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ORIGINAL PAPER

Impacts of conservation agriculture on crop yield and soil carbon sequestration: a meta-analysis in the Indian subcontinent

Rajeev Padbhushan · Upendra Kumar · Abhas Kumar Sinha · Ashim Datta · Surajit Mondal · D. S. Rana · Biplab Mitra · Prateek M. Bhattacharya · Megha Kaviraj · Rajkishore Kumar · Bijay-Singh

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Abstract In the quest of achieving sustainable crop productivity, improved soil health, and increased carbon (C) sequestration in the soil, conservation agriculture (CA) is increasingly being promoted and adopted in the Indian subcontinent. However, because some researchers from different regions of the world have reported reduced crop yield under CA relative to agriculture based on conventional tillage (CT), a meta-analysis has been conducted based on published research from India to evaluate the effects of CA on the yield of crops, accumulation of soil organic C as an index of soil health, and C sequestration in the soil in different regions and soil textural groups in the country. The meta-analysis is based on 544 paired observations under CA and CT from 35 publications from India was carried out using Meta Win 2.1 software. The results showed an overall significant ($p < 0.05$) reduction of 1.15% crop yield under CA compared to CT. Yearwise data showed a reduction of yields under CA from 2009 to 2016, but an increase from 2017 to 2020. Yield reduction was observed in the eastern, north-eastern, and southern regions of India but in western, northern, and north-western regions of the country, an increase was observed under CA rather than CT. Sandy loam and clayey soils exhibited higher crop yield under CA than under CT. Compared to CT, soil organic C content and soil C sequestration under CA increased by 8.9% and 7.3%, respectively. Also, in all the regions and soil textural groups both soil organic C accumulation and soil C sequestration were higher under CA than under CT. Factors such as rainfall, soil depth, available nitrogen (N), and total N significantly influenced the extent of

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R. Padbhushan (✉) · R. Kumar
Department of Soil Science and Agricultural Chemistry, Bihar Agricultural University, Sabour, Bhagalpur 813210, India
e-mail: rajpd01@gmail.com

U. Kumar (✉) · M. Kaviraj
ICAR-National Rice Research Institute, Bidyadharpur, Cuttack, Odisha 753006, India
e-mail: ukumarmb@gmail.com

A. K. Sinha · B. Mitra · P. M. Bhattacharya
Uttar Banga Krishi Viswavidyalaya, Pundibari, Cooch Behar, West Bengal 736165, India

A. Datta
ICAR-Central Soil Salinity Research Institute, Karnal, Haryana, India

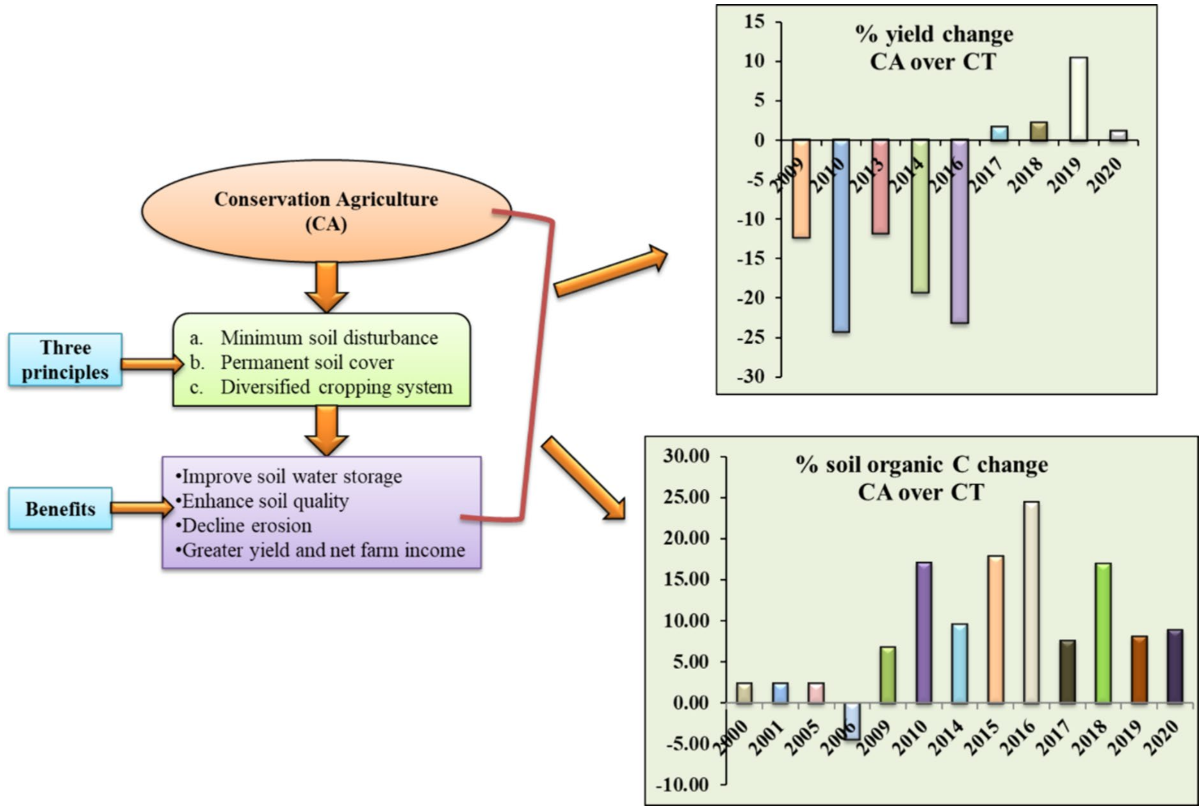
S. Mondal
ICAR-Research Complex for Eastern Region, Patna, Bihar 800014, India

D. S. Rana
International Maize and Wheat Improvement Center-India Office, NASC Complex, Pusa, New Delhi 110012, India

Bijay-Singh
Punjab Agricultural University, Ludhiana 141004, India

yield increase/decrease and soil organic C accumulation under CA. Overall, results of the meta-analysis suggest that the promotion of CA in India will have to be location-specific taking into consideration the crops, soil attributes, and climatic conditions.

Graphical abstract



Keywords Tillage · Crop yield · Soil organic carbon · Soil texture · Meta-analysis · India

Introduction

Intensive conventional tillage-based agriculture (CT) supported by mineral fertilizers and pesticides has been able to increase crop productivity to meet global food demands since the 1950s. However, excessive use of synthetic fertilizers and pesticides in CT had a negative impact on soil quality and the environment by reducing biodiversity, pollution, and eutrophication of water reservoirs and increasing the emission of greenhouse gases (Bijay-Singh & Craswell, 2021; Foley et al., 2011; Godfray & Garnett, 2014; Knapp & Heijden, 2018; Rakshit et al., 2018; Tilman et al., 2011). Thus, there is a challenge in terms of ensuring food security through sustained agricultural production and controlling the environmental impacts of farming (Padbhushan et al., 2021). In recent decades, several studies have been conducted to identify appropriate site-specific and implementable farm management strategies that will lead to sustainable food production and environmental security. Conservation agriculture (CA) is one such strategy in this direction and it is gaining momentum in several countries including India to achieve sustainability goals.

Conservation agriculture is a practice that is being promoted as an environmentally sustainable alternative to CT (Hobbs et al., 2008; Pradhan et al., 2018; Li et al., 2023). It is founded on three guiding principles: (a) minimum traffic on agricultural operations, i.e. no-till or reduced tillage, (b) Crop residues or cover crops to provide permanent soil cover, and (c) Cropping system diversification (both temporal and spatial) (Kassam et al., 2009). Several studies showed the benefits of CA and its components on improved soil water storage (Lampurlanés et al., 2016; Page et al., 2019; Verhulst et al., 2011), improved soil quality (Jat et al., 2019; Somasundaram et al., 2019), reduced erosion (Montgomery, 2007), and in some cases, higher yield, and net return (Page et al., 2019; Pradhan et al., 2018; Thierfelder et al., 2015). Therefore, CA has been perceived as a critical tool for improving crop productivity and protecting crops from extreme weather events caused by climate change, such as flooding and heat waves, as well as poor fertile soil, such as eroded and problematic soils (FAO, 2019).

The concept of minimal soil disturbance was introduced in the 1930s but no-tillage agricultural practices were introduced in the United States in the 1960s. Zero or minimum tillage (ZT) in field crops in India began in the western Indo-Gangetic plains (IGPs) during the mid-1990s. CA has been promoted as a Climate-Smart Agriculture Practice (CSAP) since 2012 when it was combined with precise water and nutrient management (Sidhu et al., 2019). In 2015–16, the total cultivated area under CA was 180 million hectares (Mha) globally (12.5% of total cropland) in around 78 countries; it was only 106 Mha in 2008–09. The scenario analysis predicted a potential area of 533–1130 Mha (38–81% of global arable land) under CA (Prestele et al., 2018). In India, CA is already being practiced over 1.5 Mha, accounting for 1.1% of the total net sown area. The major technology adopted is ZT wheat in the rice–wheat cropping systems and in other crops and cropping systems there is a gradual shift from conventional to reduced tillage/ZT in the IGPs of India (Bhan & Behera, 2014). One of the key drivers of the improvements observed under CA is soil organic C (SOC) content, one of the sensitive chemical indicators that detect the impacts of management practices in farming systems. The SOC stored in the terrestrial environment can lead to an increase in C sequestration and reduced losses of CO_2 from the soil. Thus, curtailing SOC losses through management practices such as CA will lead to an increase in the sequestration of C in the soil.

Studies comparing CA and CT conducted in India or elsewhere have generally focused on crop-specific, short-term, or long-term changes in a specific soil type or in a region. However, when considering food security and soil sustainability, one critical issue is crop yield stability regardless of cropping pattern, and duration of experimentation in different soil textural groups or in different regions. It is not very clear whether CA produces a higher yield and sequesters C regardless of cropping pattern, and duration of experimentation on different soil textural groups in different regions. This information is particularly lacking in India. Some meta-analyses based on information from all over the world have revealed the impacts of CA on SOC and yield stability regardless of crops, cropping system, or duration of experimentation (Knapp & Heijden, 2018). However, so far, limited attempt has been made to evaluate the effects of CA on crop yield and soil C sequestration in India.

The primary goal of this research is to obtain a quantitative assessment of crop yield and soil quality when crops are grown under CA and CT under Indian climatic and edaphic conditions. This was accomplished through meta-analysis using published peer-reviewed datasets of studies conducted in various parts of India. We hypothesized that CA and CT have an impact on crop productivity in different regions of India depending upon soil type, rainfall, soil N, and SOC content. The specific objectives were to (i) assess the influence of soil textural groups and diverse geographical regions of India on crop yield under CA relative to CT, (ii) evaluate the effect of soil properties and rainfall on crop yield under CA and CT, and (iii) estimate the effect of tillage on SOC sequestration.

Materials and methods

Data sources and eligibility criteria

After conducting a review of the published literature on conservation and conventional agriculture, relevant papers were collected by searching Google Scholar and websites of peer-reviewed journals using the keywords: ‘tillage’, ‘conservation agriculture’, ‘conventional agriculture’, ‘India’, ‘carbon sequestration’, ‘soil organic carbon’, yield, and ‘soil quality’. Conservation agriculture (CA) refers to zero tillage, minimum tillage, and reduced tillage with crop residue retained, whereas CT refers to following conventional tillage practices. The papers based on experiments conducted with mulch added from outside the field were not included. The search for papers for this study was restricted to the years 2009–2020 for crop yield and 2000–2020 for SOC. Figure 1 shows the location map for the soil taxonomic group, major study sites, and rainfall data for the studied region in India. The relevant studies were then selected based on the following criteria: (i) The data pertaining to the comparison between CA and CT studies should be available, (ii) The studies should be based on field experiments, (iii) Crop yield and soil-related data should be available, and (iv) Treatments should have received the same farming and nutrient management practices and tested at the same location. If available more than one studies were included from a single publication.

Data collection

A total of 544 paired data observations were collected from 35 publications (Supplementary Table 1). Out of these, 353 crops yield paired data observations and 405 SOC paired data observations (multiple observations within individual studies) were collected. Other paired data observations were excluded as these did not pertain to yield and soil quality. Figure 2 depicts the duration of experiments: 427 data pairs were <4 years, 95 data pairs were 4–8 years, and 22 data pairs were >8 years. Yield, SOC, and soil quality data pairs were collected year-by-year regardless of

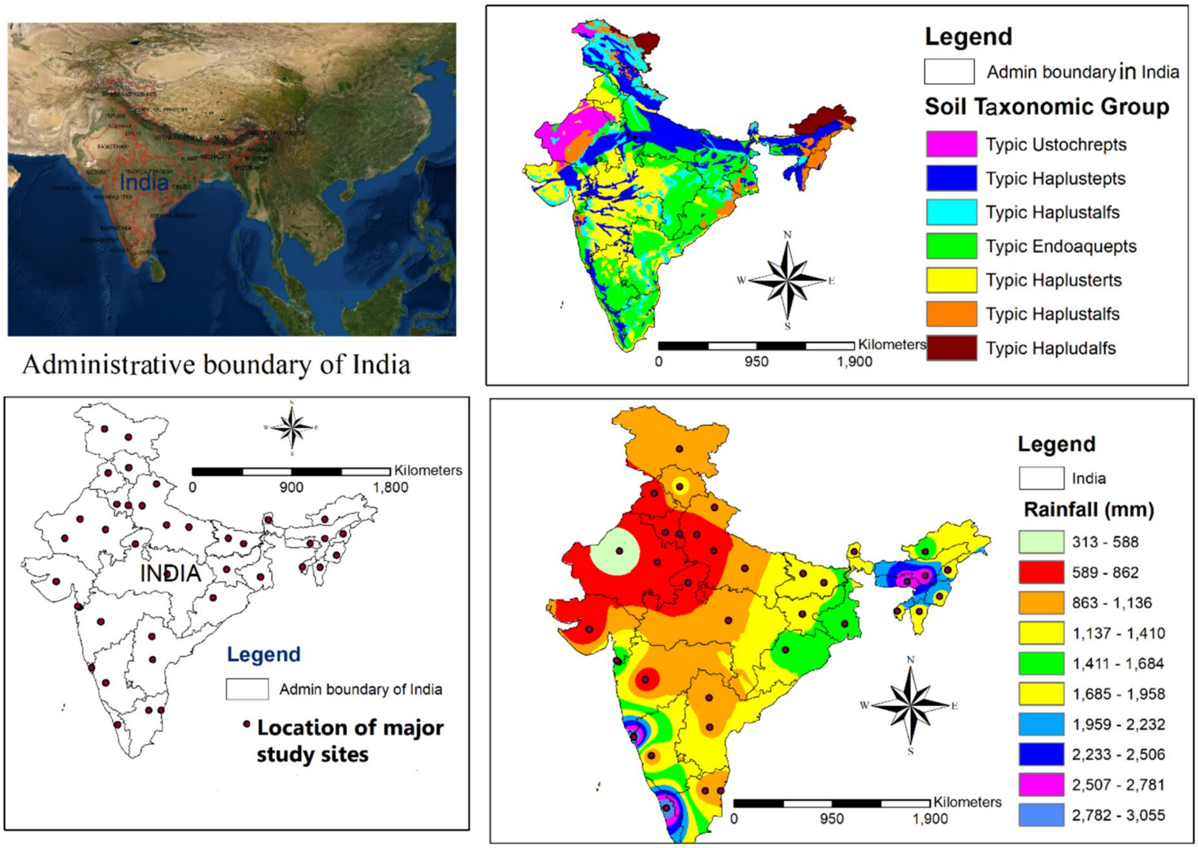


Fig. 1 Location of study sites, distribution of soil taxonomic groups, and rainfall pattern in India

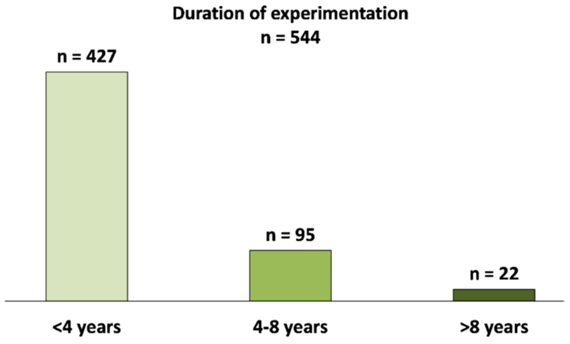


Fig. 2 Duration of experimentation in 544 comparisons between conservation agriculture and conventional agriculture from different studies in India

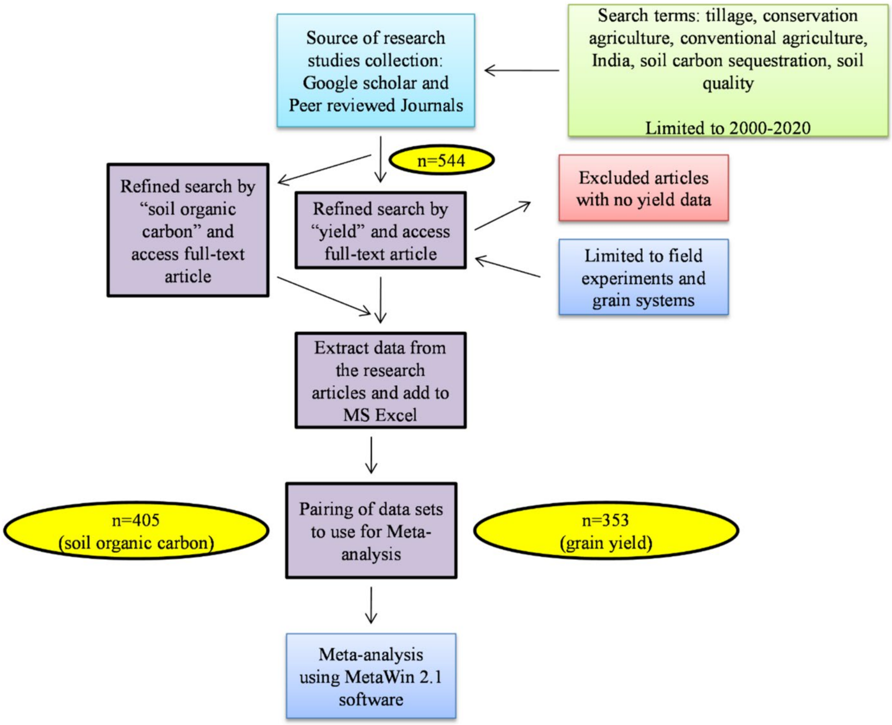
crop, cropping pattern, duration of the experiment, and year of publication of the article.

The extracted paired data sets were further analyzed using MS EXCEL., Fig. 3 shows the data collection flow chart. The data were categorized with respect to different soil textural classes (sandy loam, sandy clay loam, silty clay, silty clay loam, clay loam, and clayey) and geographical regions (eastern, western, northern, north-eastern, north-western, southern and central) in India. Along with paired data observations, soil data (pH, SOC, available N, and total N) from soil depths (0–15 and 15–30 cm) and rainfall in different regions of India were also collected. The standard units of different parameters used in this study were: kg ha^{-1} for crop yield, % for SOC, kg ha^{-1} for available N, % for total N, mm for rainfall, cm for soil depth, and no unit for soil pH (soil: water::1:2/1:2.5). CA was used as the main effect treatment, while CT was used as the control treatment.

Data analysis

The meta-analysis was carried out to compare paired observations of crop yield and SOC and other parameters such as available N, total N, rainfall, soil depths, and soil pH from field experiments under CA and CT. The meta-analysis of paired observations was carried out in two stages using MetaWin 2.1 software (Chakraborty et al., 2017; Rosenberg et al., 2000). In the first stage, effect size was determined by Eq. (1) (Hedges et al., 1999).

Fig. 3 Flow chart of data collection and processing for conducting the meta-analysis



$$\text{In R} = \text{In}\frac{[\mathrm{E_T}]}{[\mathrm{E_C}]} \quad (1)$$

where, R shows the ratio between response variables E_T and E_C; E_T stands for the mean of response variables of the main effect i.e. CA and E_C stand for the mean of response variables of the control i.e. CT.

These studies from variable situations are used to consider the multiple replications. The standard deviations (SDs) are calculated by using a number of observations using the simple statistical approach in MS EXCEL. Second stage is used to estimate the combined effect which is calculated using the weighted mean of the effects determined from the individual studies.

Weight factor was determined as follows:

Weight factor = 1/Variance, the variance of the effect size was calculated as:

$$\text{Variance} = \frac{[\mathrm{SD_T^2}]}{[\mathrm{X_T SD_T^2}]} + \frac{[\mathrm{SD_C^2}]}{[\mathrm{X_C SD_C^2}]} \quad (2)$$

where, SD_T and SD_C represent the standard deviations of treatment and control, respectively; and X_T and X_C are the number of replications for each of the main effect treatment and control, respectively. If >1 observation is included in treatment, the weight is divided by the number of observations from those studies.

Effect size from individual studies is then combined with a mixed effect model to estimate the cumulative effect size and the 95% confidence intervals through bootstrapping with 4999 iterations (Adams et al., 1997). The mixed effect model is used in meta-analysis to categorize data and assumes random variations among studies within a group and fixed variations (Bax et al., 2007; Sharma et al., 2019).

A *meta*-regression analysis was used to detect the linear trends between continuous variables (duration of the experiment, pH, rainfall, available N, total N, and SOC) and soil parameters and crop yield. The 'meta for' package (Viechtbauer, 2010) was used in the R statistical computing platform (R Core Team, 2020), and reported significant changes at *p* values. Publication bias was assessed through histograms (Rosenberg et al., 2000), and in none of the cases, effect sizes showed preferences toward positive or negative bias. Collinearity between predictor variables was checked by Pearson correlation coefficients while residual heterogeneity in *meta*-regression is used.

Outcomes of the result

Findings are back-transformed and expressed as average effect size in percentage (%) caused by the main effect's treatment compared to control and presented in the bar graphs. '*' on bars in the bar graph represents the significant differences at $p < 0.05$.

Results

Soil characteristics under different tillage practices

Soil pH ranged from acidic to alkaline with mean values of 6.65 in CA and 6.66 in CT treatments (Table 1). A similar trend was observed in soil EC; it was 0.23 dS m^{-1} under CT and was marginally higher than under CA (0.22 dS m^{-1}). SOC was higher in CA than in CT. SOC ranged from low to high with mean values of 1.04% in CA and 0.94% in CT (Table 1). Available N ranged from low to high with mean values of 216.5 kg ha^{-1}in CA and 205.3 kg ha^{-1} in CT. A similar trend was also observed in total N and the mean values were 0.76% and 0.74% in CA and CT, respectively (Table 1).

Crop yield impacts by year of reference, soil types, and regions

Across all observations (years of references), there was a 1.15% ($p < 0.05$) reduction in crop yield under CA relative to CT (Fig. 4a). Year wise data showed that there was a decline in the yield of different crops under CA from 2009 to 2016, but the yield significantly increased ($p < 0.05$) from the year 2017 to 2019 and non-significantly increased by 1.16% during the year 2020. The negative impact of CA on yield over the CT varied across the years and the lowest impact was observed in the years 2013 (−11.83%) and 2009 (−12.26%) and the maximum in the years 2010 (−24.31%) and 2016 (−23.15%) respectively. The positive impact of CA over CT was similarly the lowest in the years 2020 (1.16%) and 2017 (1.71%) and the maximum in the year 2019 (10.43%).

Table 1 Range, mean and standard error of different soil characteristics in studies from India included in the meta-analysis

	pH		EC (dS m^{-1})		SOC (%)		Available N (kg ha^{-1})		Total N (%)	
	CA	CT	CA	CT	CA	CT	CA	CT	CA	CT
Minimum	4.87	4.80	0.06	0.05	0.36	0.29	78.00	71.60	0.02	0.02
Maximum	7.92	7.96	0.54	0.52	2.57	2.37	329.80	323.10	1.33	1.18
Mean	6.65	6.66	0.22	0.23	1.04	0.94	216.50	205.29	0.76	0.74
Standard error	0.03	0.03	0.01	0.01	0.03	0.02	3.69	3.52	0.02	0.02
Interpretation	Acidic to alkaline	Acidic to alkaline	Non-saline	Non-saline	Low to high	Low to high	Low to high	Low to high	Low to high	Low to high

*Soil: water::1:2 or 1:2.5

The effect on yield reduction due to the CA in comparison to CT was more in the eastern, north-east, and southern regions of India, but the positive impact of CA was reported in the western, northern, and north-west regions (Fig. 4b). The yield reductions in the eastern, north-east, and southern regions were −4.16%, −18.89%, and −13.82%, respectively at $p<0.05$.The yield increases in the western, northern, and north-western regions were 10.97%, 1.16%, and 1.77%, respectively at $p<0.05$.

When the data were analyzed using soil types, there was yield reduction in CA mostly in the sandy clay loam (−11.0%) followed by clay loam (−7.02%), and increased yield was observed mostly in the clayey soil (10.97%) followed by sandy loam (0.42%) (Fig. 4c). The lower to upper limits of yield for sandy loam soil was −0.61% to 1.51% at $p<0.05$ (n = 202).

Effects of rainfall, soil depths, and soil properties on crop yield

In high rainfall regions (> 2000 mm), the crop yield was less in CA than in CT. However, in areas of low rainfall (< 1000 mm), the crop yield was more in CA. The positive impact of the following CA was to the tune of 0.26%under low rainfall and the negative impacts of rainfall of 1000–2000 and > 2000 mm were −5.96%and −11.28%, respectively (Fig. 5a). Adoption of CA practices utilized nutrients to the maximum in surface layers of soil (0–15 cm) compared to CT and had a negative (−2.33%) impact on crop yield. This impact of CA is assessed to be lesser in sub-surface soil layers (15–30 cm) which has a positive contribution of 1.62% toward yield increase (Fig. 5a). CA reduced yield by 5.58%over CT when soil pH was < 7.0, increased yield significantly when soil pH was 7.0–8.0 (1.75%), and decreased yield non-significantly when soil pH was > 8.0 (5.27%) (Fig. 5a).

There was always a substantial increase in SOC under CA as compared to under CT due to more addition of crop residues. The yield increase was 1.39% when SOC was < 0.50% and 1.36% when SOC was > 0.50% (Fig. 5b).The positive impact of yield was estimated to be 1.70% for available N when its content in soil was > 500 kg ha^{-1} and negative impacts when its content was 250–500 kg ha^{-1} (−9.77%) and < 250 kg ha^{-1} (−3.22%) (Fig. 5b).Similarly, a

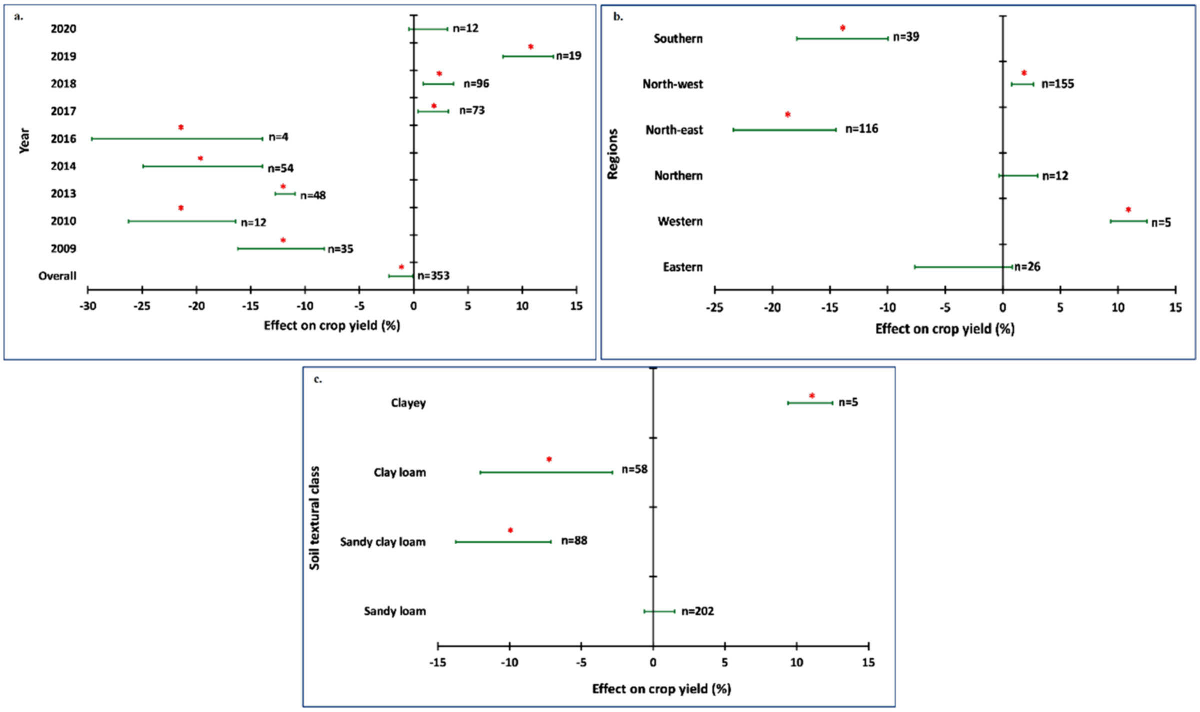


Fig. 4 Effect of conservation agriculture over conventional agriculture on crop yield from studies conducted in India **a** as per year of publication (2009–2020); **b** conducted in different geographical regions; **c** conducted in different soil textural classes. The error bars show 95% confidence intervals (CI), and the difference is significant if it does not pass zero. *indicates significant difference at p-value < 0.05

reduction in crop yield under CA in comparison to CT to the tune of 6.25% was observed when the total N in the soil was $< 0.1\%$. However, a 1.70% increase in crop yields was observed when the total N was $> 0.1\%$ (Fig. 5b).

Soil organic carbon impacts by year of reference, soil types, and regions

Across all observations (years of references), CA relative to CT increased SOC by 8.88% at $p < 0.05$ (Fig. 6a). Year-wise data showed that CA increased SOC from 2000 to 2020 except in the year 2006 when SOC decreased significantly (−4.44%) at $p < 0.05$. The positive impact of CA over CT on SOC was the smallest in the years 2000 (2.34%), 2001 (2.34%), and 2005 (2.34%); the effect was the largest in the years 2016 (24.46%) and 2015 (17.81%).

Conservation agriculture increased SOC in all the regions of India under study (eastern, northern, north-east, north-west, southern, and central) (Fig. 6b). There was a relatively higher SOC increase in the north-west (10.93%), followed by north-east (9.37%) and the lowest increase was recorded in the central region (4.96%) at $p < 0.05$. The SOC increase (at $p < 0.05$) in the eastern, northern, and southern regions were 7.58%, 8.85%, and 6.83%, respectively.

When data were analyzed on the basis of soil types, it was revealed that CA as compared to CT increased SOC to the maximum extent in the silty clay (21.23%) followed by sandy clay loam (9.23%). However, SOC decreased under CA in soils with silt clay loam texture (−0.41%) at $p < 0.05$ (Fig. 6c). The SOC increased in all other soil textural groups viz., sandy loam (7.98%), clay loam (7.83%), and clayey (5.07%).

Effects of rainfall, soil depths, and soil properties on soil organic carbon

The SOC content increased with rainfall under CA over CT. The positive impact on SOC was estimated to be

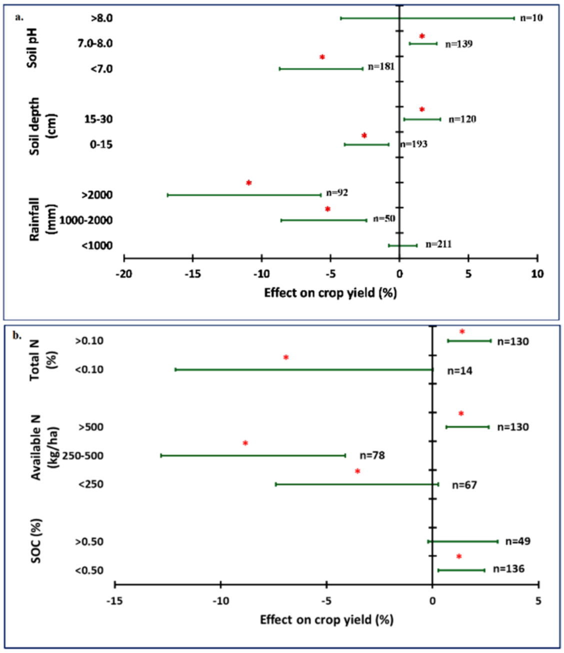


Fig. 5 Effect of conservation agriculture over conventional agriculture on crop yield in studies conducted in India under **a** different ranges of rainfall, soil depths and soil pH and **b** different soil organic carbon (SOC), available nitrogen (N) and total N. The error bars show 95% confidence intervals (CI), and the difference is significant if it does not pass zero. *indicates significant difference at p-value < 0.05

8.71% for rainfall of 1000 mm, 3.60% for rainfall of 1000–2000 mm, and 9.53% for rainfall of > 2000 mm (Fig. 7a). CA increased SOC in the soil depths of 0–15 cm (11.13%) and 15–30 cm (4.98%) compared to CT when data were analyzed based on soil depth (Fig. 7a). CA increased SOC by 8.63% over CT when soil pH was < 7.0, 11.26% when soil pH was 7.0–8.0, and 6.37% when soil pH was > 8.0 (Fig. 7a).

The SOC content increased in CA compared to CT with an increasing amount of available N and total N in the soil. The positive impact on SOC was estimated to be 10.18% for available Nin the soil to be more than > 500 kg ha^{-1}, 9.71% for available N of 250–500 kg ha^{-1}, and 10.18% for available N < 250 kg ha^{-1} (Fig. 7b). Similarly, SOC increased under CA than under CT when total N in the soil was > 0.1% (10.37%); it was 8.49% when the total N in the soil was < 0.1% (Fig. 7b).

Soil carbon sequestration impacts due to tillage practices

Adoption of CA increased SOC sequestration by 7.3% relative to CT (n = 146) at $p < 0.05$ (Table 2). The range of SOC sequestration for years of reference varied from 5.43to 9.33%. Year-wise data showed SOC sequestration in CA significantly increased over the entire period of study. Similarly, significant SOC sequestration was observed in different geographical regions, soil textural groups, and with increasing SOC, available N, and total N contents (Table 2). The region-wise SOC sequestration was increased in north-eastern, north-western, and southern India by 7.20%, 5.53%, and 11.94%, respectively. The textural group-wise analysis revealed that SOC sequestration was increased in sandy loam, sandy clay loam, and clay loam by 12.05%, 7.53%, and 3.64%, respectively when CA was adopted in different soils. A similar increasing trend of SOC sequestration was obtained in all three different rainfall zones (< 1000 mm, 1000–2000 mm, and > 2000 mm) with a percentage change to the tune of 10.49, 6.22, and 5.36, respectively. The rate of sequestration of SOC due to the adoption of CA was relatively higher (11.94%) in soils where the initial soil carbon content was less than 0.5% in comparison to soil having SOC greater than 0.50% (Table 2). Available N augmented SOC sequestration by 3.64% when it was < 250 kg ha^{-1}, by 7.65% when it was 250–500 kg ha^{-1} and, 12.68% when it was > 500 kg ha^{-1}. Total N increased SOC sequestration by 9.88% when it was < 0.10% and 12.73% when it was > 0.10%. The SOC sequestration was significantly enhanced at a soil depth of 0–15 cm (10.65%) whereas it was reduced at a soil depth of 15–30 cm (− 3.04%) under CA (Table 2).

Meta-regression

Meta-regression of the duration of the experiment, pH, rainfall, available N, total N and SOC on soil and crop parameters revealed that an improvement in the duration of the experiment, pH, rainfall, available N, total N, and SOC under CA brought impact on soil and crop parameters (Table 3). The duration of the experiment and rainfall had a significant impact on grain yield, water-soluble C (WSC), and

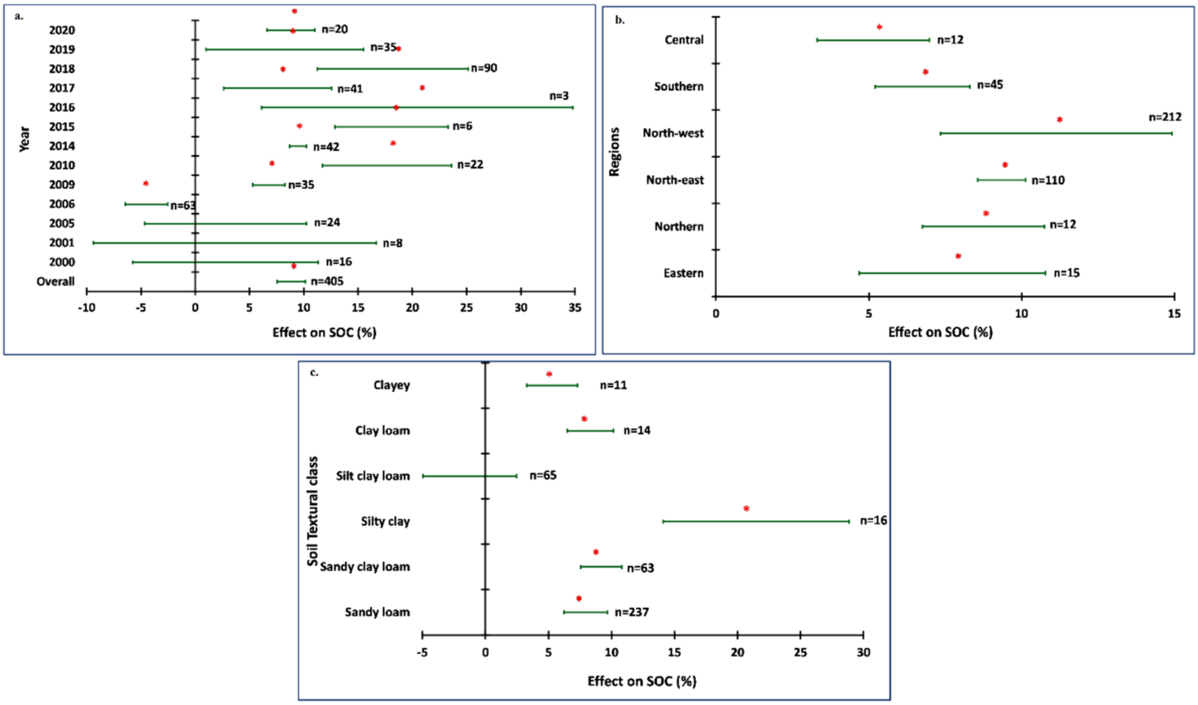


Fig. 6 Effect of conservation agriculture over conventional agriculture on soil organic carbon (SOC) studies conducted in India **a** published from 2000 to 2020; **b** different geographical regions; c) different soil textural classes. The error bars show 95% confidence intervals (CI), and the difference is significant if it does not pass zero. *indicates a significant difference at p-value < 0.05

soil C sequestration (SCS). Available N had a significant effect on grain yield and total N had a significant impact on grain yield and WSC. SOC was directly related to SCS.

Discussion

The meta-analysis revealed an overall decrease in yield by 1.15% (n = 353) under CA in comparison to CT in India. The reduced yield is revealed from studies conducted all over India irrespective of cropping systems and duration of experimentation. Yields under initial years with a reduced tillage system (CA) sometimes slightly declined due to the gap in skill in operating the ZT machines and in controlling the weeds, but the situation reversed afterward with improved technical backstopping. Global meta-analyses carried out by Pittelkow et al. (2015a) and Corbeels et al., 2014) also reflected average yield decrease of 5.7% in CA over CT. A meta-analysis of global tillage studies on maize also showed a reduction in yield under CA than under CT (Rusinamhodzi et al., 2011). The decrease was attributed to lower aggregate stability, higher soil penetration resistance, surface soil slaking, and higher water runoff.

Recently, Cusser et al. (2020) reported that long-term research avoids spurious and misleading trends in sustainability attributes of no-till-based crop production. Pittelkow et al. (2015b) in their global meta-analysis reported a decrease in yield under no-till practices for almost all the crop categories except oilseeds and cotton. Yield in no-till condition became *at par* after 3–4 years for cereals and legumes and it took even more years (5–10) for other crops. Since the data captured in the current meta-analysis were based mostly on short-term experiments (Fig. 2), it seems that an overall yield decline of about 1% due to the following of CA rather than CT may reverse with the passage of time. Kassam et al. (2009) observed enhanced crop growth and higher grain yield under

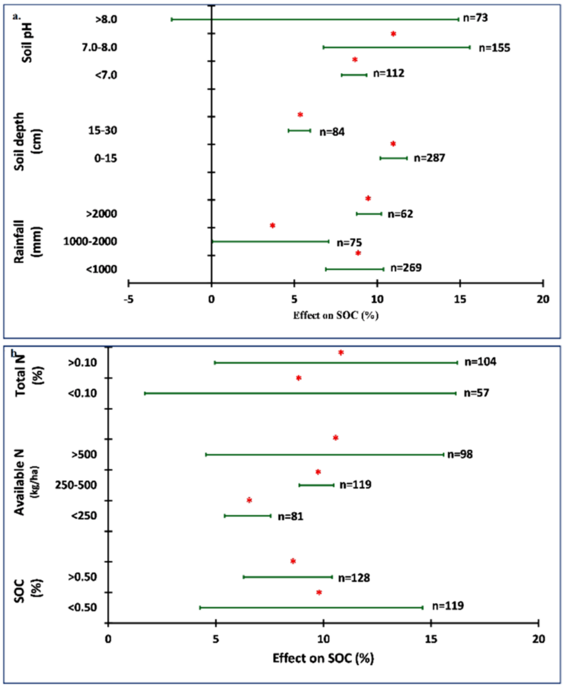


Fig. 7 Effect of conservation agriculture over conventional agriculture on soil organic carbon (SOC) from studies conducted, **a** under different ranges of rainfall, soil depths, and soil pH; **b** with different soil organic carbon (SOC), available nitrogen (N), and total N. The error bars show 95% confidence intervals (CI), and the difference is significant if it does not pass zero. *indicates a significant difference at p-value < 0.05

CA relative to CT and this was obtained due to minimal soil disturbance utilizing zero tillage/reduced tillage which ensures: (a) a favorable amount of respiration gases nearby the root system, (b) moderate organic matter oxidation, (c) better porosity for water movement, and (d) limited weed seeds exposure and their germination. Allam et al. (2021) reported similar crop yields under CA and CT when the cropping system comprised different fertilizer sources. Pittelkow et al. (2015b) showed that for root crops and horticultural crops, CT approaches may be more appropriate to avoid large yield decreases due to surface compaction inhibiting root growth and preventing appropriate drainage and soil aeration in CA (Howeler et al., 1993).

The scope of CA adoption in India during the early period was limited by small sample sizes and narrowly defined geographies and farming systems. Most of the data during the initial years were from the regions where diffusion of CA technology was initiated and it was clear from the dataset that CA practices took 6–7 years to exhibit their beneficial effects on yields (Krishna et al., 2022). Thus year-wise yield data revealed that CA had declined yield during 2009–2016 and improved during 2017–2020. Higher crop yield under CA in western, northern, and north-west parts of India was due to higher adoption of zero-till seed-cum fertilizer drills, raised-bed planting, and laser land levelling by the farmers of these regions (Bhan & Behera, 2014). However, lower adoption of this technology in the eastern, north-east, and southern regions resulted in lower crop yield under CA relative to CT (Erenstein & Laxmi, 2008; Krishna et al., 2022). One of the studies about intervention clusters highlighted that CA adoption was 25% in the north-west region whereas only 2% in the eastern region of India (Singh et al., 2012).

Soils with sandy loam and clayey textures exhibited better yield performance under CA over CT; sandy clay loam and clay loam showed lower yields in similar comparisons. The overall study showed coarse to medium-textured soils had poor performance and medium and fine-textured soils had good performance under CA compared to CT. This could be due to the availability of more microstructure in medium to fine-texture soils than in coarse to medium-textured soils which ultimately affects the water and nutrient availability for plant growth and yield (Liu et al., 2021). A meta-analysis carried out by Rusinamhodzi et al. (2011) revealed a positive effect on crop yield under CA on coarse- and medium-textured soils and a negative effect on fine-textured soils.

Soil pH ranging from 7.0 to 8.0 was found to produce a better yield than the soil pH < 7.0 (acidic) and > 8.0 (alkalinity) under CA than under CT. This could be due to problematic/poor soil fertility situations under acidic and alkaline soil reactions. The subsurface layer had a higher yield advantage over surface soil under CA than CT which could be due to more soil compaction in the surface layer. In different rice-based cropping systems, bulk density was 2.38% higher in the surface soil (soil depth 0–10 cm) under CA than under CT (Motschenbacher et al., 2011). Higher bulk density and penetration resistance in CA was also observed by Jat et al (2009) indicating higher compaction in CA than the CT. Higher rainfall (> 1000 mm) had poor crop performance than lower rainfall (< 1000 mm) under CA relative to CT which is due to the compaction of soil and

Table 2 Effect of conservation agriculture over conventional agriculture on soil carbon sequestration in studies from India included in the meta-analysis

	Number of paired observations (n)	Effect size (%)	Lower limit (%)	Upper limit (%)
Year of publication of different studies				
2013	48	4.58*	0.61	8.59
2014	40	6.45*	5.36	7.51
2017	32	12.72*	5.25	20.27
2018	8	4.15*	1.51	7.90
2019	6	9.88*	2.17	17.48
2020	12	7.20*	6.52	7.87
Overall	146	7.30	5.43	9.33
Geographical regions				
North–east	12	7.20*	6.52	7.87
North–west	92	5.53*	3.67	7.24
Southern	42	11.94*	6.48	18.22
Soil textural group				
Sandy loam	38	12.06*	6.29	17.76
Sandy clay loam	48	7.53*	6.90	8.11
Clay loam	60	3.64*	0.21	7.10
Rainfall (mm)				
< 1000	54	10.49*	6.66	14.82
1000–2000	24	6.22	− 0.55	13.11
> 2000	68	5.36*	3.82	6.81
Soil depth (cm)				
0–15	110	10.65*	8.50	12.89
15–30	36	− 3.04*	− 4.40	− 1.00
Soil organic carbon (%)				
< 0.50	42	11.94*	6.19	17.94
> 0.50	20	4.30*	2.60	5.95
Available nitrogen (kg ha^{-1})				
< 250	60	3.64*	0.59	6.63
250–500	36	7.65*	6.91	8.31
> 500	32	12.68*	5.87	19.99
Total nitrogen (%)				
< 0.10	6	9.88*	1.94	17.48
> 0.10	32	12.73*	5.87	17.82

The error bars show 95% confidence intervals (CI), and the difference is significant if it does not pass zero.

*Indicates a significant difference at p-value < 0.05

weed management problems (Chaki et al., 2021). In a moist environment, weed dynamics play a major role. Our findings revealed that CA produced a higher yield than CT ranging from 4 to 15% when SOC was < 0.50% and 6–10% when was SOC > 0.50%. This could be because SOC improves the physicochemical and biological environment of soils leading to sustainable soil systems for improving agricultural productivity (Kumar et al., 2018; Rajan et al., 2012). Higher soil available N (> 500 kg ha^{-1}) and soil total N (> 0.10%) enhanced grain yield under CA and CT because of improved soil water-nutrient-crop produce relationship, as available N is a good indicator of soil organic matter content in the soil (Bauer & Black, 1994; Sainju et al., 2007, 2017).

This study revealed an overall increase in SOC when CA was followed in comparison to CT in India. Based on 405 paired observations, the overall SOC increment was 8.88% across the studies from India irrespective of cropping systems and duration of experimentation. Under CA, the addition of crop residues helped to accumulate SOC in soils

Table 3 Slope and significance of meta-regression of the duration of the experiment, pH, rainfall, available N, total N and SOC on soil and crop parameters

Parameters	n	Slope	*p*-value	n	Slope	*p*-value	n	Slope	*p*-value
	Duration			pH			Rainfall		
Grain yield	193	−0.0047	0.02*	30	−0.0001	0.99	179	−0.0002	<0.01**
SOC	287	0.0020	0.43	85	0.0004	0.99	260	<−0.0001	0.59
TC	46	0.0005	0.94	14	−0.0165	0.82	46	<0.0001	0.98
WSC	61	0.2419	<0.01**	9	−0.0426	0.52	60	0.0003	<0.01**
POC	56	−0.0044	0.58	14	0.0302	0.84	56	−0.0003	0.69
BD	229	−0.0014	0.59	82	0.0257	0.53	215	<0.0001	0.99
MWD	60	0.0287	0.51	25	0.9989	0.15	60	<0.0001	0.87
SCS	110	−0.0039	<0.01**	10	−0.0045	0.67	110	<−0.0001	<0.01**
	Available N			Total N			SOC		
Grain yield	167	0.0006	<0.01**	82	1.0686	<0.01**	113	0.0038	0.95
SOC	235	<0.0001	0.91	111	−0.0437	0.97	176	0.0133	0.91
TC	40	−0.0002	0.77	–	–	–	22	0.1432	0.78
WSC	49	−0.0001	0.76	61	−3.2215	<0.01**	–	–	–
POC	50	0.0011	0.26	–	–	–	56	−0.1106	0.63
BD	204	<0.0001	0.93	114	−0.9266	0.74	101	−0.1764	0.45
MWD	50	<−0.0001	0.92	32	0.0451	0.99	40	0.4860	0.36
SCS	98	<0.0001	0.68	38	0.3204	0.66	52	−0.1626	<0.01**

SOC Soil organic C, *TC* Total C, *WSC* Water-soluble C, *POC* Particulate organic C, *BD* Bulk density, *MWD* Mean weight diameter, *CS* Soil C sequestration, Available N-Available nitrogen, Total N-Total nitrogen, *SOC* Soil organic C

* and ** indicate significant difference at $p < 0.5$ and $p < 0.01$, respectively

under diversified cropping. The addition of organic matter through crop biomass and the losses through decomposition, leaching as well as erosion ultimately decides the extent to which CA influences SOC. The difference in SOC between CT and CA practices was more pronounced under long-term trials which is suggestive of the requirement of a certain time (about 5–6 years) for accumulation of SOC in soil. Over-exploitation of soils under intensive conventional agriculture causes losses of SOC from the soil systems. Tadiello et al. (2021) followed the meta-analysis approach and reported that CA compared to CT accumulated 13% higher SOC in Mediterranean and humid subtropical climates. Crystal-Ornelas et al. (2021) also observed through meta-analysis that the adoption of CA increased SOC content by 14% over CT. A similar increase was observed due to the adoption of CA practices in the eastern Indo-Gangetic plain in India, Bangladesh, and Nepal (Sinha et al., 2019).

CA increased SOC from 2000 to 2020 except for the year 2006.All the regions of India had higher SOC content by following CA rather than CT. The maximum SOC content was observed in the north-west region and the minimum in the central region. Soil texture influences the accumulation of organic matter in the soils (Dexter, 2004; Li et al., 2022). Soil particles such as clay and silt protect soil organic matter by stabilizing microbial decomposition (Six et al., 2002). Corbeels et al. (2014) observed that the lack of reported data on soil characteristics in several kinds of literature did not permit a meta-analysis of the interactions, particularly between soil texture and SOC. In the present meta-analysis, it was observed that SOC was influenced by the soil texture. Medium to fine-textured soils accumulated more SOC under CA than CT. The highest SOC increase was recorded in the silty clay textural group. The conversion of crop residue to SOC might be higher under CA compared to CT as evidenced by a higher amount of mineral-associated C compared to particulate organic carbon and reducing soil to residue contact (Page et al., 2020). Interaction between soil texture and SOC is very important to determine crop yield responses to CA.

Soil pH influences SOC content because it regulates soil nutrients bioavailability, organic matter turnover, and several soil processes (Kemmitt et al., 2006; Robson et al., 1989). Soil pH ranging from7.0 to 8.0 was found more suitable to increase SOC than the soil pH < 7.0 (acidic) and > 8.0 (alkalinity) under CA compared to CT. It suggests that SOC retention was higher under soil pH ranging from 7.0 to 8.0 than when pH was higher or lower than this range. The acidic and alkaline pH hampers microbial growth which in turn influences the SOC mineralization rate in the soil (Malik et al., 2018). Among different factors influencing carbon turnover rate in saline and alkali soils, the exchangeable sodium percentage and enzyme activities play a major role. The process of carbon sequestration is more adversely affected by salinization and alkalinization than the processes governing the source of carbon (Wang et al., 2020). The surface layer had higher SOC than the subsurface layer under CA relative to CT; however, SOC in both soil depths had a positive impact under CA than CA. In comparison to underlying soil (15–30 cm), topsoil (0–15 cm) had more organic matter. CA leaves stubble from the previous crops on the soil surface, resulting in delayed residue decomposition when incorporated into the soil system. Higher C mineralization was observed when maize residues were placed over the soil surface and incorporated into the soil (Datta et al., 2019). Stubbles present in the topsoil also protects the soil surface from raindrops and wind disturbances, and transportation (Chivenge et al., 2007) and thus help in higher SOC content in the surface layer under CA. CA improves physical structure (Tisdall & Oades, 1982) enhances biological activity (Varvel et al., 2006), and increases C pools and nutrient cycling (Campbell et al., 1996).

Moisture in the soil system impacts SOC stabilization by affecting functional soil microorganisms (Canarini et al., 2016). The changes in soil microbial communities contribute to SOC accumulation in different ways (Shao et al., 2017). Repeated tillage operations in soil under CT lead to losses of SOC as the soil is exposed to microbial decay, particularly the organic matter present in soil macro-aggregates. Therefore, the amount of rainfall acts as an important factor influencing SOC accumulation in the soil–plant system. In the present meta-analysis, rainfall had a positive impact on SOC content and the highest increase in SOC under CA than under CT was when rainfall was > 2000 mm. Higher rainfall with elevation in these areas increases the availability of soil moisture throughout the growing period, directly promoting better biomass production which in turn increases the SOC content in soils (Choudhury et al., 2016; Dahlgren et al., 1997; Sinoga et al., 2012). An increase in soil organic matter increases available N and total N in the soil system. Available and total N positively affected SOC content in CA compared to CT. The quantity, quality, as well as periodicity of C inputs in soil may differ with crops grown under the two systems and influence the soil in various ways. The difference in crop rotation between CA and CT may impact SOC. Crops and rotations with higher amounts of leftover residues are mostly preferred for maintaining higher SOC stocks in the soil. In regions with favorable climatic conditions for higher biomass production, CA systems will lead to higher SOC accumulation than under the traditionally repeated tillage-based systems. Jat et al. (2018) observed a significant improvement in total N after four years of CA in cereal systems of north-western India.

Soil C sequestration is the phenomenon of offsetting C dioxide emissions in the environment by storing C in the soil system (Feng et al., 2020). Tillage practices impact organic matter accrual by disturbing soil and change in the period of residence of crop residues in the soil system (Haddaway et al., 2017). CT breaks up the plough layer, affecting the physical, chemical, and biological properties of soils, soil strength, and root development and exposing subsoil resources. On the contrary, CA mitigates the adverse effects of climate change by sequestering more C. Climate change is one of the concerns due to greenhouse gases impacting on human life is severe (Akram et al., 2018).In the present meta-analysis, soil C sequestration was 7.3% (n = 146) greater under CA relative to CT. Although there exists a large range in C sequestration rates, CA could be perceived as a better alternative through which potential benefits in soil chemical properties and soil environment may be harnessed through better recycling of plant nutrients. Yearwise references showed positive impacts of CA from the period 2013–2020. Under CA, carbon sequestration was found positively influenced in diverse regions and in soil textural groups. CA enhanced soil C sequestration over CT due to climatic factors such as rainfall, soil factors such as soil depth, and soil characteristics such as SOC content, available N, and total N. Increasing amounts of rainfall increased soil carbon sequestration in CA compared to CT. Surface soil as compared to subsurface soil had higher C sequestration under CA relative to CT. Improving the levels of available N and total N content in the soil increased the C sequestration in CA compared to CT.

Limitations of the study

As sufficient number of comparisons from more than 4 years old experiments (Fig. 2) are not yet available from different soil types and cropping systems in various regions of India, the meta-analysis did not allow to draw conclusions which can be valid for a particular region, soil type or cropping system. Many times, paired data points were not enough to conduct a thorough categorical analysis containing significant explanatory variables. Even fewer came from subsurface soil layers. Also, meta-regression for continuous variables was not adequate to reach at concrete results. Crop diversification-related data about CA was also not available for better showcasing CA findings based on crop diversification. Since software was used to extract the graphic data, there is a chance that the actual figures would differ significantly.

Conclusions

Conservation agriculture is being widely promoted in different regions in India for different crops and cropping systems. The meta-analysis based on published research to evaluate crop yield, SOC distribution/variation, and C sequestration under CA and CT in India suggests that the promotion of CA in India should be based on knowledge of appropriate crops in the specified region under specified soil textural class, amount of rainfall and in optimal soil nutrient condition. Although adoption of CA resulted in an overall decline in grain yield in the short term, the trend over the long term was reversed. There is a need for more research to refine location-specific technologies and extension efforts to promote CA in different regions of India and in various crops to attain its fullest benefits. The positive impact of CA observed in improving soil quality in terms of SOC and soil C sequestration is an important driver for the adoption of CA. Overall, the results of this study quantify the crop yield and soil C sequestration impacts on CA based on scientific evidence, establishing a foundation for conducting trade-off analyses to aid in the development and enhancement of CA crop management under a variety of scenarios in India. CA can be recommended to adapt to future climate change scenarios and as the best farming practice for sequestering C in the soil.

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Author contributions A.K.S. provided overall leadership, conceived the conceptual framework, and was in charge of overall direction and planning. R.P. and U.K. did a literature search and data analysis and wrote the manuscript. D.S.R. did statistical analysis of the metadata. A.D., B.M. S.M., M.K., B.S., and contributed to preparing different sections in the manuscript and R.K. prepared different maps of India through ArcGIS. All authors discussed the results and contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript.

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Declarations

Conflict of interest No potential conflict of interest is reported by the authors.

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