also allows for a comparison of the advantages of climate change policy decisions to other feasible environmental policies. One C credit is equal to one tonne of CO_2, or CO_2 equivalent gases in some markets. CERs are a form of emissions unit (or C credit) awarded by the CDM Executive Board for emission reductions. Under the Kyoto Protocol, greenhouse gas accounting for soil C in agriculture is based on the rate of change in C stock. As a result, credit can be gained if the old approach produces a drop and the new activity minimizes the rate of loss.

4.3 Challenges Associated with Valuation of C

The Kyoto Protocol does not include provisions for national crediting for C sequestration in agricultural soils. However, many countries and multinational companies have made investment in C sequestration projects in agricultural soil outside Kyoto Protocol. This necessitates a strong corporate social responsibility and also legislation for fair valuation of sequestered C. Robust legislation is essential to guarantee that additionality, leakage and transaction costs are all loosened. It is anticipated that converting all croplands in the United States to conservation tillage may sequester 25 Gt C over the next 50 years. Some farmers, for example, are earning money from coal-burning fields through a C trading agreement negotiated through the Chicago Climate Exchange (Baker et al. 2007). Payments are based on the adoption of conservation tillage practices, which are estimated to sequester 0.5 t CO_2 ha^{-1} $year^{-1}$ of CO_2.

Farmers in India often have modest land holdings, making it difficult to aggregate these small land holdings (1–5 acre farm size) into a major transaction for purchasing C credits. However, reputable organizations may verify C sequestration or emission reduction activities and grant VERs (verified emission reductions), which can then be sold. As mentioned earlier in the chapter, the need for yield increase is prioritized over soil C sequestration in India, and it will be a difficult task to convince the farmers to adopt technologies for C sequestration even with higher transaction costs. Many questions must be answered before soil C trading becomes a reality in agriculture, including whether agricultural soils will be approved as a means of meeting GHG emission commitments, whether incentives can be designed to avoid countervailing C losses and how emissions reduction targets will be integrated into farmers' activities at the grass-root level.

5 Conclusion

In order to understand the method, estimate and valuation of C, as well as the soil C sequestration capacity of rice-based cropping systems, namely, rice-wheat and rice-rice cropping systems, it has been attempted to consolidate and evaluate all the material currently accessible. Likewise, to understand the method, estimate and valuation of C, as well as the soil C sequestration capacity of rice-based cropping systems, namely, rice-wheat and rice-rice cropping systems, it has been attempted to consolidate and evaluate all the material currently accessible.

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CO_2 Capture, Storage, and Environmental Sustainability: Plan, Policy, and Challenges

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Abstract

Environmental management and its sustainability are a key concern today. Anthropogenic CO_2 emission and its related negative consequences on environment were observed due to industrial development, mining, deforestation, and intensive agricultural practices. This unstoppable rising CO_2 concentration impairs key environmental services and its sustainability. Recently, NOAA-based Mauna Loa Atmospheric Baseline Observatory has reported CO_2 concentration of about 419 ppm in 2021 along with 40 billion MT of CO_2 pollution every year in the environment. This figures enough to represent unstoppable CO_2 emissions which need global concern urgently. GHGs including CO_2 emissions raised global temperature are under the discussion table of IPCC and at global policy platforms during Paris Agreement and COP-21. However, many countries

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have participated in Paris Agreement and COP-21 for reducing emissions and set a target to reduce 2 °C global temperature identified by IPCC. Similarly, the target of zero emission is also discussed in several climate policy papers including IPCC and during Paris Agreement and COP-21. Introducing recent and updated climate-resilient technologies, viz. carbon dioxide capture, and storage (CCS), reduces excessive emission and performs C sequestration and storage for long term in various environmental components such as lithosphere (soil/geology), hydrosphere (ocean), and biosphere. Similarly, forest-based CO_2 removal (CDR) policy emphasized sustainable forest management (SFM) practices for greater CO_2 sink and storage in terrestrial forest ecosystem. Monitoring CO_2 concentration in environment through remote sensing is an effective tool that helps to assess CO_2 sequestration at global level. An effective policy, research, and favorable political situation are needed for greater potential of CO_2 removal and storage into the vegetation, ocean, and underground geological formation. Thus, a hawk eye remains constant on rising CO_2 in atmosphere and its sequestration through better research technologies for sustainable environment which becomes global agenda for climate policy makers.

Keywords

CO_2 sequestration · CCS · Environmental management · Sustainability · Climate policy

Abbreviations

C	Carbon
CCS	Carbon capture and storage
CDR	CO_2 removal
CH_4	Methane
CO_2	Carbon dioxide
FLR	Forest Landscape Restoration FLR
GHGs	Greenhouse gases
Gt	Giga tons
IPCC	Intergovernmental Panel on Climate Change
PPM	Parts per million
SFM	Sustainable forest management
T	Ton
UNEP	United Nations Environment Programme

1 Introduction

Anthropogenic activities including developmental projects, mining, deforestation, intensive agricultural practices, and unsustainable land-use systems have promoted continuous global emission of CO_2 into the environment (Meena et al. 2022; Roy et al. 2022; Thakrey et al. 2022). Today, energy demand has increased due to speedy economic growth. A continuous energy demand has exerted pressures for using oil, coal, and natural gas-based fossil fuels that lead to CO_2 (major potent GHG) emission into the environment. Excessive uses of fossil fuels due to industrial revolution caused degradation of environmental health and its sustainability. Carbon dioxide (CO_2) is key potent GHG (greenhouse gas) which induces global warming by heat trapping in environment. Extreme weather induces higher temperature and uncertain rainfall that greatly affect overall biodiversity and related environmental services (Anderson et al. 2016). The CO_2 emissions from power plant, chemical industries, automobiles, and other sources provoke environmental health and sustainability by global warming and climate change phenomenon (Al-Maamary et al. 2017). Similarly, other GHGs such as CH_4 (methane), nitrous oxide, hydrofluorocarbon, and sulfur hexafluoride have increased continuously that deteriorate ecosystem health and environmental sustainability (Al-Maamary et al. 2017; Ouda et al. 2016). Rising temperature-mediated global warming has resulted 6, 8, and 4% of species extinction in insects, plants, and vertebrates, respectively, which is major concern of the world (IPCC 2018). Similarly, climate change declined quality and production of poor subsistence plant communities but increased pests' outbreak (Koelbl et al. 2015).

Both ocean and terrestrial biosphere have absorbed half of this total CO_2 emission, whereas remaining CO_2 accumulates into the environment resulting into global warming and climate change phenomenon. Scientific technologies, viz., negative emission technologies and CCS (carbon capture and storage), have been allowed for reducing GHG emissions. CCS play inevitable role in climate change mitigation by capturing and storing atmospheric CO_2 into the vegetation, ocean, and underground geological formation. It employs storage and sequestration of carbon (C) into hydrosphere, lithosphere, and biosphere components of environment (Pianta et al. 2021). Further, innovative strategies that mitigate high CO_2 emission and achieve the goal of limiting warming <2 °C were discussed by Integrated Assessment Models under Paris Agreement (Edenhofer 2015; IPCC 2018). Afforestation and reforestation technologies, bioenergy with CCS, biochar application, enhanced weathering, direct air capture, and soil C sequestration-based technologies contributed 0.5–3.6, 0.5–5.0, 0.5–2.0, 2.0–4.0, 0.5–5.0, and 5.0 Gt (giga tons) CO_2/year under sustainable global net emission technology. The process of rapid decarbonization minimizes negative consequence of climate change and limits rising temperature to keep below 2 °C which is highly discussed in the Paris Agreement (IPCC 2018; Rockstrom et al. 2017). Forestry and other sustainable land-use systems have positive impacts on our environment by 11–17% decrease in CO_2 concentration. Approx. 11% of global CO_2 emission can be reduced through recovery of all forest areas; however, fossil fuel-mediated 65% of global CO_2 emissions are still major concern today (Pachauri et al. 2014). In this context, adopting scientific-based CCS technology would be helpful in combating global warming which gains global attention due to its uncountable significances including environmental management.

IPCC (Intergovernmental Panel on Climate Change) has discussed to reduce GHGs by 50–80% in the year 2050 that helps in escaping our earth from catastrophic collapse (Pachauri et al. 2014). Approx. 10 and 20 Gt CO_2 per year by the year 2050 and 2100 can be achieved through increasing CO_2 removal (CDR) from the atmosphere and its storage into the soils and biomass (United Nations Environment Programme (UNEP) 2017; National Academies of Sciences Engineering Medicine 2019). Moreover, CCS methods are viable strategies which can sequester approx. 125.0 Gt CO_2 by the year 2100 which can be utilized as fuels with lesser emissions (National Academies of Sciences Engineering Medicine 2019). Both underground CO_2 sequestration and C mineralization are key strategic solution for global warming and climate change (National Academies of Sciences Engineering Medicine 2019).

This chapter discusses CO_2 concentration, its assessment, and sequestration in environment. CO_2 sequestration in forests, soils, saline aquifers, deep ocean, and urban environment through CCS technology is comprehensively discussed. CO_2 concentration monitoring through remote sensing and several CDR policies (REDD +, Kyoto protocol, and CDM) for setting zero emission targets under IPCC and COP-21-based climate policy is reported in this paper.

2 CO_2 in Environment: Past, Present, and Future Analysis

Anthropogenic activities have released approx. 2035 ± 205 Gt CO_2 in the atmosphere from the year 1870 to 2015 (Le Quéré et al. 2015). As per Pachauri et al. (2014), the value of CO_2 has raised from 280 to 400 ppm (parts per million) along with excessive temperature due to rising temperature of 0.8 °C, respectively. This value would be 600–700 ppm during last decade of century that enhanced temperature up to 4.5–5.0 °C (Leung et al. 2014). Global atmospheric research and its emission database has reported approx. 33.40 billion t CO_2 that has been emitted globally in 2011 which is 50% more than last two decades of CO_2 emissions. Similarly, CO_2 level has increased from 280 (pre-industrial era) to 400 ppm (year 2013) with 0.8 °C of global earth temperature (IPCC 2007; NOAA 2013). Approx. 40% of global CO_2 emissions are contributed by power plants which are further expected to increase up to 60% by the end of this century (Alonso et al. 2017). 20% of global CO_2 emission was reported from transportation sectors, whereas both agriculture and building sectors have contributed 17% of the total emission (Pachauri et al. 2014). Fossil fuel burning increases approx. 10% of higher CO_2 concentration during the year 1970–2010.

3 Assessment Report on CO_2

As per IPCC (2000), CO_2 concentration will be increased from 600 to 1550 ppm which is 25 to 90% more global GHG emission by the year 2030. A total of 40.0 Gt CO_2 per year has been reported currently by IPCC (IPCC 2018). The value of CO_2 has been increased and reached up to 415 ppm as per National Oceanic and Atmospheric Administration's Mauna Loa Observatory (Keeling and Graven 2021). UNEP has predicted 3.2 °C global temperatures along with 7.60% of decreasing CO_2 leads to 1.5 °C global warming (UNEP 2019). IPCC 5 and 4 Assessment Report (AR5 and 4) has confirmed negative consequences of increasing anthropogenic GHGs on our environment and its sustainability (IPCC 2007). From 1983 to 2012 (30 years duration) was recorded the warmest years of the last 1400 years. Moreover, IPCC AR5 has given guidelines to reduce global temperature below 2 °C with reduction in global CO_2 emissions by 41.0–72.0 and 78–118% by 2050 and 2100, respectively (IPCC 2013). Similarly, participating countries have discussed about enhancing green economy for sustainable development rather than any bonded agreement for CO_2 emission control in the last COP-19 conference held in Poland, 2013. IPCC has reported various programs for GHG emission reduction through latest CCS technologies which provided important feedbacks to many researchers and policy makers in the world (IPCC 2005). However, many authors have reported different aspects of CCS technologies and its environmental impacts (Lv et al. 2012).

4 CO_2 Sequestration: Conceptual Framework

Rising CO_2 directly affects earth temperature that results into global warming and climate change phenomenon. CO_2 is key potent GHG characterized by huge volume and fast growth rate (Brierley and Kingsford 2009). The reduction in emission of anthropogenic CO_2 through C sequestration has been the key viable tool that mitigate rising global warming and climate change (IPCC 2005). Many processes such as geological (lithosphere), ocean (hydrosphere), biological (biosphere), and mineral storage of CO_2 are considered as key strategy for minimizing the negative consequences of global warming on environmental health and sustainability (Lubrano Lavadera et al. 2018). CO_2 storage/sequestration in the environment is depicted in Fig. 1 (Pianta et al. 2021; Linda and Singh 2021; Lal 2008).

CO_2 sequestration in lithosphere (as geological storage) is most prevalent practice in which CO_2 is stored as coal, gas, oil, saline aquifers, and other natural gases (Park 2005). As per Voormeij and Simandl (2004) technologically, CO_2 gas is split from offshore emitting source of flue gas which is further transported to storage site and then injected into underground reservoir as geological storage. The leakage problem is constantly observed in this entire process of storage which needs regular monitoring to avoid leakage losses (Doria 2005). Similarly, ocean storage (hydrosphere) is another important process in which CO_2 is injected into the ocean at greater depth of 1500 meter (Voormeij and Simandl 2004). Moreover, storing CO_2 in below ocean

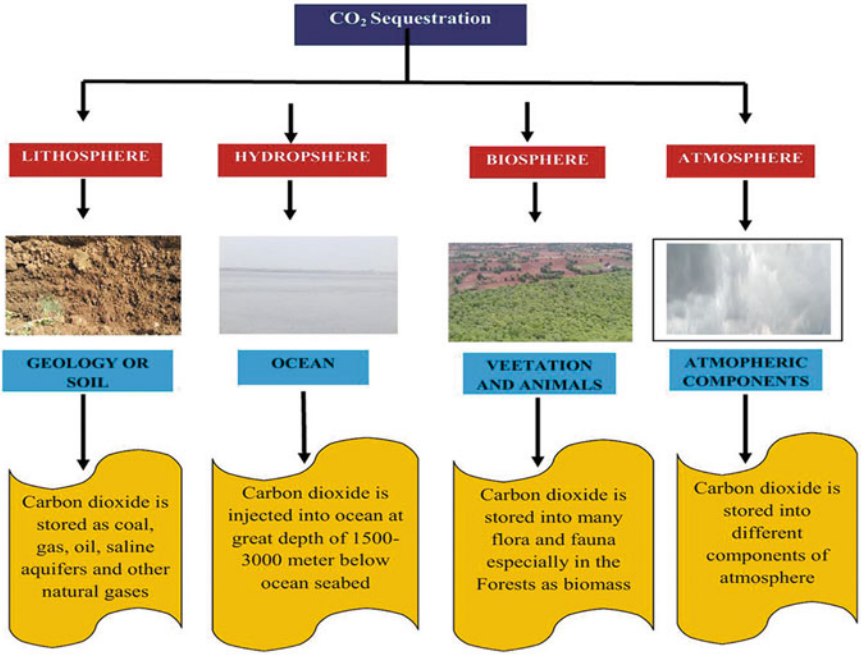

Fig. 1 CO_2 storage/sequestration in the environment (Pianta et al. 2021; Linda and Singh 2021; Lal 2008)

seabed at greater depths of 3000 meter is another form of ocean storage (Brewer et al. 2000). CO_2 becomes much denser than oceanic water at this depth which therefore does not require much care and monitoring (Voormeij and Simandl 2004). Thus, a global CO_2 sequestration projects for mitigating global warming and climate change issues is depicted in Fig. 2 (Gíslason et al. 2018; Global CCS Institute 2019; National Academies of Sciences Engineering Medicine 2019).

5 CO_2 Capture and Storage Technologies: Current Status and Overview

Increasing GHGs including CO_2 rises atmospheric temperature resulted global warming that leads to deterioration of environmental health and ecosystem processes. In this context, CCS is the key strategic solution which not only cuts CO_2 emission but also captures/sequesters atmospheric CO_2 to achieve emission reduction targets. CO_2 reduction strategies, its application area, advantages, and limitations are discussed in Table 1 (Leung et al. 2014). However, many authors have discussed about significance and processes of CCS technology which includes capture of CO_2, its separation, transportation, storage methods, leakage issue, timely monitoring, and life cycle analysis. Similarly, CCS technology is further dependent

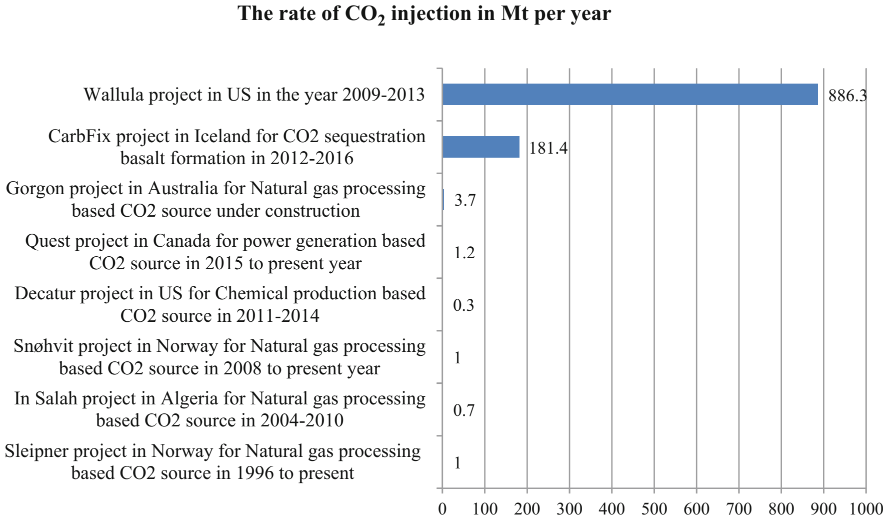

Fig. 2 CO_2 sequestration projects for mitigating global warming and climate change issues in the world (Gíslason et al. 2018; Global CCS Institute 2019; National Academies of Sciences Engineering Medicine 2019)

on plant types and fuel that generate CO_2 continuously. Absorption is important CO_2 separation process of CSS technologies which is considered most mature and regularly adopted due to lower cost and high efficiency. Pipeline is adopted for transportation of large volume of CO_2. Likewise, CO_2 storage in saline aquifers is gaining wider recognition due to its tremendous potential of storage capacity. However, a lack of capital investment and poor economic incentives are a major hurdle that affects overall CCS deployment and its processes (Leung et al. 2014). CO_2 capture technologies contribute 70–80% of the total cost employed into setup of full CCS system which includes capture, storage, and transportation of CO_2. Therefore, an effective research and development programs are needed to reduce the operating costs and energy penalty. Moreover, pre-combustion, oxyfuel combustion, and post-combustion are three key important CO_2 capture systems (Blomen et al. 2009; Leung et al. 2014). Pre-combustion is very expensive process under CCS technology but less competitive which becomes promising substitution due to greater demand for hydrogen producing technologies other than lesser availability of fossil fuels (Leung et al. 2014). Similarly, CCS becomes more productive for environmental management due to application of nanotechnology, many algae, and biochar. A high sorption potential of GHGs is observed under nanomaterials in laboratory (Alonso et al. 2017). Moreover, CO_2 can be captured by microalgae from flue gas stream which is further utilized for biofuel purposes that represent CO_2 as feedstock irrespective to pollutant (Kumar et al. 2018; Packer 2009).

Table 1 CO_2 reduction strategies, its application area, advantages, and limitations (Leung et al. 2014)

CO_2 reduction strategies	Application areas	Advantages	Limitations
Energy conservation and its efficiency enhancement	Industrial and several commercial areas are mainly uses for application of this technologies	Approx. 10–20% of energy saving is reported	Energy-saving tools needed higher capital costs for its installation and performance
Clean fuels utility enhancement	Natural gases are utilized in the substitution of coal for power generation	Coal produced highly toxic and more CO_2 than natural gas which produced 40–50% less CO_2 less C content and greater combustion capacity	Natural gases involve higher fuel cost
Clean coal technology adoption	Conventional combustion is replaced by both PFBC (pressurized fluidized bed combustor) and IGCC (integrated gasification combined cycle)	Less emission of air pollutants by coal is reported	Technology can be rolled out globally which required a significant investment
Renewable energy usage	Wind, hydro-, solar, and thermal power along with biofuels is greatly developed	Low GHG emission along with greater usage of natural resources	Faces the limitation in availability of these local natural resources. However, the cost of renewable energy is higher than conventional energy
Nuclear power development	Research and development phase are greatly initiated for nuclear fission which is highly adopted in Russia, the USA, China, France, and Japan	Zero emissions of GHGs	Nuclear power generation and its utility are controversial due to Fukushima nuclear accident occurred in the year 2011
Reforestation and afforestation program	Applied and prevalent in all countries of the world	Simple and eco-friendly approaches for greater potential of CO_2 storage	Restricts/prevents the usage of land for other purposes

6 CO_2 Sequestration in Environment

6.1 Forest

Anthropogenic deforestation and forest degradation have promoted global CO_2 emission into the environment (Pearson et al. 2017; Le Quéré et al. 2018). A total 2.30 and 1.30 m km^2 of gross forest loss and net deforestation have been reported in the year 2000–2012 and 2010–2015, respectively (Hansen et al. 2013; FAO 2018). However, 3.70 Gt CO_2 per year emitted only through deforestation activity in the year 2000–2012 (Tyukavina et al. 2015). Moreover, approx. 2.10 Gt CO_2 per year emitted due to various forest degradation by fires, fuelwood, and timber harvesting in the same period (Pearson et al. 2017). Therefore, CO_2 capturing and its sequestration are key processes that must be promoted for minimizing negative consequences of global warming impact on environment (Raj and Jhariya 2021; Yadav et al. 2022). In this context, adopting sustainable forest management (SFM) and forest landscape restoration (FLR) are key strategies that must be employed for ecological restoration of degraded land and climate change mitigation (Jhariya et al. 2019a, 2019b). However, it is poorly known about the CO_2 capture extent and its capacity through forest restoration programs which is greatly associated with climate change mitigation.

In this context, Bernal et al. (2018) performed a research on quantifying biomass accumulation and CO_2 removal rates in different FLR programs. They observed both woodlots and planted forests contribute highest value of CO_2 removal rates ranging from 4.5 to 40.7 t CO_2/ha/year. Similarly, CO_2 removal rates (t CO_2/ha/year) for mangrove tree restoration ranked second (23.10) followed by natural regeneration (9.1–18.8) and agroforestry system (10.8–15.6) during 20 years of growth.

6.2 Soil

Soil is another most important natural resource that sustains lives and harbor many flora and fauna. Soil performs variety of ecosystem services that maintains environmental health and sustainability (Jhariya and Singh 2021a, 2021b). CO_2 storage and sequestration are key services provided by soils that maintain organic C pools along with global warming and climate change mitigation. CO_2 storage and sequestration vary as per soil types and nutrient loads which further get modified by prevailing climatic factors. Mafic and ultramafic rocks need to be grind up to smaller size (even less than the size of mine trailing) which is used to spread on farming, forestry, and other land-use soils for better CO_2 removal and storage (Edwards et al. 2017; Beerling et al. 2018). Moreover, the process of CO_2 storage and sequestration is further enhanced by microbial populations in the soil (Power et al. 2013). However, the presence of both chromium and nickel in mafic- an ultramafic rock becomes health hazards once it oxidized. Technically, both DACSS (Direct Air Capture using Synthetic Sorbents) and DACEW (for carbon mineralization) are key options for enhancing global CO_2 removal constantly (UNEP 2017; National Academies of Sciences Engineering Medicine 2019).

6.3 Saline Aquifer

Storing CO_2 in saline aquifer through sequestration process becomes viable option for mitigating C footprint and global warming issues. Saline aquifers are considered for underground CO_2 storage through geological sequestration process rather than coal bed and oil and gas reservoirs (IPCC 2005; Sprunt 2006). Saline aquifer is permeable and porous types of reservoir rocks which contains saline fluid and distributed largely with a great capacity (Hesse et al. 2006). Many authors have reported the potential of saline aquifer for removal, storage, and sequestration of atmospheric CO_2 globally. As per Sengul (2006) and Jikich et al. (2003), saline sandstone aquifers have sequestered about 1.0 m MT of CO_2 year^{-1} which is just 3% of Norway's annual CO_2 emissions. Projects for CO_2 storage in saline aquifers in different region of the world are depicted in Fig. 3. Therefore, saline aquifers play important role in CO_2 sequestration which maintains environmental health and sustainability.

6.4 Deep Ocean Storage

Ocean is hydrosphere component of environment which ranked highest in natural CO_2 sink and covered >70% of earth surface. Approx. 38,000 Gt C with the rate of 1.70 Gt C/year. is reported under ocean (hydrosphere). Likewise, 50–100 Gt C is

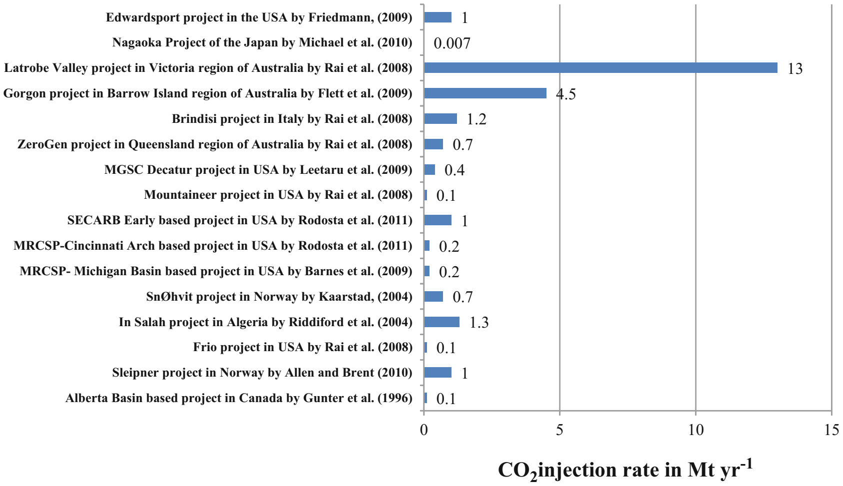

Fig. 3 Projects for CO_2 storage in saline aquifers in different region of the world

produced by ocean in the form of phytoplankton which is greater than CO_2 uptake by terrestrial vegetation (Yamasaki 2003). A 50.0 times more C is available in the ocean than atmosphere which is reported by C inventory (Rackley 2010). Further, CO_2 become liquefied and reached to the bottom due to its higher density than ocean water (House et al. 2006), whereas injecting CO_2 in this way remains many decades (Adam and Caldeira 2008). Injecting CO_2 at the greater depth of >3.0 km inside the ocean sediments promotes permanent geological storage of CO_2 (House et al. 2006). Therefore, deep ocean storage becomes viable sink of anthropogenic CO_2. A heavy and continuous CO_2 injection in ocean affects its chemistry by reducing pH that may result ocean acidification and several negative consequences on marine ecosystem (Seibel and Walsh 2001). Many studies have been conducted research in this direction. For example, Hall-Spencer et al. (2008) have reported less marine biodiversity and poor ecosystem health due to ocean acidification near volcanic CO_2 vents. Similarly, an ocean ecosystem which is resistance to acidification process could be more deteriorating in nature by rising temperature due to global warming (Rodolfo-Metalpa et al. 2011). Therefore, an effective scientific research is needed to understand CO_2 removal, storage, and sequestration into the ocean under marine ecosystem that ensures environmental management and ecological stability.

7 CO_2 Sequestration in Urban Environment: Key Insight

Urban ecosystem plays key role in CO_2 removal and its storage which minimizes negative consequences of global warming and climate change (Khan et al. 2020a, 2020b). Earth greenhouse effects and its potential enhancement are becoming the major environmental problem today. Among all, CO_2 is a major potent GHG which highly contributes in global warming phenomenon. Several development projects in the urban cities including industrial growth ensure higher CO_2 emission into the atmosphere. Thus, CO_2 emission is directly linked with high economical development through various anthropogenic activities that pertain in urban cities which directly affects urban ecosystem and health. In this context, growing plant and tree species can absorb higher CO_2 form the atmosphere and minimize deleterious impacts of rising temperature on ecosystem and environment (Khan et al. 2022; Raj et al. 2022). Urban ecosystem function as CO_2 sequestration for environment management is depicted in Fig. 4 (Gómez-Baggethun et al. 2013; Parsa et al. 2019).

CO_2 sequestration by woody perennial trees along the roadside and parks is playing viable role in checking continuous emission of CO_2 into the atmosphere. Scientifically, woody perennial trees can remove CO_2 from the atmosphere and fix as organic C and other food material in the form of biomass during the process of photosynthesis. Many authors have reported the role of urban ecosystem in CO_2 removal, its storage, and sequestration. For example, roadside plantation removed approx. 73.60 t CO_2 which accounts 22% of total CO_2 production in the urban ecosystem. Thus, urban ecosystem greenery is effective tool for offsetting CO_2 generation through anthropogenic activities. Minimizing the consumption of fossil fuels by planting trees could maximize the CO_2 sequestration effectively in the urban

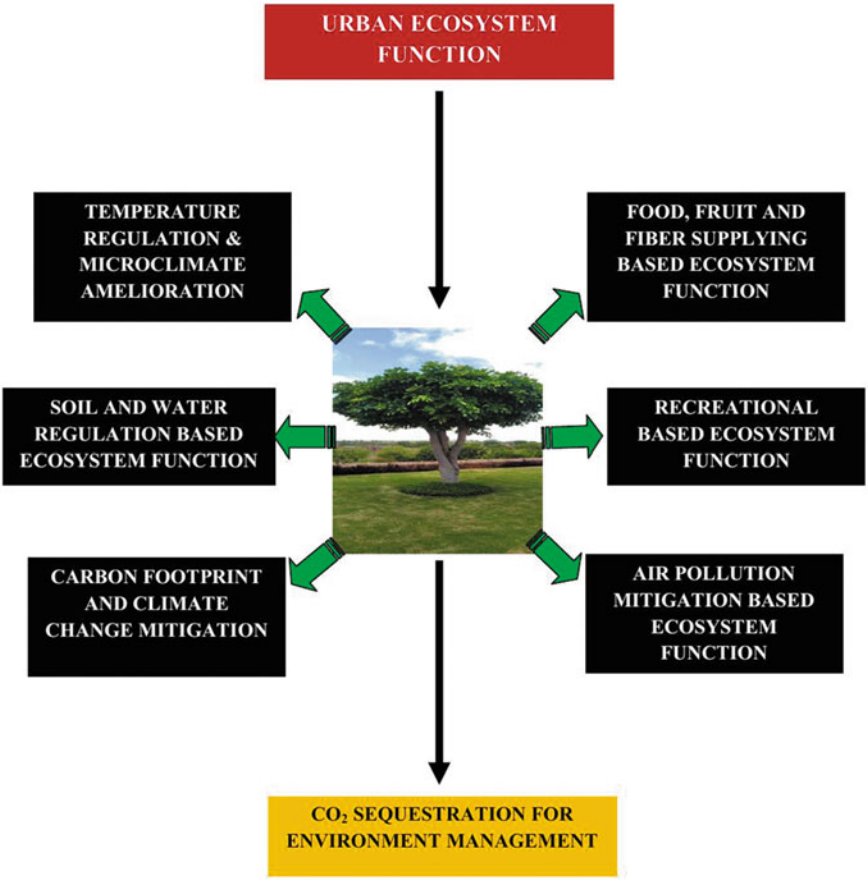

Fig. 4 Urban ecosystem function as CO_2 sequestration for environment management (Gómez-Baggethun et al. 2013; Parsa et al. 2019)

cities (Kiran 2011). Francesco Ferrini and Fini (2011) have reported about CO_2 sequestration of 18 kg/year/tree in well-managed urban cities that ensure a better environmental management and ecological stability. Moreover, the i-Tree Eco-model is recently being utilized for studying C storage and sequestration potential of urban trees and its role in climate change mitigation (Parsa et al. 2019). Thus, studying CO_2 removal, its storage, and sequestration is important for urban planning and management that ensure better ecosystem health and environmental services along with climate change mitigation.

8 Microbes for Enhanced CO_2 Sequestration in Environment

Microbes play an important role in CO_2 sequestration that minimizes the global warming along with greater optimization for production of chemical substance. Microbial CO_2 sequestration is considered as green and sustainable technology that minimizes C emission and ameliorates environment through biofuels and chemical productions. Microbial CO_2 fixation and its efficiency are declining day by day, and C yield of some desire chemical is decreased due to associated microbial CO_2 emissions. In this context, several technologies such as engineering CO_2-fixing pathways and energy-harvesting systems are employed which induce greater CO_2 fixation in autotrophic and heterotrophic microorganisms. Furthermore, both energy metabolism and several metabolic pathways are rewired to minimize microbial CO_2 emissions along with greater production of C-based value-added products. Thus, adopting some biotechnological tools could potentially enhance microbial CO_2 sequestration for better environment and ecosystem management (Hu et al. 2019).

9 CO_2 Capture and Storage: A Way Forward for Sustainable Environment

IPCC has defined CCS as a sustainable process in which CO_2 from power plants and industrial and other energy-based sources is captured, conditioned, compressed, and transported to other storage places for long term isolation from the environment (IPCC 2018). The importance and significance of CCS have been discussed by many policy makers and national and international organization globally. IEA recommended CCS for achieving the goal of net zero emission. Similarly, UK's climate change committee signifies CCS due to its necessity for environmental management and its sustainability (Climate Change Committee 2020). Oil refineries and iron, steel, glass, paper, and cement factories along with agricultural fertilizers industries contribute 20% of global CO_2 emission which is captured and stored by CCS technologies (International Energy Agency 2020). Moreover, CCS plays key role in minimizing global C footprint by offsetting 10 percent of global GHG emissions by oil and gas industry (McKinsey and Company 2020). CCS is a realistic and promising tool that fulfills the net zero emission by achieving IPCC recommendation of less than 2 °C global temperature (IPCC 2018). IEA (International Energy Agency) has reported CCS technology which helps in reducing global CO_2 emission up to zero by 2070, whereas this technology also mitigates approx 5.60 billion t CO_2/year by 2050 (International Energy Agency 2020). Thus, CCS technology protects the earth from GHGs (mainly CO_2), mitigates C footprint and global warming, and ensures environmental management and sustainability (Zhang et al. 2021).

10 Remote Sensing Techniques for CO_2 Capture and Storage

Remote sensing performs noncontact and cost-effective monitoring having extensive scope of observations in many storage sites. Many studies have been conducted on remote sensing-based monitoring technologies, its merits and demerits, and developmental trends in many software for monitoring CO_2 injection stages. Remote sensing-based different monitoring methods for assessing CCS technology under regional projects in the world are depicted in Table 2. CO_2 leakage monitoring, its proper observation, and detection of leakage point are key services provided by remote sensing. Injection well modification and monitoring well implementation are not needed due to noncontact measurement under remote sensing. Thus, monitoring data collection and background monitoring are more secure and convenient which is significantly cost-effective than underground monitoring system (Zhang et al. 2021). Remote sensing can be classified into satellite, ground-based observation, and aerial monitoring which is based on observation platforms (Queißer et al. 2019). Ground-based monitoring system has greater significance due to its high resolution and greater precision. Moreover, remote sensing monitoring system can be further divided into direct and indirect measurement. Surface CO_2 concentration comes under direct measurement, whereas surface deformation along with surrounding ecological environment and its changes comes under indirect measurement (Verkerke et al. 2014).

1 and 2 μm is appropriate wavelength recommended for proper CO_2 detection (Sakaizawa et al. 2013). Similarly, open path is considered as more appropriate due to its less maintenance as compared to close path for detection of leakage (Haslwanter et al. 2009). DIAL (differential absorption Lidar), TDL (tunable diode lasers), Raman LiDAR, FTIR (Fourier Transform Infrared), etc. are open-path active sensing techniques which are highly recommended for detecting CO_2 sequestration. However, DIAL (differential absorption LiDAR) is a promising tool for measuring GHG concentration in the atmosphere (Shi et al. 2020). Similarly, RCLD (remote carbon dioxide leak detector) is a hand-based mobile instrument which is used to detect leakage in any pipeline infrastructure. A collection and processing of Raman echo signal under Raman LiDAR are helpful for measuring the CO_2 concentration and its distribution in the environment (Ahmad and Billiet 1991). However, Raman LiDAR is poorly utilized under CCS monitoring due to weak signal of Raman echo during detection of CO_2 in the environment (Thomas et al. 2013). Recently, a RM-CW IPDA LiDAR-based instrument was designed having low-noise single-photon counting with high sensitivity which detects CO_2 concentration very accurately (Quatrevalet et al. 2017). Similarly, AVIRIS (airborne visible/infrared imagery spectrometer) has been used for detecting CO_2 leakage very accurately. Monitoring of CO_2 concentration in environment has been performed by C-observing satellite which is passive remote sensing technique. SWIR (shortwave infrared) and NIR (near-infrared)-based satellite observation perform better monitoring which covers target area in large scale for longer time as compared to ground-based operation (Zhang et al. 2014). However, GOSAT (greenhouse gas observation satellite) is world's first satellite that was launched by Japan which is equipped with

Table 2 Remote sensing-based different monitoring methods for assessing CCS technology under regional projects in the world

Project in regions	Operating start time and purposes of CCS technology	Monitoring method	References
Alberta Basin-based projects in the region of Alberta and B.C. Canada	CCS technology for “storage” purpose with operating start time was 1990	Seismic method of monitoring	Brydie et al. (2014)
Brindisi project in the Italy	CCS technology for “storage” purpose with operating start time was 2012	Microseismic method of monitoring	Gaurina-Međimurec et al. (2018)
California-based project in the region of the USA	CCS technology for “EOR” purpose with operating start time was 2014	Tracer method of monitoring	Budinis et al. (2018)
Edwardsport Project in the USA	CCS technology for “storage” purpose with operating start time was 2015	Well logging method of monitoring	Hamilton et al. (2009)
Fenn Big Valley-based project in the different location of Alberta at Canada	CCS technology for “ECBM” purpose with operating start time was 1998	Flow method of monitoring	Solomon (2007)
Frio project in the USA	CCS technology for “storage” purpose with operating start time was 2004	VSP method of monitoring	Leung et al. (2014)
Fushan oil field-based project in China	CCS technology for “EOR” purpose with operating start time was 2018	Tracer method of monitoring	Li et al. (2008)
Greengen project in China	CCS technology for “EOR” purpose with operating start time was 2015	Downhole pressure-based method of monitoring	Ziemkiewicz et al. (2016)
In Salah project in the region of Algeria	CCS technology for “storage” purpose with operating start time was 2004	InSAR-based method	Eiken et al. (2011)
Jilin oil field project in China	CCS technology for “EOR” purpose with operating start time was 2007	Gas tracer method of monitoring	Ren et al. (2016)
Jingbian project in the Ordos Basin of China	CCS technology for “EOR” purpose with operating start time was 2012	InSAR method of monitoring	Guo et al. (2019)

(continued)

Table 2 (continued)

Project in regions	Operating start time and purposes of CCS technology	Monitoring method	References
Kelly-Snyder field-based project in Texas (USA)	CCS technology for "EOR" purpose with operating start time was 2004	InSAR method of monitoring	Yang et al. (2015)
Weyburn-Midale project in Saskatchewan region of Canada	CCS technology for "EOR" purpose with operating start time was 2000	Gas Tracer, InSAR	Zaluski et al. (2016)
Salt Creek-based project in Wyoming region of the USA	CCS technology for "EOR" purpose with operating start time was 2006	InSAR method of monitoring	Zhao et al. (2012)
Qinshui Basin project in China	CCS technology for "ECBM" purpose with operating start time was 2003	InSAR tracer method of monitoring	Wong et al. (2010)
Permian Basin-based project in Texas region of the USA	CCS technology for "ECBM" purpose with operating start time was 2005	Seismic method of monitoring	Ren and Duncan (2019)
RECOPOL project in the region of Poland	CCS technology for "ECBM" purpose with operating start time was 2003	Tracer method of monitoring	Li et al. (2013)

FTS (Fourier transform spectrometer) and CAI (cloud and aerosol imager) used for CO_2 distribution in environment (Tian et al. 2018). Similarly, OCO-2 (Orbiting Carbon Observatory) was firstly launched by the USA which is equipped with high-resolution spectrometers and detect CH_4 and CO_2 with greater precision (Zeng et al. 2020).

11 CO_2 Removal Policy: Recent Advances and Challenges

Many scientific papers and technical reports are available for CDR policy which is further gaining importance after Paris Agreement which focused on CDR governance and policy making (Minx et al. 2017). Today, net zero emission is becoming major targets for researchers, scientists, stakeholder, and policy makers. The target of zero emission is discussed in several climate policy papers including IPCC special report 2018 and during Paris Agreement in 2015. Both stakeholders and climate policy makers have diverted their attention on CDR technology which helps in achieving zero emission targets for better environmental management. Several countries have set a target for C emission and are trying to achieve zero emission which reflects the importance of CDR technology. However, scientific papers including case studies on various CDR technologies, its governance, and policy are still lacking. Meanwhile, several political actors and policy makers are emphasized on net-negative emission targets during the adoption of the Paris Agreement and the publication of the IPCC's Special Report on Global Warming of 1.5 °C (SR1.5). Similarly, ensuring balance between GHG emission and its proper removal (CO_2 removal) are the key targets for climate policy makers which further needs to be strengthened at political levels. Thus, increasing attention on net zero emissions can be under operational phase by accompanying the principle of anthropogenic CDR technologies (Fuss et al. 2020). Net-negative emission and CDR recover the C budgets and its management which is further discussed in IPCC globally (IPCC 2018). However, a proper governance of CDR technology and its configuration formulated updated design of CDR policy under various climatic events towards net zero emissions societies (Geden and Schenuit 2020). Many challenges are being faced during promotion and development of CDR technology and related policies. Social debates, public perceptions, sociopolitical prioritization, innovation updation, and incentive structure for R&D-based key challenges have been observed in promotion and development of CDR technology and related policies (Colvin et al. 2020; Cox et al. 2020; Rodriguez et al. 2020; Woroniecki et al. 2020; Fridahl et al. 2020; Bellamy et al. 2021). The failure of CDR design for convention mitigation and emission reduction due to poor policy is also a key issue and challenge (Geden and Schenuit 2020).

12 CDR Integration into Climate Policy and Political Approach: Analytical Framework

Integrating CDR with climate policy regimes introduce a different routes of approaching CDR politically. Climate policy is well deserved, and organized institutional-based policy domain includes clear-defined actors, path dependencies, and various political positions. As per Schenuit et al. (2021), participated countries have chosen variety of techniques and ambitions for designing the CDR to achieve the emission reduction targets. They also choose different policy instrument for fulfilling zero emission target that is discussed in many domestic climate policies after political changes of adopting Paris Agreement and IPCC SR 1.5. However, both the USA and Australia have not yet confirmed for adopting zero emission target at national level. CDR methods are already discussed in climate policy, but it is often divided into natural and technological approaches due to several political debates. Thus, certain CDR methods are reframed into natural or nature-based under many political implications (Bellamy and Osaka 2020; Woroniecki et al. 2020). EU has mobilized climate science and plays a key role in finance of integrated assessment modeling community which performs CDR issue diffusion at various political agenda (Low and Schäfer 2020).

13 Forest-Based CO_2 Removal: Policy Tool, Design, and Management Approach

Forests are largest natural resources that harbor many flora and fauna and provide uncountable ecosystem services including climate change mitigation through CDR technology (Jhariya and Singh 2021c). It plays significant role in C sink and maintain C mobilization, storage, and flux (Manral et al. 2022). CDR through forestry and its integration with policy tools and design are key topic of discussions. However, applying effective and scientific management approaches would be more viable for forest-based CDR performance (IPCC 2014; Wear and Coulston 2015). A rewiring of policy tool, design, and various management approaches is a prerequisite for better CDR in forest ecosystem. Managing forest for offsetting C emissions through CDR technology is a global concern today. This can be further achieved by shifting of land-use systems to others for improving C storage and sequestration in forest ecosystem. Moreover, nature-based climatic solutions signify various ecological processes to ensure C storage and sequestration (Awasthi et al. 2022). CDR potential under nature-based climatic solution can be increased up to 50% through checking forest conversions and promoting reforestation, fire management, and various SFM practices in the USA (Fargione et al. 2018). About 25% of current world atmospheric C pool can be stored into the forest ecosystem (Bastin et al. 2019).

The successful promotion of forest-based CDR requires effective policy designs and tools including regulatory, informational, educational, incentive, and procedural tools. However, in past the CDR policy tools have stressed upon information gathering on C stocks, and fluxes correlated with forest disturbance. It is urgent need to rewire existing forest CDR policy into new and updated policy tools and designs which performs a significant role in environmental management and society development. Moreover, rewiring of CDR tools and design would be helpful in managing forests that ensure resilient landscapes, environmental management, and its sustainability at global scale. This CDR tool and design updating also helps in mitigating C footprint and climate change along with delivery of other ecosystem services (von Hedemann et al. 2020). REDD$^+$-based policy, Kyoto Protocol, and the Clean Development Mechanism (CDM) are three key policy initiatives that use international funds for ensuring forest-based CDR for environmental sustainability. However, several international policy for ensuring forest-based CDR is depicted in Table 3 (von Hedemann et al. 2020).

13.1 REDD$^+$-Based Policy for Negative Emission/Net Zero Emission

REDD$^+$-based international policy is considered the best tool for strengthening forestry-based CDR process that performs climate mitigation mechanism which is highly discussed in Paris Agreement 2015. The basic principle and premise of REDD+ remain unchanged and under which economically developing countries are financially compensated for forest-based CDR (Turnhout et al. 2017). REDD+ is

Table 3 International policy for ensuring forest-based CDR (von Hedemann et al. 2020)

International policy initiatives	Description	Scale	Financing/funding	Benefits	Major concerns
CDM (Clean Development Mechanism)-based policy	Countries can buy offsets which bound by Kyoto protocol-based climate treaty, a small part of which are forest-based reforestation and afforestation program only	At international scale in which projects utilized in economically developing countries	Kyoto Protocol-based regulated stream	Mechanism is greatly flexible for minimizing C. Sustainable development-based funds in developing countries	Forest projects are observed as risky and much costly C accounting uncertainty Leakage risks along with permanence and additionality lacking
REDD+ (Reducing Emissions from Deforestation and Forest Degradation) policy	It is paying for avoided forest degradation and deforestation along with focusing on forest conservation, SFM, and enhancing forest C pools	At international scale in which projects utilized in economically developing countries	Multilateral and bilateral funds for development along with allocations of state budgetary	Safeguards and integrated-based co-benefits Forest work-based funds in developing nations	Concern of equity. Non-C forest-based benefits and its trade-offs, minor livelihood, policy coherence lacking, leakage risks along with permanence and additionality lacking
Voluntary carbon markets (VCM)	Anyone can purchase voluntary C offset payments	At international scale	Financing from those who select to buy offsets	Production and price flexibility, desired co-benefits selected by buyers	Variation in small and local market volume, C accounting uncertainty, leakage risks along with permanence and additionality lacking, source reduction can be less focused by offsetting C
USFS (US Forest Service) climate	Climate-related activities assessment in	USFS (US Forest Service) lands	Not any financing or funding sources for C sequestration	Primary benefits are collecting information for each unit's C stocks	Binding activities and incentives are not available

(continued)

Table 3 (continued)

International policy initiatives	Description	Scale	Financing/funding	Benefits	Major concerns
change performance-based scorecard	USFS (US Forest Service) lands			and its stewardship potential	
US Forest Service (USFS) 2012 planning and rule	A baseline C pool assessment are needed on USFS (US Forest Service) land and keep record of C sequestration in writing	USFS (US Forest Service) lands	Not any financing or funding sources for C sequestration	Primary benefits are collecting information for each unit's C stocks, promoted ecosystem services-based C sequestration and its importance	USFS (US Forest Service) management and its priorities had no any fundamental changes
NRCS (Natural Resources Conservation Service's)-based Healthy Forests Reserve Program	US government shares price/costs of habitat restoration plans and conservation easements based on private lands	Tribal and private-based US forests	US-based funds designated	Private landowners has less burden of cost, technical assistance is easily provided C is prioritized by one and few federal program	Limited scope, both endangered and threatened species are in forests having poor C value
California Carbon Market (CCM)	Emission regulations bound several industries which can buy offsets for a tiny proportions of the emissions	Some few projects in the region of Mexico and Canada but mostly utilized in US private lands	A regulated industries	Permanence is proven at rigorous standards	C accounting uncertainty Leakage risks along with permanence and additionality lacking Source reduction can be less focused by offsetting C

firstly emphasized under UNFCCC (United Nations Framework Convention on Climate Change), and its scope expanded over promising CDR strategies along with C stock management through SFM practices (den Besten et al. 2014).

13.2 The Kyoto Protocol and the Clean Development Mechanism

The first agreement of Kyoto Protocol was signed in the year 1997 that discussed limited role of forest resources in C footprint and climate change mitigation due to uncertain and fair discussion on CDR mechanism. Both industrialized and economically developing countries were signatories to this protocol of which GHG reduction targets have been discussed enormously (Boyd et al. 2009). Similarly, economically developing countries can sell all certified emission reductions (CERs) to industrialized countries which are highly permitted by CDM protocol. This protocol has integrated many policy tools which include market based and regulatory tools for ensuring CDR effectively. Therefore, these two international policies highly emphasized the forest-based CDR which is utmost important for environmental management that ensure SDG. However, the first project on CDM was accredited in 2000 and extended up to the year 2012 (van der Gaast et al. 2018). Both afforestation and reforestation programs through SFM were initiated under CDM, although many projects are focused on net zero emission or CDR (van der Gaast et al. 2018). Thus, Kyoto Protocol and many CDM projects have initiated forest-based CDR which gets further strengthened by adopting SFM that minimize C footprint and global warming for achieving climate-resilient environment and sustainability.

14 CO_2 Capture and Storage: Crucial for UN COP-21

For checking excessive emission of CO_2, a total 190 countries were involved in Paris (Conference of Parties-COP-21) in the year 2015 for minimizing global temperature below 2 °C by the end of this century. It has directed IPCC to set a target for reducing global temperature through CCS technology that helps in sequestering atmospheric CO_2 unconditionally (IPCC 2014). COP-21 has directed to utilize several negative emission technologies along with BECCS (bioenergy with CCS) and direct air capture which helps in limiting global warming <2.0 °C. Furthermore, it has discussed to keep CO_2 level below 450 ppm and predicted CO_2 storage 120 to160 Gt CO_2 with the rate of 10.0 Gt CO_2/year by the year 2050 (Bui et al. 2018). C neutrality concept performs zero balance between C emission and its absorption which is already discussed by many countries under COP-22 conference. Similarly, Paris Agreement has been rectified by several countries for introducing CCS technologies which was discussed at the COP-24 meeting in Poland (Balibar 2017). Moreover, COP-21 has recommended several strategies including energy conservation and its efficiency promotion, adopting renewable and low C fuels, afforestation program along with developing of CCS technologies (Leung et al.

2014). Paris Agreement suggested less than and in between 1.5 and 2 °C of average atmospheric temperature (UNFCCC 2015). For achieving the goal of 1.5 °C global average atmospheric temperature, zero emission technologies need to remove 10 Gt CO_2 per year (IPCC Special Report 2018).

15 Future Research-Based Roadmap for CO_2 Capture and Storage

CO_2 storage and sequestration are key strategies for mitigating global warming and C footprint which ensure environment management and its sustainability (Banerjee et al. 2021). Ongoing research on CO_2 sequestration under CCS technology must be more scientific and policy-oriented. Recent scientific technology and its updation helps in CO_2 sink storage and transportation under CCS technology. Roadmap for future research must be reframed for enhancing the capacity of CO_2 sequestration under CCS technology and its transportation to storage site and then injected into underground reservoir as geological storage. Moreover, CCS technology, viz., pre-combustion, oxyfuel combustion and post-combustion must be strengthened for enhancing CO_2 storage potential and its transportation in ocean and geological sites. Poor infrastructure and high operational cost, along with vigorous energy intensive processes, are key problems observed in CCS technology. High operational cost, CO_2 storage issues, and injection rates constraint are key factors that hamper smooth function and adoption of CCS technology (Lane et al. 2021). This is the reported key area of research that needs to be further resolved urgently through effective policy and scientific research-based future roadmap. Further, a combined research, policy, and global countries' coordination under Paris Agreement and COP-21 would strengthen CO_2 sequestration technology for ensuring climate-resilient environment (Anwar et al. 2018). A future research roadmap on recent technologies is needed for successful remote sensing application in monitoring CO_2 concentration in environment and identifying leakage problems. Similarly strengthening forest-based CDR technology through adoption of better scientific research and management in SFM ensures higher CO_2 sequestration for ecological stability and environmental sustainability. Moreover, a balance among technical, social, economical, and political situation would be helpful for successful deployment of CCS technology (Williamson 2016). Thus, scaling up of CO_2 sequestration technology through proper research, policy, and management are key solution for ensuring climate security (Jhariya et al. 2022).

16 Conclusion

Anthropogenic CO_2 emission induces global warming and climate change issues which affects environment health and sustainability. Offsetting CO_2 emission through C sequestration is a viable tool that helps in maintaining C flux and balance in the environment. CO_2 sequestration through better CCS technology ensures climate security with greater environmental services. However, CDR technology and its adoption require updated scientific research under reframing policy which must be integrated with sound political situation. The net zero targets and zero emissions are already discussed by IPCC and several other climate policy under Paris Agreement and COP-21. Achievement of this target can be possible through adopting recent scientific technology of CCS. Moreover, SFM and other sustainable land-use system check excessive CO_2 emission and stored into vegetation and soil for long term. Furthermore, CO_2 concentration monitoring through remote sensing and its sequestration under CCS technology would be helpful in mitigating C footprint and global warming issue. Therefore, an effective research and policy are needed for higher CO_2 sequestration that helps in achieving the targets of zero emission and promise environmental management and its sustainability.

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Plan and Policies for Soil Organic Carbon Management Under Agroforestry System

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Abstract

Soil degradation is a major issue through various countries across the globe. During the present century, it was observed that land degradation has become a

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predominant phenomenon among different environmental perturbation. As per one estimate, 3 billion people (1/3) across the globe are suffering crisis situation in terms of land degradation. Anthropogenic process such as deforestation and land-use changes causes 30% reduction in C (carbon) stock. Further, faulty and unscientific agricultural practices cause more than 50% depletion of soil organic C. This in turn causes reduction of 5–7 tons C/hectare. Therefore, proper soil management along with maintenance of soil C pool becomes important from the context of arresting further soil degradation. In this connection, 122 countries across the globe have already initiated land restoration and rehabilitation programs. Considering this fact sustainable land-use practices in the form of agroforestry and ecofriendly farming become essential component for well-being of human civilization. Agroforestry has huge potential to provide 50% demand of fuelwood, 60% of small timber, 75% of plywood, 60% of paper pulp raw material, and up to 10% green fodder requirement with a ground coverage of 29.38 million hectare (8.94% of country's area). This in turn contributes up to 38% of C sink to the total sink of forest and other vegetation of the country. Proper policy and planning are essential requirement to properly manage soil C and maintain the long-term soil sustainability. Key policy issues include 4p1000; Bonn Challenge has been initiated throughout the world for proper management of soil health and sustainability. For C management and maintenance of soil fertility practices such land degradation neutrality, sustainable land management is the effective measure. In this perspective, key policy agenda includes Agenda 2030 Target 15.3 on Land Degradation Neutrality which has already been initiated for public awareness regarding soil resources. Further, more than 60 countries are working in the field of integrated soil fertility management for soil organic C buildup through agroforestry. Agroforestry implementation through National Agroforestry Policy 2014 is a masterstroke for India to implement agroforestry practices under diverse land use prioritizing 20 multipurpose tree species under policy perspective. Overall, suitable policy and planning on case-to-case basis are required to formulate to achieve the 2030 goal of sustainable development.

Keywords

Agroforestry · Carbon · Land use · Organic matter · Policy · Soil health · Sustainability

Abbreviation

C	Carbon
LDN	Land degradation neutrality
OC	Organic carbon
SLM	Sustainable land management
SOC	Soil organic carbon
SOM	Soil organic matter

1 Introduction

Soil ecosystem is an important component on the earth. The soil quality and health regulate the agricultural production and systems. Soil organic carbon (SOC) is major constituent which maintains the soil nutrients, fertility, productivity, and overall sustainability (Lal 2004a, 2004b). The tropical soils are poor in nutrient contents and reflect low soil organic C especially in the subhumid, arid, and semiarid climate region which limits the productivity of agroecosystem. The rising human population increases the pressure on the natural resources and requires more food for human civilization. This also leads towards tropical deforestation for increasing the agricultural land for fulfilling the food requirement (Jhariya and Singh 2021a, 2021b, 2021c). For producing more agricultural commodities, most people undergo intensive agricultural practices that are unsustainable and decrease the soil C stock. Conversion of forest lands to agricultural land alone causes the reduction of 30% C stock (Lal 2004a, 2004b; Mandal 2020).

Tropical regions are most diverse and threatened region due to anthropogenic encroachment, over use of resources, mismanagement, lack of technological adaptation and advancement, land use, changing climate, population rise, etc. (Raj et al. 2018a, 2018b). These regions cover approximately 8 billion-hectare area globally. As per a report, nearly one third to half of the topsoil SOC is lost due to alteration in land-use system (Lal 2004a; Mandal 2020). Managing C in the tropics and subtropics addresses the motto of global significance. C is an important aspect in different ecosystem in the present context and linked with ecosystem services towards natural balance and human civilization (Samal et al. 2022). Globally, the deforestation and faulty land-use practices along with unscientific exploration of the natural resources are causing the depletion of SOC pool of various ecosystems through degradation process (Raj and Jhariya 2021a, 2021b; Jhariya et al. 2022; Yadav et al. 2022).

The intensive agriculture practices can affect the soil organic matter (SOM) quality and quantity in great extent (Meena et al. 2020, 2022). Matson et al. (1997) mentioned that agriculture cultivation can cause 50% decline of SOC in a time span of 25 years. Further, Lal (2002) mentioned that in the USA, the converted natural habitat of farming purposely removed 30–50% of SOC which is approximately 4.4–7.2 Mg C/ha. Therefore, the judicious management of land resources is essential from soil health point of view. In this context, agroforestry (cultivating trees+crops+animal husbandry, etc. with various combination and design) seems to be promising due to its diversified outputs and ecological functions under the changing climatic scenario as well as a key instrument to deal with food crisis, nutritional, food security, and soil sustainability (Singh and Jhariya 2016). Agroforestry helps to meet the international agenda of sustainability and sustainable development (Jhariya et al. 2019a, 2019b; Raj et al. 2020; Banerjee et al. 2020).

Managing soil organic carbon (SOC) is challenging, and its timely monitoring is important for sustainable land management (SLM) practices. SOC density varies from region to region, even in meter or data fluctuation over the time. These regional variations of SOC pools are due to diverse practices of agroforestry models in the world. SOC changes under various agroforestry models. Therefore, SOC mapping and tracking of organic carbon (OC) fluctuation and its dynamics over time is very much essential followed by managing SOC through better soil study. Further, advancement in the technological process involves use of software tools, for agroforestry modeling is the need of the hour. Policy for better management of SOC includes monitoring of SOC status and its changes, giving appropriate guidance to land managers, adopting agroforestry models as per SOC status, and enhancing SOC through SLM practices (Roy et al. 2022). Addressing poor SOC content through adopting climate-resilient agroforestry system is a smart choice which needs more scientific plan and policy reformation. Land degradation neutrality (LDN) is novel management policy that can be achieved through practicing SLM. The plan of adopting LDN is discussed in many policies which is already adopted by 122 countries and has committed for land restoration and rehabilitation programs. Thus, LDN is policy-oriented strategy which can achieved through SLM including agroforestry system that ensure higher SOC pools through better C (carbon) sequestration (Chotte et al. 2019). Different SLM practices and its impact on SOC for strengthening LDN are depicted in Table 1 (Sanz et al. 2017).

Scientifically oriented agroforestry system enhances OC into the vegetation and soils that manage ecosystem health and its sustainability. Therefore, an attempt has been made to critically address the key issue of soil C management, plan, policy, and their effectivity towards soil sustainability under agroforestry system. Further, it would provide a deep insight on various policies and planning that is ongoing in an efficient manner throughout the globe for mitigating climate change, optimizing soil C sequestration, and betterment of soil health.

2 SOC in Ecosystem: Policies, Plans, and Potentials

A long-term C storage in soils as stable form of organic matter for more than 20 years is termed as SOC sequestration (Chenu et al. 2019). Globally, mineral soils have potential to sequester C in between 0.40 and 8.6 Gt CO_2eq and minimize net GHGs emissions up to 71% ($\sim$10–12 Gt CO_2eq year^{-1}) annually from AFOLU (Agriculture, Forestry and Other Land Use) (IPCC 2014; Jia et al. 2019). Lal (2004a) has reported C content in various ecosystems which plays key role in C storage and flux for ecosystem health and sustainability. For example, biotic and atmospheric C contributes 560 and 760 Gt, whereas soil ecosystem stores 2500 Gt C (1550 and 950 Gt in soil organic and inorganic components). Similarly, peatland ecosystem stores 600 Gt C which is also C-rich ecosystem which needs protections for greater ecological stability and environmental sustainability (Rumpel et al. 2020). These figures represent global C sequestration potential in different ecosystems that ensure a variety of ecosystem services including greater biodiversity, food availability, and climate change mitigation (Sykes et al. 2020). SOC retention through SLM practices improves flora and fauna habitat, increases biodiversity and water availability, provides greater moisture retention, enhances soil fertility, and minimizes erosion problems in various ecosystem (Griscom et al. 2017; Paustian et al. 2019).

Table 1 Different SLM practices and its impact on SOC for strengthening LDN

Different land-use practices under SLM technologies	Impact on SOC ranges from high impact (1) to low impact (3)	Example of SLM practices	Potential impacts on land degradation neutral (LDN)
Agricultural land system			
Vegetation management practice-based SLM technology	2.40	1. Practicing conservation agriculture system ensures less soil disturbance through minimum tillage. Soil covers through crop residues as mulching is also observed. Adopting intercropping and better crop rotation practices are also key practices for higher crop diversification and sustainable agricultural production 2. Contour hedge-based SLM practices are also recommended for better crop-soil management in agriculture system	Soil enrichment as fertility enhancement, C management through better sequestration potential, water regulation, erosion control, etc.
Integrated soil fertility management (ISFM) based land-use system under SLM	2.30		
Less soil disturbance-based land-use system under SLM	2.30		
Integrated pest management (IPM)-based SLM technology	2.20		
Soil erosion control (SEC)-based land-use system	2.0		
Water management under SLM technologies	1.60		
Grazing/pasture land system			
Integrated soil fertility management (ISFM) based land-use system under SLM	2.50	1. A sustainable nutrient management is observed in this system 2. Contour hedge-based SLM practices are recommended for better pasture-soil management in this system	Higher C sequestration and SOC pools, erosion control, efficient nutrient cycling, degraded grazing land restoration, etc.
Vegetation management practice-based SLM technology	2.30		
Sustainable land-use system for grazing pressure management	2.20		
Land-use practices for animal waste management under SLM technologies	2.0		
Forests or woodland system			
Forest restoration-based land-use practices under sustainable forest	3.0	1. Assisted regeneration is promoted which is a good example of SLM practices 2. Establishment of	Biodiversity conservation, higher C sequestration and SOC pools, erosion control,

(continued)

Table 1 (continued)

Different land-use practices under SLM technologies	Impact on SOC ranges from high impact (1) to low impact (3)	Example of SLM practices	Potential impacts on land degradation neutral (LDN)
management (SFM) technology		protected forest areas in different localities	and efficient nutrient cycling
Afforestation/ reforestation under SLM practices	2.80		
Reducing deforestation through better SLM technology	2.50		
Fire control, pest and disease control under SLM technology	2.0		
Soil erosion control (SEC)-based land-use system in forest ecosystem	1.80		
Sustainable forest management (SFM) technology	1.70		
Proper drainage system under forest-based SLM technology	1.0		
Mixed systems			
Agroforestry system-based SLM technology	3.0	1. Adopting plantation crop/fruit trees in mixed system as agroforestry 2. Integrating multipurpose trees (MPTs) on crop and grazing lands 3. Kitchen garden	Biodiversity conservation, higher C sequestration and SOC pools, erosion control, efficient nutrient cycling, microclimate moderation, windbreaks, better resource use efficiency, and sustainable production with high ecosystem services
Vegetation management practice-based SLM technology	2.30		
Sustainable land-use system for grazing pressure management	2.20		

Globally, 60% of total SOC pool is shared by top ten countries of which 50% are covered by top five countries as Russia, Canada, the USA, China, and Brazil (FAO and ITPS 2018). SOC sequestration potential (Mt C year^{-1}) in croplands and peat C stock (Mt C) in different countries of the world is depicted in Fig. 1a, b (Zomer et al. 2017; Crump 2017). As per figure SOC sequestration potential (Mt C year^{-1}) in croplands is as follows: the USA (124.7) > India (103.8) > EU (84.5) > China

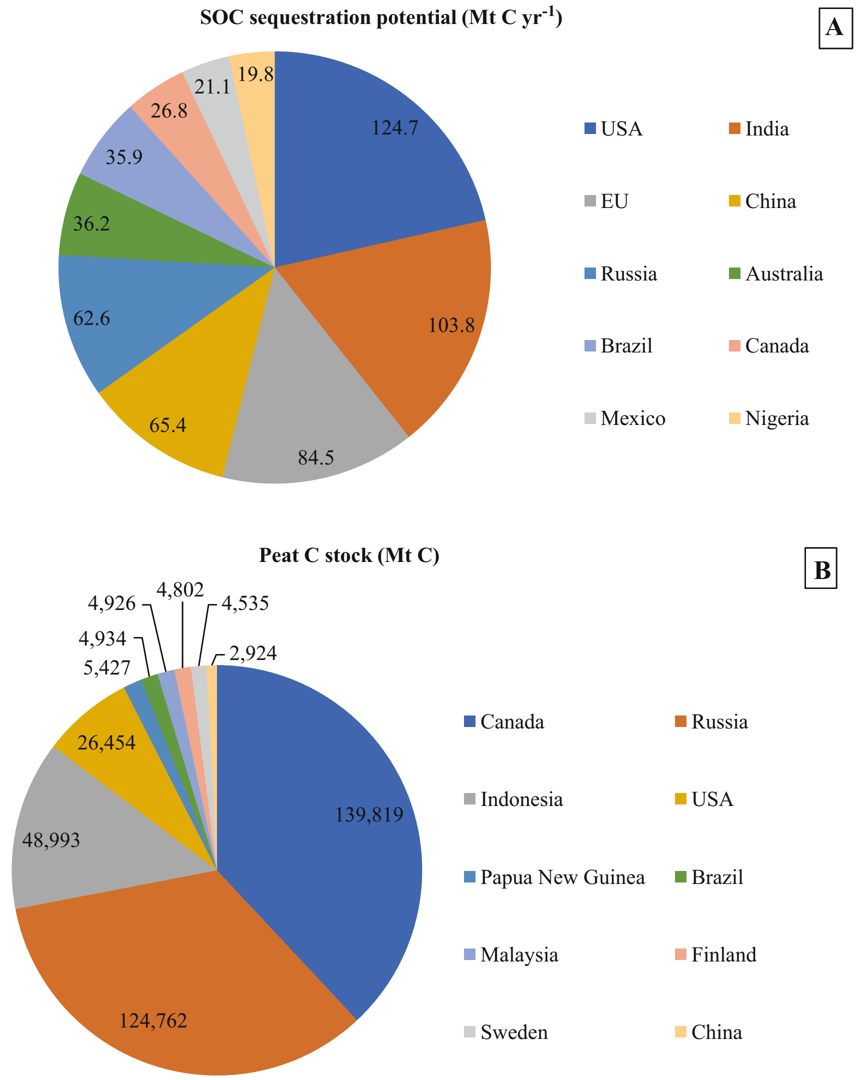

Fig. 1 (**a**, **b**) SOC sequestration potential (Mt C year^{-1}) in croplands and peat C stock (Mt C) in different countries of the world

(65.4) > Russia (62.6) > Australia (36.2) > Brazil (35.9) > Canada (26.8) > Mexico (21.1) > Nigeria (19.8), respectively. Highest peat C stock (Mt C) is contributed by Canada (1,39,819) followed by Russia (1,24,762) and Indonesia (48,993), whereas least value was recorded by China (2924), respectively (Zomer et al. 2017; Crump 2017).

Strategic plan and policies are needed to retain SOC pools in different ecosystems for welfare of biodiversity and environmental health. Effective crop residue management, grassland and pasture land management, peatland management, cover crops and uses of green manures, application of organic amendments, conservation and zero tillage practices, agroforestry, and silvopastoral systems are some of the key strategies for greater SOC restoration in the ecosystems (Boddey et al. 2010; Crump 2017; Zomer et al. 2017; Minasny et al. 2017; Cardinael et al. 2018; Chotte et al. 2019; Meena et al. 2021).

Concerning the C sequestration in different land-use system, Lal et al. (1998) addressed the two key points, i.e., management aspects and policy instrument. From management point of view, they suggested the components such as land-use and agricultural practices, soil conservation and management, plant types, and agricultural waste management for betterment of soil environment. Further, effective management policies and supportive agricultural policy are the essence of sustainability (Jhariya et al. 2021a, 2021b, 2022).

The best management practices of agriculture, forestry, and conservation approaches helps in net SOC gain. Higher SOM gain into soil system can enhance the productive traits of soil environment as well as quality of climate (Kumar et al. 2022a). The interlinking between soil fertility regimes with management practices such as agroforestry can accelerate C sequestration and soil C sink for long time period (Jhariya et al. 2018). The C sequestration dynamics and potential are strongly linked with the land use, management practices, cultivation practices, types of agroforestry, and carrying capacity of the ecosystem (Fig. 2, Mandal 2020).

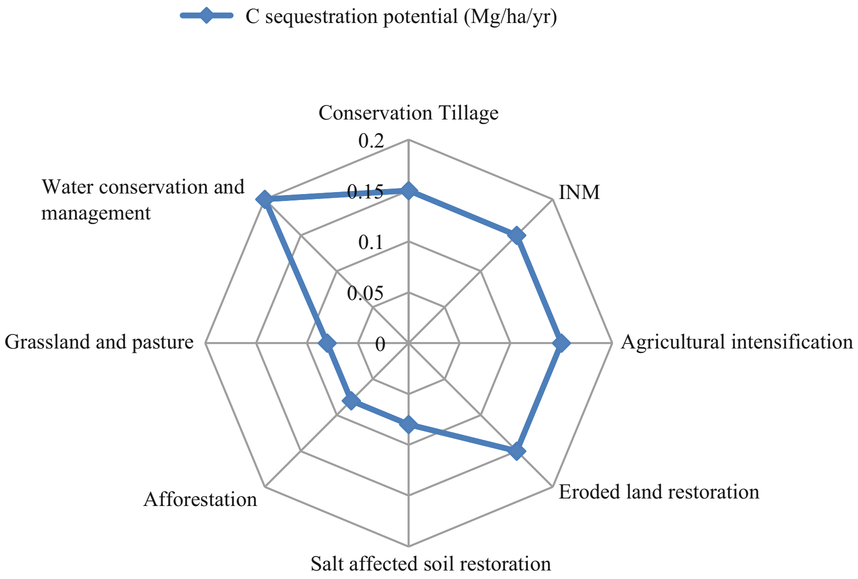

Fig. 2 Potential of C sequestration under various options in the tropics

3 Plan and Initiatives for SOC Restoration and Climate Change Mitigation

Organic carbon sequestration into the soils can remove 0.79 to 1.54 Gt C/year from the atmosphere which helps in stabilizing carbon and mitigating C footprint and climate change issues (Fuss et al. 2018; IPCC 2019). However, recognizing the value of SOC, many plans and policies were initiated towards addition of C into the soils through various SLM practices which helps in restoration of degraded land. Several countries have prepared effective plan and policy for SOC restoration through adoption of global land restoration initiatives, i.e., Bonn Challenge and 4 per 1000 are key initiatives (Bonn Challenge 2017). Similarly, 20 and 100 m ha of degraded land is under planning for restoration in America and Africa, respectively (WRI 2017). Recently, three high level initiatives have been recognized due to soils as global C agenda for C footprint and climate change mitigation. 4p1000 initiative, Koronivia workshops on agriculture, and RECSOIL program (re-carbonization of soils) are three key initiatives those have similar messages towards SOC enhancement in parallel to climate resilience agricultural system and practices (Rumpel et al. 2018; FAO 2019a, 2019b; Banerjee et al. 2021). Moreover, different measures and its potential effects on major soil groups for C sequestration in the world are depicted in the Table 2 (Driessen et al. 2001; IUSS Working Group WRB 2015; Amelung et al. 2020).

4 Monitoring SOC Towards LDN Achievement

Limited studies are found on SOC tracking and its accurate estimation under SLM intervention in the tropics. Assessment by using affective methods, tools, and technologies is prioritized for achieving LDN target. Monitoring SOC in agroforestry systems scale up the LDN concept and its sustainability. Soil sampling framework and related scientific methodologies face many challenges due to wider soil variability in agroforestry models (FAO 2019a, 2019b). MODIS-based remote sensing models are considered effective software tools and models for SOC assessment but not in accurate figures due to changes and fluctuation in SOC dynamics (Vagen et al. 2016). Thus, adopting latest modeling tools, remote sensing-based scaling technology along with recent soil databases is used for accurate SOC estimation in agroforestry system in the tropics (Winslow et al. 2011; Kumar et al. 2022b).

5 Agroforestry and C Dynamics

Agroforestry appears to be a key model for managing the natural resources, production of agriculture, and achieving the national target of forest cover for sustainable production and development (Raj et al. 2019a, 2019b). Various scientific reports are available citing the role of agroforestry in soil productivity and sustainability.

Table 2 Different measures and its potential effects on major soil groups for C sequestration in regions

Different measures	Potential effects	Major soil groups for C sequestration	Regions
Organic residue management and fertilizer inputs	Organic residue and fertilizer inputs enhance soil fertility and plant productivity. It can enrich saline soil of poor in nutrient and SOC	Major target soil groups are Ferralsols, Acrisols, and Lixisols which are highly weathered soils. Arenosols for sandy soils and Gypsisols for semiarid soils are also targeted for enhancing C sequestration potential	Regions of Australia, Africa, Brazil, and China are comprised target soil groups
Liming practices	N_2O emission reductions and fertility enhancement in acidic soils	Ferralsol, Cambisol, Phaeozem, Andosol Acrisol	China, Brazil, and African region
Application of biochar	Emission reduction of N_2O and NH_4 and improved soil properties	Soil is highly weathered (Ferralsols, Podzols Acrisols)	Columbia, Brazil, Eastern Asia
Mulching/cover cropping and no-tillage practices	SOC enhancement, erosion control, and water preservation in cropping period	Lixisols, Ferralsols, Acrisols, and Nitisols	China and Ethiopia
No-tillage practices and other soil management through bed and furrow management	Soil structure maintenance	Acrisols, Vertisols, Ferralsols, Phaozems, Chernozems	India, the USA, Ethiopia, Brazil, Russia, China, Zaire
Process of deep soil loosening	SOC enhancement, with higher yield productivity	Luvisols, Anthrosols, Durisols	European countries, Australia, New Zealand,
Precision farming, cover cropping including other crop systems management	Higher SOC pools and resource use efficiency	Cambisols, Luvisols, Acrisols, Fluvisols	Western Europe, China, Australia, Vietnam
Water management through flooding system	SOC decomposition reduction through proper drainage system	Anthrosols, peatlands, Fluvisols, Histosols, Gleysols, Stagnosols, Planosols	South Eastern Asia and Central Africa
Irrigation system	Salinity maintenance and higher yield productivity	Lixisols, Kastanozems, Calcisols, Solenetz	Australia, South Africa, the USA

However, the degree of its performance and outputs depends upon the site conditions, ecological amplitude of species, compatibility of trees, crops, and other components under the given set of environments. The sole production in the form of either crop or tree has some limitation in terms of soil, resource utilization, economics, environment, and ecological aspects (Singh et al. 2022). In this context, agroforestry has positive outputs which includes efficient nutrient cycling, reducing the loss of soil and nutrients, improving the soil characteristics (physical, chemical, and biological), resource conservation, and food security as well as sustainability (Bhatt et al. 2006; Jhariya et al. 2015).

C trading and financing in global context have put the agroforestry as dynamic and potential mechanism which makes it attractive in developing nations. Agricultural intensification with agroforestry can enhance the C pools beside the food production. The research and innovation towards biophysical, economical, and management aspects related to C sequestration and eco-friendly production are the needs of the present time. In India, substantial areas are degraded and can be utilized for afforestation and reforestation which subsequently serve as C sink and land development and improvement. The soil C pool is an important aspect from global climate change perspective. These sinks are promising and can be efficiently improved through proper research and development. The research-based evidence gives the road map for judging the potential practices with least harm to the soil and the environment (Jhariya 2017). Koppad and Tikhile (2014) mentioned about different land-use systems that reflect different SOC values which include 1.29% in dense forest, 1.22% horticulture plantation, and least 0.75% in agricultural land. The natural forest with higher species diversity can sequester more C than the single-species plantations. Thus, agroforestry has got wider application in terms of biodiversity restoration, biomass accumulation, and more C sequestration.

Agroforestry contributes up to 50% demand of fuelwood, more than 60% of small timber, nearly 75% of plywood, 60% of paper pulp raw material, and up to 10% green fodder requirement besides the households needs with an area coverage of 25.32 M ha (approx. 8.20% of country’s area) (Dhyani 2018). Further, nearly 15% of total cultivated area has diverse form of agroforestry which comprises of 11.2% irrigated and 16.5% of rainfed areas. The higher plants and shrubs significantly support the fodder quantity in arid and semiarid region especially in the lean or dry period when there is least or nonavailability of green fodder. Therefore, silvipastoral system is one of the promising land uses for degraded lands (Dhyani 2018). The restoration of alkali soils thorough silvipastoral practice was mentioned by Dagar et al. (2001) by using the combination of tree and grass species. An estimate by Nair et al. (2010) revealed that the agroforestry system has the C sink potential of 0.29–15.21 Mg/ha/year aboveground and 30–300 Mg/ha C up to 1 m depth of soil. Further they mentioned it has the potential of 12% of terrestrial C of world. Therefore, it is essential to put stress upon the underutilized area that can be utilized efficiently through agroforestry adoption and development by linking the World Bank initiatives on the Community Development Carbon Fund and the BioCarbon Fund towards improving the ecosystem resilience (Nair et al. 2010).

Managing C through various forestry schemes is pivotal to enhance the C sequestered in vegetation and soil pool. The agroforestry system has shown wider potentiality of C sequestration, and it varied from 25 to 96 Mg C/ha, depending upon the species and site interactions, biomass production, and ecological amplitude of the species (Dhyani 2018). Various researches confirmed that agroforestry is a promising system for increasing plant and soil C stock as well as adapting and mitigating the climate change. Further, Ram Newaj and Dhyani (2008) mentioned the tropical agroforestry can sequester C up to 12–228 Mg/ha with average rate of 95 Mg C/ha.

As per the study of Reddy (2002), the SOC and C mitigation potential in various land-use systems reflected that the higher values were under the alternate land-use practices than the farming and fallow land use. The highest SOC was recorded in the order of agri-silviculture (19.93 Mg/ha) > silvi-pasture (17.47 Mg/ha) > agri-silvi-horticulture (17.02 Mg/ha) > *Leucaena leucocephala* (15.68 Mg/ha) > *Acacia albida* (15.23 Mg/ha) > *Eucalyptus camaldulensis* (13.22 Mg/ha) > *Tectona grandis* (12.54 Mg/ha) > *Dendrocalamus strictus* (11.65 Mg/ha) > *Azadirachta indica* (11.43 Mg/ha) > agricultural system (9.4 Mg/ha). Further, C mitigation potential was reported to be higher in agri-silviculture (4.23 Mg/ha) than the fallow and agricultural land (Reddy 2002).

6 Agroforestry Practices for SOC Management

The SLM technologies play key role in land/soil management by controlling land degradation and productivity enhancement through various approaches (WOCAT 2007). The World Bank has estimated 0.2–2.0 Mg C/ha/year under 1000 SOC sequestration under SLM technologies through various meta-analysis approaches in the world (World Bank 2012). Science-Policy Interface (SPI) has reported various SLM practices in agriculture, agroforestry, forestry, and other grazing lands for ensuring climate-resilient practices through enhancing higher SOC pools (Sanz et al. 2017). Overall, agroforestry system is the greatest technology that enhances OC into the soil, and in turn greater SOC pools ensure higher agroforestry productivity which leads to LDN concept and soil sustainability. Thus, climate-resilient agroforestry practices under SLM technology strongly influence a SOC pool which is the basis of land/soil management (Fig. 3, Sanz et al. 2017).

Further, different measures for SOC implementation in the countries are depicted in Fig. 4 (Wiese et al. 2021). Agroforestry and silvo-pastoralism are key important SOC relevant measures practiced by 67 countries for agricultural mitigation and adaptation. Likewise, other measures such as conservation agriculture, grassland or pastureland management, organic amendment applications, and erosion control practices are followed by 34, 30, 22, and 50 numbers of countries for agricultural mitigation and adaptation. No-tillage, mulching, use of cover crops, and fallow systems are utilized by least numbers such as 11, 6, 3, and 2, respectively. Integrated soil fertility management (ISFM) is also an important SOC relevant measure adopted by 19 countries globally which not only maintains SOC pools but also enhances soil

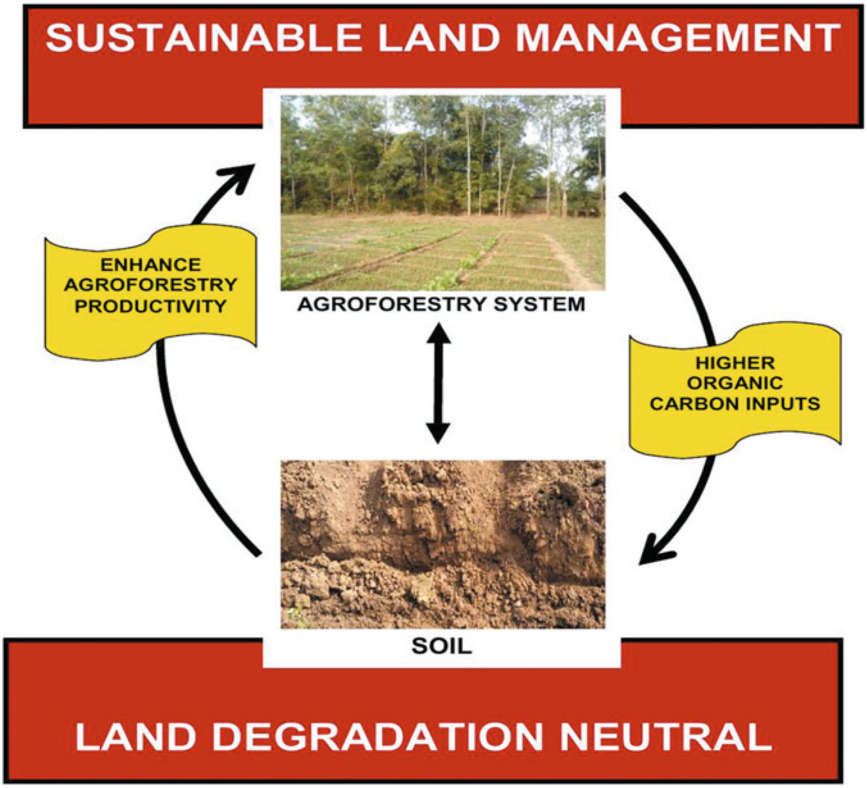

Fig. 3 Sustainable land management including agroforestry system for land degradation neutral (LDN) through better SOC pools

biodiversity and related ecosystem services (Wiese et al. 2021). Therefore, these are key strategic measures that enhance SOC pools through higher C sequestration potential under agricultural mitigation and adaptation.

7 Utilization of Diverse Land Under Agroforestry to Improve C Reserve

Wasteland and dryland formation are the major example of environmental degradation that is taking place at an unprecedented rate throughout the globe. Ecological approaches for resolving these issues could be effectively managed through agroforestry practices.

In dryland condition, soil contributes 33% of SOC and soil biological diversity. It has also proved their potential to mitigate global climate change and address food security. Drylands occupy nearly 42% of the earth's land comprising of 44% of cultivable land and nearly ½ of global livestock. These drylands are essential due to

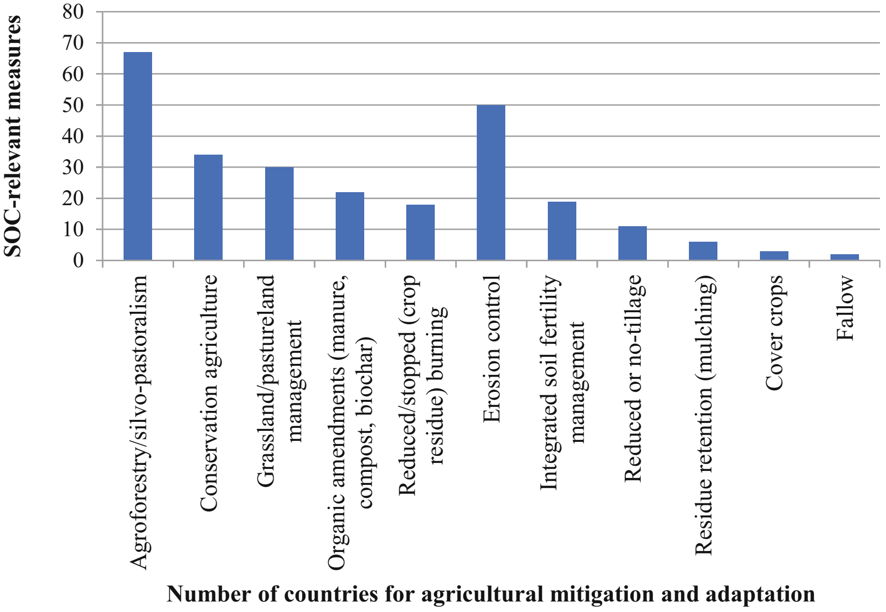

Fig. 4 Different measures for SOC implemented across various countries

its valuable C storage of high degree of permanence and long period into the soil as compared to humid regions. Drylands have substantial biodiversity and important land use. They support nearly 2 billion people and 1/4 of global endangered species (Davies et al. 2012). These ecosystems are culturally and biologically diverse and rich and reflect tropical and temperate climates with 0.65–1.0 aridity index. Based on this index, drylands are classified into arid, semiarid, hyper-arid, and dry subhumid lands. Most of the drylands (about 72%) are found in the third-world nations. The extent of degraded and drylands are mostly equal in terms of their quantity at world level, but the solutions for its management towards utilization may vary than the humid lands. High level of poverty and underdevelopment scenario in drylands needs different nature of plan, management regimes, policies, and investments towards addressing the desertification and further from land degradation. Further land restoration and managing soil biota and soil C need adoption of SLM and diversified production system like agroforestry.

The agroforestry practice gradually builds the soil biodiversity and overall ecosystem productivities. The Agenda 2030 Target 15.3 on Land Degradation Neutrality emphasized on the creating awareness of people towards land resources, soil biota, and soil C for sustainable development. Laban et al. (2018) mentioned that soil biodiversity contributes up to 1.5–13.0 trillion US dollar per annum in the form of ecosystem services. The agroforestry, scientific cropping system, management practices, and improvement of the environmental condition with ecofriendly practices enhance the C stabilization and hence improve the C sink. Changes in agriculture, land use, and tree covers are likely to modify the material cycling and soil environment as well as C reservoir which influences the overall sustainability and equilibrium of environment and ecosystem (Li and Mathews 2010; Bastida 2006).

The terrestrial C is changing due to biotic interferences such as deforestation, change in land use, and biomass burning (Bhattacharyya et al. 2000). As per the land use in the global C stock, agroecosystem contributes 17%, 39% by forest and 34% by the grassland ecosystems (WRI 2000). The agroforestry model which has multistory vegetation including seasonal crops, grass, shrubs, small trees, and higher plants can perform efficiently than low canopy stratum. The combination of various plants species can enrich the biodiversity of the region. Lal (2004a, 2004b) mentioned that the ecosystem sinks more C that has rich biodiversity than the ecosystem possesses less biodiversity.

The dryland ecosystem has various limiting factors specially soil condition and water availability. The planting of trees, shrubs, and grasses have the potential to reduce the soil loss, increase the ground water recharge, and improve the microclimate. This tree facilitates the shelter for birds and mammals and the nutrient gets deposited in the form of dung and other form of organic materials. Such kind of nutrients deposition are called as *resource island* or *islands of fertility* generated by trees, shrubs, and bushes that commonly occur in desert areas. Further these strata also influence the ground vegetation, earthworm activities, and soil ecosystem. The plant species in agroforestry system also serve the nutrient loading through stem flow and other processes. These are some key indicators of stability or risk of desertification in drylands. Planting of various tree species in agroforestry practice offers the alternatives to soil improvement and farming systems and leads towards sustainability of tropical soils and farming systems (Lal 2004a, 2004b).

8 Agroforestry Policy Instrument

Agroforestry has become a burning issue all over the world at the present context of climate change, biodiversity loss, environmental degradation, ecosystem imbalance, population explosion, loss of productivity of agroecosystem, and overall natural balance of earth ecosystem. As an integrated approach, it includes diverse form of land use which boosts up the productivity of the integrated unit. But the major hurdle lies between successful implementation of agroforestry practices. Various countries across the globe have successfully formulated and implemented agroforestry policies to a broader scale (Table 3).

In this context, India framed its first agroforestry policy in the year 2014 to focus on boosting the agricultural production, proper marketing of agroproduce along with extension activities. Such initiatives were taken both at global level and from Indian perspective due to its multifaceted benefits. For instance, it addresses the issue of food security through sustainable food system and provides sustainable ecosystem services and above all the net economic gain for well-being of human civilization. The need is to develop suitable strategy in order to move towards production on

Table 3 Global initiatives towards policy and reforms in the agroforestry (compiled: Chavan et al. 2010; Bernard et al. 2019; Smith 2019; USDA 2019; Pande 2021)

Schemes	Activities	Ministry	Nation
The India National Agroforestry Policy 2014	Plantation of TOF in the form of urban, recreation, rural, and semi-urban landscape	Ministry of Agriculture and Farmers Welfare	India
Ethiopian National Watershed and Agroforestry Multi-stakeholder Platform	Interlinkage between the stakeholders on broader spatial scale of agroforestry and watershed development	Ministry of Agriculture and Livestock	Ethiopia
Rwanda agroforestry and action plan 2018–2027	Integration of leadership and synergistic approach for successful implementation of agroforestry	Ministry of Environment	Rwanda
National Agroforestry Policy 1986	Research and developmental activities through training, education, awareness, and extension activities	Ministry of Food and Agriculture	Ghana
National Agroforestry Policy 2019	Selection of suitable agroforestry system, species, germplasm, and financial security in terms of subsidy, insurance and incentives	Ministry of Agriculture and Livestock Development	Nepal
Reinterpretation and implementation of the Forest Code	Improving accessibility to on-farm trees, legal framework for felling, and access rights	Ministry of Environment	Niger
Agroforestry Strategic Framework 2019–2024	Latest technology and their application for successful agroforestry adoption	US Department of Agriculture	The USA
Rural Development Policy 2007–2013	Proper economic incentive, funding, proper training, extension activity for agroforestry promotion	Agriculture and Rural Development Ministry of member States	European Union
The National Program for Strengthening Family Farming 2003	Allocating of optimum funds through economic reforms along with improvement in the extension activities	Ministry of Agrarian Development	Brazil

sustainable basis (Jhariya et al. 2019c). The benefits of having proper agroforestry policy across the country have been reflected through various countries across different continents. Considering all these policies, the major issue is improving the economic output while minimizing environmental loss for the rural livelihood which is highly beneficial for the people of developing countries. In this context, the case of National Steering Committee on Agroforestry of Malawi plays significant role by disseminating the positive results of agroforestry and also tries to explore the hindrances and unsuccessful factors that may hamper the success of agroforestry. Economic dropdown in agroforestry has been accompanied by subsidy in the European Commission in order to promote the agroforestry practices.

In Central America, the Republic of Guatemala has framed separate policy for the small land holdings farmers to introduce trees in their farmland for promoting agroforestry. Similarly, the government of Kenya has converted policy into legal framework by enactment of law in which 1/10 of land area of the land owner should come under tree cover. The USDA (United States Development Agency) has strengthened the extension activities by bringing it as key policy issue. From Indian perspective, numerous policy initiatives in the field of agriculture, forest, wildlife, and allied fields have been implemented successfully that both directly and indirectly contribute to the promotion of agroforestry. The initiation of landmark policy of agroforestry in India was originated through a program organized by the World Congress on Agroforestry in New Delhi. Under this program the major focus was given to identify the hurdles of agroforestry implementation. Under the presence of representatives of more than 80 nations, the president of India launched the NAP (National Agroforestry Policy) 2014. This was a landmark decision in order to recognize the multiple benefits of agroforestry as well as better promotion throughout the country. This was a transforming policy that promoted the socioeconomic upliftment of economical weaker rural poor farmers. The policy emphasized to develop institutional infrastructure development to promote agroforestry at national level. It also framed the guidelines of proper marketing of agroforestry produce that would bring economic security for the small landholders. Further, major issues such as economic subsidy, insurance cover, maintenance of germplasm, and interlinkage between industry and rural livelihood for betterment of the poor people systematized the markeing chain of forest produce. At the initiation phase, 20 different species of multipurpose tree were selected as agroforestry species that are to be used for economic gain (Jhariya et al. 2019c; Pande 2021). Another, bigger transformation of NAP 2014 was to bring various departments under as single banner to work in collaboration for better output. Various nodal centers and boards were framed for monitoring of agroforestry practices. The policy also promotes massive extension and reserach and development activities under differnt agroclimatic zones for betterment in terms of productivity, profitability, and sustainability (Jhariya et al. 2019c).

All these policies were aimed to improve the forest cover up to 33% of land area of the country. In this context, Chhattisgarh is playing a significant role that helps to eradicate the poverty and increase the income of rural farmers. Similarly, in Madhya Pradesh the Lok Vaniki scheme was implemented since 1999 for the same purpose. Under the scheme, the major focus was effective management of the degraded forest area of the private farmlands onwed by a farming community. This in turn would be helpful for the farmers to increase their economic gain as well as rural livelihood. The scheme was distributed to more than 40 districts of the concerened state and consists of more than 600 active management plans. Many of the farmers were given proper training in the form of sensitization, awareness, capacity building, and adoptability for successful implementation of the scheme. In other parts of the country, plantation on fallow lands and farm bunds were done following standard guidelines to get more economic output. Such initiatives serve numerous purposes in the form of valuable ecosystem services. It includes climate change mitigation, bioenergy, biomass production, soil health and fertility management, and above all proper C cycling within the forest and agroecosystem (Chavan et al. 2015; Jhariya et al. 2019b).

9 Affords Towards Soil Management and Ecological Restoration

Soil is a key component that promotes the agricultural productivity as well as socioeconomic upliftment of rural dwellers that enhances prosperity and well-being of humankind. With gradual passage of time throughout the globe, soil resources are getting depleted rapidly under the pressure of agricultural production. This framed the pathway of conservation of soil resources through proper planning and strategy formulation. Subsequently most of the planning and policy formulation were aimed towards sustainable utilization of the soil resource with proper management (Meena et al. 2022; Jhariya et al. 2022).

The concern for soil resource raised from 1980 onwards under the circumstances when FAO included *Global Soil Chapter* in the year 1982. Further, soil policy at the global level was published by UNEP (FAO 1982; UNEP 1982). Similar reports in relation to soil and land quality were addressed in the UN convention for combating desertification in which proper measures were taken to address the issue of depletion of soil and land quality. Further, under the *Millennium Ecosystem Concept*, agroecosystem was given top priority to provide optimum protection and conservation (FAO 2007). In 2008, an emerging issue in relation to agricultural productivity came to forefront in the form of food crisis, and, thus, the entire scientific community of the globe became committed to think about various soil resources to cope with the problem. According to the latest development UNCCD the “Zero Net Land Degradation” scheme was launched so that policy can be framed to reduce the soil degradation. It was supported by the sustainable development conference organized by UN who addressed land degradation neutrality throughout the world for protection of soil resource (UN 2012). FAO along with other renowned organization tends to work together in collaboration to promote soil conservation and wise use of land resources. Subsequently this leads to development of *Global Soil Partnership* which involved awareness generation in the issue of soil, food security, land degradation, and declaration of 2015 as *International Year of Soils* (FAO and ITPS 2015).

From Indian perspective, the central government launched various programs for combating soil erosion loss and restoration of degraded lands across the country. The Ministry of Agriculture developed watershed programs, soil conservation programs, and soil reclamation and restoration programs at various levels for protection of soil and land resource development (Chaudhari 2018). Considering the effective management of soil and ecological restoration of degraded habitat agroforestry practices can be fruitful option to perform the aforesaid task. As an integrated unit, it adds biomass to the soil and thus increases the SOC content which helps to improve the quality and fertility of the soil. Further, in the present era of soil degradation, agroforestry also helps in effective soil C management by maintaining the balance of soil C dynamics.

10 Plans for Improving SOC and Stock

Globally, the land resource is depleting due to unsustainable practice and mismanagement of soil resources. The problem is further aggravated by frequent occurrence of natural hazards. This in turn leads to rapid depletion of SOC from the lithosphere. More soil gets depleted, and ecosystem services gets hampered which is reflected from tropical world of third-world nations (Mandal 2020; Khan et al. 2021a, 2021b).

For effective management of soil resource, soil C management is an important step to look over (Fig. 5). In this context, proper management and alteration of SOC pool needs to be studied to evaluate the problem. Understanding the problem leads to its solution in the form of C capture or sequestration which is a potential process to maintain the C balance. Research reports reveals that both SOC and stock significantly vary as per varied climatic and soil condition which is important to regulate C flux and maintain soil ecosystem balance. Soil ecosystem is an important ecosystem that tends to have significant amount of C pool and is also a potential site to act as C sink (Lal 2004a, 2004b).

Utilization of proper agroforestry practices along with suitable species is a key component for improvement of SOC and C stock of any soil resource. This should give prior consideration in order to promote soil C buildup as well as its related fertility (Khan et al. 2021c). Various site-specific models including leguminous and nonleguminous crop have shown significant promise in the context of SOC buildup and nitrogen balance in order to promote conservation and sustainable utilization of soil resource. Cropping pattern and maintenance of suitable cropping calendar could also help in SOC management.

In order to manage soil and land resource, understanding the C dynamic is an important and crucial issue. Farmers are directly connected with the soil, and, therefore, they should be properly trained and made aware about the facts of soil resource depletion and sustainable management policy. This should be supported from the government sector through proper action plan and implementation of suitable policy and scheme at grassroot level. This in turn requires proper monitoring of soil as well as implementation of strict regulation from small to large spatial scale.

11 Research and Development for Soil Health Protection and Management

Gradual shrinkage of land areas became the inhabitable truth under the pressure of humankind throughout the world. Among this issue, soil health is the key component as better soil health leads to productive agricultural unit; therefore research and developmental activity should be aimed towards proper protection and management of soil health (Kumawat et al. 2021; Mechergui et al. 2021). This can be achieved through sustainable agricultural practices that fulfil the food demand along with optimum soil health. Agroforestry has the potential to act as a major C reserve or sink. Research and development should be aimed for screening of suitable agroforestry system that has the ability of maximum C sequestration followed by gradual

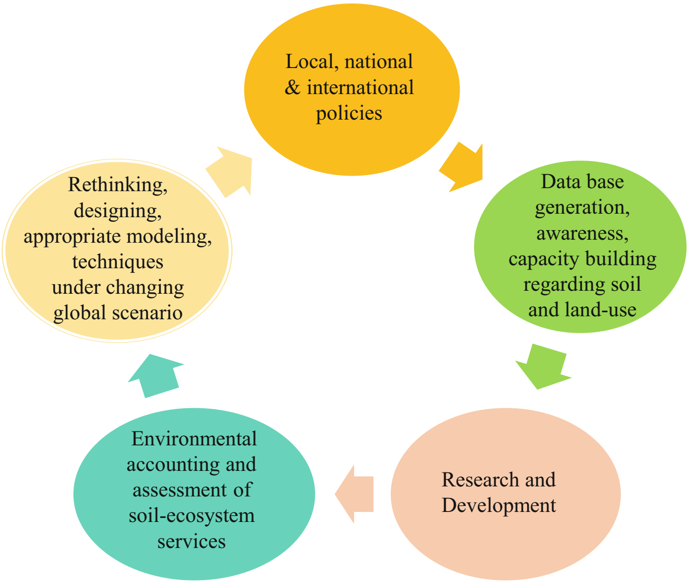

Fig. 5 Sustainable soil and environmental management

buildup of soil C pool. This would help to maintain the fertility and quality of soil and can be considered as suitable policy measure for protection and management of soil health.

Further, proper management of soil health and effective conservation measures may lead to protection of soil in terms of fertility and quality. Conservative measures should also aim for maximum sequestration of C to combat changing climate. Policy should be aimed to evaluate the process of soil protection in terms of addressing food security. Proper soil management would also lead to improve the water use efficiency. Study should be aimed to understand the interaction between soil and climatic factors that would govern the land use and cropping pattern. Research findings should be converted into extension activities under the aggies of policymakers that would help to prioritize the soil protection measures for the benefit of the society and sustainability of the ecosystem.

12 Agroforestry Plans and Policies for Soil and Environmental Protection

Soil is the most important resource for humankind in terms of productivity and sustaining the life on earth surface. Therefore, proper management and sustainable use of the soil are the key mandate for humankind in the coming times. In order to do that, suitable steps for proper policy formulation and strategic implementation of the policies are the gross requirement for sustainable land-use practices (Lal 2010). In the Asian subcontinent, rapid growth of industry, urban expansion, as well as alteration of land use have caused drastic effect on land resource. As a consequence of that, depletion of soil quality and soil health reduced the productivity of the soil. Thus, suitable practices need to be implemented for minimization of depletion of soil resources and for their sustainable use. In this connection, agroforestry is a revolution giving different benefits and ecosystem services for betterment of soil health and production. The major focus in implementation of agroforestry practices should be given on site-specific basis so that the productivity and conservation come hand to hand in the form of win-win strategy. This particular approach was incorporated in NAP 2014 to improve the agroforestry cover of the country as well as sustainable land use (Jhariya et al. 2019c; Pande 2021).

Nowadays, government initiatives aimed towards implementing various ecological farming processes in the form of organic farming, precision farming, and other allied eco-friendly practices. Agroforestry seems to be occupying a significant position among those practices in order to achieve the sustainable goal of food security and sustainability. This in turn would improve the soil health and fertility and do world good to restore the quality of the degraded soil (Bouma 2020).

13 Planning for High SOC Buildup Through Different Land Use

Degeneration of soil is taking place at an unprecedented rate due to industrialized pattern of agriculture. Various problems such as soil salinity, acidity, loss of nutrients and C pool, and erosion are leading to formation of drylands that ultimately converts into desert (Blanco and Lal 2008). Therefore, proper monitoring of soil resources in the context of soil degeneration is the need of the hour and suitable policies, and planning should be aimed towards gradual buildup of SOC to fulfil the sustainable goals. Mechanical tillage is a suitable option for SOC buildup and maintains the soil to perform efficiently. SOC is an important component for maintaining soil health and quality and therefore requires technological boosting for its development and enhancement (Lal 2016). Agroforestry as a technological tool is also important for gradual buildup of SOC in the soil resource. Agroforestry increase the resource use efficiency of soil resource through sustainable land-use practices in the form of SOC buildup followed by active reserve of C in the soil environment (Meena et al. 2021; Jhariya et al. 2022).

Basic agricultural procedures such as maintaining cover crop and sustainable utilization of crop residue may help to protect the SOC pool that has a secondary impact of improving soil moisture, nutrient, and diversity. Further, it helps to reduce the loss of the top soil layer. Cropping pattern can be arranged on the basis of proper utilization of indigenous species as well as precipitation pattern that helps resilience of soil ecosystem along with good soil health (Jhariya et al. 2019a, 2019b). Crops with wider adaptability are preferred in this context as they tend to improve the efficiency in utilization of resources. On the other hand, integrated management on farm level may combat numerous problems that lead to decline in agricultural productivity.

14 Action Plans for Policymakers

Since human beings learned agricultural practices, the major aim was to view it as the production unit that fulfils the daily needs of livelihood along with net economic return. Thus, soil has become a precious resource considering its degeneration trends. Proper policies and planning in this context are yet to be implemented properly in terms of maintaining SOC pool and stock throughout the globe. Thus, humankind is facing the challenges of improper land use, desertification, dryland formation, and above all decline in productivity and yield. Therefore, formulation of proper policies to frame the context of sustainable soil resource for the policymakers is the need of the hour. In doing this, one needs to develop proper monitoring of the soil health, quality, soil functioning, land use and land cover mapping, land capability classification, etc. (Jhariya et al. 2022; Meena et al. 2021). On the basis of these aspects and findings, proper policies should be framed for sustainable management of soil resources. Now, from implementation perspective, local condition, geology, climate, and topography should be given due consideration for its effective management. Another, important aspect includes ecological restoration of degraded site which should be a key agenda for policy formulation.

Proper training and skill development towards maintaining soil health and SOC buildup should be emphasized with new technological intervention. R & D activities and extension services should be laid down among the farming community for successful implementation of the policies at government and policymakers' level. It should be such that it would fulfil the demand of farmers and local people (Katyal et al. 2001). Multidisciplinary approaches towards sustainable agroecosystem should be framed with implementation of sound knowledge base on soil health and their management. This would help in identifying the key areas of management of soil resource and would work for the well-being of people (Raj et al. 2020; Kumar et al. 2020; Banerjee et al. 2020). Integration of various components of agroecosystem through various practical approaches would be also helpful to address the bigger issue such as changing climate, mitigation, and overall sustainable development.

Agroforestry has a potential role towards conservation of natural resources in terms of SOC buildup, soil health and fertility, as well as soil biodiversity. Agroforestry has worked as a remarkable revolution to combat deforestation activities, promote reforestation, restore degraded lands, and above all improve soil health and quality for better production. Policymakers have a key role to play in the form of developing proper markets and marketing chain for the agroforestry produce along with proper pricing, market value, and local demand. This would help in higher level of agroforestry adoption at grassroot level. This would help to achieve the sustainability goal in terms of conservation and management of soil resource (Raj et al. 2022a, 2022b).

15 Conclusion

Soil C management is key process for maintaining soil health and productivity. Maintenance of SOC pool helps to arrest soil erosion, topsoil layer, as well as conservation of soil resource. Further, as a technology it provides multiple benefits in terms of increasing productivity and yield. Addressing larger issues, such as preventing desertification and soil erosion loss, and combating climate change are some of the important role of agroforestry in agroecosystem. Policies and planning need to be developed in order to promote the successful implementation of agroforestry schemes across the globe with proper involvement of planners, decision-makers, government officials, scientist, and academicians, along with the target people who would be benefitted the most by adopting such technology. In this context, NAP 2014 is a significant step that has promoted the increase of agroforestry cover over the country which would provide additional benefits in the form of various ecosystem services. This would help in all-around development of soil ecosystem and would help to achieve the goal of sustainable development.

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Carbon Sequestration in Degraded Lands: Current Prospects, Practices, and Future Strategies

Raj Kumar, Awtar Singh, Ashim Datta, Ram Prakash Yadav, D. Dinesh, and Kamlesh Verma

Abstract

The productivity of soil depends on its quality, which is mainly governed by the soil organic carbon (SOC) stock and its dynamics. Degraded lands are undoubtedly getting much attention as the demand for food, feed, and fuel continues to increase at the unprecedented rates, whereas productive agricultural land is shrinking in many parts of the world. It has been computed that ~3.6 million hectares area worldwide have been already degraded, and at present world is losing agricultural land comparable to 26 football fields per minute. Degraded lands are extremely poor in the SOC stock; hence, great opportunity exists to restore the SOC stock of such lands. Soil plays a vital role in carbon (C) capturing and storage; therefore the management practices aiming at restoring SOC stock in degraded lands are needed to be identified. The estimated global potential for sequestration of total C is between 78 and 106 million Mg year^{-1}, where 12.9% is contributed through restoring degraded soils and 45.6% through controlling erosion as well as its management. Among the different management practices, the application of organic amendments, conservation agriculture, soil conservation measures, tree plantations, and agroforestry practices have shown enormous potential to sequester C in the soils. The application of organic amendments can ameliorate and enhance SOC stock as well as improve soil fertility of degraded soils. Conservation agriculture practices especially zero tillage and residue retention enhances soil C content in the soil under long-term perspectives.

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Afforestation of degraded lands has a tremendous potential to sequester atmospheric C and could be major sink of carbon dioxide (CO_2) if their potential is fully utilized. Agroforestry systems also play an important role in mitigating climate change, having the ability to sequester atmospheric CO_2 both in plant parts and soil systems. Despite the immense potential of soil to store C, the several constraints and challenges, such as, lack of land use planning, technological limitation and their poor dissemination, and ineffective action plans are creating obstacles in devising strategies for sequestering C in the soils. Therefore, devising of appropriate futuristic strategy on soil C sequestration in degraded lands could bridge the gap between the constraints and opportunities.

Keywords

Carbon · Degraded lands · Soil · Agricultural practices · Tree plantations · Agroforestry

Abbreviations

AFS	Agroforestry system
C	Carbon
CA	Conservation agriculture
CO_2	Carbon dioxide
CT	Conventional tillage
DOC	Dissolved organic carbon
DSR	Direct seeded rice
EC	Electrical conductivity
FYM	Farm yard manure
GHGs	Greenhouse gases
ha	Hectares
IPCC	Intergovernmental Panel on Climate Change
PB-SSNM	Permanent bed along with site-specific nutrient management
RT	Reduced tillage
SOC	Soil organic carbon
SOM	Soil organic matter
SWCM	Soil and water conservation measures
ZT	Zero tillage

1 Introduction

Degradation of natural resources is one of the major issues faced by the technocrats and policy planners across the globe. Globally, at present, about one-third of the land is degraded, which is affecting 3 billion people, and the situation is expected to worsen further with the increasing demand of food grain (FAO 2020). It has been estimated that about 3.6 million hectares (ha) land area across the global is degraded (UNCCD 2004), and currently world is losing productive agricultural land equivalent to 26 football fields per minute. As part of the Bonn Challenge, India has pledged to restore 13 million ha of degraded and wasteland by 2020 and an additional eight million ha by 2030. Despite the known fact that degraded lands are relatively less productive and more susceptible to climate change, they are at much attention at across the globe. It is well-known that greenhouse gases (GHGs) emission was projected to escalate 40–110% during 2000–2030 as a result of the human-induced activities (IPCC 2007). Consequently, climate change will further worsen land degradation to impend environment and threaten agricultural sustainability.

In India, at present, the estimated degraded land is 147 M ha which formed as a consequences of water erosion (94 M ha), acidification (16 M ha), flooding (14 M ha), wind erosion (9 M ha), salinity (6 M ha), and combination of the different factors (7 M ha) (Bhattacharyya et al. 2015). The rehabilitation of these degraded land is a major issue because India supports a major chunk of world's human (18%) and livestock population (15%), while the total land area of country is 2.4% of the global land area. Despite low land area in proportion to total human and livestock population, India ranks second in term of agriculture production worldwide. As per 2018 estimates, around 50% of the Indian workforce were employed in agriculture and contributed 17–18% to GDP of the country (Patil and Khan 2019). The eroded, salt-affected, desert, deforested, and abandoned lands constitute the major category of degraded lands. The several anthropological activities, such as improper land use, illicit mining, excessive grazing, deforestation, and land-use change, erosion, desertification, waterlogging, salinization, intensive cultivation, and imbalanced use of fertilizers and pesticides, etc. accelerate the degradation process that subsequently transforms a productive land to a unproductive one (Fig. 1). Degradation strongly affects soil quality by decreasing the SOC stock, which subsequently affects the plant growth and yield (Mehta et al. 2018). Soil degradation affects SOC stock through reduction in biomass production, and C losses due to the decomposition and erosion process, which influences their long-term storage capacity in the soils (Kumar et al. 2021a). The degraded lands are also adversely affected by changing climate which severely affects the agricultural production, water resources, ecology and biodiversity, human well-being, and wildlife habitat (Sivakumar 2007; Stavi and Lal 2015).

SOC stock acts as a core driver in regulating ecosystem services, sustaining agricultural productivity, and mitigating climate change across the globe (Bispo et al. 2017). The reduction in SOC stock is one of the major issues faced by the farmers and land owners worldwide. The large numbers of factors are responsible for alteration of the SOC stocks. The poor SOC stocks leads to change in the soil physical, chemical, and biological properties. However, large number of practices have been developed and implemented to restore the SOC stock. Despite that, the planned practices have failed to achieve the restoration target fixed by the resource conservationist, although projections of scientific advancement and new

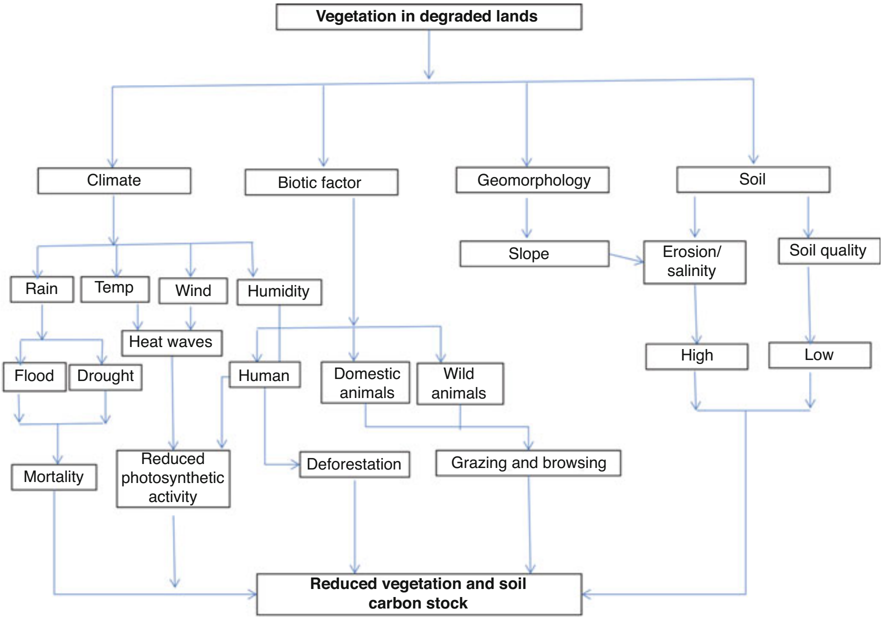

Fig. 1 Factors responsible for loss of soil carbon

technological development suggest a greater success in this aspect (Bagdi et al. 2017). This formidable challenge has led for urgent research/land-use planning to devise advance agriculture practices and systems for assessing their feasibility, applicability, profitability, and sustainability in degraded lands (Bhattacharyya et al. 2015). The estimated global potential for sequestration of total C is between 78 and 106 million Mg year^{-1}, where 12.9% is contributed through restoration of degraded soils and 45.6% by erosion prevention as well as its management (Lal 2005). Erosion transports around 4.9 Pg of soil and 115.4 Tg of C every year in India, resulting in emission of around 34.6 Tg of C into the atmosphere (Mandel et al. 2019). Mandel et al. (2019) also outlined that between 19 and 27 Tg C year^{-1} could be sequestered by soils via adopting suitable technological alternatives in the erosion-afflicted areas of India, which creates opportunity to reduce around 24.5% of the total GHGs emissions from agricultural soils in India (94 Tg C).

In order to restore SOC stock of degraded lands, the various organic matter enriching practices, such as, application of organic amendments, conservation agriculture (CA), agroforestry, afforestation, and soil and water management practices have indicated enormous potential to improve and restore the SOC stock, as these measures have been strongly recommended in such lands by the previous researchers (Kurothe et al. 2014; Bhan 2016; Ali et al. 2017). These practices in such lands can provide a large number of benefits, for example, controlling run-off, improve soil physico-chemical properties, mitigating climate change, promoting plant growth, enhancing biomass/C stock which directly or indirectly can restore the SOC stock. As soil plays a vital role in C capturing and storage, the quantification of its stock is a crucial task (Bhattacharyya et al. 2008). Moreover, the role of different agricultural practices deserves attention to plan soil C restoration measures, as presently extensive information is available regarding this throughout the globe. Therefore, studies available worldwide are needed to comprehensibly analysed and discussed to devise policy and programmes at national and international level for resorting the SOC stock.

2 Good Agriculture Practices for Enhancing Soil Organic Carbon Stock in Degraded Lands

The anthropogenic activities contribute GHGs emission into atmosphere which is one of the major factor responsible for the climate change (IPCC 2013). Soil is a major reservoir of terrestrial C (2500 Gt), which either is in soil organic (1550 Gt) or in inorganic (950 Gt) form (Lal 2004). Any loss of C from the Soil C pool considerable contributes to the increase of CO_2 concentration in atmosphere (Smith 2008). SOC stock is an important component in soil that contributes to soil quality, productivity, and land sustainability. In the present context of climate change, good agricultural practices—such as application of organic amendments, farm yard manure (FYM), biochar, composts, crop residues, CA practices, adoption of agroforestry model, etc.—are considered important strategies which can significantly improve the SOC stock in the degraded lands (Corbeels et al. 2019).

2.1 Balanced Fertilization with Organic and Inorganics

In India, farmers follow both balanced and imbalanced fertilization to their crops. The soil C sequestration is influenced indirectly due to effects of these practices on the crop performance. The rhizodeposition of C in below-ground C inputs through roots, rhizodeposition, etc. is approximately 54–63% in cereals (Hirte et al. 2018). In general, an apparent increase in SOC stock upon balanced fertilization through organic and inorganic sources was reported by the many researchers (Fig. 2). The greater addition of organic C through plant residues and root biomass C in soils under balanced fertilization as evidenced by higher crop yields under balanced fertilizer treatments (Majumder et al. 2007). However, such build-up of SOC varied with the ecology, soil type, and regional climate. Crops capable of producing higher residues and root biomass C should be included in the cropping systems for increasing net C sequestration in the soil.

2.2 Application of Organic Amendments

Organic amendments are the C-based substance of biological origin. The application of these amendments (farm manure, poultry manure, compost, and biochar) has

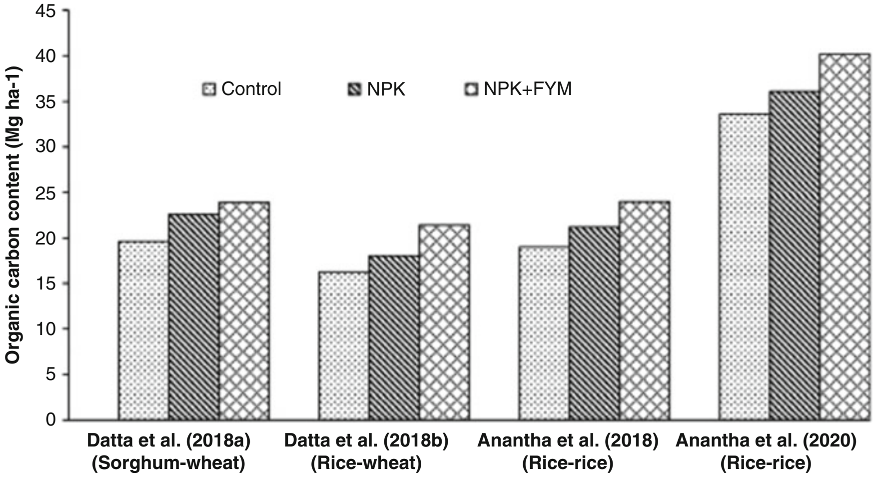

Fig. 2 Influence of balanced and imbalanced fertilization on organic C content (Mg ha^{-1}) in soils

potential to enhance the SOC stock and ameliorate properties of degraded soils (Srivastava et al. 2016; Meena et al. 2019). For example, organic amendments apart from the amelioration action also improve the quality of salt-affected soils by (1) accelerating the native calcite ($CaCO_3$) dissolution through formation of carbonic acid (H_2CO_3) in the soil that results in release of inherent Ca^{2+} in soil solution to facilitate the exchange of Na^+, (2) enhancing porosity of the soil that improves the air and water movement in soils, and (3) further improving the water-stable aggregates and permeability in soil (Fig. 3) (Rezapour et al. 2022). Application of organic amendment in salt-affected soil is the effective approach in reducing toxic saline condition. Recently Leogrande and Vitti (2019) conducted a comprehensive review on the efficiency of different organic amendments on reclamation of salt-affected soils and reported that organic matter inputs can be an excellent option for sodicity reclamation along with improving SOC stock in these soils.

2.3 Conservation Agriculture

Conservation agriculture (CA) is the amalgamation of minimum soil disturbance mainly zero tillage (ZT) or reduced tillage (RT) with retention of crop residues and diversified cropping systems, especially inclusion of legumes. The negative impact of green revolution was visible in the late 1990s that resulted in the yield stagnation of cereal crops, lowering of ground water table, depletion of soil organic matter, deterioration of soil physical health, emergence of micro- and macronutrient deficiency, and degradation of overall soil quality. All these factors triggered the adoption of CA to address these above-mentioned issues. CA has been accepted as an updated crop production technology for better soil physical health, better nutrient recycling, and enhanced microbial activity and biological diversity along with

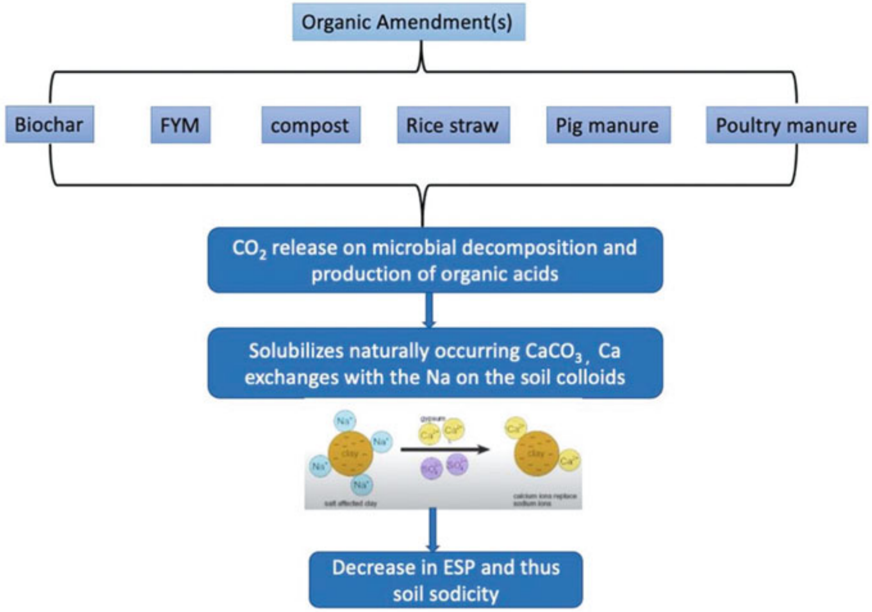

Fig. 3 Different organic amendments and their role in amelioration of salt-affected soils

enhanced soil C sequestration vis-à-vis lowering GHGs emission. Soil C sequestration is the prime need for restoring soil fertility as C plays key role in maintaining soil quality. In India, tropical and subtropical climate coupled with conventional tillage (CT) and practices like residue burning decelerates SOC build-up. CA practices especially ZT; residue retention enhances soil C content in the soil under long-term perspectives. In large number of studies, the soil C accumulation under CA was clearly observed in top soil layer (0–5 cm) irrespective of soil and climate (Das et al. 2013; Bhattacharyya et al. 2015; Veloso et al. 2020). When cotton (*Gossypium herbaceum*)-wheat (*Triticum aestivum*) were grown under CA, ZT with bed planting and ZT with flat planting recorded 28% and 26% higher SOC stock, compared to CT with bed planting (5.5 Mg ha^{-1}) at 0–5 cm layer in North India (Das et al. 2013). Inclusion of summer mung bean (*Vigna radiate*) in between ZT wheat and direct seeded rice (DSR) resulted in soil C build-up in North-western Indo-Gangetic Plain in 0–5 cm soil layer (Bhattacharyya et al. 2015). In Eastern India, after 7 years of CA practices, Samal et al. (2017) concluded that adoption of full CA practices like DSR-ZT wheat-ZT mung bean along with full residue retention resulted in highest SOC stock of 48 Mg C ha^{-1}, which was 15% higher over farmer's practice in 0–30 cm soil layer.

In a study, Yadav et al. (2019) reported that double rice cropping system with RT, integrated nutrient management practice, and partial residue retention (30%) recorded highest C accumulation (1.3 Mg C ha^{-1}) and highest sequestration rate (428 kg ha^{-1} $year^{-1}$) over other treatments in Eastern Himalayan region. In rice

(*Oryza sativa*)-mustard (*Brassica nigra*) cropping system, higher SOC sequestration, SOC pools (29.9 vs. 29.1 Mg ha^{-1} and 29.7–29.8 vs. 29.0 Mg ha^{-1}), C sequestration rate (450 vs. 265 kg ha^{-1} year^{-1} and 391–428 vs. 221 kg ha^{-1} year^{-1}), and C retention efficiency (7.7 vs. 4.6% and 6.6–6.9% vs. 4.7%) were observed in ZT with residue retention and mulched treatments over CT with residue incorporation, and no mulched treatments (Yadav et al. 2019). He further suggested that growing of cow pea (*Vigna unguiculata*) in pre-rainy season as cover crop doubled the C sequestration rate (478 kg C ha^{-1} year^{-1}).

In Northwest India, enrichment of SOC content under CA is more pronounced with maize (*Zea mays*)-based (7.7 g kg^{-1}), compared to rice-based (7.5 g kg^{-1}) cropping system and farmer's practice (4.5 g kg^{-1}) in 0–15 cm layer after 4 years of cropping cycle (Jat et al. 2018). Further, Jat et al. (2019) reported that adoption of ZT and full residue retention for 4 years recorded maximum improvement of SOC stock (70%) under ZT maize-ZT wheat-ZT mung bean treatment compared to farmer's practice (16.2 Mg C ha^{-1}) and ZT DSR-ZT wheat-ZT mung bean at 0–15 cm soil depth. Similarly, soil C pools were also higher under the above full CA treatments over the farmer's practice. Adoption of permanent bed and flatbed ZT practices in maize-based cropping systems for 6 years improved C content and SOC stock over flatbed CT at 0–5, 5–15, and 15–30 cm depths, respectively, in a sandy loam soil (Parihar et al. 2018a; b). Parihar et al. (2020) further calculated C sequestration and soil quality under maize-wheat-mung bean cropping system with varying tillage and nutrient management options. Permanent bed along with site-specific nutrient management (PB-SSNM) recorded highest C content (44.1%) over unfertilized CT plot. Similarly, maximum SOC stock, C input (3.41 Mg ha^{-1} year^{-1}) and C sequestration rate (1.15 Mg ha^{-1} year^{-1}) were also obtained in PB-SSNM treatment. In Central India, higher proportion of large size water-stable aggregates, aggregate-associated-C, and higher proportions of non-labile C under no tillage over CT were reported by Somasundaram et al. (2018) in 0–5 and 5–15 cm layers after four cropping cycles. After 6 years of cropping cycles, Dey et al. (2020) reported that double ZT + residue retention in rice-wheat system sequestered ~2 Mg ha^{-1} total SOC in the 0–15 cm soil layer, where significant losses were registered in CT. Maize-based CA system showed higher SOC and stability of humic acid C compared to CA based rice system (Datta et al. 2022).

2.4 Tree Plantations

Afforestation has been considered as the most important tool to prevent the soil degradation (Hu et al. 2015). In most cases, the degraded lands are dominated by dwarf trees and bushes which have insignificant ecological and economic value; therefore the plantation of native and superior tree species is generally preferred in such lands for greater biomass production and higher C sequestration, which is the ultimate goal to address the issue of climate change (Kaul et al. 2010). Under degraded soil conditions, vegetation biomass production and SOC stock in degraded environment may be better sustained and improved if afforestation measures are

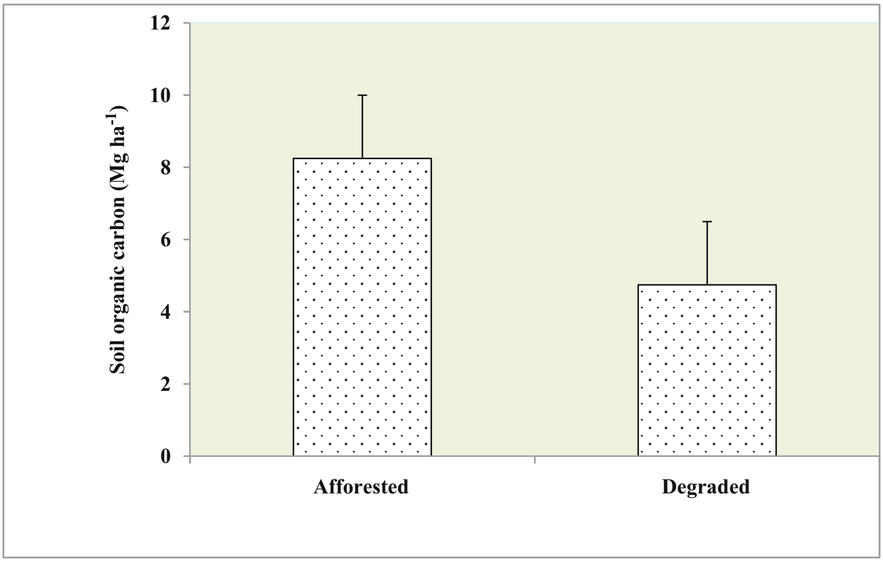

Fig. 4 Soil carbon stock variation in the afforested and degraded ravine (data sources: Kumar et al. 2022)

adequately implemented (Sanwal et al. 2017). Afforestation of degraded land can provide multifarious ecosystem services which include provisioning services, viz. fodder, timber, fuel, non-timber forest product, medicine, and gum; regulating services, viz. nutrient cycling, controlling soil erosion, moderating climate, and C sequestration; supporting service, viz. net primary production and soil formation; and cultural services, viz. recreation (Kumar et al. 2021b). Selection of appropriate tree species is another important criterion that greatly influences the success of afforestation. Species such as *Azadirachta indica*, *Acacia catechu*, and *Emblica officinalis* produced higher biomass and C stock in the dry degraded lands (Parandiyal et al. 2006; Singh et al. 2012a, b). Therefore, assessing species performance in term of growth, biomass production, and C stock is also required for a successfull afforestation plan.

Afforestation has the potential to produce greater biomass which may contribute to the increased C stock in the degraded lands. In contrast, degradation of land decreases the vegetation C stock as a consequence of poor survival and low biomass of the tree species. Therefore, afforestation of degraded land has potential to sequester greater atmospheric C and could be a major sink of CO_2, if their potential is fully utilized (Kaushal et al. 2016). Kumar et al. (2020) advocated the promotion of agroforestry to enhance the climate resilience and C sequestration in highly degraded ravine to fulfil the climate change mitigation and adaptation objectives (Fig. 4). Some previous investigations have equally advocated the increased C stock in degraded lands (Návar 2008; Deng et al. 2017; Mehta et al. 2018). Moreover,

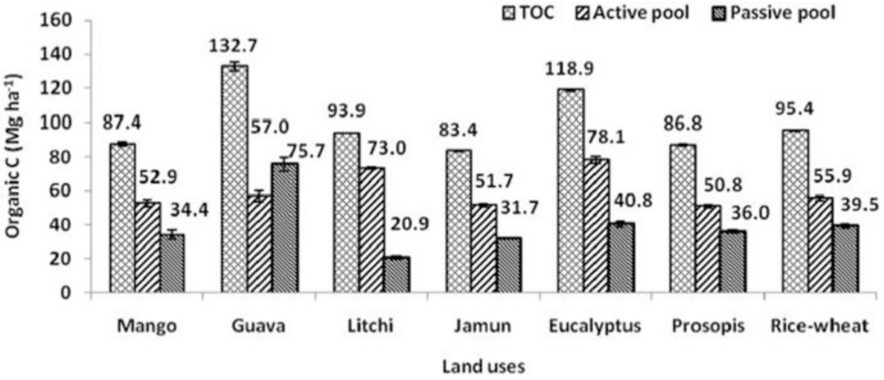

Fig. 5 Overall soil organic carbon storage into different pools under different land uses in a reclaimed sodic soil. Vertical bars indicate ±S.E. of mean of the observed values (Data sources: Datta et al. 2015)

continuous efforts (every year) of selective species planting and adoption of sustainable practices in degraded lands could balance and manage global C cycle.

Besides vegetation C, enhancing soil CO_2 sequestration in degraded lands is considered as one of the high priority agenda by the technocrats and policy planner. Most of the analysis showed that the degraded lands are extremely low in the SOC stock (Pande et al. 2021). The deforestation coupled with soil erosion is considered as the major factor in low SOC stock in these lands. This may results in poor soil physico-chemical properties to adversely affect the vegetation growth and biomass production. In contrast, tree plantation improves SOC stock in degraded lands that might positively influences soil health and quality, which improves the overall productivity of such ecosystem. Large number of previous researchers has also noted the increased soil C as a consequence of afforestation (Forrester et al. 2006; Laganiere et al. 2010; Giling et al. 2013).

Tree plantation in salt-affected soils not only rehabilitate the salt-affected soils but also serve many ecosystem functions such as sequestration of atmospheric CO_2 and ensure livelihood security of the resource poor famers. In a reclaimed sodic soil, Datta et al. (2015) measured the distribution of organic C pools under different land uses, namely, guava (*Psidium guajava*), litchi (*Litchi chinensis*), mango (*Mangifera indica*), jamun (*Syzygium cumini*), *Eucalyptus* (*Eucalyptus tereticornis)*, *mesquite* (*Prosopis juliflora*), and rice-wheat cropping system and found the higher efficiency of guava plantation in sequestering SOC stock (133 Mg C ha^{-1}) and also in passive pool (76 Mg C ha^{-1}) at 2.0 m soil depth (Fig. 5). Similarly, Garg (1998) evaluated SOC build-up in an alkali soil under four tree land uses, such as, acacia [*Acacia nilotica* (L.)], shisham [*Dalbergia sissoo*], mesquite [*Prosopis juliflora*], and arjuna [*Tamarind arjuna*]) and showed that shisham and mesquite recorded higher organic C with higher microbial activities in upper 60 cm soil depth. A study showed that the C sequestration rate was 0.2–0.8 Mg C ha^{-1} $year^{-1}$ after 20 years of planting of

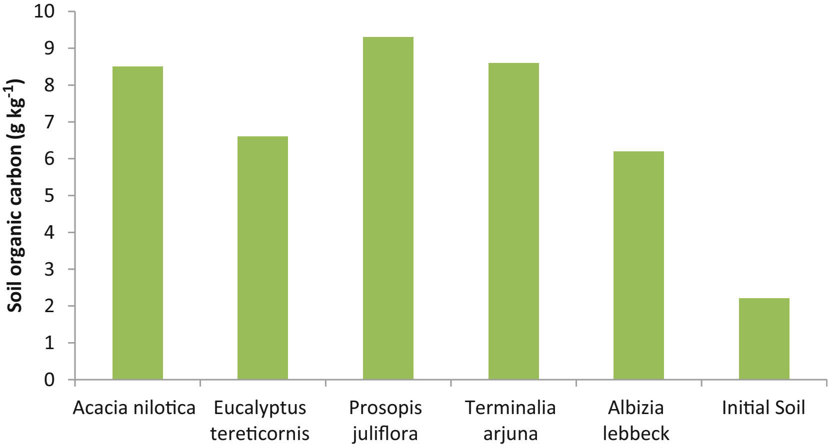

Fig. 6 Ameliorative effect of 20 years old tree plantations on soil organic carbon enrichment at 0–15 cm of an alkali soil (Data sources: Singh and Gill 1990).

different trees species in an alkali soil with maximum C sequestration under mesquite (9.3 g kg^{-1}) (Fig. 6) (Singh and Gill 1990).

The planting trees is a viable option for those situations where salt-affected soils cannot be reclaimed through conventional techniques. In salt-affected soils, due to lesser plant growth/vegetation, the C input to soil are very low which is the main cause of is lower SOC in salt-affected soils (Minhas et al. 2021). At ICAR-CSSRI, for commercial cultivation in salt-affected soils, a number of salt-tolerant agroforestry and fruit trees, shrubs, grasses, and medicinal and aromatic plants have been identified. Some of the promising agroforestry species are mesquite, acacia, *Tamarix articulata*, and *Casuarina equisetifolia*. In high pH soils, for sustained fuel wood and forage production, the *P. juliflora-Leptochloa fusca* based silvipasture system has been found promising. Appropriate planting techniques have been standardized for raising tree plantations in saline (subsurface planting, ridge-trench method, subsurface planting, and furrow irrigation system) and sodic (ridge-trench method, auger-hole method, pit auger-hole method, pit-auger hole and furrow method) soils. Different fruit-based agroforestry systems with bael (*Aegle marmelos*), amla, and karonda (*Carissa carandas*) as tree components and cluster bean (*Cyamopsis tetragonoloba*) (in *Kharif*) and barley (*Hordeum vulgare*) (in *Rabi*) as subsidiary components, have been found practically feasible and remunerative. These tree species significantly increased the C input to soil through roots and enhanced the SOC content in salt-affected soils. Moreover, SOC stock in soil can be improved under properly managed agroforestry system with the potential C sequestration rate of 1.5 to 3.5 Mg C ha^{-1} $year^{-1}$particularly in smallholder agroforestry system of tropics (Montagnini and Nair 2004).

“Biosaline agriculture” is another promising technology developed at ICAR-CSSRI. Here, salt-tolerant tree or plant species are successfully grown under highly saline soil or saline ground water. Halophytes such as *Salicornia*, *Atriplex*, and

Salvadora species are successfully grown in otherwise unproductive saline soils. Another promising technology is “biodrainage” which involves growing of salt-tolerant trees for lowering of the ground water table in waterlogged areas (Sharma and Singh 2019). The main criteria for selection of trees in biodrainage are salt tolerance and higher transpiration rate. *Eucalyptus tereticornis* is the most preferred tree species used in biodrainage. ICAR-CSSRI also developed a technology for the sustainable disposal of wastewater in tree plantations (Sharma and Singh 2019). Rehabilitation of salt-affected soils serves many ecosystem functions like atmospheric CO_2 sequestration and contributes to livelihood security of famers. Recently, C dynamics in salt-affected soils was reviewed by Datta et al. (2019), and they emphasized the tremendous potential of the salt-affected soils to sequester C which improved the quality of those degraded soils besides serving many ecosystem functions.

2.5 Soil and Water Conservation Measures

It is widely known that soil erosion destabilizes the productive agriculture land; leading to the reduced crop yield and soil C stock. Research in mountainous regions has observed that agricultural practices augment soil erosion, resulting in the adverse effects on the SOC stock (Lizaga et al. 2020). For the tropic region, influence of crop cultivation on inducing soil erosion is expected to be substantially on the lower side. In most cases, intensive agriculture activities or other anthropogenic-related activities generate high soil erosion, resulting in the formation of degraded lands devoid of any productivity (Pani 2020a, b). Under such conditions, plant growth and biomass production in areas having degraded soil environment may be better sustained and improved if soil and water conservation measures are undertaken.

To recover unproductive degraded lands, various soil and water conservation measures (SWCM), e.g. contour bund, terrace, check dams, trench, tree plantations, and agroforestry, have been found highly effective in controlling soil erosion. The trench and terrace creates favourable physical, chemical, and biological environment as well increase the SOC stock (Tenge and Hella 2005; Kebede 2014). In particular, higher SOC and soil water in terrace and trench have been reported to increases soil nutrients availability to facilitate the plant growth (Singh et al. 2020). The SWCM improve the soil physico-chemical properties through conservation of the soil nutrients in degraded lands. In particular, SWCM decrease the moisture, carbon, and nutrient loss through run-off and soil loss (Lal 2016). For instance, SWCM increased the availability of C, nitrogen, phosphorous, and potash in the soil (Singh et al. 2012b; Kaushal et al. 2021a; b). Further, Jiao et al. (1999) proved that SOC content increased by 25% in terraced land compared to slope after 20 years. This suggests that the SWCM have potential in improving soil physico-chemical properties of the degraded land (Moradi et al. 2012, 2014).

The soil conservation have been extensively reported to increases SOC which improves soil quality, resulting in the increased vegetation cover of degraded lands (Ran et al. 2013). For example, in China, Zhuang et al. (2016) found that SWCM improved tree canopy and the sapling survival up to 98% with spruce (97.0%) and cedar (98.0%). Similarly, Zhang et al. (2014) observed that the terraces and pits increased growth and canopy cover of *Pinus orientalis* in degraded land. In general, Singh et al. (2012a) also concluded that trenching improved SOC that increased the plant growth in the degraded lands. The quantity of water and nutrient conserved in soil and their availability determines the level of biomass production in plants (Hishe et al. 2017). For instances, SWCM were observed to increase the OC and nutrient availability in soils that contributed to the enhancement of biomass and C in sapota (Kumar et al. 2021b). By and large, reshaping degraded lands creates a congenial soil environment that results in greater biomass accumulation and consequently improved the SOC stock (Kurothe et al. 2014). In recent years, great interest has been generated in the ability of SWCM to accumulate SOC stock in the degraded lands (Chave et al. 2004; Navar 2008; Mugasha et al. 2013; Deng et al. 2017). For example, contour trench improved biomass in *Acacia catechu* that contributes in increasing the SOC in the degraded lands (Singh 2012; Singh et al. 2012a). In general, the SWCM-induced SOC enrichment in degraded lands could contribute to the climate change mitigation through enhanced CO_2 sequestration.

2.6 Agroforestry Practices

Globally agriculture accounted for 25% of CO_2, 50% of CH_4, and 70% of N_2O emission (Hutchinson et al. 2007). Emission of CO_2 is mainly due to burning of fossil fuels, clearing and burning of forest, and expanding and intensification of agriculture. Sequestering atmospheric C and storing it in the terrestrial biosphere are one of the best strategies for mitigating the GHG emission. Intergovernmental Panel on Climate Change (IPCC) reported that the land-based mitigation—agriculture and forestry—can be highly effective measure to mitigating GHGs emission. These measures can abate approximately 94–343 Pg C equivalent of GHG emission, which is 15–40% of the total abatement required for mitigating the climate change effects. Among all types of land use considered in the IPCC report, the agroforestry land use was observed to possess the highest potential for C sequestration. Agroforestry system (AFS) has a strong potential in the mitigation of atmospheric GHGs through accumulation in soil and plant systems (IPCC 2000). Estimating the amount of C sequestered by agroforestry poses unique opportunity and has indicated a mitigation potential of 1.1–2.2 PgC in terrestrial ecosystems over the next 50 years (Makundi and Sathaye 2004; Solomon et al. 2007). Similarly, it was estimated that the average C sequestration rate of the agroforestry is 0.2–3.1 t Cha^{-1} (Watson et al. 2000; Pandey 2002). Across the globe, several researchers have discussed the benefits and limitations of agroforestry in term of C sequestration (Schroeder 1994; Dixon 1995; Albrecht and Kandji 2003), but limited literatures are available on comprehensive comparisons of various practices in each eco-region. Lal (1999) estimated the C sequestering potential in dry lands to be fairly low and ranging between 0.05 and 0.3 Mg C ha^{-1} $year^{-1}$. Overall, degradation would also lead to a decline in SOC stock and an increase in CO_2 emission from such soils. Moreover, quantifying soil degradation induced production and C loss and factors that influence erosion, such as different agricultural practices, tree plantations, and native grasses either individually or in combination-based system is important. As there have been lack of agroforestry research conducted in degraded lands, the roles and relevance of agroforestry in restoring degraded soil, enhancing productivity, and sequestering SOC in these ecosystems are still unclear and non-existent; consequently continuous faulty agricultural practices have caused the huge loss of C from the soils. Therefore, a combination of different practices in agroforestry (annual + perennial) may greatly improve the systems hydrological conditions, plant productivity, and SOC sequestration potential (Kumar et al. 2020, 2021b).

Stefano and Jacobson (2018) conducted a meta-analysis of 53 published studies to assess changes in SOC stock after transforming different land-use systems to agroforestry. Findings showed a decrease in SOC stock of 25% in the land-use change from forest to agroforestry. The change from agriculture and pasture/grassland to agroforestry increased SOC stock by 34% and 9%, respectively. The conversion to agroforestry produced significant SOC stock increases at 0–30 cm (10%). Among AFS, significant SOC stocks increases were reported at various soil horizons and depths in the land-use change from agriculture to agrisilviculture and to silvopasture, pasture/grassland to agrosilvopastoral systems, forest to silvopasture, forest plantation to silvopasture, and uncultivated/other to agrisilviculture. Nevertheless, the IPCC (2000) estimated that 630 million ha of unproductive crop lands and grasslands could be converted to agroforestry worldwide, with the potential to sequester 586,000 Mg C year^{-1} by 2040. These AFS offers solutions to some of these climate change-related ecosystem management problems (Fig. 7). Therefore, agroforestry can be one of the tools for climate change adaptation and mitigation throughout the globe.

Global Status

Across the globe, diverse agroforestry practices have shown enormous potential to sequester atmospheric C (Tables 1 and 2). A comprehensive meta-analysis of soil C sequestration rates derived from 43 studies in agroforestry systems (0–60 cm depth) was undertaken in China which showed highest C sequestration rates in shelter belt (0.52–0.92 Mg ha^{-1} year^{-1}), followed by agrosilvicultural systems (0.43–0.70 Mg ha^{-1} year^{-1}) and silvopastoral systems (0.02–0.23 Mg ha^{-1} year^{-1}) (Hübner et al. 2021), indicating the highly effectiveness of shelter belts and agrosilvicultural systems to increase SOC stock.

In Europe, agroforestry relative to conventional agriculture contributes significantly to C sequestration, increases a range of regulating ecosystem services, and enhances biodiversity (Kay et al. 2019). The wide range of agroforestry practices was identified, and their C sequestration potentials were ranged between 0.09 and 7.29 t C ha^{-1} year^{-1}. Moreover, promoting agroforestry in the priority areas would improve the ecological and environmental services. The strategic and spatially targeted establishment of AFS could provide an effective means of meeting EU policy objectives on GHG emissions. The mean SOC stock of various AFS in North America was observed to be 3.6 Mg C ha^{-1} in riparian buffers, 6.9 Mg C ha^{-1} in

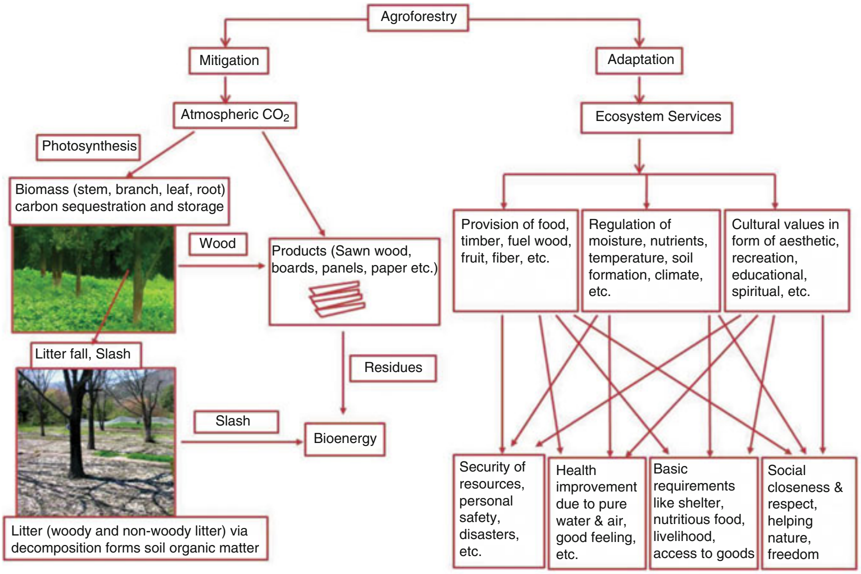

Fig. 7 Climate change mitigation and adaptation process in agroforestry

Table 1 Carbon sequestration potential of different agroforestry systems across globe

Ecological region	System	Potential (Mg ha^{-1})	References
Humid tropical high, Africa	Agrosilvicultural	29–53	Murthy et al. (2013)
Humid tropical low dry lowlands, South America		39–102 39–195	
Humid tropical dry lowlands, Southeast Asia		12–228 68–81	
Humid tropical low, Australia	Silvipastoral	28–51	
Humid tropical high humid tropical low dry lowlands, North America		133–154 104–198 90–175	
Humid tropical low, northern Asia		15–18	
Sub-Saharan, Africa	Agroforestry	8.4–33.7	Unruh et al. (1993)
Faidherbia albida parkland, Sahel, West Africa	Agroforestry	59.8	Takimoto et al. (2008)

alley cropping, 1.21 Mg C ha^{-1} in silvopasture, and 6.4 Mg C ha^{-1} year^{-1} in windbreaks (Udawatta and Jose 2011). Fontes (2006) studied the system of cacao (*Theobroma cacao*) with erythrina (*Erythrina variegata*) and reported the C sequestration rate of 2.7 Mg C ha^{-1} year^{-1}in Brazil. In Europe, a silvopastoral system based on Monterey pine (*Pinus radiata*) showed the C stock ranged between 40.8 and 102.4 Mg C ha^{-1} (Mosquera-Losada et al. 2011). The C sequestration rate in

Table 2 Carbon stock and sequestration rate in different agroforestry systems of the world

Region	System	Components	C stocks (Mg C ha^{-1})		C sequestration rate (Mg C ha^{-1} year^{-1})	References
			Range	Mean		
North America	Riparian buffers	Above-ground	7.5–269	123	2.6	Udawatta and Jose (2011)
		Below-ground	2.0–14.4	4.6		
		Soil	1.8–5.5	3.6		
	Alley cropping	Above-ground	0.05–96.5	26.8	3.4	
		Soil	0.05–25	6.9		
	Silvopasture	Above-ground	1.17–12.2	4.9	6.9	
		Soil	1.03–1.38	1.21		
	Windbreaks	Above-ground	0.68–105			
		Soil	23.1		6.4	
		Hybrid poplar		367.0	0.73	
		White spruce		186.0		
Canada	Shelter belt trees	Deciduous (green ash, Manitoba maple, hybrid poplar, and Siberian elm)	110–367			Kort and Turnock (1998)
		Conifers (white spruce, scot pine, and Colorado spruce)	107–186			
		Shrubs (choke cherry, villosa lilac, Buffalo berry, *Caranga* and sea buckthorn)	160–387			
Brazil	Cacao with *Erythrina*				2.7	Fontes (2006)

(continued)

Table 2 (continued)

Region	System	Components	C stocks (Mg C ha^{-1}) Range	C stocks (Mg C ha^{-1}) Mean	C sequestration rate (Mg C ha^{-1} $year^{-1}$)	References
Europe	*Pinus radiata*		40.8–102.4			Mosquera-Losada et al. (2011)
Africa	*Faidherbia albida* plantation				0.22–0.77	Woomer et al. (2004)
	Home gardens				0.4–0.8	Batjes (2004), Henry et al. (2009)
Eastern Tanzania	Rotational woodlot system		18–26	2.32–5.10		Kimaro et al. (2011)
Claveria, Philippines	Smallholder farming system	Above-ground	3.9 to 159.7	0.3–17.9		Brakas and Aune (2011)
Chilean Patagonia	Silvopastoral	AG + BG		224		Dube et al. (2011)

different AFS in African region was studied, and it was reported that the rate of C sequestration was in the range of 0.22–0.77, 0.4–0.8, and 0.22–5.8 Mg C ha^{-1} $year^{-1}$ in West, South, and East Africa, respectively.

Kimaro et al. (2011) reported C stock of 18–26 Mg C ha^{-1} and C sequestration rate of 232–5.10 Mg C ha^{-1} $year^{-1}$ in rotational woodlot system. The different AFS of the Claveria, Philippines, like home garden, mango plantation, multi-strata agroforest, and coffee plantation had C stocks >100 Mg ha^{-1} (Brakas and Aune 2011). The systems such as corn with mango, corn with timber trees, coconut plantation, coconut with banana, bush fallow, and corn with banana had relatively low C stocks (<20 Mg ha^{-1}). Some other AFS had C stocks within the range of 40–100 Mg ha^{-1}, i.e. corn with coffee (*Coffea arabica*), banana (*Musa paradisiacal*) with fruit trees, banana (*Musa paradisiacal*) plantations, fallow with indigenous and fruit trees, corn with timber and fruit trees, and woodlots (Brakas and Aune 2011). The C stock of above-ground and below-ground components together in silvopastoral systems and plantation was recorded 224 and 199 Mg C ha^{-1}, respectively, in Chilean region of Patagonia (Dube et al. 2011).

Indian Status

Agroforestry practices are considered sustainable land management tools to enhance biodiversity and increases C sequestration, compared with tree-less systems in India. In a study Kumar et al. (2020) showed that the sapota (*Manilkara zapota*)-based tree

Fig. 8 Total greenhouse gas emission and net carbon balance in different systems (Jinger et al. 2022)

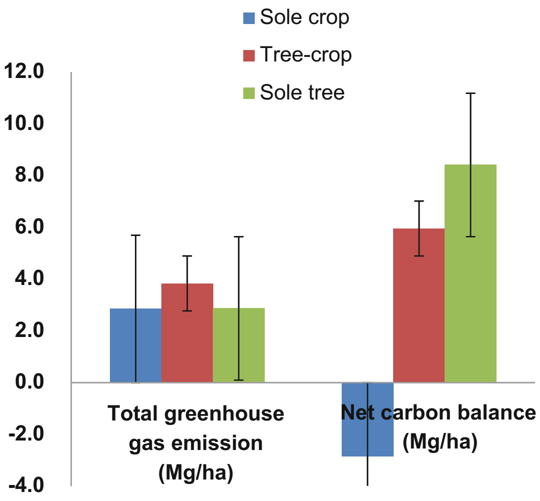

Table 3 Carbon sequestration potential through restoration of eroded lands in India

Erosion type	Area (M ha)	C sequestration potential (t C ha^{-1} $year^{-1}$)	Total potential (million t C $year^{-1}$)
Water erosion in arable lands	73.27	0.08–0.12	5.86–8.79
Ravine lands	3.97	0.14	0.56
Shifting cultivation	4.91	0.74	3.63
Water erosion in open forest	9.30	0.50	4.65
Pasture and grazing lands	10.26	0.53	5.44
Riverine lands torrents	2.71	0.15	0.41

Data source: Mandel et al. (2019)

plantation and soil–water conservation enhances C sequestration of agroecosystem in semi-arid degraded ravine lands. Findings showed that the cultivated terrace, trenching, and uncultivated terrace recorded 4.8%, 25.8%, and 43.4% lower C stock in sapota tree, respectively, compared with sole slope. Under similar set of conditions, the maximum total GHG emission was observed in tree-crop system, followed by sole crop system and minimum in sole tree system (Fig. 8). However, net biomass C stock and C sequestration were observed higher in sole tree system, compared to the tree-crop system (Jinger et al. 2022) which indicates that the tree plantation in degraded ravine land also improves the SOC stock. Kumar et al. (2022) further showed that the afforestation of degraded ravine practice improved the SOC stock by 73% (0–80 cm depth), compared to non-afforested ravine, as the SOC stock in afforested ravine was 3.50 Mg ha^{-1} higher as compared to the degraded ravine.

The increase in C sequestration potential through restoration of eroded lands in India is explained in Table 3. These studies indicate that degradation negatively affected the SOC stock in the degraded lands.

One of the paramount oil seed tree is coconut (*Cocos nucifera*) in tropical region and cultivated in >80 countries globally. This tree has a potential that can act as a net sink for atmospheric C besides supply of many other ecosystems services. The AFS of Karnataka and Tamil Nadu dominated by coconut and mango including other tree species recorded C stock of 0.81–4.73 and 0.66–6.59 Mg ha^{-1}, respectively (Murthy et al. 2013). Similarly, study also revealed that coconut tree can store C ranging from 47.01 to 107.60 Mg ha^{-1} in the coastal region of West Bengal (Mitra et al. 2018). Bhagya et al. (2017) studied coconut based intercropping with mango, jamun, and kokum (*Garcinia indica*) in Kerala and revealed that above-ground C stock varied from 53.02 (coconut + kokum) to 60.93 Mg ha^{-1} (coconut + jamun) and below-ground C stock (0–60 cm) ranging from 78.69 (coconut + kokum) to 82.47 Mg ha^{-1} (coconut + mango). However, coconut alone stored 51.14 Mg ha^{-1} as above-ground C and 47.06 Mg ha^{-1} as below-ground C.

In arid region of Rajasthan, India the agroforestry covers ~1.49 million ha area that play a vital role in mitigation and adaptation of climate change via trapping CO_2 from atmosphere and storing it in tree biomass. The major woody species, viz. *Prosopis cineraria*, *Capparis decidua*, *Tecomella undulate*, *Acacia tortilis*, *Ziziphus mauritiana*, and *Azadirachta indica* are dominant on farming land in scattered patches which are the backbone of livelihood of people in arid environment. These traditional AFS have stored biomass C in the range of 1.0 to 8.6 Mg ha^{-1} and organic C in soil ranging from 4.5 to 16.5 Mg ha^{-1} with a tree density varying from 1.4 to 14.9 trees ha^{-1} (Chavan et al. 2021). Agroforestry on farming land of Rajasthan has potentiality of 0.26 Mg C ha^{-1} year^{-1} and 0.95 CO_2 Mg ha^{-1} year^{-1} to reduce C footprints and mitigate climate change. A fruit tree-based orchard recorded soil organic C stock of 14.5 Mg ha^{-1} in surface soil layer (0–30 cm) with highest (19.5 Mg ha^{-1}) in Khejri block (Singh and Singh 2015).

In Northern part of India, the block plantation of multipurpose tree species such as *Eucalyptus* (2.5–3.5 year age) with 2500–2777 trees ha^{-1} and *Tectona grandis* (10 to 30 year age) with 494–570 trees ha^{-1} has the potentiality of C sequestration of 4.40–5.90 and 2.25–3.74 Mg C ha^{-1} year^{-1} (Dhyani et al. 1996). *Populus deltoids* (7 year age) in agroforestry with 400 to 740 trees ha^{-1} have been reported C sequestration potential ranged between 1.98 and 9.40 Mg C ha^{-1} year^{-1} in Indo-Gangetic region (Chauhan et al. 2010; Rizvi et al. 2011). In the tropical region mixed tree species which are being grown in the form of home garden have been sequestered 1.60 Mg C ha^{-1} year^{-1} which was 71 years old with 667 individuals ha^{-1} (Saha et al. 2009). The mitigation and adaptation strategies of AFS have been illustrated in the Fig. 7. Mitigation includes long-term and short-term sequestration of C in biomass and soil and emission reduction. Ecosystem services are the major contributor in adaptation to reduce the vulnerability that ultimately leads to improvement of security, health, and social status. The C sequestration potential of various AFS in India is explained in Table 4.

Table 4 Carbon sequestration potential of various agroforestry systems in India

Agroforestry systems	Region	C sequestration potential (Mg C ha^{-1} year^{-1})
Agri-horticulture	Northwestern Himalayas	2.08
Agrisilviculture	Northwestern Himalayas	0.63–0.8
Silvopastoral system	Northwestern India	6.82
Agrisilviculture system	North India	34.61
Home gardens	Kerala	1.60
Silvi-pasture	Semi-arid areas of India	1.89–3.45
Agrisilviculture	Uttar Pradesh	3.70
Agrisilviculture	Central India	31.37
Agrisilviculture	Central Himalaya	0.256

Data source: Zahoor et al. (2020)

3 Soil Organic Carbon Behaviour

The behaviour of SOC varies with the soil physico-chemical properties. For instances, soil salinity decreases the global SOC stock as world soils may lose 6.8 Pg SOC due to salinity by the year 2100 (Setia et al. 2013). Higher sodicity and the presence of Na^+ make SOM more mobile and cause erosion loss of dissolved organic matter (DOC) and labile SOC pools in the salt-affected soils (Mavi et al. 2012; Singh et al. 2022). Further high sodicity imparts recalcitrant character to the SOC as the basic electrolytes (Ca^{2+}, Mg^{2+} and Na^+) block the functional groups of organic matter such as COOH and OH forming polymers of dense inflexible molecules resistant to microbial attack (Oades 1988). Incorporation of organic amendments in sodic soils is a better management option with great advantage of improvement in soil biological properties compared to chemical fertilizer. Application of organic amendments leads to increased partial pressure of CO_2 within soil profile that lowers the pH value in soil solution and subsequently increases the dissolution of native $CaCO_3$ mineral and reduces the soil sodicity. Sodic soils generally have poor structural stability attributed to low organic matter and high sodium contributing soil dispersion (Wang et al. 2021; Minhas et al. 2021). The organic amendments incorporation in sodic soils binds the small particles of soil in to large water-stable aggregates thus sequesters more C in the soil aggregates. Salt-affected soils have a great potential to sequester organic C upon application of organic amendment. Saline soils are a better niche for organic C sequestration due to better aggregation (Deb et al. 2020). Qu et al. (2019) also observed reduction in the decomposition rate of soil C and DOC with increase in salinity level. Contradictory to this, in arid regions the saline water application reduces the SOM content from 0.34% to 0.25%. However, the incorporation of organic amendments results in a significant increase in SOC under canal water irrigation with FYM treatment (0.68%). Similarly, FYM treatment enhances SOC content even under saline water irrigation. Chandel et al. (2021) also reported that alternate application of saline and fresh water helps in the build-up of soil C while maintaining the soil nutrient pools compared to sole application of saline or fresh water application. Thus, saline water application alone and alternatively with organic amendment can enhance SOC content in soil.

Biochar plays an important role in soil C fixation. Biochar improves the SOC significantly in the surface soils (Sun et al. 2020), and the total organic C is not affected by the biochar application. Biochar has the great potential to store large quantity of C in soil. It acts as a soil conditioner that enhances the crop productivity and soil quality along with decreasing the GHG emission (Singh et al. 2019a; b; Wu et al. 2019). Biochar increases the recalcitrant SOC pool that further leads to C sequestration (Yanardağ et al. 2015). The recalcitrant fraction/passive pool of C increased with carbonization temperature that enhances C storage in the soil (Saleem et al. 2022). Conclusively, biochar produced at higher temperature (>500 °C) sequesters more C compared to biochar produced at lower temperature. Chahal et al. (2017) also reported that biochar application to saline soils can be used as an important source to sequester C while minimizing nutrient losses in the salt-affected soils. Biochar application at different rate significantly increases DOC at all the salinity levels (Singh et al. 2018). They also reported that application of biochar at the rate of 2–4% enhances DOC by 52–89% in EC 8 dSm^{-1} and 81–119% in EC16 dSm^{-1} soil, respectively. Chahal et al. (2017) reported that DOC was highest in glucose amended soil followed by rice straw > farmyard manure > = biochar> = unamended soils as glucose decomposes more rapidly than the other amendments.

The addition of vermicompost is also proved to be a good strategy for the full recovery of saline-sodic soils. Application of 10% vermicompost reduces 50% of the exchangeable sodium percent. Similarly, application of pressmud mitigates the adverse effect of saline irrigation by reducing the soil sodium adsorption ratio and increasing the SOM content (Muhammad and Khattak 2009). Neutralization of alkalinity by pressmud and gypsum+pressmud increases crop yield that returns more C to soils (Basak et al. 2021). Pressmud increases the very labile pool of the C which was associated with higher organic matter, cellulose, hemicellulose, and lignin nutrient availability through pressmud application compared to gypsum and control.

4 Challenges of Carbon Sequestration in the Degraded Lands

Soil C sequestration as stable SOM provides a long-term solution to reduce the CO_2 concentration in the atmosphere (Gupta and Sharma 2011a; b) and supports the resilience of agroecosystems and environmental sustainability (Yadava 2010). Soil C sequestration plays a crucial role in enhancing soil health and agricultural productivity (Cowie et al. 2011) and prevents the degradation of soil (Rajan et al. 2010). Despite the huge potential of soil to store C, several constraints and challenges are hindering the C sequestration potential in these soils. The multifold constraints, such as various biotic and abiotic disturbances, are causing land degradation and are also posing difficulties in their rehabilitation (Tomar et al. 2021). At present, best agricultural and forest-based ecosystem models are not available that may support restoration of degraded lands. In arid regions, SOC is limited by the accelerated rate of oxidation under prevailing high temperatures (Lal 2003). The unavailability of moisture in arid zones may further worsen the soil C storage potential. Moreover, depletion in SOC is one of the most deceptive and hidden processes of soil degradation that negatively affects agricultural production through altering soil properties and microbial activities and occurrence of essential nutrient deficiencies.

Some of the major limitations that are hindering the reclamation progress include the outdated database of degraded lands, limited technological options for managing and reclaiming the degraded lands, increased vulnerability of degraded lands to changing climate, and barriers in technology adoption and implementation by the stakeholders (Kaushal et al. 2021b). Demenois et al. (2020) reveal the predominance of social and economic barriers such as lack of knowledge or training, increased difficulties of fieldwork, workload, risk handling, funding, and social pressure. Biophysical constraints such as limited potential of SOM storage or rainfall scarcity and variability also appear more to be important.

The harmonizing remote sensing data generated at different scales and adopting modelling approaches could help in the rapid assessment of C status in the degraded lands of the country. Identification of hotspots through high-resolution data and their ground-truthing improves the accuracy of remote sensing data. To gain progress in this direction, both understanding basic processes and effective technology implementation would be important for effectively managing and restoring the soil C of degraded lands. The changing circumstances require a multidisciplinary approach to tackle multiple challenges of degraded lands such as water scarcity, salinity stress, soil erosion, heat stress, drought, nutrient deficiencies, and elemental toxicity as these factors are responsible for decline of soil C. Moreover, there is a need to address the multiple stressors simultaneously rather than focusing on single stress alone, and an integrated land management package is needed to be developed by taking into consideration a large number of factors together to revive soil C of degraded lands.

Climate change has been posing a huge risk to the farming community especially in the arid and semi-arid degraded lands. Therefore, in degraded rain-fed areas of the country, building resilience to climate change is urgently required through adaptation and mitigation measures. The precise delineation of climate change effects and devising adaptive strategies especially for crop production and farmer livelihood security could reduce the vulnerability to climate-induced risks. The climate change has caused an increase in degraded lands and loss of soil C in the different states of India. The IPCC (2021) has also emphasized that desertification and land degradation are the two most important concerns of the changing climate. The development of a crop and agroecosystem specific package of practices could enhance agroecosystem resilience and adaptive capacity in degraded lands, especially in the direction of water management and agroforestry development in the rain-fed areas.

Despite massive yearly CO_2 exchanges between the atmosphere and agricultural areas, the net flow is expected to be nearly balanced when land-use change is taken into account (Alscher 2011). The conversion of the degraded land into different productive systems like cropland, forest, alley cropping, pasture land, and other vegetation for atmospheric CO_2 capturing is a challengeable task in view of the financial constraints and lack of skilled manpower (Meena et al. 2020). India has already accepted the “Bonn Challenge” in a worldwide initiative to rehabilitate 26 million ha of deforested and degraded land by 2030 (The Hindu 2020) for that effective technological implementation is urgently required to achieve the desirable outcome. During the Conference of the Parties (COP) 2015 in Paris, India has made one of the most significant commitments in Asia to join the hand in fighting against climate change (ICAR 2020). As a result, there is an urgent need to increase areas under arable lands by transforming degraded lands into different agricultural ecosystems through sustainable intensification (IPCC 2021).

5 Futuristic Strategies for Carbon Sequestration in Degraded Lands

The soil C sequestration is recognized as a cost-effective strategy to mitigate climate change during first two to three decades of the twenty-first century. At present, the GHGs in atmosphere are increasing at the rate of 0.5%, 0.6%, and 0.25 ppb for CO_2, CH_4, and N_2O, respectively, and the contribution to global warming to an extent of 20% is due to agricultural activities and 14% is due to land-use changes and unregulated deforestation. Major agricultural activities that contribute to emission of GHGs include ploughing, application of manures and fertilizers, soil drainage, biomass burning, and crop residue removal. The soil degradation factors such as erosion, compaction, decline in soil quality, and salinization are also responsible for emission of GHGs, especially loss of soil. Historic global C loss due to agriculture is estimated at 55 Pg to 100 Pg from soil C pool and 100–150 Pg from the biotic C pool. Adoption of recommended agricultural practices can lead to an enhanced SOC storage and accumulation as well as contribute to the restoration of soil quality. Improved agricultural practices include mulching and conservation tillage, growing cover crops, eliminating summer fallow, using balanced fertilizer inputs including precision farming and use of biosolids, adopting improved cropping systems and CA, applying integrated nutrient management and soil amendments including biochar, promoting afforestation and agroforestry, managing soil-water through drainage and irrigation, and restoring degraded soils has enormous potential to sequester C in the vegetation and soil systems. Establishment of perennial pastures can also sequester 0.84 ± 0.11 Mg C ha^{-1} $year^{-1}$ in different kinds of lands. The long-term solution to the risk of potential global warming lies in finding alternatives to fossil fuel. Stratification of SOC with depth was common under conservation agricultural management and appears to be integrally linked to abatement of soil erosion, improvement in water quality, and SOC sequestration. Conservation and management of degraded land have the potential to build soil fertility, restore soil functions, and mitigate GHGs emissions due to accumulation of organic matter on soil surface. Land management practices such as water management, fencing, and biodiversity improvement may also improve C sequestration (Stavi and Lal 2015; Meena et al. 2020). Therefore, the strategy of soil C sequestration in degraded land is a bridge to a brighter future.

African continent contributes around only 3% of the total global CO_2 emissions from fossil fuel burning and cement production, and it could participate in the management of the global C cycle through C sequestration. Improvements in agricultural techniques and land-use practices could lead to a higher agricultural productivity and soil C accumulation. Soil C constitutes a significant part of the total C stock in Africa, and land-use systems and agricultural practices increasing the soil C stock could produce GHG offsets that foreign investors might purchase under the clean development mechanism. In the Southeastern United States, land owners have great potential to restore soil fertility and mitigate greenhouse gas emissions through adoption of improved conservation agricultural systems (e.g. continuous no-till, high-residue crop rotations, high organic matter inputs).

Overall, the cause of the degradation must be recognized and treated to rehabilitate and improve productivity of degraded land. Designing the agriculture and tree plantation ecosystem models based on the land and local identified resources may immensely support in restoring the degraded land. It could also support the ecological services and soil biodiversity for maintaining the long-term sustainability of land resources under the changing climate.

6 Policies and Programmes

The restoration of degraded lands requires devising appropriate policy and action plans. Accordingly, various centrally sponsored schemes, policies, and programmes have been implemented in India to restore and address the issues associated with such soils, which are as follows:

6.1 National Mission for a Green India

The National Mission for a Green India, sometimes also abbreviated as the Green India Mission (GIM), is one of eight missions formed as part of the National Action Plan on Climate Change (NAPCC). It was started in February 2014 with the objective of maintaining, restoring, and increasing India's declining forest cover, as well as adapting and mitigating the effects of climate change. It envisions a comprehensive approach to greening that goes beyond tree planting and prioritizes multiple ecosystem services such as biodiversity, water, and biomass conservation. The protection of mangroves, wetlands, and critical habitats, as well as provisioning services such as fuel, fodder, and timber and non-timber forest products, as well as increased income from forest-based livelihoods for households living in and around forests were also priotrized under this scheme. The objective might also enhance C sinks, particularly via sustainable management of forests and degraded lands, in order to assist fragile species/ecosystems and forest-dependent populations in adapting to changing climate.

6.2 National Afforestation Programme

The National Afforestation Programme (NAP) was formed through the consolidation of four ninth plan centrally sponsored afforestation schemes administered by the Ministry of Environment, Forests and Climate Change, namely, the Conservation and Development of Non-timber Forest Produce including Medicinal Plants Scheme (NTFP), the Integrated Afforestation and Eco-Development Projects Scheme (IAEPS), the Area Oriented Fuel Wood and Fodder Projects Scheme (AOFFPS), and Association of Scheduled Tribes and Rural Poor in Regeneration of Degraded Forests (ASTRP) in year 2000. This programme is operated by the National Afforestation and Eco-Development Board and Ministry of Environment, Forest and Climate Change, Government of India (MoEFCC), for afforestation of degraded forest lands. The main objective of NAP is ecological restoration of degraded forests and to develop the forest resources with peoples' participation with focus on improvement in livelihoods of the forest-fringe communities, especially the poor.

6.3 Compensatory Afforestation Fund Management and Planning Authority

Compensatory afforestation means whenever forest land is diverted for non-forest purposes such as mining or industry, the user agency pays for forest planting on an equal area of non-forest land, or twice the area of degraded forest land, if such land is not available. In summary, Compensatory Afforestation Fund Management and Planning Authority are intended to encourage afforestation and regeneration operations while also ensuring sustainability as a strategy to compensate for forest land that has been transferred to non-forest uses. The funds are mostly used to treat watershed regions, support natural generation, manage forests, preserve and manage wildlife, relocate communities from protected areas, manage human-animal conflicts, provide training and awareness, and offer wood-saving equipment, among other things.

6.4 National Action Programme to Combat Desertification

As a signatory to the United Nations Convention to Combat Desertification (UNCCD), India, developed the National Action Programme for Combating Desertification in 2001 to address the issues of desertification.

6.5 Green Highway Policy 2015

The Ministry of Road Transport and Highways introduced the Green Highway initiative in 2015 to encourage the greening of highway corridors with the involvement of the community, farmers, non-governmental organizations, and government institutions. The policies' particular aims were to encourage greening and construction of environmentally friendly national highway corridors that would overcome issues and prepare the way for sustainable development. Simultaneously, it will mitigate the impact of air pollution and dust on the national highways by planting trees and bushes which function as natural sinks for pollutants in the air and will help prevent soil erosion on embankment slopes. It will also improve the C sequestration in areas that would otherwise be barren and unutilized.

6.6 National Agroforestry Policy, 2014

India becomes the first country to adopt a comprehensive policy on agroforestry, i.e. National Agroforestry Policy, 2014. In order to address the agroforestry sector's challenges which include adverse policies, weak markets, and a scarcity of institutional finance for transforming lives of rural farming communities, protecting ecosystems, and ensuring food security through sustainable means. The primary objectives were to encourage and increase tree planting in an integrated manner and complementarily way, to protect and stabilize ecosystems, and to promote resilient farming. In India, the total area under agroforestry is predicted to double by 2050 due to restoration of fallows, cultivable fallows, pastures, and groves, as well as rehabilitation of degraded and problematic soils.

6.7 Reducing Emissions from Deforestation and Forest Degradation

Globally, anthropogenic emissions from land use, land-use change, and forestry account for between 9% and 11% of global GHGs emissions, owing to widespread deforestation and forest degradation in developing nations (IPCC 2014). To combat this, the agenda of "Reducing emissions from deforestation and forest degradation in developing countries (REDD)" was first introduced in United Nations Framework Convention on Climate Change (UNFCCC) as a climate change mitigation option to address the emission from deforestation and forest degradation in 2005. With time, the notion of "forest conservation, sustainable management of forests and enhancement of forest C stocks in developing countries" was introduced and the concept is now collectively referred to as "REDD+." All five REDD+ programmes are focused on increasing and improving forest and tree cover (FTC), which aligns with the National Forest Policy's target of bringing 33% of the country's land area under FTC. Trees outside forests (TOF), particularly on degraded areas, can considerably contribute to the country's C sink. Particularly, TOF action will be a critical component of the country's REDD+ plan, which aims to increase forest C sinks by 2.5 to 3 billion tonnes of CO_2 equivalent by 2030, as stated in the country's Intended Nationally Determined Contributions (INDC) to the UNFCCC.

7 Conclusion

Land degradation is threatening the livelihood of global population as well as adversely affecting the carbon stock of soils. The application of organic amendments, conservation agriculture, soil conservation measures, tree plantation, and agroforestry practices has indicated strong potential in enhancing productivity and increasing net soil carbon stock in degraded lands. Although the large number of practices have been developed for restoring soil carbon, the validation and comparison of best practices is still needed to be further explored. More studies examining how much C can be sequestered or stored in different degraded lands around the world are needed. Moreover, the sustainable land management via restoring land productivity and soil carbon stock is the most promising tools for halting and reversing land degradation and desertification and therefore could contribute in achieving the food security and land degradation neutrality.

8 Future Prospective

The soil C sequestration can be enhanced through reclamation of the degraded lands. Globally, a large area is available for the plantation activities and other similar activities. There is a need to focus on afforestation, reforestation, and agroforestry plantations on degraded lands in order to reclaim targeted 26 million ha area of degraded lands by 2030 in India. This will help in providing a boot to the ecology and economy of the regional populations, besides availability of raw material to the industries. Agroforestry and organic matter enrichment practices will improve the soil fertility and store huge amount of the carbon via stabilizing the atmospheric CO_2. Degraded lands are often characterized by acidic pH, low levels of key nutrients, poor soil structure, and limited moisture retention capacity, and these practices will also improve the soil physio-chemical properties. Moreover, good deal of information is available about the ways to improve degraded soils, but the cost of implementation is often a limiting factor. However, the additional financial and environmental benefits of C sequestration may compensate the economics of land reclamation activities. Therefore, there is a need to devise appropriate policy and action plans to restore SOC stock of the degraded lands.

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