Sustainable Production and Consumption 35 (2023) 697–708

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Carbon sequestration potential of sustainable agricultural practices to mitigate climate change in Indian agriculture: A meta-analysis

Kiran Kumara T.M. *, Suresh Pal, Prem Chand, Ankita Kandpal *

ICAR - National Institute of Agricultural Economics and Policy Research, New Delhi, India

ARTICLE INFO

Article history:
Received 5 August 2022
Received in revised form 8 December 2022
Accepted 16 December 2022
Available online 22 December 2022

Editor: Prof. Shabbir Gheewala

Keywords:
Sustainable agricultural practices
Climate change
Carbon sequestration
Economic benefits
India
Meta-analysis

ABSTRACT

India's agricultural sector ensures food and livelihood security for millions of rural households. However, the adverse effects of climate change pose a severe threat to agricultural sustainability. Compared to conventional practices, sustainable farming offers significant environmental benefits and helps to mitigate climate change impacts. In this article, we examined the effects of integrated nutrient management, organic amendment, no-tillage, crop rotation, residue retention, intercropping, and biochar on C sequestration and the influencing factors and associated economic benefits. A total of 2362 pair-wise observations from 295 studies were included in the meta-analysis framework. The result shows that biochar was the most effective practice for enhancing C sequestration (+41.28 %). Maize-wheat and legume-based cropping systems, medium fine-textured soils, humid-subtropical climate, rainfall, irrigation, and time period were the significant factors that affect carbon sequestration. In addition, our study demonstrated that C sequestration is a dynamic process, and only a limited amount of sequestration is possible from a piece of land. Further, we found that all the improved farming practices that enhance C sequestration were technically feasible and economically profitable. Thus, soil C sequestration through improved crop management practices represents a win-win strategy to combat climate change and conserve natural resources. Therefore, efforts should be directed towards outscaling of sustainable agricultural practices to enhance resilience and adaptation to climate change.

1. Introduction

Ensuring food and nutritional security for an ever-growing population under climate change is one of the critical challenges of the present times. The impact of climate change on food security is visible through the rise in temperature, erratic rainfall, and extreme weather events. Global temperature is projected to increase by 1.5 °C above pre-industrial levels between 2030 and 2050 (IPCC, 2018). The negative effects of climate change further aggravate the scarcity of natural resources, pollution levels, and land degradation. Consequently, millions of the population's livelihood and food security are rigorously threatened by climate change impacts and vulnerabilities of food production systems. Although agriculture provides various ecosystem services but also contributes to global warming through greenhouse gas emissions.

India is regarded as one of the fastest-growing developing nations in the world. The country's real GDP is expected to grow by 6.7 % in 2021 and 9.9 % in 2022 (OECD, 2021). Agriculture and allied sectors play a pivotal role in rural economies' sustainable growth and development. These sectors contribute 19.9 % of the total GDP and 11.4 % of total exports and support livelihood for more than two-thirds of the population (GoI, 2020, 2021). Besides, it plays a vital role in national food security and provides raw materials to various agro-based industries. However, despite higher economic growth, about 208.6 million (15.3 %) population of the country is still undernourished (FAO et al., 2021), and 21.9 % of the population is in extreme poverty (UNDP, 2021). Further, population growth and degradation of natural resources coupled with the detrimental impacts of climate change have threatened India's food and nutritional security.

Although conventional agricultural practices help to achieve food security but often lead to indiscriminate use of farm inputs, higher GHG emissions, and degradation of natural resources. Further, intensive farming practices and the cultivation of degraded lands resulted in the removal of soil organic carbon and other essential nutrients (Lal, 2016; Feng et al., 2018). Consequently, it deteriorates soil health and makes it infertile and unsuitable for further cultivation. Therefore, it is essential to enhance soil organic matter content in agricultural lands to enrich soil fertility and productivity while mitigating greenhouse gas emissions. Numerous studies highlighted that soil organic matter increases crop yield by sustaining soil health and positively impacting soil quality and process (Lal, 2016; Manlay et al., 2007). However, it is

* Corresponding authors.
E-mail addresses: kiran.tm@icar.gov.in (K.K. T.M.), spl.econ@gmail.com (S. Pal), Prem.Chand@icar.gov.in (P. Chand), ANKITA.KANDPAL@icar.gov.in (A. Kandpal).

https://doi.org/10.1016/j.spc.2022.12.015
2352-5509/

also a fact that in stressful environments, soil organic matter hurts water holding and nutrient capacity (Lal, 2020a). Gregory et al. (2009) observed that a 7 % to 3 % decline in soil organic matter content had decreased 10 % soil water retention in arable and grassland soils. A global meta-analysis by Oldfield et al. (2019) shows that an increase in soil organic matter can increase crop yield in maize and wheat by 10 % and 23 %, respectively. Similarly, a positive correlation between soil organic carbon content and crop yield was also reported by Arunrat et al. (2020). Nevertheless, agriculture also acts as a natural carbon sink and provides a huge opportunity to capture atmospheric carbon through sustainable agricultural practices. Therefore, it is indispensable to identify the farming practices which enhance carbon sequestration without affecting other ecosystem services. To tap the carbon sequestration potential in agricultural lands, '*4 per 1000*' was also initiated to enrich soil organic carbon by 0.4 % yearly (Nath et al., 2018; Lal, 2020b).

Sustainable agricultural management practices (SAPs) are widely recognized and promoted as sustainable strategies to mitigate climate change (FAO, 2013). A wealth of evidence shows that sustainable agricultural practices provide a wide range of socio-economic and environmental benefits compared to conventional practices (Hazra et al., 2020; Kumara et al., 2019). The most widely recognized SAPs to enrich carbon sequestration in cultivated lands include integrated nutrient management, organic amendment, no-tillage, crop rotation, residue retention, intercropping, biochar, and agroforestry. Growing awareness regarding the importance of SAPs and field-level evidence has led to increased adoption of these practices in the recent past (Clark et al., 2017; Chen et al., 2009). For example, converting land to no-tillage increases soil organic carbon while limiting greenhouse gas emissions (Curtin et al., 2000; Kumara et al., 2020). In addition, integrated nutrient management positively affects yield and soil carbon and enhances plant nutrient availability (Choudhury et al., 2018). Similarly, retaining residues in the field after harvest improves soil health, carbon storage, and soil moisture (Turmel et al., 2015). Further, adding biochar improves soil aggregation and delays the decomposition rate (Han Weng et al., 2017). Other practices, viz., crop rotation, organic amendment, intercropping, and agroforestry also been proven to enhance soil carbon stock. Furthermore, these improved management practices are also recognized by Intergovernmental Panel on Climate Change (IPCC) as a prominent land-based management solution (with medium cost) to address global climate change issues effectively (IPCC, 2019).

Meta-analysis is popularly used in synthesizing individual studies and deriving broad conclusions about the impact of a particular treatment in recent years (Sharma et al., 2019; Padbhushan et al., 2021). Globally, many meta-analysis studies reported the impact of improved crop management practices on soil organic carbon (Oldfield et al., 2019; Haddaway et al., 2017; Qin et al., 2016). In the case of India, although many on-station studies have been conducted to assess the carbon sequestration potential of sustainable agricultural practices, very minimal efforts have been made to synthesize the evidence through meta-analysis. Adequate information on the magnitude of soil carbon sequestration and its significant drivers is still lacking. Many factors influence the soil organic carbon (SOC) content of SAPs, such as climate, rainfall, geographical region, soil condition, and agronomic management (Bai et al., 2019). Though the concern over the impacts of climate change on food security is growing over the period, the systemic evidence of improved management practices and their impacts on soil carbon stock still needs to be improved. Further, some studies reported negative and neutral effects of SAPs on soil carbon sequestration (Justine et al., 2015). Therefore, building a clear vision of the role of carbon sequestration potential in productivity enhancement and identifying crucial SAPs that improve soil carbon sequestration is necessary. This study attempts to synthesize the evidence of various studies on the carbon sequestration potential of improved crop management practices in Indian agriculture by using a meta-analysis framework. This study systematically collates the evidence on the carbon sequestration potential of sustainable agricultural management practices in Indian agriculture with the help of a meta-analysis framework. In this study, we examined the (i) impacts of integrated nutrient management, organic amendment, no-tillage, crop rotation, residue retention, intercropping, and biochar on C sequestration, (ii) to determine the factors that influence carbon sequestration, and (iii) economic feasibility of improved crop management practices for C sequestration.

2. Methods

2.1. Data collection

An inclusive search of peer-reviewed research articles comprising various SAPs in India using online search engines viz., Google Scholar, Science Direct, Web of Science, and Scopus up to June 2021. The combinations of search keywords used to identify the peer-reviewed studies are "soil organic carbon", "soil organic matter", "carbon sequestration", "integrated nutrient management", "organic amendment", "no-tillage", "minimum tillage", "crop rotation", "residue retention", "intercropping" and "biochar", "India", "Indo-Gangetic Plains". The studies included in the final analysis were selected based on three criteria which were followed by Bai et al. (2019); (i) the study should be based on field experiments with at least any of the SAPs, (ii) soil organic carbon is reported in tables or graphs with a side-by-side comparison of SAPs and their controls, and (iii) detailed information about the experiment, such as location, duration, soil depth, and other agronomic practices is provided. The details of improved management and control practices included in this study are given in Table 1. The data reported in graphical formats were extracted using DigiPlot software (https://apps.automeris.io/wpd/). Further, if the information on SOC stocks was not reported, then stocks were estimated using bulk density and soil depth. All the observations of SOC stocks were expressed in Mg C ha^{-1}. The data has been collected from all the agro-climatic zones and major soil groups of India (Fig. 1 shows the location of on-station trials of improved farming practices). Based on the duration of the experiments conducted, studies were classified as short (<5 years), medium (6–20 years), and long-term (>20 years) (Bai et al., 2019). The soil texture was broadly classified into moderately coarse, medium, moderately fine, and fine. The climates of the study region were grouped according to Köppen's climate classification as humid subtropical, semi-arid and semi-arid subtropical. The mean annual rainfall was grouped into four categories: <750 mm, 750-1150 mm, 1150-2000 mm, and >2000 mm (See the Supplementary file, Fig. S4).

Table 1
Details of improved crop management practices used in this study.

Improved management practices	Treatment	Control
Integrated nutrient management	Incorporation of organic and inorganic sources of nutrients.	100 % NPK
Organic amendment	Addition of 100 % organic sources of nutrients.	100 % NPK
No-tillage	Minimal soil disturbance	Conventional tillage
Crop rotation	Growing a variety of crops in succession over a period on the same field.	Growing of monocrop
Residue retention	Residue retained in the cropping system	Residue removed
Intercropping	Simulations cultivation of two or more crops in the same field	Cultivation of sole crop
Biochar	Addition of biochar into soil	No biochar added

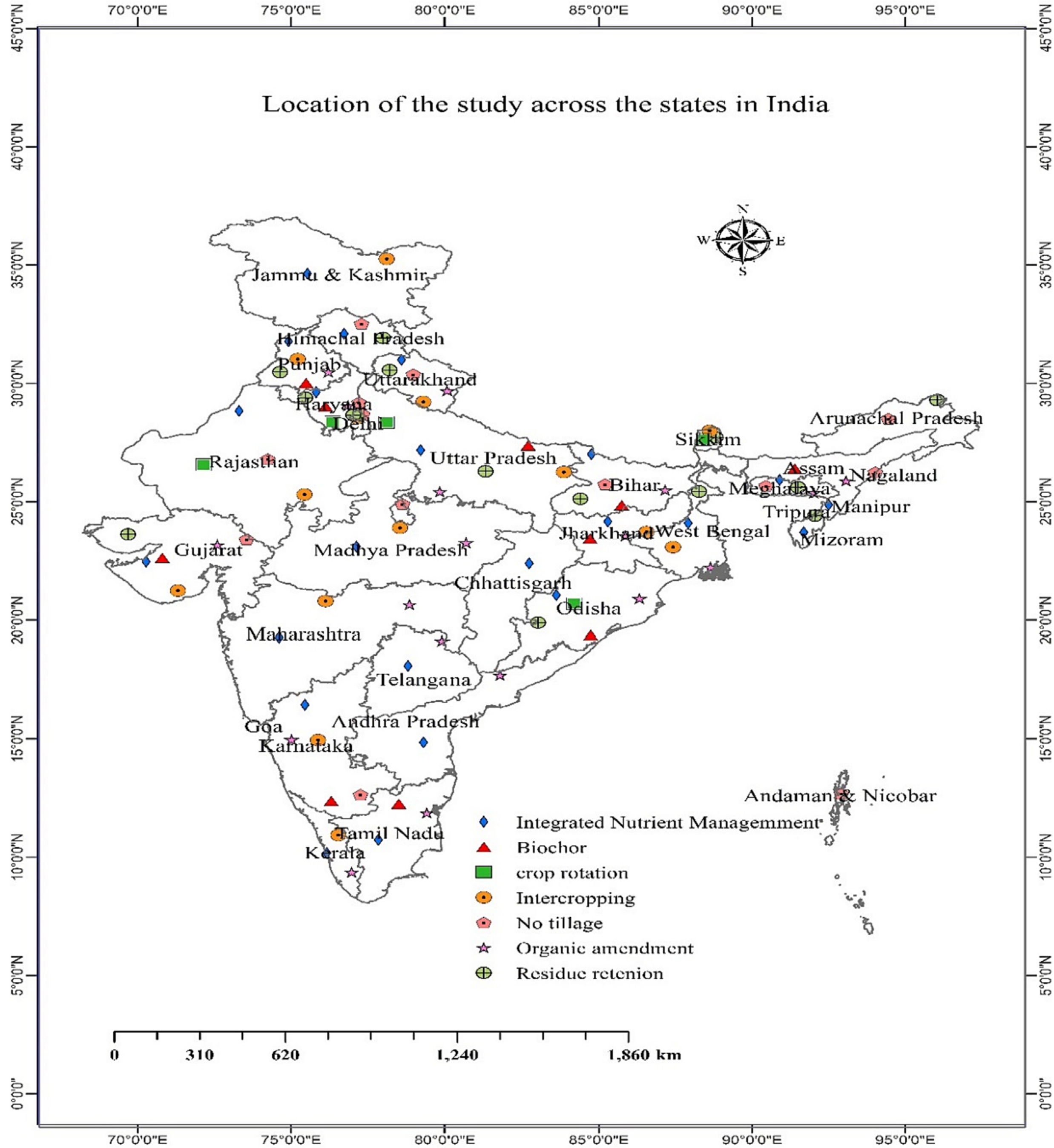

Fig. 1. Location of studies conducted on different sustainable agricultural practices in India.

2.2. Database

A summary of the data used in this study is presented in Table 2. After excluding extreme data points, a total of 2362 pair-wise observations from 295 studies were considered for the final analysis (see the Supplementary file, Fig. S1). The number of observations under each SAPs is integrated nutrient management (40.64 %), residue retention (14.73 %), no-tillage (13.29 %), organic amendment (11.64 %), intercropping (8 %), crop rotation (7.24 %), and biochar had 4.45 % observations (Table 1). Further, the data set had 81crops representing cereals, legumes, fruits and vegetables, and other crops. Under each crop category, out of the total number of observations followed the order of legume-based system (23.79 %), rice-

Table 2
Summary of studies conducted on different sustainable agricultural practices in India.

Category	Observations	Studies	Crops	Duration (years)[a]
All	2362	295	81	11.21 ± 11.26
Integrated nutrient management	960	148	38	16.29 ± 12.94
Organic amendment	275	52	28	17.75 ± 12.05
No-tillage	314	44	18	4.25 ± 2.33
Crop rotation	171	20	21	5.92 ± 2.30
Residue retention	348	48	15	5.14 ± 3.43
Intercropping	189	21	64	4.61 ± 3.86
Biochar	105	14	11	2.68 ± 0.48

[a] Mean ± Standard Deviation.

wheat (13.12 %), finger millet-based system (8.21 %), horticultural crops (15.83 %), and miscellaneous crops (15.83 %).

2.3. Statistical tools

The collected data were analyzed using a meta-analysis framework. Meta-analysis is becoming a popular tool in the recent past due to its flexibility in data analysis compared to other methods. Several studies have used meta-analysis in environmental and natural resource economics studies (Cadotte et al., 2012; Nelson and Kennedy, 2009).

The effect size of each study was estimated as response ratio (RR), a ratio of the outcome variable of SAPs and their control group. The natural log of response ratio (LRR) is estimated using the below equation (Hedges and Gurevitch, 1999):

$$\text{Effect size} = \ln \text{RR} = \ln\left[\frac{\overline{X}_T}{\overline{X}_C}\right] = \ln \overline{X}_T - \ln \overline{X}_C \quad (1)$$

where $\overline{X}_T$ and $\overline{X}_C$ are the soil organic carbon stocks under SAPs and conventional practices, respectively. Since many studies did not report the variance of means, observations were weighted by the number of replications. For studies where the number of observations was more than one, then weights were divided by the total number of observations from that study. The weights were estimated by using the following equation.

$$\text{Weights (w)} = \frac{N_T \text{ X } N_C}{N_T + N_C} \quad (2)$$

where N_T and N_C are the number of replications under treatment and control groups, respectively (Van Groenigen et al., 2011; Lam et al., 2013). Further, a random-effect model was used to understand carbon sequestration response under different SAPs. Finally, the obtained LRR was transformed in terms of percentage change in SOC stocks of treatment groups compared to the control group. The meta-analysis was performed using the “metafor” package in R software (Viechtbauer, 2010). Percent change = (exp(LRR) − 1) ∗ 100. Further, heterogeneity and the publication bias of the studies were also assessed before final statistical analysis (see the Supplementary file, Table S2 & Fig. S3).

To identify the agronomic and environmental factors affecting the carbon sequestration potential of SAPs, a mixed linear model was estimated by using the response ratio as a dependent variable (Toliver et al., 2012).

$$IN(RR) = Wa + U\beta + \varepsilon \quad (3)$$

where α and β are unknown fixed and random effects vectors, and W and U are given known and incidence matrices (McLean et al., 1991). The sign and significance of the parameter estimates were used to identify the factors influencing carbon sequestration. Finally, the random intercepts for states and study locations were added to capture regional differences in the explanatory variables. The final model was specified as follows:

$$\begin{aligned}\text{lnRR} = {} & \alpha_0 + \sum \alpha_i \text{CroppingSystem} + \sum \alpha_j \text{Climate} + \sum \alpha_k \text{Soil} \\ & + \alpha_{16}\text{Rainfall} + \alpha_{17}\text{Irrigation} + \alpha_{18}\text{Durationlog} \\ & + (1|\text{state}|\text{studysite})\end{aligned} \quad (4)$$

where the cropping system represents one of the four systems (i = maize-wheat, legume-based, soybean-wheat, finger millet based, horticultural based, and others), climate represents one of the five climate types (j = semiarid tropical, semi-arid, semi-arid-subtropical, subtemperate, and arid), and the soil represents one of the four soil textures (k = coarse, fine, medium and moderately fine). The reference categories for cropping systems, climate, and soil texture are rice-wheat, humid subtropical, and moderately coarse soil, respectively. Irrigation is a binary variable (value = 1 if irrigation was applied, 0 = otherwise), and rainfall (mm) is a continuous variable. The variable duration log is a continuous variable representing the natural logarithm of the year of the experiment. The duration log variable is a continuous variable representing the natural log of the years for which an experiment lasted. The value of the duration log was used to test whether a lag existed between SAPs and conventional practices at the start and end of the experiment and to see the effect of the time period on carbon sequestration potential. All equations were estimated using STATA 14.2. As the preliminary analysis shows the presence of heteroscedasticity, the states/study location of the experiment was included in the model as a random effect variable and modelled using an identity covariance matrix. To select a better-fitted model, Akaike information criteria (AIC) was used.

2.4. Economic valuation

Since India does not have a regulated carbon credit market, the economic valuation of carbon sequestration was performed by using the social cost of carbon as a shadow price. The social cost of carbon depicts the economic cost of climate damage due to emission of one tonne of CO_2 into the atmosphere and thereby represents the economic gains from reduction. Hence we used a country-level social cost of carbon of US\$86 Mg^{-1} of CO_2 for the valuation of C stock (Ricke et al., 2018; MoSPI, 2021). Further, the cost of urea (46%N) at US\$ 87.29 Mg^{-1} of Urea as the cost of stabilization for carbon storage in soil. Costs of other nutrients and other costs were not included in the analysis. Finally, the economic return was estimated as follows (Lam et al., 2013):

(i) Value of carbon stock (US\$$ha^{-1}$ $year^{-1}$) = CO_2 equivalent (Mg CO_2 ha^{-1} $year^{-1}$) ∗ Social cost of Mg^{-1} of CO_2
(ii) Economic return (US\$$ha^{-1}$ $year^{-1}$) = Value of carbon stock (US\$$ha^{-1}$ $year^{-1}$) − Cost of stabilization of carbon storage (US\$$ha^{-1}$ $year^{-1}$)

Additionally, to determine the carbon credit potential of SAPs, we also conducted the analysis by using the 2021 global carbon price for agriculture sector in the voluntary carbon market (VCM) as US\$8.81 Mg^{-1} of CO_2 (Donofrio et al., 2022).

3. Results

3.1. Trends from the systematic review

Our study indicated that the response of soil organic carbon to sustainable agricultural practices (SAPs) was predominantly positive, with 88 % cases of positive, 10 % negative and 3 % neutral effects (Fig. 2). Out of seven SAPs, integrated nutrient management, and residue retention had the highest number of positive effects. In contrast, crop rotation (−22 %) and no-tillage (−15 %) accounted for the highest proportion of negative effect sizes as compared to other practices. Although several studies have investigated the carbon sequestration potential of improved crop management practices, the most frequently examined SAPs were integrated nutrient management, residue retention, no-tillage, and organic amendment. However, biochar and crop rotation were less investigated and therefore call for further in-depth studies in this area.

3.2. Impact of sustainable agricultural management practices on carbon sequestration

The meta-analysis shows significantly higher carbon sequestration under improved management practices compared with conventional practices. Application of biochar resulted in a higher carbon sequestration rate (3.27 Mg C ha^{-1} $year^{-1}$), whereas crop rotation and no-tillage had a slightly lower sequestration rate compared to

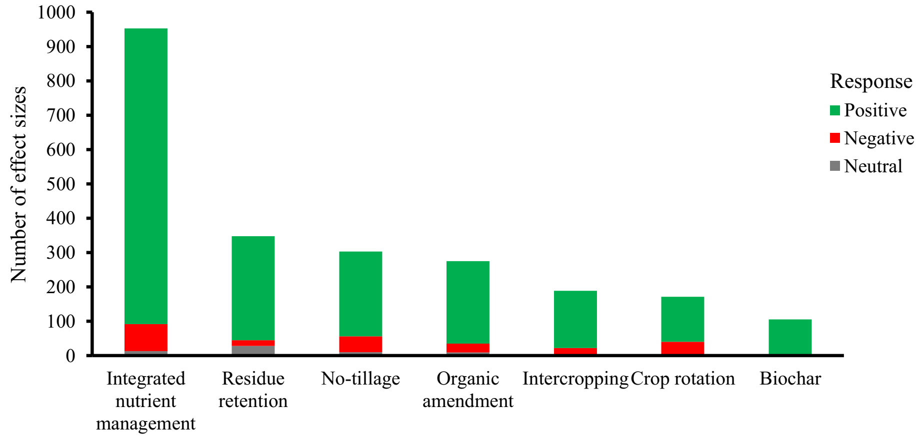

Fig. 2. Number of effect sizes of soil organic carbon in response to sustainable agricultural practices, India.

other practices (Fig. 3). The analysis of effect size shows that the addition of biochar into the soil was a most effective practice to enhance carbon sequestration (33.75 % to 49.26 %) with a mean effect of 41.28 % (Fig. 4). Similarly, organic amendment, intercropping, integrated nutrient management, and no-tillage were also having a significant influence over SOC with a mean effect ranging from 28.27 % to 12.79 % higher than conventional practices. On the other hand, crop rotation showed a lower yet significant impact on soil C stocks with a mean effect of 7.19 %. All the results were statistically significant.

Cropping system-based analysis presented in Table 3 showed that legume-based systems had highest carbon sequestration under integrated nutrient management (17.3 %), no-tillage (15.04 %), residue retention (17.94 %), and organic amendment (40.03 %). Under the maize-wheat system, integrated nutrient management (18.71 %) and no-tillage (14.43 %) positively affected soil C stock. However, crop rotation and no-tillage were less effective and insignificant in improving C sequestration under the rice-wheat system. Further, we also found a positive relationship between carbon sequestration and yield (see the Supplementary file, Fig. S2). The increase in yield was observed with an increase in soil organic carbon stocks. However, the largest gain in yield was witnessed within 1 % of soil organic carbon concentration.

3.3. C sequestration potential of sustainable agricultural practices under different climatic conditions

Climatic conditions play an important role in enhancing the carbon sequestration potential of SAPs. The results show that overall, higher carbon sequestration was found in the semi-arid region followed by the semi-arid subtropical region and humid subtropical region (Fig. 5). Implementation of crop rotation, no-tillage, and integrated nutrient management had increased additional C sequestration by 18.01 %, 13.02 %, and 11.13 % than humid subtropical climate. In contrast, residue retention (15.84 %) and intercropping (8 %) practices had higher C sequestration under semi-arid subtropical regions than in humid subtropical areas. Interestingly, SOC stocks of biochar have not varied significantly under all the climates considered in this study. However, the organic amendment had increased 27.82 % additional soil organic carbon in the humid-subtropical region compared to the semi-arid region.

3.4. Impact of soil texture and duration on C sequestration potential of sustainable agricultural practices

Soil texture is also a major driving force that governs the magnitude of C sequestration. Overall, moderately fine-textured soils had higher C sequestration than other groups (Fig. 6). The organic amendment, biochar, and crop rotation under these groups had increased C sequestration by 56.11 %, 51.11 %, and 26.28 %, respectively. In contrast, integrated nutrient management, no-tillage, and intercropping practices performed better under moderately textured soils and increased SOC by 20.29 %, 12.61 %, and 22.58 %, respectively. At the same time, medium-textured soil groups had shown a positive effect on residue retention and increased SOC by 21.82 %.

Further, our results showed the effect of the time period on the carbon sequestration potential of improved farming practices (Fig. 7). It is

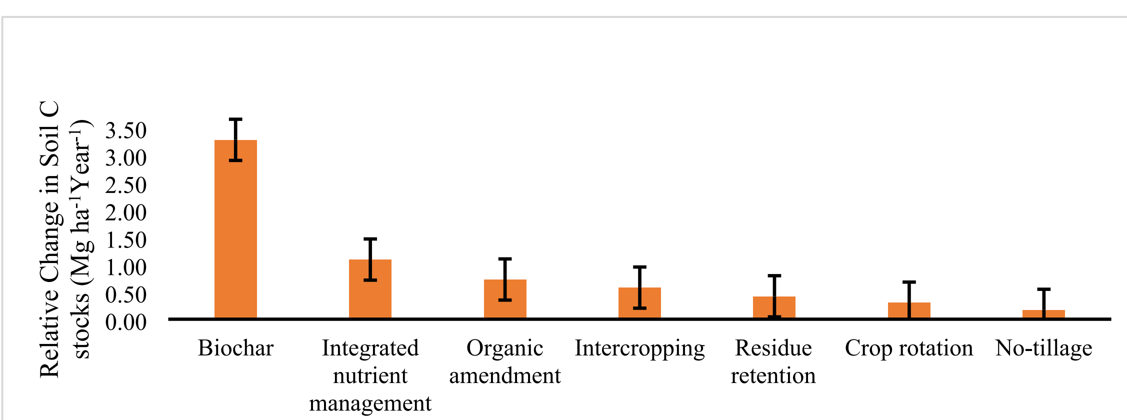

Fig. 3. Rate of change in annual soil carbon stock due to sustainable farming practices in Indian agriculture (Mg C ha^{-1} year^{-1}).

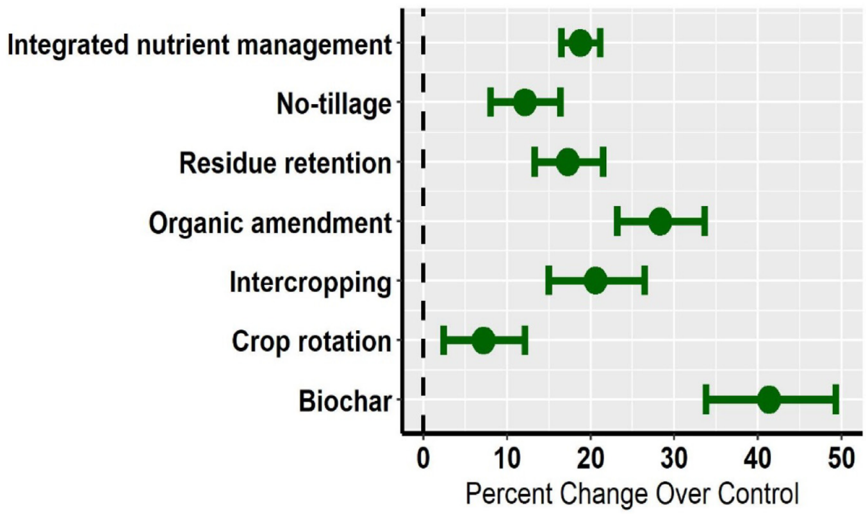

Fig. 4. Effect of sustainable agricultural practices on change in soil carbon stocks in India.

observed that an additional 2.62 Mg C ha $^{-1}$ can be sequestrated till 40 years of implementation of SAPs. However, after 40 years, the additional gain in SOC has shown a declining trend. Further, integrated nutrient management had increased C sequestration by 14.66 %, 19.91 %, and 27.62 % in all three experimental durations, i.e., short-term, medium-term, and long-term, respectively. Similarly, the organic amendment also showed similar results of increased SOC in the range of 9.91 % to 14.78 % under all three experimental durations. No-tillage practices significantly increased C sequestration by 18.60 % in the medium-term experiments and 9.44 % in short-term duration experiments. Residue retention increased SOC in both short and medium-duration experiments by 9.51 % and 17.98 %, respectively. Intercropping also increased C sequestration by 7.96 % and 15.77 % in both short-term and medium-term experiments. However, crop rotation augmented higher C sequestration under short-term duration (13.86 %) than in the medium-term duration experiments (12.70 %) (see the Supplementary file, Table S1).

3.5. Influence of agro-climatic factors on C sequestration

The model specified in Eq. (4) was used to identify the role of cropping systems, soil texture, climate, and related factors on relative C sequestration difference in SAPs. Coefficients in Table 4 are shown as the effect of the variable on the C sequestration potential associated with its reference category. C sequestration responded differently to crop production systems. Carbon sequestration under legume-based, maize-wheat, soybean-wheat, and finger millet-based systems was found higher than in the rice-wheat system. Further, moderately fine-textured soils showed significantly higher C sequestration potential than coarse and fine soils. Although the overall highest effect size was observed under a semi-arid climate, regression result shows that C sequestration favors humid-subtropical climate over semiarid-tropical, semi-arid, and semiarid-subtropical environments. Further, rainfall, irrigation, and duration parameters were also found to be major driving factors for the higher C sequestration potential under improved management practices.

3.6. Economic valuation

Sustainable agricultural practices can be targeted as potential technologies to improve soil C sequestration and increase farm income for small and marginal holders. Our result shows that all the SAPs considered in this study emerged as economically feasible and have the potential to tap the carbon credit market. The additional economic value of carbon sequestration from each practice was estimated at US$1033 ha^{-1} year^{-1} by applying biochar, 297 US$ ha^{-1} year^{-1} through organic amendment, US$224.07 ha^{-1} year^{-1} by practicing integrated nutrient management, US$181.54 ha^{-1} year^{-1} from the implementation of intercropping, US$ 99.84 ha^{-1} year^{-1} from residue retention, US$ 95.26 ha^{-1} year^{-1} through crop rotation and US$ 50.03 ha^{-1} year^{-1} for no-tillage during initial ten years of adoption of SAPs (Table 5). The economic value of carbon stock was estimated using the social cost of carbon US$ 86 Mg^{-1} of CO_2. Further, even if we consider the cost of N as a stabilization cost for C storage, the positive net economic return was still found for all the SAPs in the range of US$47.9 to 988.96 ha^{-1} year^{-1}.

Table 3
Effect of sustainable agricultural practices on soil organic carbon across major cropping systems of India.
(% change over control)

Cropping systems	Rice-wheat		Maize-Wheat		Legume based systems	
	Mean	CI	Mean	CI	Mean	CI
Integrated nutrient management	15.48*	9.68 to 21.58	18.71*	7.30 to 31.31	17.30*	9.16 to 26.05
No-tillage	5.30	−10.30 to 23.59	14.43*	0.38 to 30.43	15.04*	8.50 to 21.97
Residue retention	24.33*	17.90 to 31.13	–	–	17.94*	5.04 to 32.41
Crop rotation	16.03	−0.99 to 35.97	–	–	–	–
Organic amendment	–	–	–	–	40.03*	20.56 to 62.65

Note: CI: Confidence Intervals.
* Significant at 1 % level of significance.

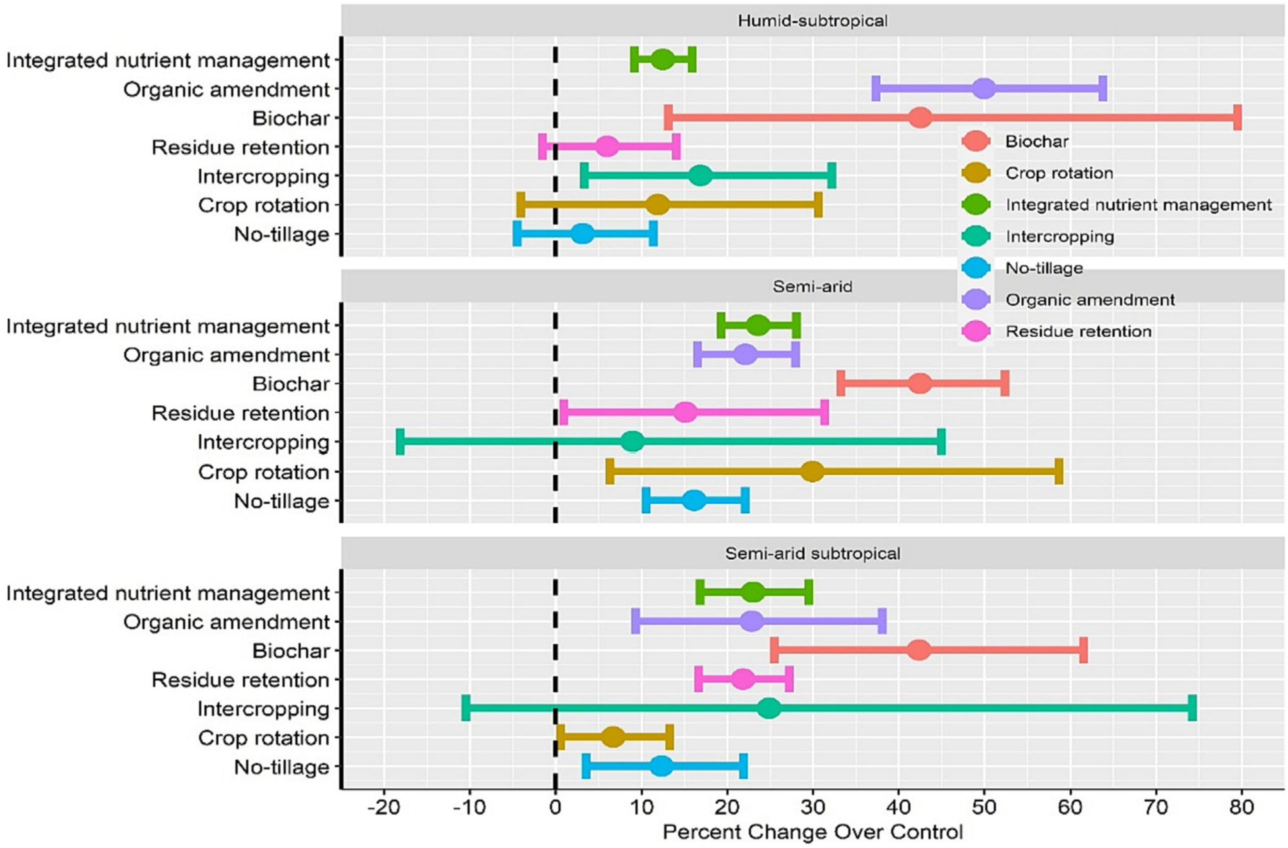

Fig. 5. Effect of sustainable agricultural practices on soil organic carbon under different climatic regions of India.

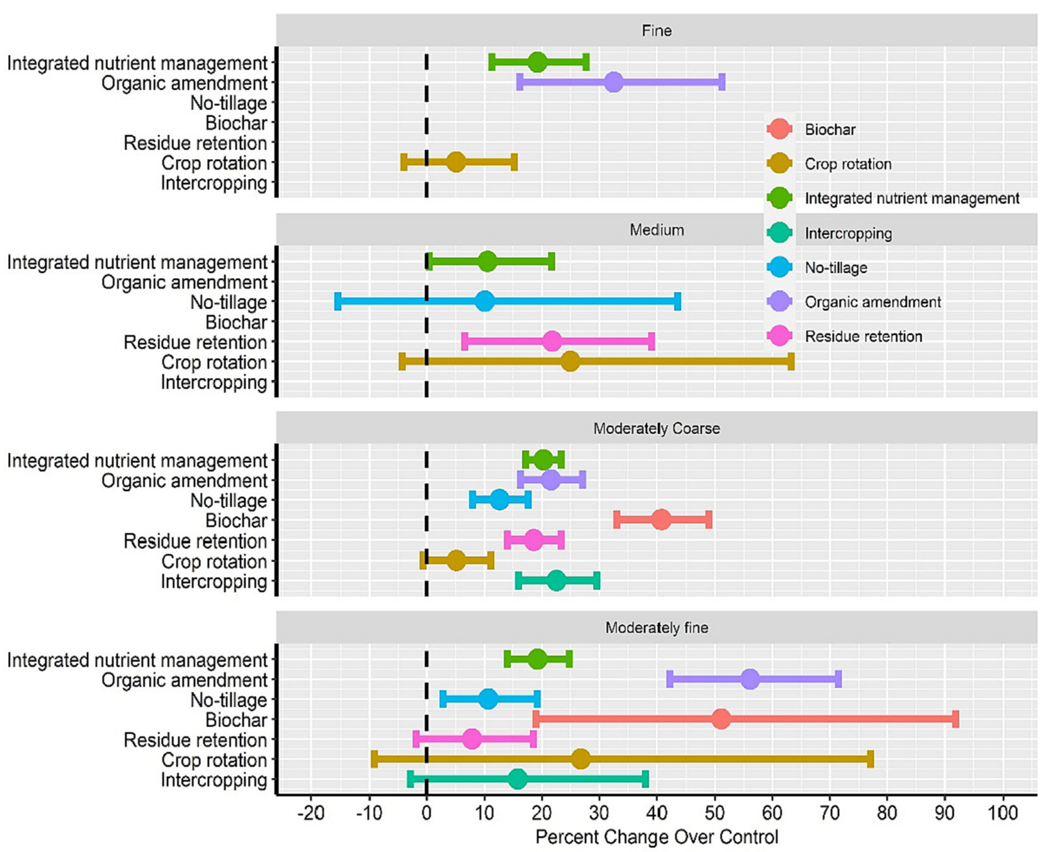

Fig. 6. Effect of sustainable farming practices on soil organic carbon under different soil textures in India.

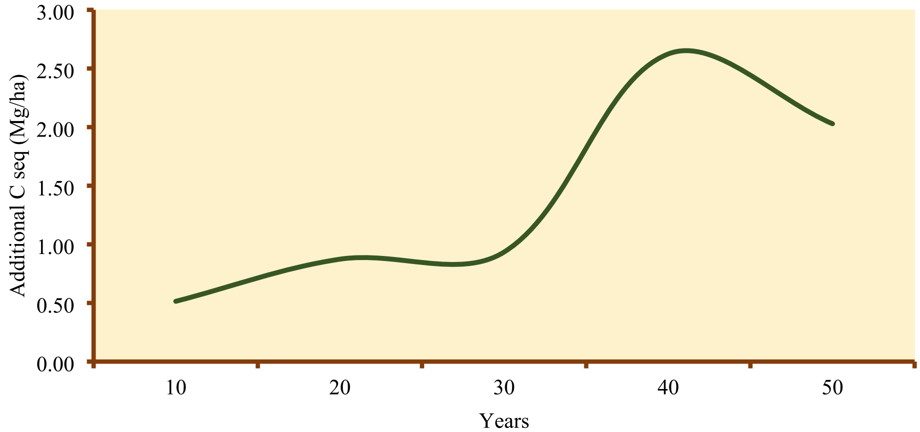

Fig. 7. Stylized dynamics of carbon sequestration potential of sustainable agricultural practices in the Indian agricultural landscape.

The carbon credit potential of SAPs based on global voluntary carbon market price shows that the relative C credit gain from each practice is estimated in the range of US\$5.12 ha^{-1} $year^{-1}$ to 105.74 US\$ ha^{-1} $year^{-1}$ during ten years of adoption (see the Supplementary file, Table S3). Further, the positive net economic return was also observed in the range of US\$2.97 to 61.36 ha^{-1} $year^{-1}$ for all the SAPs considered in this study. The value of carbon credit is estimated based on the 2021 global voluntary carbon market price at US\$ 8.8 Mg^{-1} of CO_2.

4. Discussions

4.1. Carbon sequestration potential

Sustainable agricultural management practices effectively mitigate the adverse effects of climate change through increasing soil C sequestration, thereby avoiding carbon emissions from conventional farming practices. Our results indicated that improved management practices positively and significantly affected soil organic carbon at different scales. The addition of biochar into soil had the highest C sequestration due to improved CO_2 flux, delay in carbon decomposition rate, and stabilization of soil organic carbon (Wu et al., 2021). Das et al. (2022) observed that the use of biochar increased soil organic carbon by 23 % over control. Further, biochar is also recognized as a sustainable land management response option to mitigate climate change by IPCC. A global analysis predicted that biochar has the potential to remove 0.03–6.6 $GtCO_2e$ yr^{-1} from the atmosphere (IPCC, 2019). Besides carbon sequestration, biochar application also increases yield by 25 % in the tropics.

Table 4
Parameter estimates of mixed linear regression model comparing Carbon sequestration potential of sustainable agricultural practices.

Explanatory variables	Coefficient	Std. err.
Intercept	−0.03	0.08
Cropping system		
Maize-wheat	0.05**	0.02
Legume based	0.04**	0.02
Soybean-wheat	0.2***	0.03
Finger millet-based system	0.1*	0.06
Horticultural crops	0.16***	0.05
Other crops	0.05***	0.02
Soil texture		
Coarse	−0.06	0.09
Fine	−0.01	0.03
Medium	0.03	0.03
Moderately fine	0.03**	0.01
Climate		
Semi-arid-tropical	−0.12***	0.05
Semi-arid	−0.09***	0.04
Semi-arid-subtropical	−0.09***	0.04
Sub-temperate	−0.04	0.06
Arid	−0.11	0.16
Rainfall	0.0001***	0.00001
Irrigation	0.04**	0.02
Duration log	0.03***	0.01
No. of observation	2196	
Log-Likelihood	567.81	
Akaike information criterion	−1091.62	
Bayesian information criterion	−966.345	

Note: ***, **, and ** indicate 1, 5, and 10 % levels of significance. Intercept includes reference categories of rice-wheat cropping system, moderately coarse-textured soils, and Humid-subtropical climate.

Further, our study indicated that soil organic carbon stocks under the organic amendment and integrated nutrient management were significantly higher than chemical fertilizer. Previous studies have also supported an increase in SOC stocks under organic amendments. Wu et al. (2021) reported 34 % higher soil organic carbon content under organic amendment than chemical fertilizers. Similar trends of increasing soil organic carbon with an organic amendment were also reported by Bai et al. (2020) and Li et al. (2021). A global meta-analysis by Han et al. (2016) showed a 36 % increase in topsoil organic carbon under integrated nutrient management practice. Padbhushan et al. (2021) also performed a meta-analysis and revealed that the addition of organic inputs leads to a 16–23 % increase in soil organic carbon over NPK. Similarly, Maillard and Angers (2014) also observed a relative increase in soil organic carbon of 26 % (for 18 years). Further, findings revealed that integrated nutrient management had lower carbon sequestration in the rice-wheat system over other systems. It may be due to rice cultivation in the puddled system, which hinders the oxygen supply required for the soil chemical process (Fageria et al., 2011). In addition, a decrease in aggregate stability and cracks in the Indian soil lowers soil organic carbon (Hobbs et al., 2008).

This study postulates higher carbon sequestration potential in no-tillage practice over conventional tillage. Our findings were supported by Kumara et al. (2020) and Das et al. (2022), who reported a 16–18 % higher C sequestration under conservation tillage. Further, Crop residue retention in the agricultural field after crop harvest plays a pivotal role in increasing C sequestration, influencing C dynamics in soil, and improving water-holding capacity (Beehler et al., 2017). The present study shows that, on average, there is a 17.28 % more relative change in carbon sequestration under crop residue retention. Mafongoya et al. (2000), also reported the positive influence of soil cover on carbon sequestration. On the other hand, Ghimire et al. (2012) and Reicosky et al. (2002) reported the neutral and/or zero effect of land cover on carbon sequestration. In addition, this study also observed higher carbon sequestration under crop rotation over mono-cropping systems. A similar study by West and Post (2002) estimated that globally an average 20 ± 12 g C m^{-2} $year^{-1}$C sequestration could be increased through crop rotation.

Table 5
Economic valuation of carbon sequestration from sustainable agricultural practices in India (10 years).

Practice	Relative change in C stock (Mg C ha^{-1} $year^{-1}$)[***]		C stock (CO_2 eq Mg CO_2 ha^{-1} $year^{-1}$)	Value of C stock (US\$ ha^{-1} $year^{-1}$)[a]	N input to stabilize C storage (Kg ha^{-1} $year^{-1}$)[b]	N cost to stabilize C storage (US\$ ha^{-1} $year^{-1}$)[c]	Economic return (US\$ ha^{-1} $year^{-1}$)
	Mean	95 % CI					
Integrated nutrient management	0.71	0.53 to 0.89	2.61	224.07	110.24	9.62	214.45
Organic amendment	0.94	0.63 to 1.26	3.46	297.15	146.19	12.76	284.39
No-tillage	0.16	0.10 to 0.22	0.58	50.03	24.61	2.15	47.88
Crop rotation	0.30	0.22 to 0.38	1.11	95.26	46.87	4.09	91.17
Residue retention	0.32	0.26 to 0.38	1.16	99.84	49.12	4.29	95.56
Intercropping	0.58	0.30 to 0.86	2.11	181.54	89.31	7.80	173.74
Biochar	3.27	1.57 to 4.98	12.02	1033.34	508.38	44.38	988.96

Note: CI: Confidence Intervals.
[***] Indicate 1 % level of significance.
[a] Estimated based on social cost of carbon US\$ 86 Mg^{-1} of CO_2e.
[b] Estimated by taking soil C: N ratio of 14:1 of arable lands.
[c] Estimated by taking N cost of US\$ 87.29 Mg^{-1} of urea (46%N).

Improved land management practices represent a potential global response option to address critical issues, viz., adaptation, mitigation, combating desertification and land degradation, and enhancing food security (IPCC, 2019). For example, many studies reported that improved farming practices have the potential to mitigate carbon emissions in the range of 1.4 to 2.3 Gt CO_2e per year (Smith et al., 2014; Pradhan et al., 2013). Further, the rejuvenation of degraded lands and improved rice management practices have the potential to cut emissions by 0.2 to 0.7 GtCO_2e per year (Smith et al., 2014). However, carbon sequestration rates in different management practices are primarily determined by agronomic practices and different environmental and climatic factors (Shi et al., 2018).

4.2. Impact of climatic conditions, soil texture, and duration on soil carbon sequestration

Climatic conditions play a crucial role in C sequestration and its distribution by regulating microbial mechanisms and biomass production (Callesen et al., 2003). The rate of C sequestration is highly dependent on temperature, rainfall, and prevailing environmental conditions. A slight temperature variation can alter C sequestration by influencing the magnitude of organic matter decomposition (Zhao et al., 2019). The higher temperature generally does not favor C sequestration due to the mineralization of soil organic carbon under such conditions (Li et al., 2020). In contrast, high rainfall positively influences C sequestration, supporting microbial and vegetation growth (Han et al., 2019; Luo et al., 2017). Integrated nutrient management, no-tillage, and crop rotation practices had a higher accumulation of SOC stocks in semi-arid regions than in humid subtropical areas, probably due to low SOC turnover in semi-arid subtropical areas than humid subtropical regions (Mureva et al., 2018). In contrast, residue retention and adoption of intercropping practices enhance more extensive C sequestration under semi-arid subtropical conditions compared to humid subtropical regions. The supportive environment for forming pedogenic $CaCO_3$ is the probable reason for higher C sequestration under semi-arid areas (Bhattacharyya et al., 2011; Srinivasarao et al., 2014). Further, the total soil organic carbon stock in the semi-arid region of India is estimated at 2.9 Pg (30 % of the total SOC storage).

The present study suggests that the C sequestration potential of biochar does not vary significantly by climatic factors and performs better in all the environments considered in this study. In contrast, many studies also reported that biochar application in the arid region results in higher C sequestration than in humid areas (Karhu et al., 2011; Abel et al., 2013). The organic amendment increases SOC stocks higher in humid-subtropical areas than in semi-arid regions. Organic amendments enhance SOC storage and delay the decomposition rate in humid areas with proper management practices. As a result, the organic amendment has higher C sequestration potential under humid-subtropical conditions than in semi-arid areas. However, in highland agricultural regions, the rate of soil carbon sequestration significantly varies compared to lowland areas. In addition to climatic conditions, carbon sequestration in these regions is determined by other factors such as elevation, altitude, and slope (Arunrat et al., 2020; Griffiths et al., 2009). Many studies have shown a direct relationship between elevation and soil organic carbon in highland regions. Choudhury et al. (2016) reported a 53.7 % increase in soil organic carbon concentration and 27–31 Mg C ha^{-1} at an altitude of 2000 masl compared to the baseline. Dinakaran et al. (2018) and Kumar et al. (2017) reported a similar observation of higher altitudes and higher soil carbon stock. In contrast, a decrease in soil organic carbon stock with altitude has also been reported by Sheikh et al. (2009).

Soil texture significantly influences the C sequestration process under improved crop management practices. The organic amendment, biochar, and crop rotation practices promote SOC stocks under moderately fine-textured soil groups. Clay loam and sandy clay loam soils under this group positively affected carbon sequestration and increased SOC stocks (Stronkhorst and Venter, 2008). These soil groups provide physical and chemical support to soils that help in increasing C sequestration (Six et al., 2002). Organic amendment and biochar addition under fine-textured soils increases soil organic matter, improves soil physical, chemical, and microbial properties, and enhances soil organic carbon stock (Omondi et al., 2016). In contrast, Lu et al. (2014) and Zhang et al. (2020) reported a limited effect on improved SOC under fine-textured soils due to the application of biochar. This happens when the soil has reached its inflection point and has minimal scope for further increase in SOC (Six et al., 2002). On the other hand, C sequestration under integrated nutrient management, no-tillage, and intercropping practices was found to be better in sandy loam soils as it accelerates physical and chemical reactions in the soil by forming bonds (Jobbágy and Jackson, 2000). In contrast, residue retention improves SOC stocks under medium-textured soil groups as it augments the soil organic matter, porosity, and cation exchange capacity, which in turn increases SOC stocks (Blanco-Canqui, 2017).

The duration of adoption of SAPs in agricultural production systems determines the rate and dynamics of C sequestration. When SAPs are implemented, C sequestration initially increases but at a decreasing rate until it reaches a saturation point (Hoyle et al., 2013). Thus, only a certain amount of carbon can be sequestered through improved farm practices from a given piece of cultivated land (Thamo et al., 2020). To preserve accumulated SOC stock, the adoption of practice must be sustained; as the sequestration process is reversible, returning to the earlier practice leads to the re-emission of CO_2 (Thamo et al., 2020). Further, studies reported that about a decade is required for soil to respond to the changes in farming practices (Brahma et al., 2018). In our study, the C sequestration potential of SAPs responded differently to the time period. It is observed that integrated nutrient management and organic amendment influenced much higher C sequestration in long-term experiments. In contrast, no-tillage, residue retention, and intercropping significantly influenced SOC stocks under medium-term experiments. Conversely, short-term experiments had the highest effect on C sequestration under crop rotation. Similar findings were reported by Das et al. (2021) and Bai et al. (2019). However, over time, the accumulation of soil carbon stocks will be limited (Sommer and Bossio, 2014).

4.3. Influence of agro-climatic factors on C sequestration

C sequestration potential of cropping systems responded differently under SAPs and conventional practices. Among cropping systems, the relative gain in terms of C sequestration was higher in maize-wheat, soybean-wheat, and legume-based systems than in the rice-wheat system. The ability to fix atmospheric nitrogen, the addition of large biomass below and above ground, and leaf shedding capacity were the possible explanations for higher C sequestration (Ganeshamurthy, 2009). In addition, moderately fine-textured soils showed significantly higher C sequestration potential as these soil forms strong bonds in soils and facilitate SOC accumulation (Six et al., 2002). Further, the parameter estimate of the regression model shows that humid-subtropical areas favor higher C sequestration than other regions as the rate of accumulation of SOC is more than the decomposition in humid conditions (Jobbágy and Jackson, 2000). Similarly, adequate precipitation is needed to promote the C sequestration process under SAPs, as sufficient moisture is crucial for microbial growth and regulation of the process of decomposition (Lai et al., 2013). However, in highland agricultural areas, factors viz., altitude, bulk density, and fertilizer (N&K) application were reported as the significant drivers of C sequestration (Arunrat et al., 2020).

4.4. Economic valuation

Sustainable agricultural practices have potential economic benefits and can be regarded as economically feasible alternatives to improve C sequestration in the Indian agricultural landscape. This study estimated a positive net economic return of US\$47.9 to 988.96 ha^{-1} $year^{-1}$ from all the improved management practices (Table 5). Grace et al. (2010) performed the economic feasibility of carbon sequestration using carbon supply curves and observed higher net economic return in no-tillage over conventional tillage. Similarly, Williams et al. (2004) indicated that the implementation of no-tillage practice resulted in higher carbon credit gain and estimated net return in the range of \$8.62 to \$64.65 Mg^{-1} $year^{-1}$. These results advocate that sustainable agricultural practices to enrich carbon sequestration and the value of carbon preservation are technically feasible and economically profitable. In contrast, Lam et al. (2013) reported that improved farming practices, viz., no-tillage, crop residue retention, and pasture use, resulted in an economic loss of 8 to18 AU\$ ha^{-1} $year^{-1}$ during the first decade of implementation.

However, to make it more profitable, changes in C sequestration need to be measured carefully at the farm level using the international carbon offset standards (Walcott et al., 2009). We also estimated that all the improved crop management practices considered in this study could potentially increase soil organic carbon stocks by 0.16 to 3.27 Mg of C ha^{-1} $year^{-1}$ in the Indian agricultural landscape. Regarding environmental benefits, the area under SAPs (excluding biochar) is estimated as 68.66 million ha (Gupta et al., 2021) with a gain of 100.28 Tg CO_2e $year^{-1}$ from Indian agriculture. This is an optimistic estimate as it does not include the impact on methane and nitrous oxide emissions by implementing these practices. Further, the amount of carbon sequestration is based on climatic and environmental factors and field-level data, which provide estimates that are more realistic.

Our study also indicated that implementing improved crop management practices could generate carbon credits worth US\$2.97 to 61.36 ha^{-1} $year^{-1}$ in global voluntary carbon markets (Supplementary file, Table S3). Therefore, farmers are able to receive additional returns by selling sequestered carbon as carbon credits in the global carbon markets. Voluntary carbon markets (VCM) are dominated by private players and provide an opportunity to achieve voluntary climate targets through carbon credits. These markets function outside the regulated national and international carbon markets with international carbon credit standards such as VERRA, Gold standard, and American carbon registry. The VCM is growing rapidly in the past few years and generated about 493 Million $MtCO_2e$ emission reduction worth \$1.98 Billion in 2021 (Donofrio et al., 2022). However, the carbon price in these markets is highly volatile in the range of 5 to US\$10, mainly driven by market forces through demand and supply. Nevertheless, there is a huge potential in carbon markets that can be reaped by farmers through the adoption of improved crop management practices. For instance, linking farmers with farmer-producer organizations could help farmers to avail benefits from carbon credit markets.

4.5. Limitations of the study

According to our knowledge, the compiled dataset is the largest for assessing the carbon sequestration potential of improved farming practices in the Indian agricultural landscape. However, a few limitations also need to be considered while transforming the results of this study. The first limitation is that about 25–30 % of the studies did not directly report the soil organic carbon stock. This is because the prime objectives of these studies are intended to investigate other parameters such as yield and other properties. However, soil organic carbon concentrations reported in these studies alone are not adequate to estimate carbon sequestration potential. Another limitation is that most of the studies did not report the standardized procedures employed to estimate the SOC concentration, which may hinder the potential benefits. Further, due to the lack of published on-farm data on soil organic carbon, this study is entirely based on data reported from on-station studies. Therefore, sufficient data from the farmer's field is necessary for a more realistic comparison. Another important limitation is due to the lack of data, we have not considered the impacts of improved farming practices on other GHG emissions. Further, valuation of soil carbon in monetary terms is a very complex process as it requires an in-depth understanding of carbon credit mechanism. Thus, variations in actual carbon sequestration and economic gain from these practices may differ, as reported in this study.

5. Conclusions and policy implications

To address the adverse impacts of climate change on agriculture, there is a need to develop sustainable production strategies considering biophysical and climatic factors. This national-level meta-analysis study has identified various sustainable farming options for climate change mitigation and adaptation. We found that improved crop management practices lead to a 7.19 % to 41.29 % increase in soil organic carbon stocks, indicating that implementing these practices has higher carbon sequestration potential in the Indian agricultural landscape. However, to reap the maximum C sequestration potential, SAPs should be targeted in maize-wheat and legume-based cropping systems in humid-subtropical regions and moderately fine-textured soils. Findings from this study also suggested that all SAPs considered enhancing C sequestration were economically profitable and have the potential to contribute to India's net zero emission by 2070 and climate target (creating an additional carbon sink of 2.5–3 billion Mg of CO_2e by 2030). However, an effective policy instrument is required to address the technological, economic, and sociocultural barriers to adopting SAPs. Hence, efforts should be directed towards the promotion and outscaling of SAPs by (i) Extending incentives for the generation of ecosystem services in the form of agri-environmental payments, (ii) Investment in agricultural R&D to improve agricultural productivity and livelihood of smallholders, (iii) Strengthening technology transfer and extension services, (iv) by linking smallholders to carbon credit markets, and (v) designing appropriate policy mix by including synergies and trade-offs from improved management practices. Thus, carbon sequestration through improved agricultural management practices represents a win-win strategy to improve livelihood while mitigating climate change impacts in the region.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.12.015.

References

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., Wessolek, G., 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. Geoderma 202–203. https://doi.org/10.1016/j.geoderma.2013.03.003.

Arunrat, N., Pumijumnong, N., Sereenonchai, S., Chareonwong, U., 2020. Factors controlling soil organic carbon sequestration of Highland agricultural areas in the mae Chaem Basin Northern Thailand. Agronomy 10 (2), 305. https://doi.org/10.3390/agronomy10020305.

Bai, X., Huang, Y., Ren, W., Coyne, M., Jacinthe, P.A., Tao, B., Hui, D., Yang, J., Matocha, C., 2019. Responses of soil carbon sequestration to climate-smart agriculture practices: a meta-analysis. Glob. Chang. Biol. 25. https://doi.org/10.1111/gcb.14658.

Bai, Y., Zhou, Y., He, H., 2020. Effects of rehabilitation through afforestation on soil aggregate stability and aggregate-associated carbon after forest fires in subtropical China. Geoderma 376. https://doi.org/10.1016/j.geoderma.2020.114548.

Beehler, J., Fry, J., Negassa, W., Kravchenko, A., 2017. Impact of cover crop on soil carbon accrual in topographically diverse terrain. J. Soil Water Conserv. 72. https://doi.org/10.2489/jswc.72.3.272.

Bhattacharyya, T., Pal, D.K., Chandran, P., Ray, S.K., Mandal, C., Wani, S.P., 2011. Carbon status of Indian soils: an overview. In: Srinivasarao, Ch., et al. (Eds.), Soil Carbon Sequestration for Climate Change Mitigation and Food Security. Hyderabad, India, Central Research Institute for Dryland Agriculture, pp. 11–30.

Blanco-Canqui, H., 2017. Biochar and soil physical properties. Soil Sci. Soc. Am. J. 81, 687–711. https://doi.org/10.2136/sssaj2017.01.0017.

Brahma, B., Pathak, K., Lal, R., Kurmi, B., Das, M., Nath, P.C., Nath, A.J., Das, A.K., 2018. Ecosystem carbon sequestration through restoration of degraded lands in Northeast India. Land Degrad. Dev. 29, 15–25. https://doi.org/10.1002/ldr.2816.

Cadotte, M.W., Mehrkens, L.R., Menge, D.N.L., 2012. Gauging the impact of meta-analysis on ecology. Evol. Ecol. 26, 1153–1167. https://doi.org/10.1007/s10682-012-9585-z.

Callesen, I., Liski, J., Raulund-Rasmussen, K., Olsson, M.T., Tau-Strand, L., Vesterdal, L., Westman, C.J., 2003. Soil carbon stores in nordic well-drained forest soils-relationships with climate and texture class. Glob. Chang. Biol. 9, 358–370. https://doi.org/10.1046/j.1365-2486.2003.00587.x.

Chen, H., Marhan, S., Billen, N., Stahr, K., 2009. Soil organic-carbon and total nitrogen stocks as affected by different land uses in Baden-Württemberg (southwest Germany). J. Plant Nutr. Soil Sci. 172, 32–42. https://doi.org/10.1002/jpln.200700116.

Choudhury, B.U., Fiyaz, A.R., Mohapatra, K.P., Ngachan, S., 2016. Impact of land uses, agrophysical variables and altitudinal gradient on soil organic carbon concentration of north-eastern himalayan region of India. Land Degrad. Dev. 27, 1163–1174. https://doi.org/10.1002/ldr.2338.

Choudhury, S.G., Yaduvanshi, N.P.S., Chaudhari, S.K., Sharma, D.R., Sharma, D.K., Nayak, D.C., Singh, S.K., 2018. Effect of nutrient management on soil organic carbon sequestration, fertility, and productivity under rice-wheat cropping system in semi-reclaimed sodic soils of North India. Environ. Monit. Assess. 190, 117. https://doi.org/10.1007/s10661-018-6486-9.

Clark, K.M., Boardman, D.L., Staples, J.S., Easterby, S., Reinbott, T.M., Kremer, R.J., Kitchen, N.R., Veum, K.S., 2017. Crop yield and soil organic carbon in conventional and no-till organic systems on a claypan soil. Agron. J. 109, 588–599. https://doi.org/10.2134/agronj2016.06.0367.

Curtin, D., Wang, H., Selles, F., McConkey, B.G., Campbell, C.A., 2000. Tillage effects on carbon fluxes in continuous wheat and fallow-wheat rotations. Soil Sci. Soc. Am. J. 64, 2080–2086. https://doi.org/10.2136/sssaj2000.6462080x.

Das, S., Bhattacharyya, R., Das, T.K., Sharma, A.R., Dwivedi, B.S., Meena, M.C., Dey, A., Biswas, S., Aditya, K., Aggarwal, P., Biswas, A.K., Chaudhari, S.K., 2021. Soil quality indices in a conservation agriculture based rice-mustard cropping system in north-western indo-Gangetic Plains. Soil Tillage Res. 208, 104914. https://doi.org/10.1016/j.still.2020.104914.

Das, S., Chatterjee, S., Rajbanshi, J., 2022. Responses of soil organic carbon to conservation practices including climate-smart agriculture in tropical and subtropical regions: a meta-analysis. Sci. Total Environ. 805. https://doi.org/10.1016/j.scitotenv.2021.150428.

Dinakaran, J., Chandra, A., Chamoli, K.P., Deka, J., Rao, K.S., 2018. Soil organic carbon stabilization changes with an altitude gradient of land cover types in the Central Himalayas, India. Catena 170, 374–385. https://doi.org/10.1016/j.catena.2018.06.039.

Donofrio, S., Maguire, P., Merry, W., Daley, C., Calderon, C., Lin, K., 2022. The art of integrity: State of voluntary carbon markets, Q3 insights briefing. Available online Washington DC: Forest. https://www.ecosystemmarketplace.com/carbon-markets/. (Accessed 30 November 2022).

Fageria, N.K., Carvalho, G.D., Santos, A.B., Ferreira, E.P.B., Knupp, A.M., 2011. Chemistry of lowland Rice soils and nutrient availability. Commun. Soil Sci. Plant Anal. 42, 1913–1933. https://doi.org/10.1080/00103624.2011.591467.

FAO, 2013. Climate-smart agriculture: Sourcebook. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

FAO, 2021, IFAD, UNICEF, WFP, WHO, 2021. Transforming food systems for food security, improved nutrition, and affordable healthy diets for all. The State of Food Security and Nutrition in the World 2021. FAO, Rome. https://doi.org/10.4060/cb4474en.

Feng, J., Li, F., Zhou, X., Xu, C., Ji, L., Chen, Z., Fang, F., 2018. Impact of agronomy practices on the effects of reduced tillage systems on CH4 and N2O emissions from agricultural fields: a global meta-analysis. PLoS One 13, 1–17. https://doi.org/10.1371/journal.pone.0196703.

Ganeshamurthy, A.N., 2009. Soil changes following the long-term cultivation of pulses. J. Agric. Sci. 147 (6), 699–706. https://doi.org/10.1017/S0021859609990104.

Ghimire, R., Adhikari, K.R., Chen, Z.S., Shah, S.C., Dahal, K.R., 2012. Soil organic carbon sequestration as affected by tillage, crop residue, and nitrogen application in rice-wheat rotation system. Paddy Water Environ. 10 (2), 95–102. https://doi.org/10.1007/s10333-011-0268-0.

Government of India (GoI), 2020. Agricultural Statistics at a Glance 2020. https://eands.dacnet.nic.in/PDF/Agricultural%20Statistics%20at%20a%20Glance%20-%202020%20(English%20version).pdf.

Government of India (GoI), 2021. Economic Survey. Department of Economic Affairs Economic Division, Ministry of Finance, North Block New Delhi-110001. https://www.indiabudget.gov.in/economicsurvey/doc/echapter.pdf.

Grace, P., Antle, J., Ogle, S., Paustian, K., Basso, B., 2010. Soil carbon sequestration rates and associated economic costs for farming systems of South-Eastern Australia. Soil Res. 48, 720–729. https://doi.org/10.1071/SR10063.

Gregory, A.S., Watts, C.W., Griffiths, B.S., Hallett, P.D., Kuan, H.L., Whitmore, A.P., 2009. The effect of long-term soil management on the physical and biological resilience of a range of arable and grassland soils in England. Geoderma 153, 172–185. https://doi.org/10.1016/j.geoderma.2009.08.002.

Griffiths, R.P., Madritch, M.D., Swanson, A.K., 2009. The effects of topography on forest soil characteristics in the Oregon Cascade Mountains (USA): implications for the effects of climate change on soil properties. For. Ecol. Manag. 257, 1–7. https://doi.org/10.1016/j.foreco.2008.08.010.

Gupta, N., Pradhan, S., Jain, A., Patel, N., 2021. SustainableAgriculture in India 2021: What We Know and How to Scale Up. Council on Energy, Environment and Water, New Delhi.

Haddaway, N.R., Hedlund, K., Jackson, L.E., Kätterer, T., Lugato, E., Thomsen, I.K., Jørgensen, H.B., Isberg, P.E., 2017. How does tillage intensity affect soil organic carbon? A systematic review. Environmental Evidence. BioMed Central. https://doi.org/10.1186/s13750-017-0108-9.

Han Weng, Z., Van Zwieten, L., Singh, B.P., Tavakkoli, E., Joseph, S., Macdonald, L.M., Rose, T.J., Rose, M.T., Kimber, S.W.L., Morris, S., Cozzolino, D., Araujo, J.R., Archanjo, B.S., Cowie, A., 2017. Biochar built soil carbon over a decade by stabilizing rhizodeposits. Nat. Clim. Chang. 7 (5), 371–376. https://doi.org/10.1038/nclimate3276.

Han, P., Zhang, W., Wang, G., Sun, W., Huang, Y., 2016. Changes in soil organic carbon in croplands subjected to fertilizer management: a global meta-analysis. Sci. Rep. 6 (1), 1–13. https://doi.org/10.1038/srep27199.

Han, X., Gao, G., Li, Z., Chang, R., Jiao, L., Fu, B., 2019. Effects of plantation age and precipitation gradient on soil carbon and nitrogen changes following afforestation in the Chinese loess plateau. Land Degrad. Dev. 30 (18), 2298–2310. https://doi.org/10.1002/ldr.3422.

Hazra, K.K., Nath, C.P., Ghosh, P.K., Swain, D.K., 2020. Inclusion of legumes in rice-wheat cropping system for enhancing carbon sequestration. Carbon Management in Tropical and Sub-Tropical Terrestrial Systems. https://doi.org/10.1007/978-981-13-9628-1_2.

Hedges, L.V., Gurevitch, J., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150–1156. https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2.

Hobbs, P.R., Sayre, K., Gupta, R., 2008. The role of conservation agriculture in sustainable agriculture. Philos. Trans. R. Soc. B Biol. Sci. 363, 543–555. https://doi.org/10.1098/rstb.2007.2169.

Hoyle, F.C., D'Antuono, M., Overheu, T., Murphy, D.V., 2013. Capacity for increasing soil organic carbon stocks in dryland agricultural systems. Soil Res. 51 (8), 657–667. https://doi.org/10.1071/SR12373.

IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. In: Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P.R., Pirani, A., Moufouma-Okia, W., Péan, C., Pidcock, R., Connors, S., Matthews, J.B.R., Chen, Y., Zhou, X., Gomis, M.I., Lonnoy, E., Maycock, T., Tignor, M., Waterfield, T. (Eds.), Summary for Policymakers. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–24. https://doi.org/10.1017/9781009157940.001.

IPCC, 2019. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In: Shukla, P.R., Skea, J., Buendia, E. Calvo, Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Pereira, J. Portugal, Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Summary for Policymakers.

Jobbágy, E.G., Jackson, R.B., 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecol. Appl. 10 (2), 423–436. https://doi.org/10.1890/1051-0761(2000)010[0423:TVDOSO]2.0.CO;2.

Justine, M.F., Yang, W., Wu, F., Tan, B., Khan, M.N., Zhao, Y., 2015. Biomass stock and carbon sequestration in a chronosequence of Pinus massoniana plantations in the upper reaches of the Yangtze River. Forests 6 (10), 3665–3682. https://doi.org/10.3390/f6103665.

Karhu, K., Mattila, T., Bergström, I., Regina, K., 2011. Biochar addition to agricultural soil increased CH 4 uptake and water holding capacity - results from a short-term pilot field study. Agric. Ecosyst. Environ. 140 (1–2), 309–313.

Kumar, D., Sharma, M., Taxak, A., 2017. Effect of vegetation communities and altitudes on the soil organic carbon stock in kotli bhel-1A catchment, India. CLEAN - Soil, Air, Water 45. https://doi.org/10.1002/clen.201600650.

Kumara, T.K., Kandpal, A., Pal, S., 2019. Determinants and impacts of conservation agriculture in South Asia: a meta-analysis of the evidences. Indian J. Agric. Econ 74 (3), 311–320.

Kumara, T.K., Kandpal, A., Pal, S., 2020. A meta-analysis of economic and environmental benefits of conservation agriculture in South Asia. J. Environ. Manag. 269. https://doi.org/10.1016/j.jenvman.2020.110773.

Lai, L., Li, Y., Tian, Y., Jiang, L., Zhao, X., Zhu, L., Chen, X., Gao, Y., Wang, S., Zheng, Y., Rimmington, G.M., 2013. Effects of added organic matter and water on soil carbon sequestration in an arid region. PLoS One 8, 1–9. https://doi.org/10.1371/journal.pone.0070224.

Lal, R., 2016. Global food security and nexus thinking. J. Soil Water Conserv. 71 (4), 85A–90A. https://doi.org/10.2489/jswc.71.4.85A.

Lal, R., 2020a. Soil organic matter content and crop yield. J. Soil Water Conserv. 75, 27–32. https://doi.org/10.2489/JSWC.75.2.27A.

Lal, R., 2020b. Food security impacts of the “4 per thousand” initiative. Geoderma 374. https://doi.org/10.1016/j.geoderma.2020.114427.

Lam, S.K., Chen, D., Mosier, A.R., Roush, R., 2013. The potential for carbon sequestration in australian agricultural soils is technically and economically limited. Sci. Rep. 3 (1), 1–6. https://doi.org/10.1038/srep02179.

Li, J., Pei, J., Pendall, E., Reich, P.B., Noh, N.J., Li, B., Fang, C., Nie, M., 2020. Rising temperature may trigger deep soil carbon loss across Forest ecosystems. Adv. Sci. 7, 1–8. https://doi.org/10.1002/advs.202001242.

Li, X., Zhu, W., Xu, F., Du, J., Tian, X., Shi, J., Wei, G., 2021. Organic amendments affect soil organic carbon sequestration and fractions in fields with long-term contrasting nitrogen applications. Agric. Ecosyst. Environ. 322. https://doi.org/10.1016/j.agee.2021.107643.

Lu, S.G., Sun, F.F., Zong, Y.T., 2014. Effect of rice husk biochar and coal fly ash on some physical properties of expansive clayey soil (Vertisol). Catena 114, 37–44. https://doi.org/10.1016/j.catena.2013.10.014.

Luo, Z., Feng, W., Luo, Y., Baldock, J., Wang, E., 2017. Soil organic carbon dynamics jointly controlled by climate, carbon inputs, soil properties and soil carbon fractions. Glob. Chang. Biol. 23 (10), 4430–4439. https://doi.org/10.1111/gcb.13767.

Mafongoya, P.L., Barak, P., Reed, J.D., 2000. Carbon, nitrogen and phosphorus mineralization of tree leaves and manure. Biol. Fertil. Soils 30, 298–305. https://doi.org/10.1007/s003740050007.

Maillard, É., Angers, D.A., 2014. Animal manure application and soil organic carbon stocks: a meta-analysis. Glob. Chang. Biol. 20, 666–679. https://doi.org/10.1111/gcb.12438.

Manlay, R.J., Feller, C., Swift, M.J., 2007. Historical evolution of soil organic matter concepts and their relationships with the fertility and sustainability of cropping systems. Agric. Ecosyst. Environ. 119, 217–233. https://doi.org/10.1016/j.agee.2006.07.011.

McLean, R.A., Sanders, W.L., Stroup, W.W., 1991. A unified approach to mixed linear models. Am. Stat. 45, 54–64. https://doi.org/10.1080/00031305.1991.10475767.

MoSPI, 2021. Ecosystem accounts for India-report of the NCAVES project. MOSPI GOI.

Mureva, A., Ward, D., Pillay, T., Chivenge, P., Cramer, M., 2018. Soil organic carbon increases in semi-arid regions while it decreases in humid regions due to Woody-Plant encroachment of grasslands in South Africa. Sci. Rep. 8 (1), 1–12. https://doi.org/10.1038/s41598-018-33701-7.

Nath, A.J., Lal, R., Sileshi, G.W., Das, A.K., 2018. Managing India's small landholder farms for food security and achieving the “4 per thousand” target. Sci. Total Environ. 634, 1024–1033. https://doi.org/10.1016/j.scitotenv.2018.03.382.

Nelson, J.P., Kennedy, P.E., 2009. The use (and abuse) of meta-analysis in environmental and natural resource economics: an assessment. Environ. Resour. Econ. 42 (3), 345–377. https://doi.org/10.1007/s10640-008-9253-5.

OECD, 2021. OECD Economic Outlook, Interim Report March 2021. OECD Publishing, Paris https://doi.org/10.1787/34bfd999-en.

Oldfield, E.E., Bradford, M.A., Wood, S.A., 2019. Global meta-analysis of the relationship between soil organic matter and crop yields. Soil 5, 15–32. https://doi.org/10.5194/soil-5-15-2019.

Omondi, M.O., Xia, X., Nahayo, A., Liu, X., Korai, P.K., Pan, G., 2016. Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. Geoderma 274, 28–34. https://doi.org/10.1016/j.geoderma.2016.03.029.

Padbhushan, R., Sharma, S., Kumar, U., Rana, D.S., Kohli, A., Kaviraj, M., Parmar, B., Kumar, R., Annapurna, K., Sinha, A.K., Gupta, V.V.S.R., 2021. Meta-analysis approach to measure the effect of integrated nutrient management on crop performance, microbial activity, and carbon stocks in Indian soils. Front. Environ. Sci. 9, 1–13. https://doi.org/10.3389/fenvs.2021.724702.

Pradhan, P., Reusser, D.E., Kropp, J.P., 2013. Embodied greenhouse gas emissions in diets. PLoS One 8, e62228.

Qin, Z., Dunn, J.B., Kwon, H., Mueller, S., Wander, M.M., 2016. Soil carbon sequestration and land use change associated with biofuel production: empirical evidence. GCB Bioenergy 8, 66–80. https://doi.org/10.1111/gcbb.12237.

Reicosky, D.C., Evans, S.D., Cambardella, C.A., Allmaras, R.R., Wilts, A.R., Huggins, D.R., 2002. Continuous corn with moldboard tillage: residue and fertility effects on soil carbon. J. Soil Water Conserv. 57 (5), 277–284.

Ricke, K., Drouet, L., Caldeira, K., Tavoni, M., 2018. Country-level social cost of carbon. Nat. Clim. Chang. 8 (10), 895–900. https://doi.org/10.1038/s41558-018-0282-y.

Sharma, S., Padbhushan, R., Kumar, U., 2019. Integrated nutrient management in rice–wheat cropping system: an evidence on sustainability in the indian subcontinent through meta-nalysis. Agronomy 9. https://doi.org/10.3390/agronomy9020071.

Sheikh, M.A., Kumar, M., Bussmann, R.W., 2009. Altitudinal variation in soil organic carbon stock in coniferous subtropical and broadleaf temperate forests in garhwal himalaya. Carbon Balance Manag. 4, 6. https://doi.org/10.1186/1750-0680-4-6.

Shi, L., Feng, W., Xu, J., Kuzyakov, Y., 2018. Agroforestry systems: meta-analysis of soil carbon stocks, sequestration processes, and future potentials. Land Degrad. Dev. 29 (11), 3886–3897. https://doi.org/10.1002/ldr.3136.

Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241, 155–176. https://doi.org/10.1023/A:1016125726789.

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Abad, C.Robledo, Romanovskaya, A., Sperling, F., Tubiello, F., 2014. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Agriculture, Forestry and Other Land Use (AFOLU). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 811–922.

Sommer, R., Bossio, D., 2014. Dynamics and climate change mitigation potential of soil organic carbon sequestration. J. Environ. Manag. 144, 83–87. https://doi.org/10.1016/j.jenvman.2014.05.017.

Srinivasarao, C., Lal, R., Kundu, S., Babu, M.B.B.P., Venkateswarlu, B., Singh, A.K., 2014. Soil carbon sequestration in rainfed production systems in the semi-arid tropics of India. Sci. Total Environ. 487, 587–603. https://doi.org/10.1016/j.scitotenv.2013.10.006.

Stronkhorst, L., Venter, A., 2008. Investigating the soil organic carbon status in south african soils and the relationship between soil organic carbon and other soil chemical properties. ARC -ISCW Report No, Agricultural Research Council, Pretoria.

Thamo, T., Pannell, D.J., Pardey, P.G., Hurley, T.M., 2020. Private Incentives for Sustainable Agriculture: Soil Carbon Sequestration. 49, p. 1.

Toliver, D.K., Larson, J.A., Roberts, R.K., English, B.C., de La Torre Ugarte, D.G., West, T.O., 2012. Effects of no-till on yields as influenced by crop and environmental factors. Agron. J. 104, 530–541. https://doi.org/10.2134/agronj2011.0291.

Turmel, M.S., Speratti, A., Baudron, F., Verhulst, N., Govaerts, B., 2015. Crop residue management and soil health: a systems analysis. Agric. Syst. 134, 6–16. https://doi.org/10.1016/j.agsy.2014.05.009.

UNDP, 2021. The 2021 Global Multidimensional Poverty Index (MPI) | Human Development Reports. Hum. Dev. Rep. https://hdr.undp.org/sites/default/files/2021_mpi_report_en.pdf.

Van Groenigen, K.J., Osenberg, C.W., Hungate, B.A., 2011. Increased soil emissions of potent greenhouse gases under increased atmospheric CO 2. Nature 475 (7355), 214–216. https://doi.org/10.1038/nature10176.

Viechtbauer, W., 2010. metafor: Meta-Analysis Package for R. R package version 1.4-0. http://CRAN.R-project.org/package=metafor.

Walcott, J., S, B., J, S., 2009. Soil carbon for carbon sequestration and trading: a review of issues for agriculture and forestry. Bur. Rural Sci. Dep. Agric. Fish. For. Canberra. Soil.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Publ. Soil Sci. Soc. Am. J 66 (6), 1930–1946.

Williams, J.R., Nelson, R.G., Claassen, M.M., Rice, C.W., 2004. Carbon sequestration in soil with consideration of CO2 emissions from production inputs: an economic analysis. Environ. Manag. 33, 264–273. https://doi.org/10.1007/s00267-003-9136-z.

Wu, L., Zhang, S., Ma, R., Chen, M., Wei, W., Ding, X., 2021. Carbon sequestration under different organic amendments in saline-alkaline soils. Catena 196, 104882. https://doi.org/10.1016/j.catena.2020.104882.

Zhang, Yu., Li, C., Wang, M., 2020. National-Scale Meta-Analysis of soil carbon and nitrogen accumulation potential in China's grain for green program. Eurasian Soil Sci. 53 (7), 892–901. https://doi.org/10.1134/S1064229320070170.

Zhao, W., Zhang, R., Cao, H., Tan, W., 2019. Factor contribution to soil organic and inorganic carbon accumulation in the loess plateau: structural equation modeling. Geoderma 352, 116–125. https://doi.org/10.1016/j.geoderma.2019.06.005.