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Review

Carbon sequestration potential, challenges, and strategies towards climate action in smallholder agricultural systems of South Asia

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ABSTRACT

South Asia is a global hotspot for climate change with enormous pressure on land and water resources for feeding the burgeoning population. The agricultural production systems are highly vulnerable in the region and is primarily dominated by small and marginal farmers with intensive farming practices that had favored the loss of carbon (C) from soil. This review discusses the potential of soil and crop management practices such as minimum/reduced/no-tillage, use of organic manure, balanced and integrated plant nutrient application, precision land levelling, precision water and pest management, residue management, and cropping system optimization to maintain the C-equilibrium between soil and atmosphere and to enhance the C-sequestration in the long run. Results of meta-analysis show a potential 36% increase in soil organic C stock in the top 0–15 cm layer in this region which amounts to ~18 Mg C stocks ha^{-1}. Improved management practices across crops and environment may reduce methane em0ission by 12% resulting in an 8% reduction in global warming potential (GWP), while non-submerged condition led to a 51% GWP reduction in rice. Conservation agriculture and precision fertilization also reduced GWP by 11 and 14%, respectively. Although several innovative climate resilient technologies having significant potential for C-sequestration have been developed, there is an urgent need for their scaling and accelerated adoption to increase soil C-sequestration. Policies and programs need to be devised for incentivizing farmers to adopt more C-neutral or C-positive agricultural practices. The national governments and other agencies should work towards C farming together with global initiatives such as the "4 per 1000" Initiative and Global Soil Partnership, and regional public-private partnership initiatives on carbon credits for Regenerative Agriculture such as by Grow Indigo-CIMMYT-ICAR in India, in addition to research and policy changes. This will be vital for the success of soil C sequestration towards climate action in South Asia.

1. Introduction

Globally, the average temperature has increased more than one-degree Fahrenheit since the late 1800s, and most of this increase has occurred over just the past few decades. The world's most renowned climate scientists have warned that only a dozen years remain that global warming can be kept at a maximum of 1.5 °C, beyond which an increase of even half a degree will significantly worsen the risk of drought, floods, extreme heat, and poverty for hundreds of millions of people (The Guardian, 2018). The increase in temperature has resulted from the rising levels of greenhouse gases (GHGs) in the atmosphere: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F).

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These levels have risen by about 40% in the last 150 years, with half of that rise occurring in the last three decades.

About half of cumulative anthropogenic CO_2 emissions between 1750 and 2010 have occurred in the last 40 years (IPCC et al., 2014). From 1750 to 1970, cumulative CO_2 emissions from fossil fuel combustion were 420 ± 35 Gt CO_2, and these had tripled to 1300 ± 110 Gt CO_2 by 2010. Between 1750 and 2010, cumulative CO_2 emissions from forestry and other land use changes increased from 490 ± 180 Gt CO_2 to 680 ± 300 Gt CO_2. Of the total GHG emission in 2014, CO_2 accounted for 76%, CH_4 for 16%, and N_2O for 6% (Table 1). At the end of 2019, annual CO_2 emissions from industrial activities and the burning of fossil fuels have increased to 36.8 Gt, and total CO_2 emissions from all human activities, including agriculture and land use, have increased to 43.1 Gt of CO_2 (Harvey and Gronewold, 2019). Today, the agricultural sector has a significant carbon (C) footprint and accounts for >25% of worldwide anthropogenic GHG emissions. Besides fossil fuel burning, the decomposition of soil organic matter (SOM) and crop residue burning are major sources of CO_2 emissions. Methane emission in agriculture occurs from flooded soils under rice cultivation, enteric fermentation in the digestive systems of livestock, and the decomposition of manure and crop residues under wet conditions. Emissions of N_2O in agriculture result predominantly from soils fertilized with nitrogen, manure, and compost that release inorganic nitrogen into the soil. Among the largest emitters in agriculture are enteric fermentation (40%), manure left on pasture (16%), synthetic fertilizer (16%), paddy rice (10%), manure management (7%), and burning of savannahs (5%) (FAO STAT, 2014).

Carbon dioxide and other gases emitted from industrial and agricultural sources trap heat in the atmosphere, resulting in an increase in global average temperatures and thus global climate change (IPCC, 2018). The increase in concentration of GHGs in the atmosphere has a wide range of effects: rising sea levels; the increasing frequency and intensity of wildfires; more extreme weather events such as changes in the amount, timing, and distribution of rain, snow, and runoff; deadly heat waves; severe droughts; and tropical storms; and is a threat to food production. Therefore, controlling the emission of GHGs into the atmosphere is considered as the greatest environmental challenges of this century (Amundson and Beaudeu, 2018). Globally, economic and population growth are the most important drivers of increasing GHG emissions and are projected to increase continuously in future. Therefore, any reduction in GHG emissions is uncertain, and further increase in emissions cannot be ruled out.

Soils constitute the largest C pool both in organic and inorganic forms. The amount of C in SOM ranges from 40 to 60% by weight. Although SOM usually constitutes less than 5% of soil weight, it is one of the most important components of a field ecosystem (Lal, 2015). Globally, approximately 2300–2500 Gt of C (about 60% organic and 40% inorganic) is stored in the top 2 m (1200–1600 Gt in 1 m) of soil, of which about 70% is stored in the subsoil below 0.2 m (Batjes, 1998; Paustian et al., 2016). The amount of C in soils is more than three times that of C in terrestrial vegetation, and at least 230 times higher than the 2009 global CO_2 emissions (Sommer and Bossio, 2014). From this amount, approximately 60 Gt of C is exchanged with the atmosphere annually (Eswaran et al., 1993; Schlesinger, 1997; Solomon et al. 2007). Because of large C pool, soils offer the potential for GHG mitigation through C sequestration in aboveground biomass or soils. Additionally, the management of biophysiochemical properties of soil and vegetation mitigates climate change by reducing emissions. Globally, there has been a strong interest in capturing C in agricultural soils, not only to mitigate the risk of global warming, but also to improve the soil quality (Bernoux et al., 2006; FAO and ITPS, 2015; Lal, 1997; 2011; Minasny et al., 2017; Paustian et al., 2016; Smith, 2008; World Bank, 2012).

Table 1
Global greenhouse gas emissions (Source: IPCC et al., 2014).

Gas	Source	Emission rate (Gt CO_2-e yr^{-1})	Percent of total GHG emission
Carbon dioxide (CO_2)	Fossil fuel burning	32.5	65
	Forestry and other land use (deforestation, land clearing for agriculture, and degradation of soils)	5.5	11
Methane (CH_4)	Agricultural activities, waste management, energy use, and biomass burning	7.8	16
Nitrous oxide (N_2O)	Agricultural activities, such as fertilizer use, are the primary source. Fossil fuel combustion also generates N_2O	3.19	6
Fluorinated (F-gases)	Industrial processes, refrigeration, and the use of a variety of consumer products [include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6)]	1.0	2

This paper reviews general aspects of soil C sequestration, including its potential and associated challenges and risks, with a special reference to South Asia. It presents a detailed account of management practices to enhance soil C storage and GHG mitigation, and a meta-analysis of published appraisals in the cropping systems of South Asia.

2. South Asia – a hot spot for soil C loss and GHG emissions

Agriculture in South Asia is predominantly cereal-based, i.e. the cultivation of about 40 million hectares with multiple cereal crops or a single cereal crop, followed by a non-cereal crop such as legumes, vegetables, or potatoes, in an annual rotation (http://www.fao.org/3/y1860e/y1860e07.htm). Rapid population growth and climate unpredictability in South Asia will increase the demand for food by at least 40% by 2050 (Bodirsky et al., 2015). Meeting this projected need is doubly challenging, considering that 94% of the land suitable for farming is already under production and that 58% of agricultural areas face multiple hazards such as water shortage and extreme heat stress (Amarnath et al., 2017). It is anticipated that the current situation will worsen with climate change, which includes rising temperatures (Muthukumara et al., 2018). The region is undergoing rapid economic growth, resulting in an increase in the emission of GHGs into the atmosphere. As of 2017, South Asia accounted for 7.5% of the world's total CO_2 emission from burning fossil fuels, of which India's share was 6.6% and the remaining less than 1% was shared by seven other countries in the region (Table 2). A large proportion of the total GHG emission from agriculture in South Asia comes from CH_4 and N_2O, representing 17% of the world's total in 2017 with 179% increase since 1990 (Table 3). India accounted for 11.8% and the other seven countries for the remaining 5.2% of total global CH_4 and N_2O emissions. Among the major sources of GHG emissions, rice cultivation is responsible for both CH_4 and N_2O emissions (Table 4). In South Asia, on a CO_2-equivalent (CO_2-e) basis, rice cultivation (134697 Gg) and N fertilization (141935 Gg) are responsible for the largest emissions. Other sources of CH_4 emissions include crop residue burning (3447 Gg

Table 2
Fossil CO_2 emissions by country/region in 2017.

Country	Total (Mt CO_2 yr^{-1})	Percent of world	Per land area (t CO_2 km^{-2} yr^{-1})	Per capita (t CO_2 cap^{-1} yr^{-1})	% increase from 1990
World	37077.4	100	73	4.9	63.5
South Asia	2782.5	7.5	654	1.1	561
Afghanistan	11.4	0.03	18	0.3	349
Bangladesh	84.5	0.23	573	0.5	510
Bhutan	1.45	0.00	38	1.8	599
India	2454.7	6.62	747	1.8	305
Maldives	0.96	0.00	3213	2.2	1383
Nepal	8.21	0.02	56	0.3	671
Pakistan	197.3	0.53	224	1.0	198
Sri Lanka	23.98	0.6	365	1.1	473

Table 3
Methane and nitrous oxide emissions (CO_2-e) in 2017 and CO_2 emission in 2012 from agriculture in south-Asian countries (Source: FAOSTAT).

Country	Emission (Mt yr^{-1})			Emission (% of world)			Increase from 1990 (%)		
	CO_2[a]	CH_4	NO_2	Total (CH_4+N_2O)	CH_4	N_2O	Total	CH_4	N_2O
World	817.5	2984.19	2426.28	100	100	100	59.7	11.8	26.0
South Asia	165.02	615.13	337.15	17.0	20.6	13.9	178.7	23.7	66.4
Afghanistan	13.82	8.70	5.12	0.3	0.3	0.2	88.4	92.9	81.1
Bangladesh	77.30	50.13	27.16	1.4	1.7	1.1	33.2	18.6	72.4
Bhutan	0.46	0.35	0.11	0.0	0.0	0.0	−17.3	−19.8	−7.5
India	639.42	415.36	224.06	11.8	13.9	9.2	27.2	13.9	62.4
Maldives	0.00	0.00	0.00	0.00	0.00	0.00	0.00	850.0	0.00
Nepal	22.45	16.57	5.88	0.4	0.6	0.2	42.1	37.2	57.7
Pakistan	163.96	106.65	57.31	3.0	3.6	2.4	112.7	109.8	118.2
Sri Lanka	4.57	3.05	1.53	0.1	0.1	0.1	−26.2	−32.1	−10.4

[a] Associated with fuel burning and generation of electricity used in agriculture including fisheries estimated in 2012.

Table 4
Major sources of greenhouse gas emissions from agriculture in South Asia during 2017 (Source: FAOSTAT).

	Emissions of GHG in terms of CO_2-e (Gg)					
	Rice cultivation		Synthetic fertilizer	Applied manure	Crop residue	Burning of crop residue
	CH_4	N_2O	N_2O	N_2O	N_2O	CH_4
South Asia	134697	1434	141935	24052	34757	3447
Afghanistan	322	23	909	495	403	59
Bangladesh	23529	148	8007	1830	3935	386
Bhutan	50	1	5	14	13	2
India	97070	1050	109466	15644	26148	2744
Nepal	3414	45	591	708	762	119
Pakistan	8528	156	22249	5273	3318	409
Sri Lanka	1774	11	708	88	178	28

CO_2-e), and other sources of N_2O emissions include the application of manure (24052 Gg CO_2-e) and crop residues (34757 Gg CO_2-e) to soils.

Meeting the increased demand for food during the Green Revolution was associated with intensive cropping, soil management, and the use of agrochemicals, hence, resulted in the gradual loss of SOM (Singh et al., 2009; Yadvinder-Singh et al., 2004). Although crop productivity has doubled or tripled during the last decades, negative impacts on the environment, biodiversity, soil, and air quality are common consequences (Godfray et al., 2014; Tilman et al., 2011). Conventional cultivation practices with exhaustive tillage and removal of crop residues by burning or for other uses in South Asia have not only resulted in nutrient and C losses but have also created a severe air pollution problem (Lohan et al., 2018). About 2 million farmers in northwest India burn an estimated 23 million tons of rice residues every year (NAAS, 2017). In some of the cities of northwest India, particulate air pollution in 2017 exceeded by more than five times the safe daily threshold limit, causing severe health problems both in rural and urban areas (Cusworth et al., 2018). Continuous tillage with the removal or burning of crop residues has also brought about the loss of SOM, resulting in a lower threshold, and adversely affecting soil functioning (Lal, 1997).

3. Carbon sequestration

The term "C sequestration" has been defined in many ways (Bernoux et al., 2005) but broadly it is used to describe both natural and deliberate processes by which CO_2 is either removed from the atmosphere or diverted from emission sources and stored in the terrestrial environment (vegetation, soils, and sediments), oceans, and geological formations (USGS, 2011). It is the process of capture and long-term storage of CO_2 in a stable state. This process can be direct or indirect, and can be biological, chemical, geological, or physical in nature. When inorganic CO_2 is sequestered directly by plants through photosynthesis or through chemical reactions in the soil, this process is often called "C fixation". Biological processes that occur in soils, wetlands, forests, oceans, and other ecosystems can store CO_2, which is referred as "C sinks".

Bernoux et al. (2005) argued that since soils are associated with CH_4 and N_2O as well as with CO_2 fluxes, the concept of "soil C sequestration" should not be limited to considerations of C storage or CO_2 balance. All GHG fluxes must be computed at the plot level, or preferably at the level of the entire soil-plant pools of agroecosystems in C–CO_2 or CO_2-e, incorporating as many emission sources and sinks as possible for the entire soil-plant system. These fluxes may originate from different ecosystem pools: solid or dissolved, organic or mineral. Bernoux et al. (2005) proposed that "soil C sequestration" or better, "soil-plant C sequestration", should be considered as the result of the net balance of all GHGs, expressed in C–CO_2 or CO_2-e, computing all emission sources and sinks of a given agroecosystem in comparison to a reference agroecosystem, for a given period.

Beyond its role in climate-change mitigation, SOM is not only a key component in nutrient cycling, but also influences a wide range of ecosystem services including water availability and quality and soil erodibility and is a source of energy for the soil biota that act as biological control agents for the pests and diseases of plants, livestock and even humans (Swift et al., 2004). SOM is most beneficial when it decays and releases energy and nutrients, and therefore its turnover is more important than the accrual of non-productive organic matter deposits (Lehmann and Kleber, 2015). We propose that a definition of C sequestration should encompass not only the components of SOM in C storage (or soil C sequestration) and GHG mitigation, but also the characteristic dynamic turnover that results in labile pools essential for maintaining soil health. Therefore, there are two highly related aspects of C sequestration that aim to attain food security under a changing climate: (1) reducing GHG emissions for mitigating climate change, and (2) increasing soil C storage and linked C recycling for improving the efficient use of resources (i.e. water, energy, and nutrients).

4. Soil C sequestration potential

4.1. Global

Soils act both as a C sink (gain) and a C source (loss). There is a continual gain and loss of soil C that establishes a dynamic equilibrium. Eventually, the ability of a soil system to sequester C lies in the balance between net gains and net losses. Before the dramatic increase in C emissions during the industrial revolution, the global C cycle, or "C flux" was maintained at a near balance between uptake of CO_2 (sinks) and its release back into the atmosphere (sources). Therefore, soil organic carbon (SOC) can be characterized as a dynamic equilibrium between gains and losses. Practices that either increase gains (i.e. increase inputs) or reduce losses can promote soil C sequestration. The soil C gain occurs largely from photosynthetically captured C (referred to as NPP, net primary productivity) and from the recycling of a part of the NPP as crop residues, including root biomass, rhizodepositions or manure/organic waste. The loss of soil C occurs largely from respiration by plants and the microbial decomposition and mineralization of organic residues to CO_2 and CH_4. In addition, soil erosion (Lal, 2004c) and photodegradation of surface litter (Austin and Vivanco, 2006) are other important forms of C loss.

Natural ecosystems are undisturbed and strike a balance of C gains over C losses, hence maintain greater C storage or C sinks. But the conversion of stable natural ecosystems to disturbed agricultural systems promotes soil C loss, converting soil from a net sink to a source of GHGs. It is interesting to note that globally, about 50% of vegetated land surface has been converted to agriculture (Zomer et al., 2017). A recent estimate indicated that since the beginning of agriculture about 10–12 millennia ago, 456 Gt of C has been lost from the terrestrial biosphere (Lal et al., 2018). There are two components: (1) from the prehistoric era to about 1750, the loss is estimated as 320 Gt; and (2) from 1750 to the present era, there has been a further loss of 136 Gt. Another estimate reported the reduction of soil C by 128 Gt during the 10,000 years of cultivation (Sanderman et al., 2017). On the other hand, Paustian et al. (2016) reported a soil C loss of 0.5 to >2 Mg C per hectare per year following the conversion of a natural ecosystem to cropland. This would result in the loss of 30–50% of the total C stock in the top 30 cm layer of topsoil until a new equilibrium was established.

The large historic losses over a large time frame, and the fact that soil possesses two to three times more C storage capacity than the atmosphere, have led to a belief that soil has the potential to mitigate GHG emissions and climate change via sequestering soil C. During the last few decades, several researchers have published a range of estimates of soil C sequestration/C storage potential in agriculture. Based on 22 published studies, Fuss et al. (2018) reported global estimates of technical potential annual C sequestration rates ranging from 0.51 to 11.37 Gt of CO_2 (0.13–3.09 Gt C). A large range of reported estimates represented diverse agroecologies/systems (croplands, desertified area, and drylands), and management practices (soil reclamation, zero tillage, agroforestry, restoration of degraded land, and grazing management). The discrepancies in the areas assumed for extrapolation (e.g. all cropland is amenable to sequestration as opposed to areas of degraded land that are not) were reported to be the main reason for the large variation in the reported rates of SOC sequestration. In addition, variations in soil depths and the SOC equilibrium durations used for extrapolation cannot be ruled out. Nevertheless, based on the median values of minimums/maximums ranges, the best estimate of technical potential was 3.8 (2.3–5.3) Gt CO_2 yr^{-1} or 1.03 (0.62–1.44) Gt C yr^{-1}.

It is encouraging that a strong interest in this area is not limited to the scientific community only. Recently in the global C agenda for climate-change mitigation and adaptation, soils have become a part through the initiation of three high level programmes (Amelung et al., 2020). Firstly, in 2015, the French government launched the "4 per 1000" (4p1000) initiative at the 21st Conference of Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) as part of the Lima Paris Climate Agreement. The agreement recommended a voluntary plan of 4p1000 to sequester C in world soils at the rate of 0.4% or 4‰ (4 per mille) annually (Minasny et al., 2017; Rumpel et al., 2020; Soussana et al. 2019; UNFCCC, 2017). Secondly, at COP23 in 2018, the Koronivia workshops on agriculture were launched, giving emphasis on soils and SOC for climate-change mitigation. And finally in 2019, the FAO launched a program for the recarbonization of soils, called RECSOIL (FAO, 2019).

In 4p1000 initiative, the value of 0.43% is based on the ratio of global anthropogenic C emissions and total SOC stock (3.7 Gt/860 Gt) (Fig. 1). Annual GHGs emissions from fossil C are estimated at 3.7 Gt per year and a global estimate of soil C stock of 860 Gt at 40 cm of soil depth. The value of 3.7 Gt C of emissions per year comes from the range of 2–5 Gt C estimated by Fuss et al. (2018). For agricultural soils, Smith (2016) estimated the value of 0.45%, which is based on 1.3 Gt C of emissions per year and an agricultural SOC stock of 286 Gt C at 0–40 cm depth (Jobbagy and Jackson, 2000). For a 0–30 cm depth, the same annual sequestration potential would be equal to 0.53% of emissions and 0.56% of global and agricultural soil stocks (690 and 23 Gt C, respectively). Considering the land area of the world as 149 million km^2, the average amount of C is calculated to be 161 tonnes of SOC per hectare, and 0.4% of this would be 0.6 tonnes of C per hectare per year.

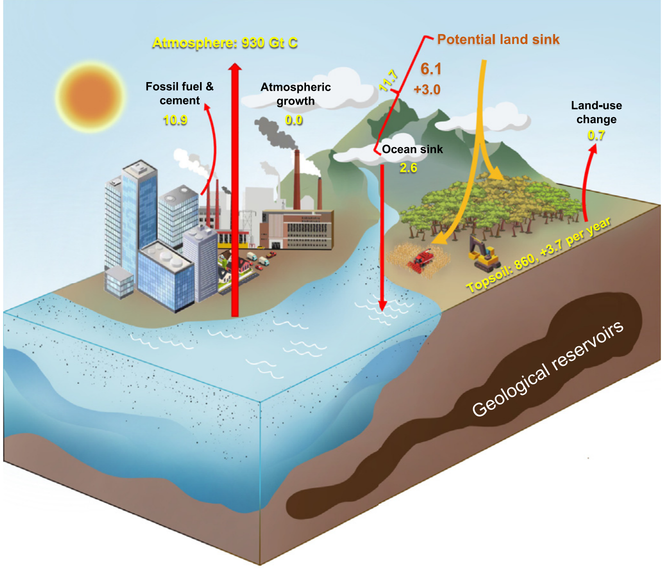

Fig. 1. The '4 per 1000' soil carbon sequestration initiative (Soussana et al. 2019) [Full technical potential of soil C sequestration at 3.7 Gt C y^{-1} in 2030-40 with enhanced land C sink scenario; Fossil fuel and cement emissions of 10.9 Gt C y^{-1} follow Paris agreement for 2030; 0.7 Gt C emission by net land use change (a reduction of 25% from current estimates); atmospheric growth of CO_2 is zero by halting net deforestation].

It has been argued that the initiative's target of 4p1000 is highly ambitious, and important questions have been raised as to whether it is feasible to increase SOC stocks by 0.4% per year on average around the world (Baveye et al., 2018; De Vries, 2018; Poulton et al., 2018; VandenBygaart, 2017; van Groeningen et al., 2017; White et al., 2018). Soussana et al. (2019) and Rumpel et al. (2020) mentioned that 4p1000 initiative is indeed an aspirational goal with much uncertainty about what is achievable but aimed to promote concerted research and development programs on good soil management that could help mitigate climate change. They discussed various specific criticisms of the initiative in relation to biophysical, agronomic, and socioeconomic issues, and provided a more realistic scenario of what was possible and not possible. Subsequently, Amundson and Beaudeu (2018) further elaborated on the challenges and complexities involved in achieving this goal, and opined that adaptation may be more relevant than mitigation. They proposed the concept of "weather proofing soils" which would involve the development and promotion of improved soil C management approaches that are more adaptable. Recently, Amelung et al. (2020) suggested a soil-specific perspective on feasible C sequestration and some of its trade-offs. They also highlighted that crop land soils with large yield gap and/or large historic SOC losses have major potential for carbon sequestration. A greater need for local, reusable, and diversified knowledge on preservation and restoration of higher SOC stocks has been suggested (Beillouin et al., 2021). A few promising sustainable management options with higher SOC sequestration potential were identified for farmers in America (Cerri et al., 2021).

4.2. South Asia

South Asia accounts for less than 5% of the world's total land area and supports around 25% of the world's population (FAO STAT, 2017). Around 50% of the land area is used for agricultural purposes and is characterized by tropical, dry, and temperate climates along with diverse ecosystems, land uses, and management practices. The region is densely populated, and per capita land availability in some countries is less than 0.1 ha and is continuously decreasing. The possibility of increasing crop area is limited. The region is undergoing rapid industrialization contributing to greater emission of GHGs. In addition, there is rapid degradation of soil quality with low SOM content due to fertility-mining practices (removal and burning of residues, unrestrained and excessive grazing, and imbalanced use of nutrients). Lal (2004a, b, c) reported a C sequestration potential of 7–10 Tg C yr^{-1} and 18–35 Tg C yr^{-1} from restoration of degraded land in India and South Asia, respectively. With the adoption of recommended management practices on the cropland of South Asia, SOC potential was estimated to be 11–22 Tg C yr^{-1} (Lal, 2004c). The underlying assumptions included were the implementation of appropriate policies to promote recommended management practices such as conservation agriculture (CA), mulch farming, cover crops, integrated nutrient management with manuring and biological nitrogen fixation, and water conservation and harvesting. Lal (2004a, c) also reported a soil inorganic C sequestration potential of 19–27 Tg C yr^{-1} of secondary carbonates and 26–38 Tg C yr^{-1} of leaching of carbonates in the arid regions of South Asia. Using International Soil Reference and Information Centre (ISRIC) Soil Grids 250 m and FAO GLC Share Land Cover database, Zomer et al. (2017) reported a C sequestration potential of 0.11–0.23 Pg C hr^{-1} in South Asia. Assuming that C sequestration continues for 20 years, the current soil C stock of 7.68 Pg is likely to increase to 9.87 or 12.18 Pg for medium and high sequestration scenarios, respectively. Grace et al. (2012), using IPCC methodology together with local data, calculated a sequestration potential of 44.1 Mt C over 20 years from the implementation of zero tillage practices in rice-wheat systems of India.

5. Challenges associated with SOC sequestration

SOC sequestration is a dynamic process, and the amount and duration of C storage depends on the pools (active/labile vs. recalcitrant/passive) and their cycling (Six et al., 2001), the form of stabilization (chemical/physical), and the physical location (inter/intra-aggregate vs. free) of the C in the soil (Balesdent et al., 2000; Six et al., 2001). Rates of turnover of organic matter depend on soil properties such as clay content and nutrient status. Clay is one of the key carbon-capture materials and tends to bind organic matter in soil and helps to protect it from microbial breakdown (Yang et al., 2021). Yang et al. (2021) also showed that the quasi-irreversible sorption of high molecular-weight sugars within clay aggregates, inaccessible by the microbes is responsible for clay-C protection. In addition, temperature plays a crucial role, which is complex because of variation in the temperature sensitivities of different SOM fractions (Conant et al., 2011). The impact of temperature becomes more crucial with a rise in ambient temperature due to climate forcing, resulting in microbially-driven increases in decomposition. Therefore, there are limits to C sequestration which are not only biophysical but also include technical and economic barriers.

5.1. Retention of C in a soil is not unlimited (C saturation)

Over time, SOC reaches a steady-state equilibrium, balancing C gains and losses. Since organic inputs vary in quality, quantity, and subsequent interactions with soil constituents and environment, the ability of a soil to retain C is not unlimited. Carbon saturation is often used to describe the maximum capacity of a soil to retain C as a stabilized fraction based on soil properties (Stewart et al., 2007). Sanderman et al. (2009) opined that while the term ‘soil C saturation’ is conceptually and theoretically appealing, the results from some of the long-term experiments may not support it. For example, Blair et al. (2006) found that total C stocks increased linearly with input levels of up to 200 Mg dry weight ha^{-1} for 15 years, without showing any signs of saturating behavior. However, Stewart et al. (2008) found some evidence of saturation. Likewise, Johnston et al. (2009) reported that the annual addition of farmyard manure (FYM) in the Broadbalk long-term experiment at Rothamsted increased C over the 160-year period, but the higher increase in early years was followed by a slower increase in later years, arriving at a new equilibrium. The time taken for soil to reach a new equilibrium tends to vary not only between soils within a temperate or tropical environment but also between the environments. It normally takes a longer time to reach equilibrium in a temperate soil than in a tropical soil (Jenkinson, 1988; Paustian et al., 1997; Smith et al., 1996). It has been suggested that SOC saturation depends on clay and silt content and that there is a critical C concentration below which a soil's function is reduced (Stockmann et al., 2015). Nevertheless, most current SOC models assume first-order kinetics for the decomposition of various conceptual pools of organic matter (McGill, 1996; Paustian, 1994), which means that equilibrium C stocks are linearly proportional to C inputs (Paustian et al., 1997).

5.2. Carbon storage in soil is not permanent (Non-permanence)

Carbon stored in soils is non-permanent. With changes in land use and land management, soil loses C, which can only be maintained or increased with the continuous addition of C input. By changing agricultural management or land use, soil C is lost more rapidly than it accumulates (Smith et al., 1996). Soil clay plays an important role in retaining C. Agricultural soil with a 50% clay content requires >2.2 Mg C ha^{-1} annually to maintain a given C level, while agricultural soil containing a 30% clay content requires more than 6.5 Mg C ha^{-1} annually. In addition, the rate of C input must be higher at existing soil C levels to maintain a level stock of C in the soil (Biala, 2011).

Microbial decomposition and mineralization to CO_2 is the major outcome of organic C. Approximately 1–2% of crop residues are stabilized as humified SOM for a period (Schlesinger, 1990) that are composed of large complex macromolecules, carbohydrates, proteinaceous materials, and lipids. This could be 60–85% of the total SOM (Haider and Guggenberger, 2005). However, this notion, which was based on chemical analysis of the extracted materials has been challenged, and recent understanding suggests that humic substances are marginally important (Kleber and Johnson, 2010). Based on direct high-resolution *in situ* observations with non-destructive techniques, it has been established that humic substances are rather simple, smaller biomolecules (Kelleher and Simpson, 2006). Although Hayes and Swift (2020) however, strongly disagreed with these views. They presented a detailed account of decomposition processes leading to the formation of a range of products including soil humic substances with a degree of resistance to microbial degradation. The new thinking in SOM research suggests that the molecular structure of plant inputs and organic matter has a secondary role in determining C residence times over decades to millennia, and that C stability depends mainly on the biotic and abiotic environment (Schmidt et al., 2011). The biotic and abiotic factors along with dynamics of labile C pools are required to evaluate management, land use, and climate change effects on SOC changes and soil functionalities (Kopittke et al., 2022). New findings suggest that microbial decomposition actually facilitates long-term C sequestration by maintaining C flow through the soil profile (Dynarski et al., 2020; Roth et al., 2019), and that infrequent tillage may not cause sufficient disruption of soil aggregates leading to C loss (Cooper et al., 2016). Schmidt et al. (2011) proposed that a new generation of experiments and soil C models will be needed to make advances in our understanding of SOM and our responses to global warming.

5.3. Socio-economic constraints

While many land and crop management practices are known to enhance SOC sequestration, benefit accrual is constrained by the existence of numerous adverse forces on the ground. Table 5 provides key adoption constraints to an effective SOC sequestration strategy, the existing practice, and their implications. There are major barriers for farmers to adopt SOC sequestration practices because of the trade-offs

Table 5
Socioeconomic constraints to adoption of potential SOC sequestration practices.

SOC sequestration Practices	Adoption constraint	Major reasons for mismanagement (trade-offs)	Implications or risk of mismanagement
No open grazing	Lack of dedicated pastureland for grazing, shortage of fodder, poor economic conditions of farmers especially landless livestock farmers	Excessive uncontrolled grazing, community/social structure, lack of regulations	Results in bare fallow and soil surface exposure to wind and water erosion and loss of SOC
Scientific land use plans and sustainable soil management	Ineffective policies	Good quality soils used for other purposes such as brick making, urbanization	Loss of soil and SOC, virgin/forest soils are put under agricultural use
Zero or reduced tillage	Lack of knowledge and machinery, conventional tillage-based mindset legacy and misconceptions, lack of locally adapted packages	Conventional/intensive tillage (CT)-based mindset, lack of incentives for eco-system services	CT results in loss of SOC and GHG emissions
Crop residue retention/ recycling	Other economic usages of crop residue such as fodder, fuel and fencing/no cheaper and easy options of burning, lack of knowledge and capacity	Residue removed or burned	Wrong use of crop residue and burning results in loss of C and GHG emissions
Application of biochar	Technology constraint, economic constraints	Biochar application is not a common practice	Increase in GHG emissions, risk of respiratory diseases, toxicity
Balanced use of nutrients including organic amendment	Knowledge gap, non-availability, affordability	Imbalanced or inadequate and inefficient use of nutrients	Loss of soil fertility and sub-optimal crop yields due to loss of C and GHG emissions
Crop need based N application	Knowledge gap, fertilizer subsidy in many developing countries	Inefficient including either inadequate or excess use of N fertilizer	Low levels of SOC from inadequate N use or loss of SOC and increase in N_2O emissions from excess of N
Controlled water application	Poor irrigation infrastructure, bad policies such as heavy subsidy on energy and water	Inefficient water management	SOC loss and increased GHG emission from frequent soil wetting and drying
Use of crop varieties with SOC associated traits such as deep rooting	No breeding efforts for deep rooting traits	Use of varieties with shallow rooting	Inadequate root biomass
Fallow management: cover crop, weedy fallow	Poor land management and lack of financial incentives	Bare fallow	SOC loss and GHG emissions
Crop rotation optimization	Knowledge gap, poor infrastructure, lack of incentives	Sub-optimal crop rotation, i.e. rotations with long fallow or rotations with contrasting edaphic management requirement (rice-wheat rotation)	SOC loss of GHG emissions

involved. For example, the removal of crop residues from the field for other uses such as fodder, fuel, and fencing are traditional practices for managing residues. Not only is this an economical option for farmers, but there is also a lack of knowledge and capacity which discourages the adoption of practices promoting SOC sequestration. Likewise, shifting to zero- or reduced-tillage requires altering farm implements/equipment and the substitution of conventional crop and weed-control methods. The adoption of practices to enhance SOC also involves additional costs and the risk of getting lower yields in the short term. Much remains unknown about SOC storage, so it is difficult to estimate total benefits and to know which soil management practices offer the most potential for a given soil type, climate, and crop.

6. Risks associated with SOC sequestration

Not only does SOC sequestration involve economic and biological costs but there can also be environmental cost. When mismanaged, some management practices that are known to result in C sequestration and GHG mitigation risk losing SOC and/or enhancing GHG emissions. Notably, N fertilization, either from organic (manure) or inorganic (synthetic fertilizer) source, has negative consequences when applied sub-optimally–used either insufficiently or excessively. On one hand, when applied in inadequate amounts over time, for example in Africa, then there is no or negligible soil C build up (Ladha et al., 2020). On the other hand, when applied in excess, for example in China and India, then soil C decreases from enhanced decomposition, which increases N_2O emission, NH_3 volatilization, and/or NO_3 leaching. No-till compared to conventional tillage is another example of a practice that is reported to result in higher N_2O emissions (Van Kessel et al., 2013). No-till adoption may also increase the use of herbicides and pesticides, potentially affecting the environment (Friedrich et al., 2012). Sub-optimal or excess organic amendment to soil can also have an adverse effect on grain yield from nutrient immobilization. A growing interest in biofuel, resulting in a competition for fixed C, could also be a threat to SOC sequestration (Janzen, 2006), as the use of biofuel involves burning of C which originated recently from photosynthetic activity.

7. Management practices to enhance C sequestration

Lal et al. (2007) proposed six soil C management strategies to increase SOC: (1) minimum disturbance of soil, (2) maintenance of permanent ground cover, (3) intensification of nutrient recycling mechanisms, (4) creation of a positive nutrient balance, (5) enhancement of biodiversity, and (6) reduction in losses of water and nutrients. These strategies are generally applicable in South Asia and could be achieved notably through conversion of degraded land to perennial vegetation, increasing the NPP of agricultural ecosystems, and converting conventional tillage to no-till farming (Lal et al., 2007) opined that a C-management strategy should not only be able to increase SOC content, but also should have some potential for reducing GHG emissions. Carbon management practices are aimed at increasing the ecosystem C balance by adding more C into the soil (e.g. through planting crops), increasing below- and above-ground biomass (e.g. forests and agroforestry), sequestering SOC (all ecosystems) (Soussana et al. 2019), and also reducing C losses from the soil (Paustian et al., 2016). In the eastern Indo-Gangetic Plains of India, CA management practices like zero tillage with partial residue retention in rice-wheat systems could increase SOC content by 4.7 $\mathrm{Mg\,C\,ha^{-1}}$ after seven years of practice (Sapkota et al., 2017). Avoidance of adverse land use, management strategies, and restoration of degraded land can help in maintaining SOC stocks in soil (Paustian et al., 2016; Soussana et al. 2019). Table 6 provides details of various management options for increasing soil SOC stocks and reducing GHG emissions.

7.1. Precision land leveling

Proper land leveling is known to enhance input use efficiency, crop growth, and yield (Aryal et al., 2015). In South Asia, the majority of agricultural lands are poorly leveled by traditional land-leveling practices (Jat et al., 2006; Ladha et al., 2009). Precision land leveling (PLL) is laser-assisted, and very fine leveling of land is achieved with the desired grade within ±2 cm of its average micro elevation (Jat et al., 2015). PLL is known to lower GHG emission by improving water and N use efficiency (Jat et al., 2015). Under Indian conditions, PLL could reduce almost

Table 6
Key management options for SOC benefits.

Practices	GHG mitigation	Soil C stocks	SOC sequestration net balance	Other value addition
Land leveling	Lower GHG emissions from improved water use efficiency	No or negligible change	+	Improvements in crop productivity through better crop establishment and input (i.e. water) use efficiencies
Tillage: zero or reduced tillage with drill/direct-seeding	Lower GHG emissions from energy saving associated with zero tillage	Increase in SOC in surface soil layer	+	Improvements in soil aggregates, resource efficiencies and economic returns
Crop residue management: no burning/residue retention as soil mulch	No burning is known to reduce GHG emissions. Residue retention will increase CO_2 emissions	Soil mulch increases soil C stocks	+++	Organic amendment including soil mulch and biochar application stimulate soil biological activity and slow nutrient release
Application of biochar	Increase in net CO_2 removal from atmosphere.	Increases soil C	++	Biochar enriches soil and stores SOC in a stable form and it improves pasture management and effectively controls soil erosion
Use of manure with or without inorganic fertilizer	Enhances CO_2 emissions	Enhances soil C storage	++	Enhances nutrient availability after decomposition. Supports more diverse soil microbial communities and increases microbial biomass contributing to increase in SOM
Water management: controlled water application	Flooding enhances CH_4 emissions and alternate wetting/drying reduces CH_4 and increases N_2O but overall GWP is lower	Enhances soil C storage through plant and microbial growth. Flooding enhances soil C storage. Irrigation in dry lands increases C inputs and thereby C storage	++	Critical for mineralization and release of nutrients
Crop variety trait: deep rooting	Likely to reduce N_2O emission from greater crop uptake on N	Deep rooting enhances soil C storage	+	Deep rooting may enhance root activity hence better nutrient availability
Nutrient management: nitrogen, other nutrients	Smart N application reduces N_2O emissions and lower GWP	N and other nutrients enhance plant growth and soil C storage, but excess N fertilization may also burn SOC	++	N stimulates decomposition of SOM and thereby nutrient release
Pest management	No or negligible change	No or negligible change	+	Improvements in crop productivity and higher biomass return to soil
Fallow management: cover crop, weedy fallow	Soil cover with live mulch reduces GHG emissions	Soil cover with live mulch of right lignin/N enhances C storage	++	Soil cover with live mulch of right lignin/N enhances labile C and N pools. Cover crops can capture nutrients otherwise prone to losses such as nitrate leaching. Continuous soil cover of vegetation reduces vulnerability of soil to C loss
Crop rotation optimization/sustainable intensification	CO_2 emissions likely to increase but overall GWP lower	Potential to increase SOC through greater C inputs	++	Higher system productivity, input use efficiency and economic returns
Aerobic rice cultivation under conservation agriculture	CH_4 emission will reduce, may increase N_2O but overall GWP will be lower	Likely to maintain SOC with residue mulch with zero tillage	++	Higher input use efficiency and economic returns
Rice production practices that minimize CH_4 emission: growing rice cultivars that inhibit CH_4 production, more effective water and fertilizer management, microbiome manipulation to enhance C sequestration in rhizosphere	Both CH_4 and N_2O emission reduces, GWP will be lower	Likely to maintain SOC through better management, may increase through microbiome	+	Higher input use efficiency and economic returns, increase in soil C in rhizosphere

0.15 Mg of CO_2-e ha^{-1} year^{-1} of GHG emissions due to less time spent for pumping irrigation water and decreased cultivation time (Gill, 2014). PLL is critical for efficient water use and for increasing water productivity, and improves crop productivity through better crop establishment practices (Aggarwal et al., 2010; Ahmed et al., 2001; Jat et al., 2011). There has been 6–11% (Sidhu et al., 2007) and 10–25% (Singh et al., 2007) increases in wheat yields in Punjab, India due to PLL. The associated increase in NPP in terms of crop residues and below ground biomass can be a source of soil C if further managed properly.

7.2. Zero or reduced tillage with drill/direct-seeding

Loss of SOC is often attributed to the practice of tilling the soil. Adoption of zero or reduced tillage will enable SOC sequestration, and is believed to be one of the key global mitigation strategies of climate change. Zero tillage has been widely reported as a viable option in increasing the C storage in soils (Corbeels et al., 2016; Francaviglia et al., 2017; Virto et al., 2012), although few have reported no change (de Sant-Anna et al., 2017; Dimassi et al., 2014). Most of the cases where zero tillage showed SOC increase, were mostly sampled to a depth of 30 cm or less, thereby not-revealing changes down the profile. In limited studies, where soil sampling was beyond 30 cm, no apparent difference in SOC between conservation and conventional tillage was recorded (Baker et al., 2007; VandenBygaart et al., 2003). Soil aggregates are stabilized under reduced and zero tillage practice, which physically protect C from mineralization (Kumari et al., 2011; Merante et al., 2017), however, the effect is realized over the long run (Six et al., 2004). The effect of zero tillage is dependent on climate, especially on rainfall, and the effect is more pronounced in drier areas (Chenu et al., 2019). The energy requirements of zero tillage and reduced tillage are less, so GHG emissions are lower (Aryal et al., 2015a; Grace et al., 2003). GHG emissions were reduced by 1.5 Mg CO_2-e ha^{-1} year^{-1} in zero tillage-based wheat (Aryal et al., 2015a) and maize systems (Parihar et al., 2018).

7.3. Crop residue management

Crop residue return (biomass return after harvesting) has positive impacts on SOC, however, its effectiveness varies with tillage practices (Zhang et al., 2014; Zhao et al., 2017). Retaining residues on the soil surface increases the soil C sequestration (Lou et al., 2011; Wang et al., 2015; Zhao et al., 2020), whereas residue incorporation with inversion tillage may lead to higher N_2O and CH_4 emissions (Hu et al., 2016; Koga and Tajima, 2011). Amount of residue return is positively related to the C sequestration (Lou et al., 2011). Residue return with optimum fertilizer input, paddy-upland rotation, improved crop cultivars, and use of legumes in rotation are some of the improved management practices for enhancing amounts of crop residue return to the soil (Soussana et al. 2019; Wang et al., 2020). Crop retention can reduce the requirement of fertilizer (Jat et al., 2018; Prade et al., 2017) and therefore, may limit the GHG emission. The application of biochar (a synthesized product from crop residues and other organic sources) to soil has the potential to offset 12% of global GHG emissions, as it can stabilize decaying organic matter and associated CO_2 release, and can remain in soil for hundreds or even thousands of years (Levitan, 2009). The retention over longer period is due to reduction in mineralization rate by 10–100 times from that of crop biomass (Lehmann et al., 2015). A meta-analysis reported that biochar can either increase or decrease soil C depending on the types of biochar/soil and duration (Majumder et al., 2019). In addition to its effect on SOC, biochar application may decrease soil N_2O emissions (Paustian et al., 2019) to an extent of 9–12% (Verhoeven et al., 2017) or even 50% (Cayuela et al., 2014).

7.4. Water management

Improved water management enhances C sequestration by increasing NPP and the subsequent addition of biomass to soil (Soussana et al., 2019; Sykes et al., 2018). It is estimated that improved water management could mitigate 1.14 t CO_2-e ha^{-1} $year^{-1}$ of GHG emissions (Aryal et al., 2020). In dryland agricultural system, crop productivity and the above- and below-ground inputs of C to the soil can be improved through efficient water management practices which enhances the plant-available water (Plaza-Bonilla et al., 2015). However, drip irrigation with frequent wetting-drying cycles may promote soil CO_2 emission through greater microbial activities (Guo et al., 2017). Micro-irrigation/fertigation also reduces N losses and hence lower GWP (Guardia et al., 2017). In rice cultivation, soil flooding is known to emit a large amount of CH_4 (Gebremichael et al., 2017), which can significantly be reduced from improved water management such as alternate wetting and drying (AWD), also called intermittent flooding (Chidthaisong et al., 2018; Mofijul Islam et al., 2020). However, the intermittent flooding may result in higher N_2O emission (Kritee et al., 2018; Lagomarsino et al., 2016), which necessitates water management to be in synchrony with inorganic fertilizer and organic matter inputs. Reduced water application reduces the C footprint of pumping water (Nouri et al., 2019).

7.5. Nutrient management

The application of N fertilizer from the right source, at the right dose, right time, and in the right place enhances crop yield, N use efficiency, and SOC storage, and mitigates GHG emissions (Snyder et al., 2009). Optimum and balanced doses of nutrients maximize crop yields, resulting in relatively more C inputs from both above- and below-ground plant biomass to the soil. Nitrogen can be applied effectively by correlating the leaf greenness with the leaf N content, and this can be done with a chlorophyll meter, leaf color chart, or optical sensors (e.g. GreenSeeker) (Ladha et al., 2020). Decision support systems like Nutrient Expert and Crop Manager are becoming popular for efficient nutrient management (Pampolino et al., 2012; Parihar et al., 2017). 'Nutrient Expert'-based management reduced on average 13% of GHG emissions from rice, wheat, and maize compared with farmers' fertilizer practices. Studies conducted by Gaihre et al. (2015) reported that in Bangladesh, the deep placement of urea in a rice-rice cropping system reduced N loss as N_2O and improved the crop yield. Thus, deep placement of urea can mitigate global warming and improve SOC by producing more biomass than traditionally applied urea. Enhanced fertility management can improve SOC content at the rate of 0.05–0.15 Mg ha^{-1} $year^{-1}$ (Lal, 2004a). In a meta-analysis conducted by Ladha et al. (2011), it was reported that N fertilization promotes SOC storage in agricultural soils throughout the world.

Benbi and Brar (2009) reported that the application of balanced fertilization positively impacted the soil C sequestration due to its effects on crop growth. Balanced fertilization (N_{120} P_{30} K_{30}) improved SOC concentration in rice-wheat and maize-wheat cropping systems because of the greater C input associated with enhanced primary production and crop residues returned to the soil (Kukal et al., 2009).

To improve soil health and soil productivity through balanced fertilization, the Government of India has started a "Soil Health Management (SHM)" program under the National Mission for Sustainable Agriculture (NMSA, 2017). In India, the Soil Health Card (SHC) has been useful in assessing the status of soil health, and when used over time. The SHM program aims to promote Integrated Nutrient Management (INM) through the judicious use of chemical fertilizers including secondary- and micro-nutrients in conjunction with organic manures and bio-fertilizers. The SHC-based recommendations have shown an 8–10% reduction of chemical fertilizer use with a 5–6% increase in crop yields (Srinivasarao et al., 2019).

7.6. Use of manure with or without inorganic fertilizer

In India, the availability of manure as a source of nutrients and C in agricultural practice reduced from 70% of the total manure produced in the early 1970s to 30% in the early 1990s (FAO, 2006). Three hundred and thirty-five Mt of dung is produced per annum in India, out of which 225 Mt is available for agricultural use (Pathak et al., 2009). This is only one third of the FYM requirement of the country that is needed to achieve the full C sequestration potential (Pathak et al., 2011).

Use of organic manure such as compost can enhance soil C stocks (Paustian et al., 2016) but may also result in higher CO_2 emissions (Ray et al., 2020). Application of organic manure can improve SOM by supplying enzyme-producing microorganisms with C and N substrates (Zhen et al., 2014), thus enhancing the structure and diversity of the microbial community (Hedlund, 2002). However, application of inorganic nutrients (NPK) with FYM sequestered C at the rate of 0.33 Mg of C ha^{-1} yr^{-1} compared to 0.16 Mg of C ha^{-1} yr^{-1} in NPK application alone (Pathak et al., 2011). Even in a hot, semi-arid climate, balanced and integrated nutrient management along with FYM could increase SOC in soil (Anantha et al., 2018). Regmi et al. (2002), in a long-term study, reported the accumulation of soil C in a triple-cereal cropping system (rice-rice--wheat) with organic (FYM or compost) amendment. In a rice-wheat cropping system, compared to NPK, the use of organic material increased SOC ranging from 18 to 62% (Gami et al., 2001). Likewise, Duxbury (2001) reported SOC accumulation from 0.08 to 0.98 Mg C ha^{-1} yr^{-1} in rice-wheat cropping systems through addition of FYM in India and Nepal. Several researchers have reported higher GHG fluxes (CH_4 and N_2O emissions) in different types of soil when manures were added (Bhattacharyya et al., 2012; Khalil et al., 2002). In a soybean-wheat cropping systems with an organic amendment, Lenka et al. (2016) reported increases in SOC stocks and N_2O and CO_2 emissions but the annual GWP was lower.

7.7. Crop variety traits

Deep-rooted crops and crop varieties can sequester more CO_2 in lower soil profiles (Kell, 2012). Growing deep-rooted crops also (1) reduces nitrate leaching to the groundwater and thereby reduces N_2O emission (Abalos et al., 2016; Crews and Rumsey, 2017), (2) improves SOC stocks

(Culman et al., 2013; Sykes et al., 2018), and (3) extracts nutrients and moisture from deeper soil layers (Lorenz and Lal, 2014). Deep-rooted perennial crops could also significantly decrease the requirement for tillage (Sykes et al., 2018). Plants with improved root architecture can improve soil structure (Gregory et al., 2010), hydrology (Macleod et al., 2007), drought tolerance (Kamoshita et al., 2008; McKenzie et al., 2009), and N use efficiency (Trachsel et al., 2009). Van de Broek et al. (2020) compared the amount of assimilated C that was transferred belowground and potentially stabilized in the soil from old and new wheat varieties. The authors reported that old wheat cultivars with higher root biomass transferred more assimilated C down the soil profile over more recent cultivars. Recently, Dijkstra et al. (2020) proposed a new 'Rhizo-Engine framework' emphasizing a holistic approach for studying plant root effects on SOC sequestration and the sensitivity of SOC stocks to climate and land-use changes.

Mycorrhizal association is another important trait that could play a crucial role in moving C into soil through active participation with plants. It is reported that plants with mycorrhizal associations can transfer up to 15% more C to soil than their non-mycorrhizal counterparts (https://www.earthday.org/land-management-and-carbon-sequestration/). The most common mycorrhizal fungi are marked by thread-like filaments, hyphae that extend the reach of a plant, increasing its access to nutrients and water. These hyphae are coated with a sticky substance called glomalin which are known to improve soil structure and C storage. Glomalin helps the organic matter bind with silt, sand, and clay particles, and it contains 30–40% C and helps in forming soil aggregates (Wright and Nichols, 2002). Averill et al. (2014) using global data sets, observed 70% more C per unit N in soil dominated by ectomycorrhizal and ericoid mycorrhizal-associated plants than arbuscular mycorrhizal-associated plants. Another recent synthesis by Verbruggen et al. (2021) opined that the mycorrhizal fungi can increase C sequestration through "enhanced weathering" of silicate rocks through intense interactions.

7.8. *Pest management*

The excessive use of pesticides in crop production has amplified to fight against insect pests and diseases. While the use of pesticides captures more C from improved crop production, it also increases GHG emissions from the processes (i.e., manufacturing, transport, and application) involved in the use of synthetic pesticides (NPF, 2017). Integrated pest management (IPM) can reduce pesticide use and increase crop yields. A study conducted in 24 countries of Asia and Africa has shown that the use of IPM to control pests can increase crop yields by more than 40%, and can reduce pesticide use by 31% (Pretty and Bharucha, 2015). Research has shown that any pest management practices that lessen foliar spraying are able to reduce GHG emissions (Heimpel et al., 2013). Climate-smart pest management (CSPM) is a cross-sectoral approach to managing pests. CSPM is proposed by the FAO (2010), and its aim are to reduce crop losses due to pests, improve ecosystem services, reduce GHG emissions, and make the agricultural system more resilient (Heeb et al., 2019).

7.9. *Fallow management*

A cover crop used to cover the ground surface during the fallow period (Ruis and Blanco-Canqui, 2017) prevents nutrients leaching from the soil profile, and provides nutrients to the main crops (Sykes et al., 2018). Poeplau and Don (2015) reported a reduction in SOC loss by cover cropping. A significant area in South Asia, where cultivation of a single crop is the practice, provides an opportunity for cover cropping. Likewise, in intensive double-cropping areas, a short-duration cover crop such as sesbania can be grown to improve soil fertility including soil C (Kundu, 2014). In a meta-analysis, Poeplau and Don (2015) estimated that using cover crops in 25% of the world's farmland could offset 8% of GHG emissions from agriculture. Cover cropping has also been reported to reduce N_2O emissions (Eory et al., 2015; Pellerin et al., 2013). Aryal et al. (2020) reported that cover crops and fallow rotation in warm and moist climates can reduce a net loss of 0.98 Mg C ha^{-1} in 7-year period. Creating borders of permanent vegetation along the edges of the field is another way to provide continuing live cover for agricultural soils (Poeplau and Don, 2015). The possible effect of no-till in increasing SOC is more prominent when cover cropping is included in the system (Chenu et al., 2019).

Cheng et al. (2014) and Dignac et al. (2017) reported improvement in SOC stocks through rhizodeposition and root litter addition, which is greater with perennial crops than with annuals. In a policy analysis report on soil health and C sequestration in US croplands, Biardeau et al. (2016) reported that agroforestry, in which crop cultivation is intermixed with growing trees and sometimes with grazing livestock, has the highest potential to hold C, ranging from 4.3 to 6.3 MT CO_2-e per ha annually.

7.10. *Crop rotation optimization*

Inclusion of a dual- or multi-purpose legume (grain, green manure, and forage) in a rotation is likely to balance the organic and inorganic fertilizer inputs and its effect on SOC stocks (Bhandari et al., 2002; Regmi et al., 2002). In South Asia, several researchers have shown similar benefits at the system level of optimizing crop rotations in CA mode in rice-wheat and rice-rice rotations (Gathala et al., 2013; Laik et al., 2014). Legumes with the ability to fix atmospheric N benefit subsequent crops by increasing biomass production, crop residue inputs, and subsequently the total SOC in legume-cereal crop rotations (Shah et al. 2003, 2011). Reducing overgrazing (which decreases NPP and increases CH_4 flux and animal respiration); balancing SOM decomposition through manures, crop residues and litter; and enhancing the mean annual NPP, are known to improve SOC in agricultural soils (Jansson et al., 2010). Greater SOC stocks and more stabilized SOC can be obtained by increasing soil biodiversity (Chenu et al., 2019; Lange et al., 2015; Steinbeiss et al., 2008). Havlin et al. (1990) reported that instead of continuous soybean cultivation, the inclusion of grain sorghum in a rotation increased soil organic C and N and that growing high residue crops along with reduced tillage could increase productivity. Ladha et al. (2016) reported that in different parts of the Indo-Gangetic Plains, the implementation of CA along with intensive crop diversification (i.e. the inclusion of legumes and maize crops in rice- and wheat-based cropping systems) resulted in a 54% increase in grain energy yield, with 104% more economic returns, a 35% reduction in total water input, and a 43% lower global warming potential intensity (GWPi) compared to farmers' conventional management practices.

Improved agronomic practices can lead to SOC changes which are often higher than the proposed 0.4% (4p1000 initiative). Agricultural practices that increase SOC also supports higher and sustained food production, improved soil health, multiple ecosystem services, and reduced environmental footprints. This can be a win-win solution for farmers and society as a whole (Foresight Brief, 2019).

8. A meta-analysis of C sequestration estimates under various management practices

A global meta-analysis was conducted to estimate the potential SOC sequestration in the soils of South Asia, and the potential for the mitigation of GHG emissions under major management (fertilizer and tillage) options. Inventories of SOC stocks (kg ha^{-1}) at various depths of soil (a total of 507 paired data from 51 studies) and GHG emissions (250 paired data from 33 studies) under different management practices were carried out. The practices were broadly categorized into (1) synthetic fertilizer inputs, (2) INM, where fertilizer inputs were partially substituted with organic sources, (3) organic amendment as the source of nutrients, (4) CA, and (5) AWD (this included non-submergence/flooding conditions in rice). The CA included practices where at least one crop was under zero-tillage with or without residue retention. Where varying amounts of residues or different sources and doses of fertilizers were used, the conventional practice with a similar combination of treatments was taken as the control (Jat et al., 2020). Four depths of soil (0–15, 15–30, 30–45, and 45–60 cm) were considered in the analysis of soil C stock over the period. For the GHG inventory, (1) direct emissions of CH_4 and N_2O (kg ha^{-1} $season^{-1}$); (2) emission matrices, viz. GWP (kg CO_2-e ha^{-1}); and (3) yield-scaled GWP (yield-GWP, kg CO_2-e t^{-1}: ratio of GWP to the yield of a crop or system) were evaluated. To eliminate large variations reported in the studies, the CO_2-e of CH_4 and N_2O for the 100-yr period (Fifth Assessment Report (AR5) of IPCC), Myhre et al., 2013) were used to compute the total GWP in each study. Only studies where a practice was continuously followed for at least four years were selected. Data were grouped into cereal-cereal and cereal-legume rotations for soil C stock analysis, and into major cereal crops (rice, wheat, and maize) for GHG emission analysis. Data were also organized into broad soil textural groups of fine, moderately fine, medium, moderately coarse, and coarse. The meta-analysis was performed by using ‘metafor’ in R programming platform (Viechtbauer, 2010).

8.1. Increase in soil C stocks

The meta-analysis, which calculates the change over the control in respective studies, reveals an overall 36% (confidence interval (CI), 31–42%) increase ($p < 0.01$, $N = 161$) in SOC stock in the top 0–15 cm layer, which is larger than at other depths (Fig. 2). This amounts to ~18 Mg C ha^{-1} of SOC stocks in the 0–15 cm soil layer. The results varied with treatments with the largest increase in INM practice (52% or 19 Mg C ha^{-1}). Increases in SOC in other depths remained similar: 19% in 15–30, 20% in 30–45, and 16% in 45–60 cm soil layers. In a global analysis, Han et al. (2016) reported increases of 5.1, 6.0, and 0.5 Mg C ha^{-1}, respectively, in the upper 0–20 cm layer with balanced chemical fertilizer, fertilizer with straw, and manure, respectively. Ladha et al. (2011) reported an 8% increase of SOC (gravimetric) with fertilizer, and 37% with organic amendment in the 0–30 cm soil layer in more than 100 long-term experiments running globally in diverse agroecologies. Long-term experiments in Rothamsted, U.K. (>150 years) showed 1.8–4.3% SOC increase yr^{-1} (0–23 cm) in the first 20 yrs; the change became insignificant after 80–100 years (Poulton et al., 2018). A much less SOC increase of 0.3–0.8% per year was, however, recorded with low or irregular rates of application of manure (Poulton et al., 2018).

The meta-analysis carried out in this study revealed that the effect of CA on soil C stock was visible only in the surface 0–15 cm soil layer with a 20% increase equivalent to a C stock potential of 15 Mg C ha^{-1}. Other meta-analyses have estimated an average of 5.6 (±0.7) Mg C ha^{-1} increase in the upper 10 or 20 cm layers (Aguilera et al., 2013; Angers and Eriksen-Hamel, 2008; Haddaway et al., 2017; ; Luo et al., 2010; Powlson et al., 2016; VandenBygaart et al., 2003; Virto et al., 2012; West and Post,

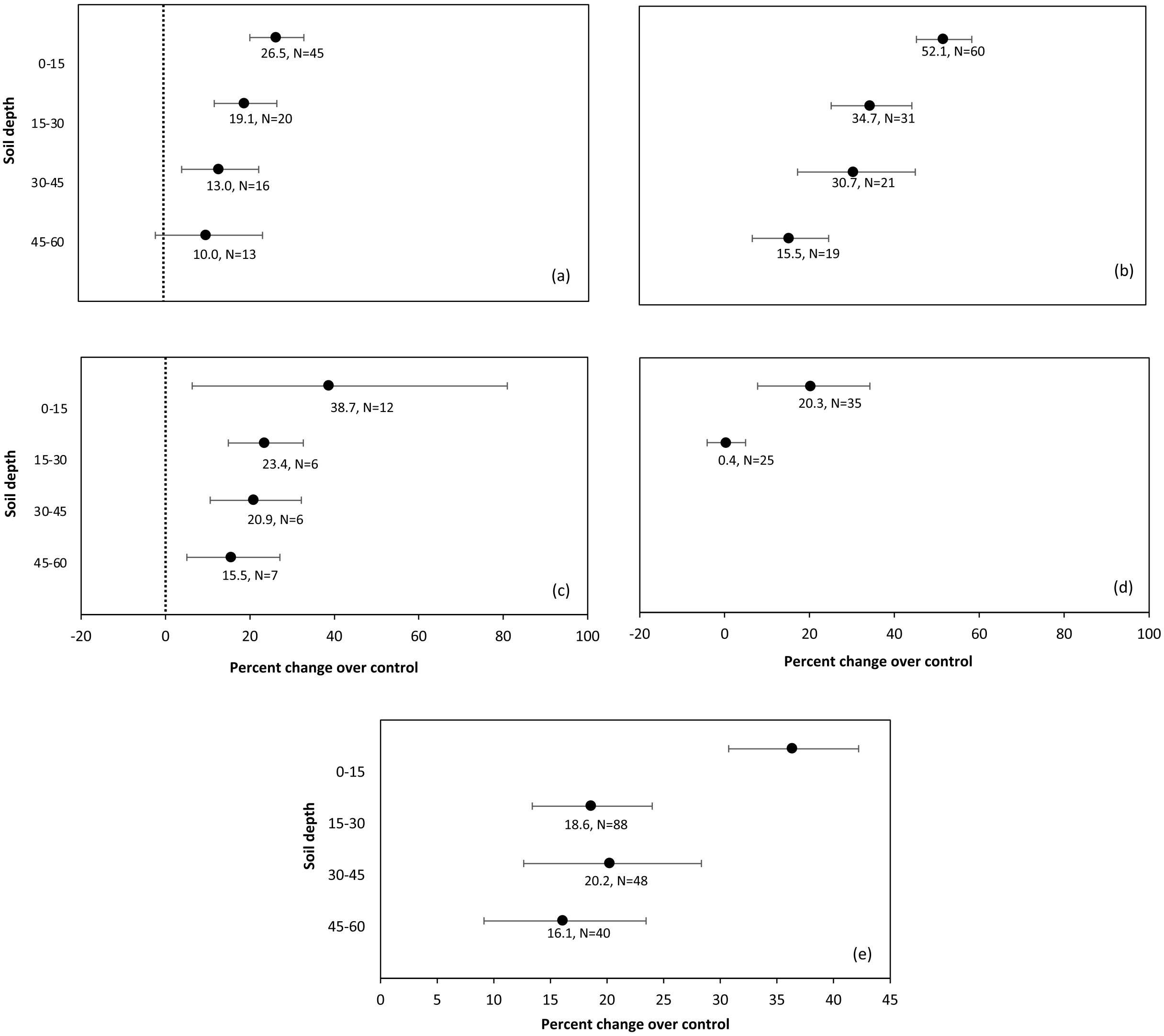

Fig. 2. Effect (% change over the control) of major management practices i.e. fertilizers (a), integrated nutrients (b), organic inputs (c), conservation agriculture (d), and a combined (pooled) effect (e) on soil organic C sequestration potential in different soil layers. Control is the no-fertilizer or organic inputs, and conventional tillage. Confidence intervals are given as horizontal bars.

2002). The C sequestration potential of zero tillage (0–30 cm) in the Indo-Gangetic Plains was estimated at 4–8 Mg C ha^{-1} (Grace et al., 2012). However, it is argued that the increases in SOC with different management practices will improve soil quality but impact on climate change mitigation will likely be limited (Powlson et al., 2014).

8.2. *Mitigation in GHG emissions*

Overall, improved management practices reduced methane emissions by 12% in rice (N = 92), resulting in an 8% reduction in GWP, and almost the same magnitude of reduction when expressed as yield-scaled changes (Fig. 3a). However, N_2O emissions in upland soils (N = 174) remained unaffected by improved management practices. Conservation agriculture and fertilization reduced the GWP by 11 and 14%, respectively, while non-submerged conditions led to a large (51%) reduction in GWP in rice (Fig. 3b). A meta-analysis from China indicated a reduction in GWP by 25% in rice paddies and 2% in upland soils (Zhao et al., 2016). Alternate-wetting-drying reduced CH_4 emissions in rice cultivation by 39–83% in the USA (Linquist et al., 2018). Estimates from a global study indicated a 66% reduction in GWP from no-till compared to the conventional tillage system (Sainju, 2016). GWP increased with the organic amendment, either with (12%) or without (32%) inorganic fertilizer. A 12% increase in N_2O emissions was reported with manure treatment compared to fertilizer treatment globally (Han et al., 2017). Studies reported increases in N_2O emissions associated with greater amounts of N applications through manure (Decock, 2014; Perala et al., 2006). Our yield-scaled GWP estimation followed similar trends except for INM, where higher yields compensated the increase in GWP (Fig. 3c). Reduction in N_2O emission was related to reduction in yield under CA through a global meta-analysis (Zhao et al., 2016). Another global analysis suggested increase in yield-scaled N_2O emissions in zero tillage with <10 yrs of duration, which decreased after 10 yrs, compared to conventional tillage (Van Kessel et al., 2013). Soil texture appeared to have no influence on CH_4 emissions in rice, while N_2O emissions increased by 36% in fine-textured soil (Fig. 4). The yield-scaled GWP was similar in wheat and maize, but lower in rice by adopting CA (Fig. 5). This agreed with the findings of Linquist et al. (2012), who reported greater mitigation opportunities in rice systems, compared to maize and wheat systems. There was no change in either GWP or yield-scaled GWP in wheat with improved management practices. In a global study, yield-scaled reduction in GWP in rice was 21% with optimal N applications (Pittelkow et al., 2014).

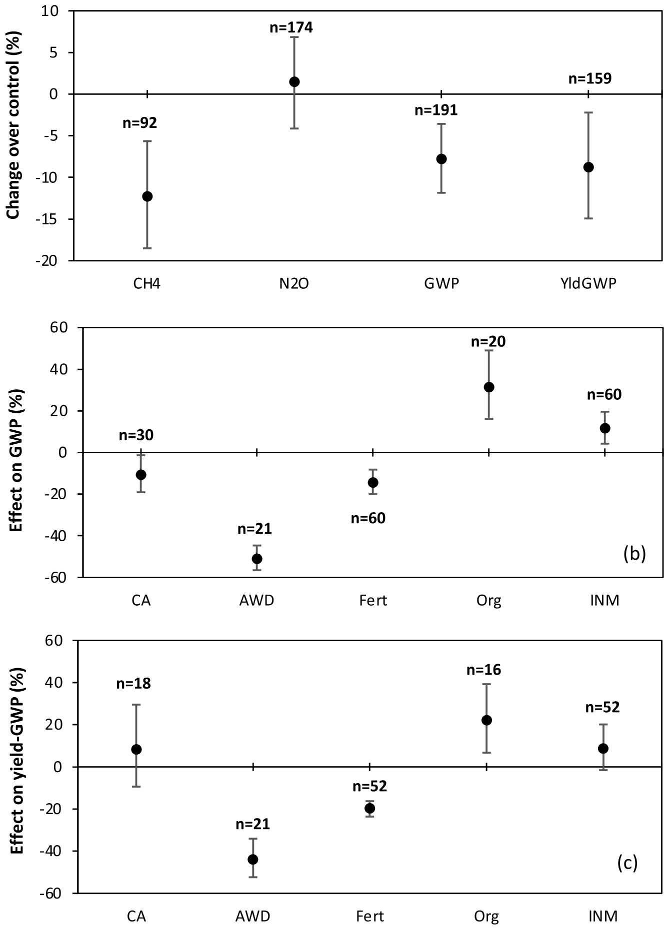

Fig. 3. Effect of improved management practices on changes in CH_4 and N_2O emissions, Global Warming Potential (GWP) and yield-scaled GWP: all inclusive (a), and under major management options (b and c). All are percent change over the control; confidence intervals are given as horizontal bars.

9. Conclusions and recommendations

South Asian agriculture is a global 'hot spot' for climate change vulnerability and rapid population growth. Meeting a projected food demand of at least 40 percent will be constrained by climate unpredictability including rising temperature. Currently, South Asia accounted for 7.5% of total world's fossils CO_2 emissions which is bound to increase with continuing agriculture expansion along with rapid economic growth. There is no argument that sequestration of C in soils, plants, and plant products holds huge potential both to improve soil health and create C sinks that reduce atmospheric CO_2 and combat climate change. There are several promising agronomic practices to enhance soil C stocks

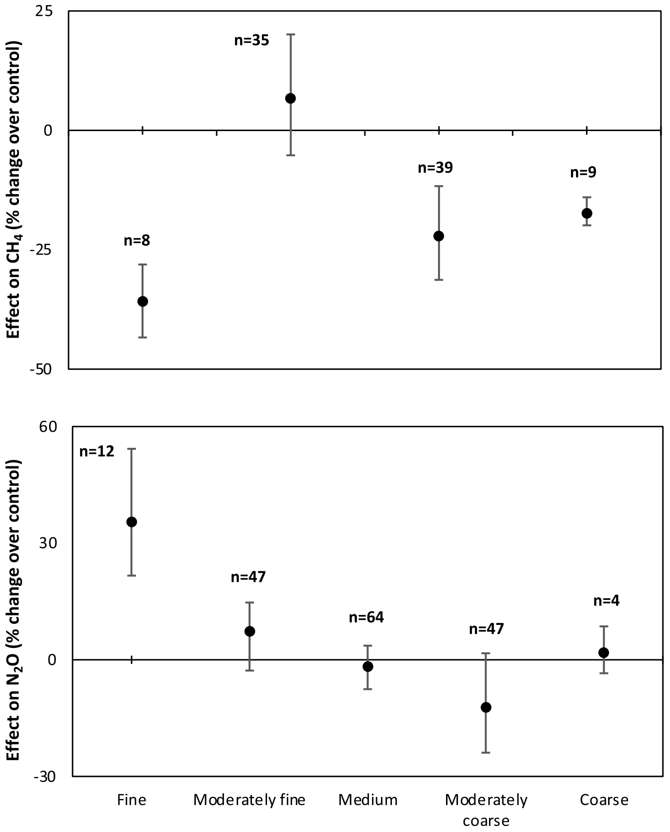

Fig. 4. Management-induced changes in CH_4 and N_2O emissions (percent change over the control) as affected by soil texture. Confidence intervals are given as horizontal bars.

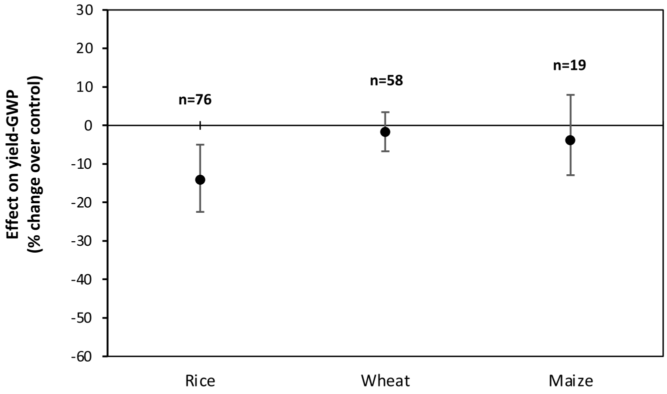

Fig. 5. Changes in yield-scaled GWP (percent change over control) through adoption of improved management options under major cereal crops. Confidence intervals are given as horizontal bars.

and mitigate GHG emissions. Notably, CA which is getting increasing attention in South Asia has proven potential. Our estimates suggest that existing soil management practices has potential to mitigate around ~18 Mg C ha^{-1} C year $^{-1}$ (0–15 cm soil layer) which can compensate up to 8% reduction in GHG emissions.

There is urgent need for supporting campaigns and efforts to increase soil C sequestration, both on a policy level and through programs which incentivizes farmers to adopt more C positive agricultural practices. Expanding support and working together with global initiatives such as the 4p1000 Initiative, regional public-private partnership (Grow Indigo-CIMMYT-ICAR; https://www.business-standard.com/article/economy-policy/indian-farmers-can-now-trade-in-carbon-credits-to-boost-income-122030300039_1.html) initiatives on C credits for Regenerative Agriculture as well as research and policy changes, will be important to the success of soil C sequestration. The current strategies to deliver knowledge, technologies, and incentives to promote the adoption of sound technical practices to the farmers are not adequate which need much support.

Our future research efforts should also be devoted to develop monitoring and verification protocols for C sequestration in South Asia which will assist economists and policy makers to assess economic value of soil C and formulate right policies. Future studies should focus more on agroforestry and crop diversification, as there is limited information available on their potential for C sequestration. Effect of climate variables on SOC have been least studied. More work is needed to better quantify benefits of C sequestration on soil quality, productivity, and water and air quality. Further, the potential impact of climate variability on the stability of sequestered C in soils and plants should be evaluated. New generation of long-term studies to assess the potential of new management practices in C sequestration and its stabilization on a long-term basis is needed to advance our knowledge.

Declaration of competing interest

The author declares that he/she has no competing interests. Author Jagdish K. Ladha (Editorial Board member) was not involved in the journal's review or decisions related to this manuscript.

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