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Organic amendment effects on cropland soil organic carbon and its implications: A global synthesis

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ABSTRACT

Increasing soil organic carbon (SOC) content can promote soil health and crop yield. Organic amendment application is a common practice to accelerate soil carbon sequestration in cropland. The effects of different organic amendments (e.g., compost, slurry) on SOC are uncertain. Previous studies have investigated SOC response to environmental factors but not well addressed the effect of organic amendment characteristics (e.g., source, liquid/solid form, pH). Depending on 1,972 comparisons from 424 articles, we undertook a meta-analysis approach to explore organic amendment effects on SOC content and the related influence factors. The results show that organic amendment addition increased SOC by an average of 26.9% (or 5.1 Mg C ha^{-1}). Specifically, organic amendments can enhance SOC over the long term (>20 years) or within 1.0 m depth. Organic-residue inputs increased more SOC in regions with an arid climate, alkaline soils, or no-mineral nitrogen application soils than the humid climate regions, acidic soils, and nitrogen application soils, respectively. Sewage sludge and municipal solid waste as organic amendments led to high SOC. The organic amendments' pH and liquid/solid form caused significant differences in SOC accumulation. Amendments with a relatively low carbon content or rich nitrogen content have great potential to increase SOC storage. Our results illustrate the importance of amendment characteristics when estimating the potential of organic amendment addition to soil carbon accumulation. This study highlights that amendment application might be a sustainable strategy to increase soil carbon storage while promoting organic waste utilization.

1. Introduction

Increasing soil organic carbon (SOC) content improves soil quality, reduces carbon dioxide emissions (Lee et al., 2009; Pan et al., 2009), and promotes agricultural productivity (Lal, 2006). Average SOC values are relatively lower in cropland than in natural ecosystems due to the high turnover rate and agricultural management such as residue removal and tillage measures (Fujisaki et al., 2015; Tian et al., 2018; Ren et al., 2020). When primary forests and pasture are converted to cropland, the corresponding SOC stocks on average are estimated to lose by 25–30% (Don et al., 2011) and 50% (Lal, 2018). Although many agricultural practices have been adopted to increase SOC in cropland, it is still far from saturation (Vaccari et al., 2011). Therefore, cropland has a significant potential to sequester carbon from the atmosphere and mitigate the warming climate (Liu et al., 2014; Prestele and Verburg, 2020). To achieve this potential, it is necessary to explore methods such as organic material input and estimate their effects on soil carbon accumulation (Bai et al., 2019).

The organic amendment has been widely used to enhance soil fertility (Diacono and Montemurro, 2011; Zhao et al., 2021). Applying organic amendment could also increase crop yield and product quality and decrease environmental impacts (Watson et al., 2002). For example, manure addition helps increase crop productivity by an average of 7.6% and soil carbon sequestration by 17.7%; meanwhile, it can reduce

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chemical fertilizer input and mitigate the environmental risks associated with agrochemicals (Du et al., 2020). Furthermore, adding organic material improves soil physicochemical and biological properties (Blanchet et al., 2016; Dai et al., 2019), including bulk density, aggregation (Bandyopadhyay et al., 2010), microbial compositions and activities, as well as macro-nutrients (nitrogen (N), phosphorus (P), and potassium (K)) supply potential and availability (Ozlu and Kumar, 2018). The improvement of soil properties further promotes carbon accumulation and stabilization in soil. For instance, Blanco-Canqui et al. (2013) revealed that soils with low bulk density and large size of water-stable aggregates are favorable to organic carbon accumulation. Soils with a high proportion of clay plus silt fractions and inorganic nitrogen contents have a great capacity to store SOC (Zhao et al., 2006; Tian et al., 2018).

The advantages of organic amendment on SOC have been reported globally. Compost addition increased SOC content by 2.9%, compared to 2.4% in control in clay soils of Ethiopia (Agegnehu et al., 2016a). Farmyard manure increased SOC by 6.4% against mineral fertilizer alone in loam soils of Swiss (Blanchet et al., 2016). In loam soils of China, NPK plus cow or pig manure increased SOC to 20.3 or 12.9 g C kg^{-1}, respectively, while NPK alone increased to only 8.3 g C kg^{-1} (Zhou et al., 2020). Manure application is positively related to SOC over deep layers (Gami et al., 2009; Abrar et al., 2020) and for long periods (Hati et al., 2008; Wang et al., 2019). In contrast, some studies show that organic amendments also have adverse or no significant effects on SOC. For example, Maltas et al. (2018) showed that cattle slurry had no significant effect on SOC in the loam soils of Swiss. During the maize growing season, 40 Mg DM ha^{-1} biogas residue application decreased SOC compared to unadded control in top 30 cm clay loam soils (Kocyigit et al., 2017). In sandy loam soils of Denmark, various organic fertilizer input rates caused insignificant changes in SOC (Chirinda et al., 2010). Mineral fertilizer plus farmyard manure either increased or did not significantly change the SOC content in a 30-year study in Burkina Faso (Manna et al., 2005). These studies illustrate that organic amendment effects on SOC storage vary greatly with local management and environmental conditions. These various effects would cause uncertainties in estimating soil carbon dynamics at large scales. Accordingly, more studies are essential to investigating the responses of global soil carbon to organic input.

The different effects of organic amendment on SOC are due to the following reasons. First, organic amendments directly promote SOC accumulation by increasing carbon inputs. Second, materials like straw left on the soil surface or incorporated into the soil can intensify soil fertility, which in turn stimulates SOC sequestration through strengthened crop rhizodeposition (Liu et al., 2014). Third, organic amendments provide nutrients and energy for microorganisms and then facilitate their activities, which boost organic matter humification and decomposition (Fontaine et al., 2003), making carbon dynamics complicated. Finally, organic amendment effects on SOC are regulated by climate (e.g., precipitation and temperature), soil properties (texture, pH, etc.), characteristics of organic materials (carbon and nitrogen content, pH, etc.), and agricultural management (irrigation and cropping system, etc.) (e.g., Du et al., 2020; Emde et al., 2021). SOC stocks depend on the balance between the amounts of carbon sequestration and decomposition. Organic amendment characteristics impact the magnitude and potential of material mineralization and related soil carbon dynamics. To the best of our knowledge, the effects of organic amendment characteristics on SOC have not been well addressed and need additional investigations.

Estimating global SOC dynamics as influenced by organic amendments is challenging through in-situ or local-scale experiments. A meta-analysis is a robust tool to synthesize abundant observations from multiple studies and draw reliable conclusions about SOC responses to organic amendment at regional or global scales. A meta-analysis estimated a 17.7% carbon increment caused by manure application in China (Du et al., 2020). Combined manure and mineral fertilizer increased SOC by 9–39% compared with mineral fertilizer alone, according to a meta-analysis focused on cropland in China (Jiang et al., 2018). Chen et al. (2018) estimated the long-term (≥10 a) effects of manure and compost application on SOC at the global scale and found a 29% increase; however, the authors acknowledged that their results were not completely independent. A recent global synthesis reported that animal manure increased SOC stocks by 7.41 or 8.96 Mg C ha^{-1} compared to mineral fertilizer or unfertilized control, respectively (Li et al., 2021). Based on 27 comparisons, a meta-analysis concluded a 7.89 Mg $CO_{2\text{-eq}}$ ha^{-1} yr^{-1} increase in SOC after applying organic amendments to vineyard agroecosystems (Payen et al., 2021).

Studies are relatively scarce when comparing the effects of different organic materials on SOC. A global meta-study showed that organic amendments increased depth-weighted SOC amount by 24% (Crystal-Ornelas et al., 2021), whereas the types of amendments were unknown, and the amendment properties were not analyzed. A meta-analysis indicated that organic amendments significantly increased SOC content by 23.5% in the Mediterranean, while the slurry effect was not significant (Aguilera et al., 2013). This result is obtained based on limited observations, with thirty-seven and three in organic amendments and slurry, respectively. Previous data syntheses have examined the influence of environmental conditions on SOC responses to organic amendments (e.g., Du et al., 2020). Nonetheless, few studies have paid attention to the impacts of organic amendment characteristics (e.g., liquid/solid form, carbon content, and pH) on soil carbon sequestration. For example, Maillard and Angers (2014) estimated the manure effect on SOC but had not shown the effect of liquid organic waste. Therefore, a comprehensive evaluation is necessary to refine the contribution of organic amendment addition to SOC and analyze the influence of other factors on carbon accumulation.

This study aims to examine the SOC responses to organic amendment addition. The objectives were to: (1) quantify the influence of organic amendments on SOC and evaluate the impact of amendment characteristics, environmental conditions, and other agricultural managements on SOC sequestration; and (2) estimate the potential of SOC storage response to organic amendment inputs.

2. Materials and methodology

2.1. Data collection

We searched peer-reviewed articles from the Web of Science published before August 2020. The search keywords were “organic waste” (“biogas digestate” or “biogas residue” or “compost” or “manure” or “organic waste” or “slurry”) and “soil organic carbon” (or SOC). Totally > 2000 articles were found, and 859 papers were left after filtering according to the abstract. We then selected studies by the following criteria: (a) experiments were carried out in the agronomic field or pot if placed in the field, but incubation and modeling results were excluded; (b) organic amendments were applied annually rather than one-time input; (c) experimental design had replications; (d) ancillary information such as soil types, climate, and other agronomic management practices, was provided besides treatments and related controls; and (e) observations were focused on cultivated grassland, horticultural land, and other cropland but not orchards because tree root and root-associated microbiota in the orchard are spatially heterogeneous, causing high heterogeneity of SOC content. Green manure was excluded because we explored the potential of organic waste utilization in this study. We ultimately extracted 1,972 comparisons from 424 articles conducted in 42 countries (Appendix A, Fig. 1). The experimental durations of these articles were from 1 to 105 years, with a median of 10 years. Sampling depths were from the 0–5 cm to the 90–120 cm layers, while 64% of total comparisons were in the top 20 cm soil. Among all articles, 150 papers were conducted in China, 126 in India, 23 in the United States, and 12 in Canada.

From the selected studies, SOC data were extracted from tables or

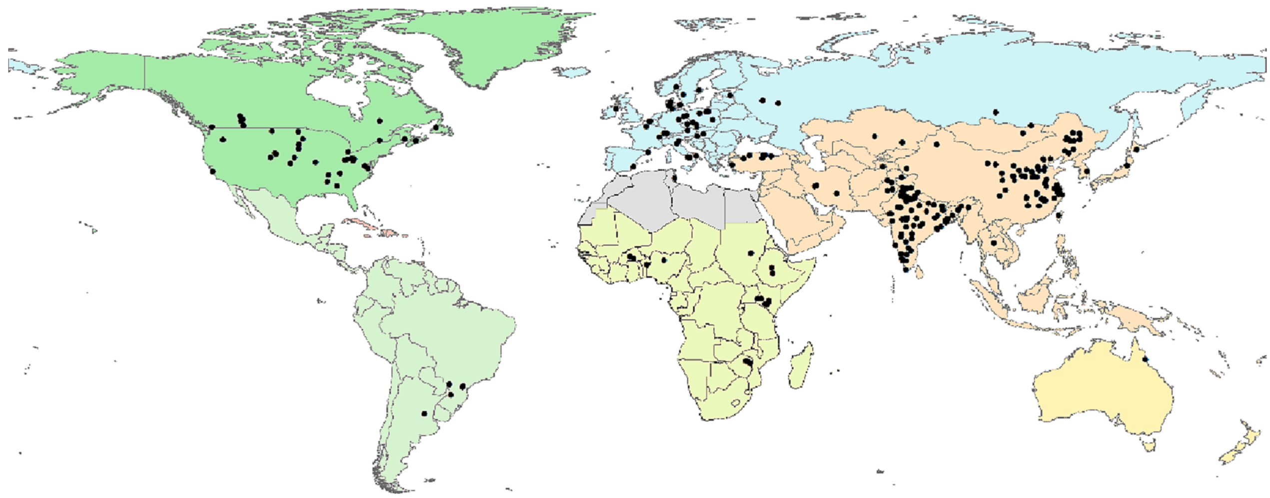

Fig. 1. Location of the study sites included in this meta-analysis (n = 247).

figures by GetData Graph Digitizer software (https://getdata-graph-digitizer.com/download.php). SOC stock data were selected if both concentration and stock were reported in articles. Other factors were also recorded to estimate their influences on SOC responses to organic materials. These factors include organic amendment characteristics (type, carbon and nitrogen content, carbon/nitrogen (C/N) ratio, pH, liquid/solid form, and material composition), experimental location (longitude and latitude), duration, climate conditions (mean annual temperature and precipitation), soil properties (pH, initial organic carbon content, total nitrogen content, C/N ratio, texture, and sampling depth), and other agronomic management practices (land type, land use, irrigation, crop residue, crop rotation, and chemical nitrogen input). The application rate of organic amendments was converted to net carbon input in Mg C ha^{-1} by multiplying organic amendment doses (Mg DM ha^{-1}) with the carbon content (%). We did not transfer the rate of organic amendments into net SOC increase because it has not been mentioned in most studies. The material composition (e.g, lignin, polyphenol) of organic residues was unanalyzed due to limited data. Because precipitation can not represent the drought severity for lack of evapotranspiration, the aridity index (UNEP, 1997) was incorporated into the study and grouped as arid or humid. Missing data on the aridity index were filled in according to the location reported in the articles. All sites were grouped into cold, cool, warm, and hot zones based on mean annual air temperature. Soil texture was grouped depending on the USDA soil texture triangle. The land type was classified into cultivated grassland, horticulture land (vegetables and flowers), and other cropland (i.e., for grain, cotton, tuber, etc.). Land-use type was grouped into upland, rice paddy, and upland paddy. Single crop-fallow was regarded as a continuous cropping system. The rainfed condition was further divided into cropland with annual precipitation $\leq$ 800 mm and $>$ 800 mm. The detailed classification of the influence factors is shown in Table 1.

As an indispensable variable for the meta-analysis, the standard deviation was calculated based on the average coefficient of variation for the known data if either standard deviation or the standard error was not given (Bai et al., 2019). If available, the standard error was transformed into standard deviation.

2.2. Statistical analyses

2.2.1. Meta-analysis

A random-effect model was used to evaluate variables that may explain the organic amendment effect on SOC. The logarithm of response ratio (lnRR) comparing organic amendment and the control was computed as equation (1) (Hedges et al., 1999):

$$\ln RR = \ln\left(\frac{X_t}{X_c}\right) \tag{1}$$

where X_t and X_c are mean SOC values (mixed concentration and stock) in the treatment and control groups, respectively. The variance (v) of lnRR was calculated as:

$$\mathrm{v} = \frac{SD_t^2}{n_t X_t^2} + \frac{SD_c^2}{n_c X_c^2} \tag{2}$$

where SD and n are the standard deviations and sample sizes, respectively, either in treatment (t) or control (c) groups.

The weighting factor (w') was used to calculate the mean effect size (RR_{++}), as the equations following:

$$w' = \frac{\frac{1}{v}}{n} = \frac{1}{vn} \tag{3}$$

$$RR_{++} = \frac{\Sigma_i \ln RR_i'}{\Sigma_i w_i'} \tag{4}$$

where $\ln RR' = w' \ln RR$, and i is the ith observation.

The 95% confidence interval of RR_{++} was calculated to show significance. The effect size was significantly different between treatment and control if the 95% confidence interval did not overlap zero. The percent change was transformed by $(e^{RR++} - 1) \times 100\%$. The fail-safe number was computed to evaluate the publication bias. Results were robust if the fail-safe number was $> 5 \times k + 10$ (k—the number of comparisons) (Rothstein et al., 2006). The data analysis and graphs were performed with "metafor" package (https://metafor-project.org/doku.php/) in R (R Core Team, 2021).

2.2.2. Structural equation model

A structural equation model was used to evaluate how the factors influence SOC stocks. The conceptual model was estimated by the ratio of chi-square to degrees of freedom < 3, comparative fit index (CFI $>$ 0.9), standardized root mean square residual (SRMR < 0.1), and root mean square error of approximation (RMSEA < 0.05). The standardized total effects were calculated by adding up all direct and indirect pathways between each factor and SOC stocks. The tests were performed using Amos (version 23.0, Chicago: IBM SPSS).

Table 1
Categories are grouped to describe the environmental conditions, organic amendment (OA) characteristics, and management practices. SOC, soil organic carbon; MSW: municipal and household solid waste; N, nitrogen. Soil depths, except 0–100 cm, were not accumulated additionally and exactly categorized according to the depth given by the articles. For example, neither 0–10 cm nor 0–20 cm was added to 0–30 cm, etc. The layer of 0–100 cm included 0–80, 0–90, and 0–100 cm due to limited observations. MAAT: mean annual air temperature; MAP: mean annual precipitation.

Factors	Categories			
Climate conditions				
MAAT (°C)	Cold (<5)	Cool (5–10)	Warm (10–20)	Hot (>20)
MAP (mm)	<400	400–800	800–1200	>1200
Aridity index	Arid (≤0.65)	Humid (>0.65)		
Soil properties				
pH	Very acid (<5)	Acid (5.1–6)	Neutral (6.1–7.9)	Alkaline (>8)
Initial SOC (g/kg)	< 6	6–12	12–20	> 20
Initial total N (g/kg)	< 0.75	0.75–1.5	1.5–2	> 2
Carbon/nitrogen	< 10	10–20	> 20	
Texture	Coarse	Medium	Fine	
Depth (cm)	0–10	0–20	0–30 ~ 0–70	0–100
OA characteristics				
Types	Cake Litter	Compost MSW	Manure Sewage sludge	Digestate Slurry
Carbon content (g/kg)	< 100	100–200	200–500	> 500
N content (g/kg)	<10	10–20	20–50	> 50
Carbon/nitrogen	< 10	10–20	20–50	> 50
pH	Very acid (<5)	Acid (5.1–6)	Neutral (6.1–7.9)	Alkaline (>8)
Input rate (Mg C/ha)	0–1	1–2	2–5	5–10
	10–20	> 20		
Liquid/solid form	Solid	Liquid		
Management practices				
Land types	Cropland	Grassland	Horticulture land	
Land use	Upland	Paddy	Upland-paddy	
N fertilizer (kg N/ha)	No N (0)	Low (<100)	Medium (100–200)	High (>200)
Crop rotation	Rotation	Monoculture		
Crop residue	Returned	Removed		
Irrigation	Yes	No (<800 mm)	No (>800 mm)	
Duration (year)	Short (1–5)	Medium (6–20)	Long (>20)	

3. Results

3.1. Organic amendment effects on SOC and associated environmental influence

Organic amendment input significantly increased SOC storage by 26.9 ± 0.7% (95% confidence interval, Fig. 2) or enhanced SOC stocks by an average of 5.1 ± 0.4 (95% confidence interval) Mg C ha^{-1}. Manure and compost, the two main types used globally, increased SOC stocks by 4.8 ± 0.5 and 5.6 ± 0.9 (95% confidence interval) Mg C ha^{-1}, respectively.

Results suggest that organic amendment increased SOC by 40.2% in warm regions, compared with 23%–25.6% in other zones (Fig. 2). The effect size was positively related to mean annual precipitation when increasing from < 400 mm to 800–1200 mm, whereas it was significantly low in areas with precipitation > 1200 mm. Aridity strongly influenced organic amendment effects on SOC. Organic input increased SOC by 32.4% in dry regions and 23.6% in humid areas (Fig. 2).

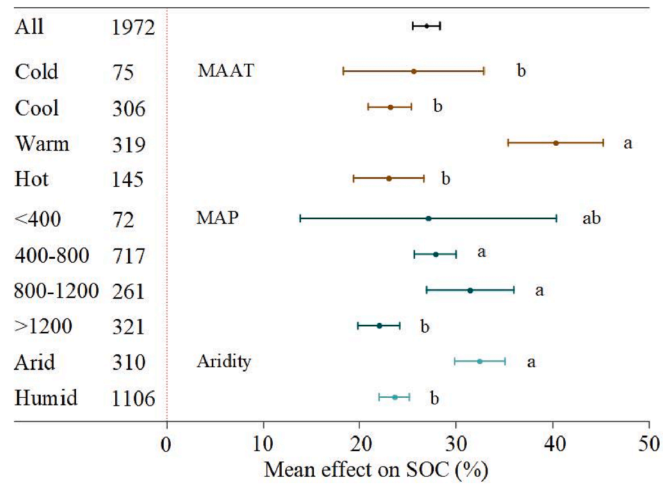

Fig. 2. Responses of soil organic carbon (SOC) to organic amendments input, shown as the whole dataset of SOC observations and the effects of climate on SOC response ratio. Numbers in the second column show the sample sizes. Error bars represent 95% confidence intervals. Different lowercase letters indicate the significant level of $p < 0.05$ in each category. MAAT: mean annual air temperature; MAP: mean annual precipitation.

Organic material input increased SOC by 27.4% in very acidic soil (Fig. 3). SOC increment was positively related to pH when ranging from acidic to alkaline soil, while the differences were statistically significant.

Soils with a lower initial carbon content had a higher SOC sequestration potential. SOC increment in the level of initial carbon < 6 g C kg^{-1} (34.2%) was twice as much as in the level of 12–20 g C kg^{-1} or > 20 g C kg^{-1} (Fig. 3). When initial carbon was 6–12 g C kg^{-1}, organic amendments increased SOC by 30%. The maximum effect size (46.1%) was at the lowest level of soil total nitrogen (<0.75 g N kg^{-1}, Fig. 3). However, the differences in SOC increment were not significant when total nitrogen varied from 0.75 to > 2 g N kg^{-1}. Organic amendment addition increased SOC by 50.5% in soils with a C/N ratio > 20, followed by 31.1% and 30.6% in soils with a C/N ratio of 10–20 and < 10, respectively.

Soil texture regulated the effect of organic amendments on SOC. Organic amendments increased SOC by 33.2% in coarse-textured soils, compared to 24.5% and 20.2% in fine- and medium-textured soils, respectively (Fig. 3).

Organic amendments enhanced SOC over the different soil depths, as shown in Fig. 3. SOC derived by organic input was 40.7% in the 0–20 cm and 27.1% in the topsoil within 10 cm (Fig. 3). The effect size was 18.7% in the 0–30 cm and 12.9% in the upper 40 cm depth, and reached 21.2% in the 1.0 m depth. The greatest increment in SOC was in the upper 70 cm depth (81%), which should be carefully interpreted considering the limited observations and insignificant effect.

3.2. Amendment properties influencing organic input effects on SOC

Our results showed that all types of organic amendments significantly increased SOC, while their differences were significant (Table 2). Sewage sludge, a by-product of the waste-water treatment, greatly increased SOC by 81% (Fig. 4). Municipal and household solid waste increased SOC by 52.9%. Manure and compost had similar contributions to SOC (26.4% vs. 28.7%), whereas the combined use of manure and compost can increase SOC by 37.1% (Fig. 4). We estimated the influence of manures from different animal species on SOC. Results showed that sheep manure had the best performance and increased SOC by 32.7%, followed by manure from pigs, cattle, poultry, and horses, with the effect size of 29.1%, 27.2%, 23.1%, and 17.5%, respectively (Fig. B.1). Press cake such as oilseed filter cake caused a 24% increment in SOC. Digestate, slurry, and poultry litter enhanced SOC between 11.9% and 14.8%.

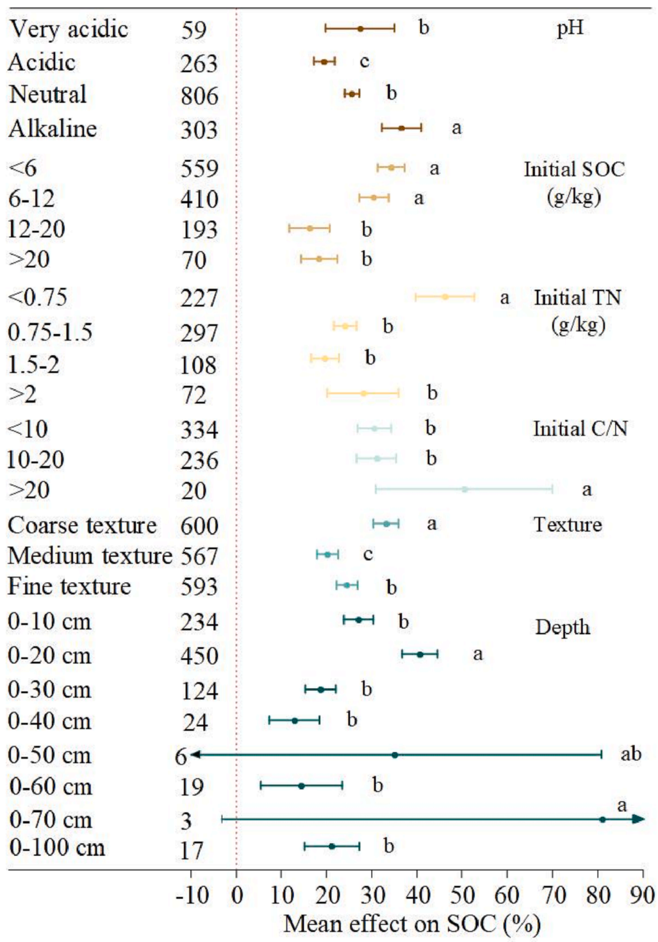

Fig. 3. Effects of soil properties (pH, initial organic carbon content, total nitrogen content (TN), ratio of carbon to nitrogen (C/N), texture, and depth) on the responses of soil organic carbon (SOC) to organic amendments input. Numbers in the second column show the sample sizes. Error bars represent 95% confidence intervals. Data in 0–100 cm includes observations in 0–80 cm, 0–90 cm, and 0–100 cm. Different lowercase letters indicate the significant level of $p < 0.05$ in each category.

Soil carbon sequestration was generally regulated by organic carbon and total nitrogen content in organic amendments. The differences in SOC increment were not significant regarding the different carbon content levels in organic amendments (Table 2). The effect size varied between 25.5% and 28% when carbon content in organic amendments was < 500 g C kg^{-1} (Fig. 4). However, SOC increased by only 18.7% if carbon content was > 500 g C kg^{-1}. Total nitrogen content in organic amendments caused significant differences in the effect size ($p < 0.001$, Table 2). Organic materials with rich nitrogen content ($>$50 g N kg^{-1}) significantly increased SOC by 39.7% (Fig. 4). The effect size varied from 29.2% to 22% when nitrogen content was < 50 g N kg^{-1}. Organic amendment application may increase SOC by 30.3% if its C/N ratio was 20–50. SOC increment was almost equal when the C/N ratio of the organic amendment was between 10 and 20 and > 50.

Organic amendment pH significantly influenced SOC storage. Very acid and acid amendments increased SOC by 73.4% and 74.1%, respectively, which were two times larger than SOC increased by neutral or alkaline amendments (Fig. 4).

Soil organic carbon generally increased with the increasing input rate of the organic amendments. The largest input rates ($>$20 Mg C ha^{-1}) caused the strongest SOC accumulation (74.4%, Fig. 4). The effect size was nearly equal when organic waste was applied at < 1 and 1–2 Mg C ha^{-1}. Both liquid and solid organic amendments noticeably increased SOC, and the promotion range displayed a certain difference. More SOC was accumulated by solid (27.9%) than liquid organic amendments (18.5%) (Fig. 4).

Table 2
Between-group variability (Q_M) of the variables controlling the effects of organic amendments (OA) on soil organic carbon (SOC). MAAT: mean annual air temperature; MAP: mean annual precipitation.

	Variables	df	Q_M	*p*
Climate	Aridity	1	35.85	<0.0001
	MAAT	3	54.96	<0.0001
	MAP	3	13.6	0.0035
Soil properties	pH	3	59.83	<0.0001
	Initial SOC	3	53.76	<0.0001
	Total nitrogen	3	71.74	<0.0001
	Carbon/nitrogen	2	5.39	0.0675
	Texture	2	54.85	<0.0001
	Depth	7	77.79	<0.0001
OA characteristics	Types	8	68.59	<0.0001
	Carbon content	3	6.07	0.1082
	Nitrogen content	3	20.55	0.0001
	Carbon/nitrogen	3	7.76	0.0512
	pH	3	13.45	0.0038
	Application rate	5	39.31	<0.0001
	Liquid/solid form	1	10.9	0.001
Management practices	Land types	2	11.2	0.0037
	Land use	2	4.9	0.0862
	Nitrogen addition	3	82.2	<0.0001
	Crop rotation	1	5.3	0.0214
	Crop residue	1	33.77	<0.0001
	Irrigation	2	2.05	0.3584
	Duration	2	28.09	<0.0001

3.3. *Effects of agricultural managements and duration on SOC*

Organic amendments significantly promoted SOC uptake by 27.2% in cropland for grain, cotton, tuber etc., followed by 21% in horticulture land and 18.4% in cultivated grassland (Fig. 5). The effect size was 27% in upland soil, 20.9% in paddy soil, and 27.2% in upland-paddy soil; however, the difference was not significant ($p = 0.0862$). Mineral nitrogen addition limited SOC increment compared to zero nitrogen input (Fig. 5). Organic input increased SOC by 35.6% in no-mineral nitrogen input soils, approximately two times larger than the increment with low-level nitrogen addition (17.2%). The effect sizes had no significant difference between medium-level and high-level nitrogen addition (23.7% vs. 25.7%).

Organic amendments increased SOC in rotational cropping systems more than in monoculture systems, with 28.1% and 24.6%, respectively (Fig. 5). Residue removal stimulated carbon accumulation, with a 32.7% increment against 18.9% in residue retention conditions (Fig. 5). The difference in SOC response to organic amendments between irrigation and rainfed was not significant ($p = 0.3584$). The effect size was 29.8% in irrigated areas, compared to 33% and 25.5% in rainfed regions with mean annual precipitation > 800 mm and < 800 mm, respectively (Fig. 5).

Organic amendment effect on SOC sequestration varied with experimental durations. The effect size was 32.8% in the long-term experiments, followed by 25.8% in short-term studies and 23.6% in medium-term observations (Fig. 5). Specifically, manure, compost, and slurry addition increased SOC by 43.1%, 22.3%, and 14.4% over the long term duration ($>$20 years), respectively (Fig. 6).

4. Discussions

4.1. *Overall effects of organic amendments on SOC*

Many studies have certified that organic manure promotes SOC accumulation, but the results vary greatly. Globally, SOC content increased by 36.2% with manure plus chemical fertilizer and 15.4%

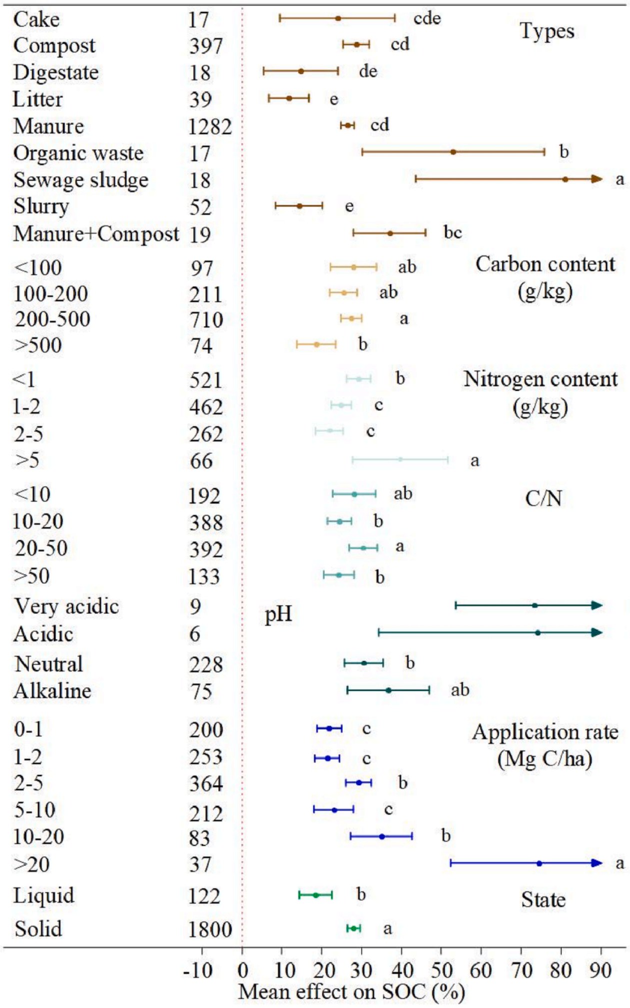

Fig. 4. Effects of amendment type, carbon content, nitrogen content, ratio of carbon to nitrogen (C/N), input rate, pH, and liquid/solid form on the responses of soil organic carbon (SOC) to organic amendments. Numbers in the second column show the sample sizes. Error bars represent 95% confidence intervals. Different lowercase letters indicate the significant level of $p < 0.05$ in each category.

with chemical fertilizer alone (Han et al., 2016). A synthesis study by Luo et al. (2018) found that the amount of SOC in organically amended soils was 38% higher than in mineral-fertilized soils. Our result (26.9%) supports the meta-analysis of Chen et al. (2018), who suggested that organic amendments increased SOC by 29%. Similarly, Aguilera et al. (2013) found a 23.5% increase in SOC induced by compost, manure, and agro-industrial wastes in Mediterranean cropping systems. Li et al. (2021) conducted a global synthesis and determined that manure input increased SOC stocks by 7.41 Mg C ha^{-1} or 8.96 Mg C ha^{-1} (vs. mineral fertilized or unfertilized reference, respectively). Accordingly, Maillard and Angers (2014) concluded that manure addition increased average SOC stock by 5.6 or 9.4 Mg C ha^{-1}. These published results are higher than ours (4.8 Mg C ha^{-1}). The discrepancy in the outcomes may be due to the organic amendment differences in various studies and the magnitude of dataset size since the results were calculated by the same method. Our results spotlight organic amendment potential for SOC accumulation and emphasize the possibility of mitigating climate change via cropland management.

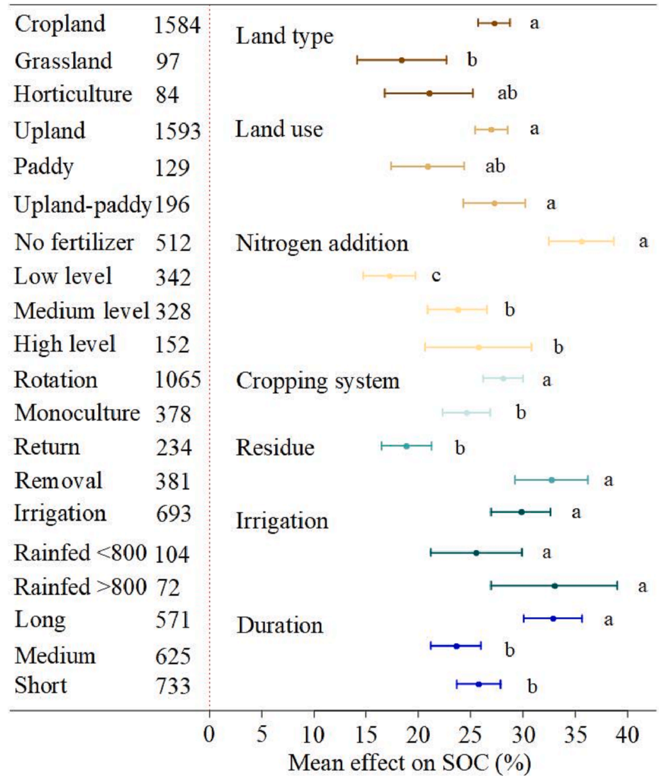

Fig. 5. Effects of agronomic management practices (land type, land use, mineral nitrogen input, crop rotation, residue, and irrigation) and experimental duration on the responses of soil organic carbon (SOC) to organic amendments input. Grassland only includes cultivated grassland for feeding livestock; horticulture land is the land for flowers and vegetables; and cropland represents land for other crops, including cereal, tuber, cotton, etc. Rainfed < 800 and > 800 are the annual precipitation lower and higher than 800 mm under rainfed condition, respectively. Numbers in the second column show the sample sizes. Error bars represent 95% confidence intervals. Different lowercase letters indicate the significant level of $p < 0.05$ in each category.

4.2. *Climate conditions and soil properties*

4.2.1. *Climate conditions*

Climate conditions alter the size and composition of the soil carbon pool, resulting in either negative or positive effects on carbon stocks (Luo et al., 2017). Precipitation has a positive relationship with soil carbon, while the temperature is negatively related to SOC in Europe (Rusco et al., 2001). Our results agree with Luo et al. (2017), who identified that precipitation was more important than temperature in influencing SOC dynamics. Drought can inhibit the loss of soluble organic carbon and reduce substrate availability to microorganisms (Davidson and Janssens, 2006), leading to a relatively high carbon accumulation. Moreover, aridity indirectly affects SOC stock by negatively affecting soil bulk density (Fig. 7) and causing low production. Precipitation promotes crop growth and biomass accumulation (especially in semi-arid and arid land), thus representing a large amount of residue retention and carbon input (Luo et al., 2017). However, humid conditions would accelerate organic matter mineralization and SOC loss by stimulating microbial activity (Dong et al., 2015; David et al., 2018). A lower increment in carbon over humid areas than in arid areas (Fig. 2), in addition to some periods of anaerobiosis, may be due to the fast mineralization of organic amendments.

Temperature impacts soil carbon dynamics by adjusting microbial community compositions and activities, which regulate the tradeoff between carbon accumulation and mineralization. Organic amendment decomposition and carbon mineralization are slow in cool areas due to

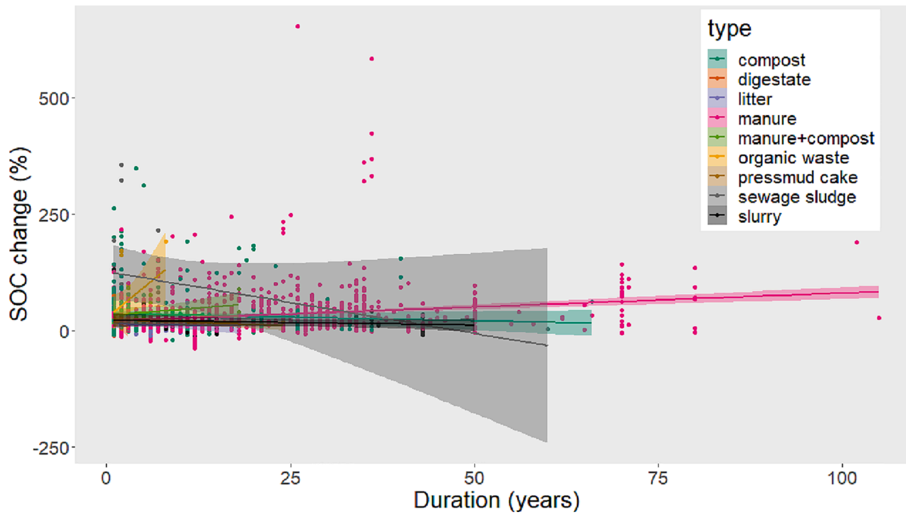

Fig. 6. Changes of organic amendments on soil organic carbon (SOC) under different experimental durations. The changes are quantified as the percent changes in organic amendments treatments compared to the unamended control. Lines and shaded areas represented overall mean ± 95% confidence intervals that were predicted based on regression against experimental duration.

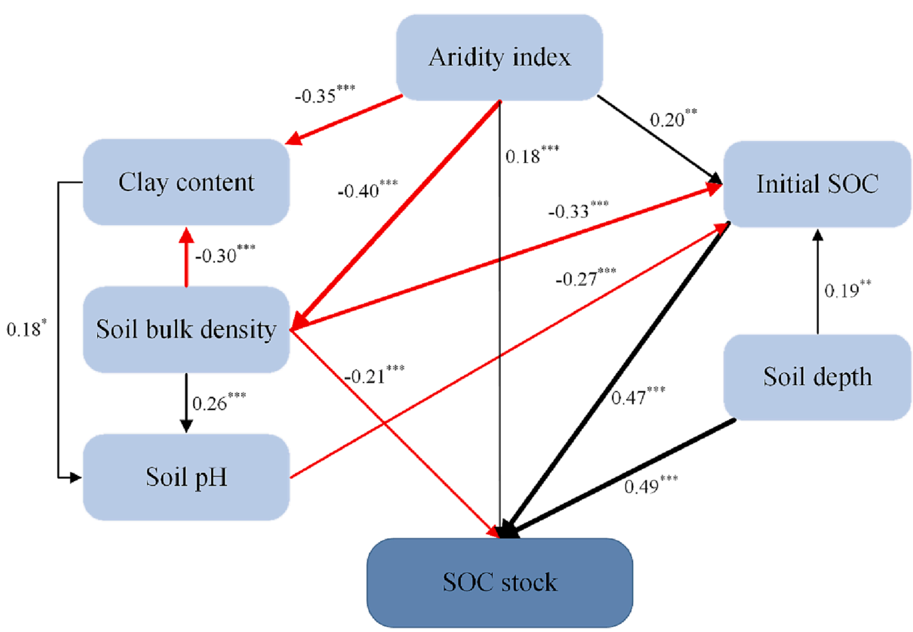

Fig. 7. Structural equation modelling for the impact of significant variables on soil organic carbon (SOC) stocks. Chi-square/degrees of freedom = 0.98, p = 0.42, comparative fit index (CFI) = 1, root mean square error of approximation (RMSEA) = 0, and standardized root mean square residual (SRMR) = 0.03. The black and red lines represent positive and negative effects, respectively. The line width is proportional to the strength of the standardized path coefficient. *p < 0.05, **p < 0.01, ***p < 0.001.

reduced microbial activity. Conversely, although organic substrate addition increases crop residue and carbon accumulation in temperate and tropical regions, the elevated temperature would stimulate microbial metabolic processes and accelerate carbon mineralization (Bååth, 2018). In this study, the effect size was largest in warm areas (10–20 °C) and had no significant differences over cold, cool, and hot areas, implying that mean annual air temperature is not a key factor for carbon storage. This finding is similar to Koven et al. (2017), who revealed no clear relationship between mean annual air temperature and soil carbon in the 1.0 m soil depth at the global scale.

4.2.2. Soil properties

Compared with acidic soils, very acidic soils favor carbon accumulation once the organic amendment is applied (Fig. 3). The similar effect size between very acidic soils and neutral soils (27.4% vs. 25.6%) suggests that the regulation mechanisms of soil pH effect on SOC increment are complicated. First, soil pH alters SOC decomposition by influencing biotic and abiotic factors, such as microbial activity and carbon availability (Bai et al., 2019). Soil acidification drives SOC sequestration by increasing mineral particle adsorption (Zhang et al., 2020b) and depressing microbial mineralization (Chen et al., 2016). Second, increasing soil pH enhances bacterial biomass and declines fungi biomass (Wan et al., 2015), resulting in uncertainties in SOC dynamics. Third, organic inputs may alter soil pH, which in turn causes differences in SOC decomposition between treated and untreated soils (Li et al., 2021). Finally, soil pH influences SOC stock indirectly through an effect on initial organic carbon (Fig. 7). Our study confirmed that the potential for carbon storage is great in alkaline soils but relatively tiny in acidic soils. The reason is probably that elevated pH restricts microbial activity and carbon turnover rate, while low pH stimulates the decomposition of organic amendments and native soil carbon. However, microbial mineralization of SOC may also be limited by lower soil pH (e.g., < 5).

Initial SOC concentration directly and positively impacts SOC stocks derived by organic input (Fig. 7). According to meta-analyses conducted in China, the largest and lowest manure-increased SOC content has been reported when initial soil carbon is 6–12 g C kg^{-1} and > 20 g C kg^{-1}, respectively (Ren et al., 2018; Du et al., 2020). Soils with higher initial carbon content have a relatively lower capacity to adopt exogenous carbon input (Gulde et al., 2008). Moreover, excessive carbon input cannot further promote accumulation if the soil has a low soil organic carbon saturation deficit (Ren et al., 2018). Greater carbon increase in soils with lower initial carbon content (Fig. 3) suggests that massive organic amendment inputs are required to improve and supplement carbon-poor cropland. Nitrogen enrichment may be in favor of soil carbon accumulation. A meta-analysis found that manure greatly increased SOC when initial soil nitrogen was > 2 g N kg^{-1} (Du et al., 2020). Conversely, the effect size was significantly high in soils with poor initial nitrogen content (<0.75 g N kg^{-1}) in our study. This result suggests that soil with poor nitrogen would limit SOC accumulation and has great potential to store carbon if organic amendments are applied.

Soil carbon capacity is correlated with soil fine fraction (Emde et al., 2021). For instance, increasing clay content is beneficial to store more soil carbon (Dal Ferro et al., 2020). Organic addition can either increase or decrease silt and clay content (Sleutel et al., 2006), making the changes in soil carbon complicated. Carbon is easily degraded in coarse-textured soils due to lacking microaggregate protection. Thus, coarse soils have a relatively high potential for carbon sequestration. Our study found the highest SOC accumulation in coarse-textured soils (33.2%) instead of in medium or fine-textured soils. Moreover, Sleutel et al. (2006) identified that manure increased coarse free particulate organic carbon but declined carbon in silt plus clay-associated soil fractions. Although carbon increment is high in coarse soils, its degradation is rapid. Future studies are necessary to estimate whether there is a net increase in carbon stocks in coarse-textured soils after the long-term addition of organic amendments.

Added organic amendments are usually incorporated into soils by tillage. This mixed depth is within the plow layer (~30 cm). Organic amendments thus increase SOC content in the upper layers. Our results indicate that organic amendments could also enhance SOC in deeper soils (Fig. 3). Besides direct input, organic substrate addition promotes biomass yield, leading to great carbon accumulation. Root litter and exudates and dissolved carbon are the sources of subsoil carbon (Michalzik et al., 2001). Root carbon is stable due to the recalcitrance of tissues (Rumpel and Kögel-Knabner, 2011). In addition, Abrar et al. (2020) found higher microbial-derived carbon compounds in subsoils than in topsoil. We highlight that 1.0 m depth should be considered when estimating SOC storage dynamics response to organic material input and climate warming.

4.3. Organic amendment properties

Carbon accumulation varied with organic amendment types, as we supposed. Sewage sludge and municipal solid waste performed better in increasing SOC than others. With the same application rate, sewage sludge increased more SOC than municipal solid waste compost or farmyard manure (Hemmat et al., 2010). Sewage sludge can reduce soil bulk density and increase water-stable aggregate content (Zuo et al., 2019), both of which help store SOC. The combined use of manure and compost should be extended to greatly accumulate carbon in cropland due to the better performance than each alone (Fig. 4). The effect size of the slurry was relatively low (14.4%). Slurry addition cannot significantly change SOC over 8–15 years (Yaguee et al., 2012; Balota et al., 2014; Domingo-Olive et al., 2016). One possible explanation is that slurry is easily decomposed and promotes microbial biomass and enzyme activities (Murugan et al., 2013; Balota et al., 2014), which in turn accelerates soil carbon mineralization.

Manure-caused SOC accumulation depends on livestock species. Cattle manure increased more SOC stock than pig manure, but the difference was not significant (Maillard and Angers, 2014; Li et al., 2021). Cattle manure can enlarge the macro-aggregate fractions, which hold more SOC content than micro-aggregates (Triberti et al., 2016). Conversely, SOC enhanced by pig manure was slightly larger than that by cattle manure in our study, although the difference was not significant (Fig. B.1). The difference between the two studies (i.e., Maillard and Angers, 2014; Li et al., 2021) and ours could be attributed to the different analysis methods and data sources, considering that the C/N ratio is not significantly different ($p = 0.36$ in our database) between cattle manure and pig manure. Organic carbon content in sheep manure could be as high as 27.9% (Hu et al., 2019) or 35.7% (Tokarski et al., 2018). This probably explains the highest SOC increased by sheep manure.

Carbon and nitrogen content should be considered if enlarging the SOC pool by organic amendment input. Organic amendments with a rich carbon content (>500 g C kg^{-1}) caused a low effect size (Fig. 4). The effect size was high when carbon content in organic materials was < 500 g C kg^{-1}. This probably shows that 500 g C kg^{-1} is a threshold that determines the ability of organic amendment to increase SOC storage. One possibility is that part of the materials derived from animal excrement has been decomposed before addition and a large proportion of recalcitrant organic compounds retain in manure (Thelen et al., 2010). The effect size decreased when the levels of nitrogen content in the amendments increased from < 1 to 2–5 g N kg^{-1} (Fig. 4). Nitrogen is easily degraded during organic amendment storage. Yang et al. (2011) reported a 26% nitrogen loss during manure storage and land application. This loss reduces fertility availability to crop growth and residue returned in soil. Nitrogen input by organic manure can increase soil microbial abundance and activities (Xu et al., 2019; Tang et al., 2020), which may boost soil carbon mineralization. It is necessary to investigate why rich carbon content in organic amendment reduces SOC accumulation, but great nitrogen content stimulates SOC storage.

Solid amendments showed better performance in SOC sequestration than the liquid (Fig. 4). First, compared with solid materials, slurry easily spreads over the soil surface due to its fluid nature, increasing the contact area between soil particles and liquid organic waste (Entry et al., 2004). This spread area may accelerate slurry decomposition because of slurry surface-air interaction, then decreasing slurry contribution to soil carbon storage. Second, most SOC is fixed or stocked in aggregates, but binding agents play a crucial role in soil aggregation. Transient or temporary binding agents, mainly from the slurry, are in favor of cementing from micro-aggregates to macro-aggregates. Still, persistent binding agents, such as humic substances and polyvalent metal cationic complexes, make clay, silt, and some free soil particles into micro-aggregates (Six et al., 2004). More liable and less highly processed SOC is contained in the macro-aggregates than micro-aggregates, increasing the probability of SOC losses. Third, if applied with an inappropriate method or time, especially after crop harvest, no vegetation cover would accelerate slurry resource loss. Therefore, considerable ammonia and nitrous oxide are released into the atmosphere, and nitrate leaches into groundwater accompanied by liquid slurry (Maris et al., 2021). Nitrogen loss is unfavorable to soil carbon sequestration. Finally, breeding species (cattle, pig, sheep), scales (small, medium, or large), methods (free or intensive), manure and slurry cleaning technology (dry collection or water housing), and livestock excrement processing methods (anaerobic digestion or aerobic aeration) all determine the composition and properties of experimental slurry, resulting in different outcomes to soil carbon accumulation.

4.4. Other agronomic management practices

Soil carbon accumulation is limited by nitrogen supply. Nitrogen addition accelerates biomass production, implying more residue retention. Nitrogen application also stimulates microbial metabolism (Börjesson et al., 2012), promoting soil respiration and carbon mineralization and declining SOC storage. On the contrary, high-level nitrogen input may also limit soil microbial and enzyme activities (Sommer and Møller, 2000), resulting in low organic matter decomposition and then relatively high soil carbon accumulation. It can be speculated that the highest increment in SOC without nitrogen fertilizer addition (Fig. 5) is due to weak microbial activities. When comparing the effect of nitrogen addition rate on carbon, organic amendments increased more soil carbon with the increasing mineral nitrogen input (Fig. B.2), suggesting that mixing mineral nitrogen with the organic amendment is superior to carbon increment than amendment alone.

Rotational cropping systems help sequestrate carbon (Fig. 5). Unlike monoculture, rotational cropping systems can provide substantial carbon input because of the greater belowground allocation of biomass (Van Eerd et al., 2014). Legume crops, which are widely planted in rotational systems, increase soil nitrogen and biomass accumulation, resulting in massive carbon storage. SOC derived from manure is higher in legume-grain rotations than in continuous winter wheat, regardless of mineral nitrogen fertilizer input or not (Hao et al., 2017). Farmers are accustomed to adding organic manure as base fertilizer before the sowing time of each crop. This management presents better conditions for carbon accumulation through enhancing nutrient utilization efficiency and producing residue compared to the application of only once a year. Besides, crop residue with a high C/N ratio is beneficial to SOC storage. The positive effect is noticeable in rotational systems because of the strong probability of crop residues with a high C/N ratio.

Crop residue retention increases soil carbon through direct input. Residue return helps form soil macroaggregates (Benbi and Senapati, 2010), which provide physical protection of SOC from mineralization. Saikia et al. (2015) observed that farmyard manure increased more SOC when residue was returned than removed. Similarly, manure plus chemical nitrogen increased SOC to 18.9 g C kg^{-1} with straw incorporation and 18 g C kg^{-1} without addition (Shen et al., 2007). However, residue removal rather than retention was superior to SOC accumulation in this study (Fig. 5). Soils with residue removal have relatively low carbon storage and would rapidly accumulate carbon once the organic amendment is added. The residue decomposition process is complicated and controlled by biogeochemical and biophysical conditions (Bai et al., 2019). For example, residue decomposition consumes nitrogen, which may impact crop growth and following carbon accumulation. The grinding degree and applying rate or time also influence residue decomposition, bringing uncertainties in soil carbon variation.

Irrigation did not noticeably alter the effect of organic amendments on SOC (Table 2). Furthermore, different levels of precipitation caused a certain but not significant difference in the effect size in rainfed areas (Fig. 5). With the same cattle manure input, results from Caron et al. (2012) showed a negligible difference in SOC between irrigated (51.2 g C kg^{-1}) and non-irrigated (50.9 g C kg^{-1}) clay loam soils. The insignificant change in SOC between rainfed and irrigated fields is due to the following reasons. First, irrigation increases SOC stocks by promoting litter and root production and inhibits carbon decomposition by increasing soil moisture (Entry et al., 2004). Second, irrigation methods, which were not discussed in our study because of no detailed information, strongly influence SOC sequestration. SOC increased when sprinkler irrigated and declined when drip irrigated, while had no variation when flood/furrow irrigated over the full 30 + cm profile (Emde et al., 2021). Third, SOC increment in rainfed land can be owed to extra annual carbon input than required to maintain organic carbon balance (Kundu et al., 2007). Finally, SOC mineralization is slow in rainfed croplands because of limited microbial activities (Yemadje et al., 2017). Further analysis indicated that in contrast to rainfed, irrigation restricted carbon accumulation in humid areas but increased carbon in arid regions (Fig. B.3).

4.5. Limitations and implications

Organic amendment application increased SOC under various conditions as we mentioned above. All results were robust when identifying publication bias (Table B.1). The material composition of organic amendments, which determines their decomposition process to some extent, has not been discussed because of the short dataset. For example, lignin content was given by only 22 comparisons from 5 articles, and thus can not be further classified to clarify its influence on SOC increment. Besides, the effect size of very acidic and acidic amendments should be carefully elucidated due to the limited observations.

Organic amendment decomposition releases more greenhouse gases than chemical fertilizer (Agegnehu et al., 2016b; Afreh et al., 2018). Greenhouse gas emissions may offset the advantages of organic amendments to soil carbon sequestration. Meta studies showed that manure application significantly increased N_2O emission by 32.7% against synthetic nitrogen fertilizer alone (Zhou et al., 2017) and insignificantly increased global warming potential by 118% (Shakoor et al., 2021). Another meta-analysis revealed that fully substituting fertilizer with manure did not alter CH_4 and N_2O emissions in upland, whereas it significantly increased CH_4 (48–82%) and decreased N_2O (34%) in paddy rice soils (Zhang et al., 2020a). Xia et al. (2017) conducted a global analysis to estimate the net global warming potential (showing as CO_2 unit) after substituting manure for fertilizer, finding that net global warming potential was –0.9 and 0.15 kg CO_2 ha^{-1} yr^{-1} per kg manure-C ha^{-1} yr^{-1} in the upland and paddy field, respectively. Their result indicates that substituting manure for chemical fertilizer makes upland a carbon sink and paddy field a carbon source. We calculated the difference in SOC between organic amendment treatment and corresponding control in each comparison. Results were negative in 124 comparisons and zero in 25 comparisons, indicating a negative effect and no effect of organic amendments on SOC, respectively. However, 92% of total comparisons showed a carbon accumulation since organic residues were applied. Additional field studies are required to analyze the effect of organic input on the balance between carbon accumulation and greenhouse gas emissions, especially in paddy soils. Furthermore, animal manure mixed with chemical NPK increased crop yield by 3.3–6.6%, whereas fully substituting NPK decreased yield by 4.1–9.6% (Zhang et al., 2020a). To enhance soil carbon storage without compromising yield, we suggest that organic input should partially rather than fully replace chemical fertilizer.

Rapid decomposition of organic amendment may weaken its effect on SOC increment. The percentage of carbon decomposed was 43.5–46.3% and 32.7–33.7% for pig manure and chicken manure over a year, respectively (Chen et al., 2019). Carbon in cattle and sheep manure was mineralized by 70.8% and 18.3% over 378 days, respectively (Zhu et al., 2020). A long-term application of organic amendments is necessary to increase soil carbon, especially in carbon-poor cropland. We then assessed the production of organic amendments and their potential for SOC storage. Annual production of manure is ~ 551 Tg in China and ~ 335 Tg in America (Linville et al., 2015; Jia et al., 2018), respectively, which could increase soil carbon by 25.9 Tg and 16.9 Tg (Fig. B.4) according to the average fraction of manure applied to cropland (Zhang et al., 2017). Annual compost production of 13 Tg (Gianico et al., 2021), if totally input, may increase carbon by 3.4 Tg in cropland in the European Union. Approximately 10, 8, and 4 Tg sewage sludge is generated annually in the European Union, America, and China, respectively (Yesil and Tugtas, 2019). These may increase SOC by 8.2 Tg in the European Union, 6.8 Tg in America, and 2.7 Tg in China if fully applied. Applying organic amendment to cropland improves soil quality and enhances resilience to climate change while providing a sustainable way to reuse organic waste.

5. Conclusions

This study quantified SOC responses to organic amendment application and associated influence factors, including environmental conditions, organic amendment properties, and agronomic management practices. Organic amendment application significantly increased SOC by 26.9% or 5.1 Mg C ha^{-1}. Organic amendment greatly increased SOC in areas with arid and warm climates and in soils with coarse texture, alkalinity, and low initial carbon or nitrogen content. Sewage sludge and household solid waste are the most efficient organic materials to increase SOC storage. Amendments with a relatively low carbon content or rich nitrogen content have great potential to accumulate SOC. Upland and cropland without nitrogen fertilizer addition are more suitable for increasing SOC via organic residue application. Long-term application of organic amendments can continuously increase SOC storage.

6. Data availability statement

All data are available in the main text or the Supporting Information are available upon reasonable request from the corresponding author.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Xiongxiong reports financial support was provided by Key Scientific Research Project of Colleges and Universities in Henan Province. Jiao Tang reports financial support was provided by Henan Institute of Science and Technology.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2023.107343.

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Organic amendment effects on SOC in cropland and its implications: a global synthesis

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Table B.1 Publication bias of the soil organic carbon (SOC) responses to organic amendments (OA) application. All results were robust (fail-safe number > 5× data number +10). n: number of observations; FSN: false-safe number.

Group	Variables	n	FSN	**Group**	Variables	n	FSN	**Group**	Variables	n	FSN
Climate	Arid	310	49471472	OA state	Liquid	122	37798	OA total nitrogen content (g/kg)	0-10	521	2793536
	Humid	1106	8850040		Solid	1800	126869208		10-20	462	21028814
	Cool	604	31417801	OA type	Cake	17	831		20-50	262	663717
	Warm	310	515337		Compost	397	1466845		>50	66	217238
Initial SOC (g/kg)	< 6	565	4576317		Digestate	18	293	Land type	Cropland	1584	95900730
	6-12	446	23288941		Litter	39	1286		Grassland	97	19927
	12-20	170	1953599		Manure	1282	84034042		Horticulture	84	173989
	> 20	51	4882		Organic waste	17	2320	Land use	Upland	1593	98391411
Soil depth (cm)	0-10	234	286177		Sewage sludge	18	3420		Paddy	129	63058
	0-20	450	4487225		Slurry	52	8840		Upland-paddy	196	203447
	0-30	124	5431043		Manure+Compost	19	2908	Nitrogen addition (kg/ha)	No	512	24189212
	0-40	24	573	OA addition (Mg C/ha)	0-1	200	178567		Low level	342	719742
	0-50	6	140		1-2	253	739480		Medium level	328	946571
	0-60	19	322		2-5	364	16986389		High level	152	1009261
	0-70	3	105		5-10	212	437968	Crop system	Rotation	1065	17061069
	0-100	17	2070		10-20	83	100227		Monoculture	378	31951709
Soil pH	Acidic	608	1845944		>20	37	53554	Residue	Return	234	2273664
	Neutral	284	674061	OA carbon content (g/kg)	0-100	102	119290		Removal	381	16333855
	Alkaline	556	30429276		100-200	211	9360087	Irrigation	Yes	693	38605772
Soil texture	Coarse	600	28365085		200-500	705	5446726		No	202	1533891
	Medium	567	2900145		>500	74	60621	Duration (year)	Long	571	12108176
	Fine	593	8019321	OA pH	pH <=7	92	1651925		Medium	625	30009019
					pH >7	226	359617		Short	733	3224009

Fig. B.1 Soil organic carbon (SOC) responses to different types of manure inputs. Numbers in second column represent the number of observations. Error bars show 95% confidence intervals. Farmyard manure was given by the articles and cannot be further classified due to limited information. The differences of effect size among manure types were not statistically significant. The difference was not significant among all types.

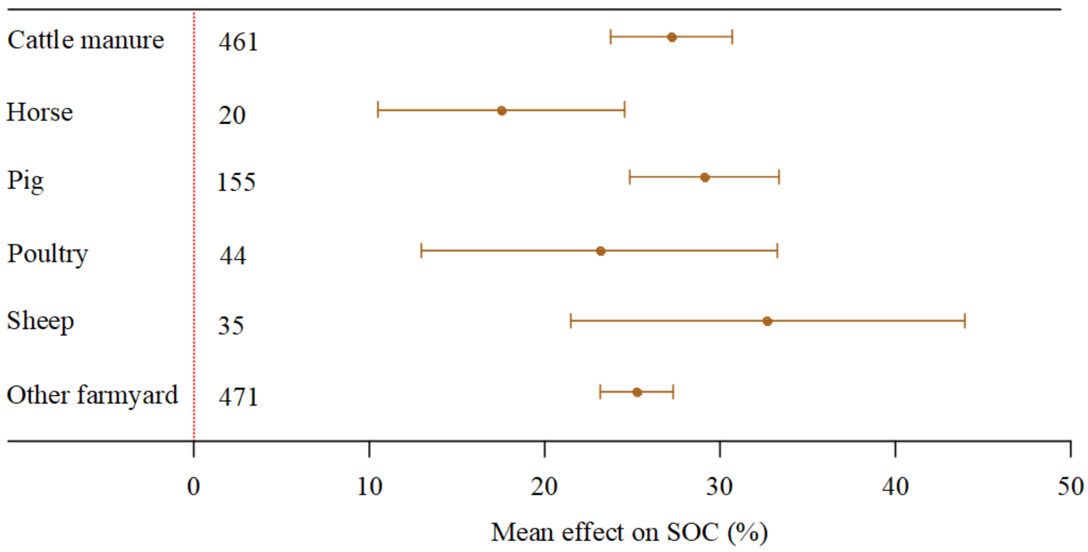


Fig. B.2 Relationship between mineral nitrogen fertilizer input rate and SOC ratio (SOC $_{treatment}$/SOC $_{control}$). Blue line and shadow area represent the regression line and 95% confidential interval, respectively. SOC ratio data were removed in this figure if the values were > Q3+3* IQR (interquartile range).

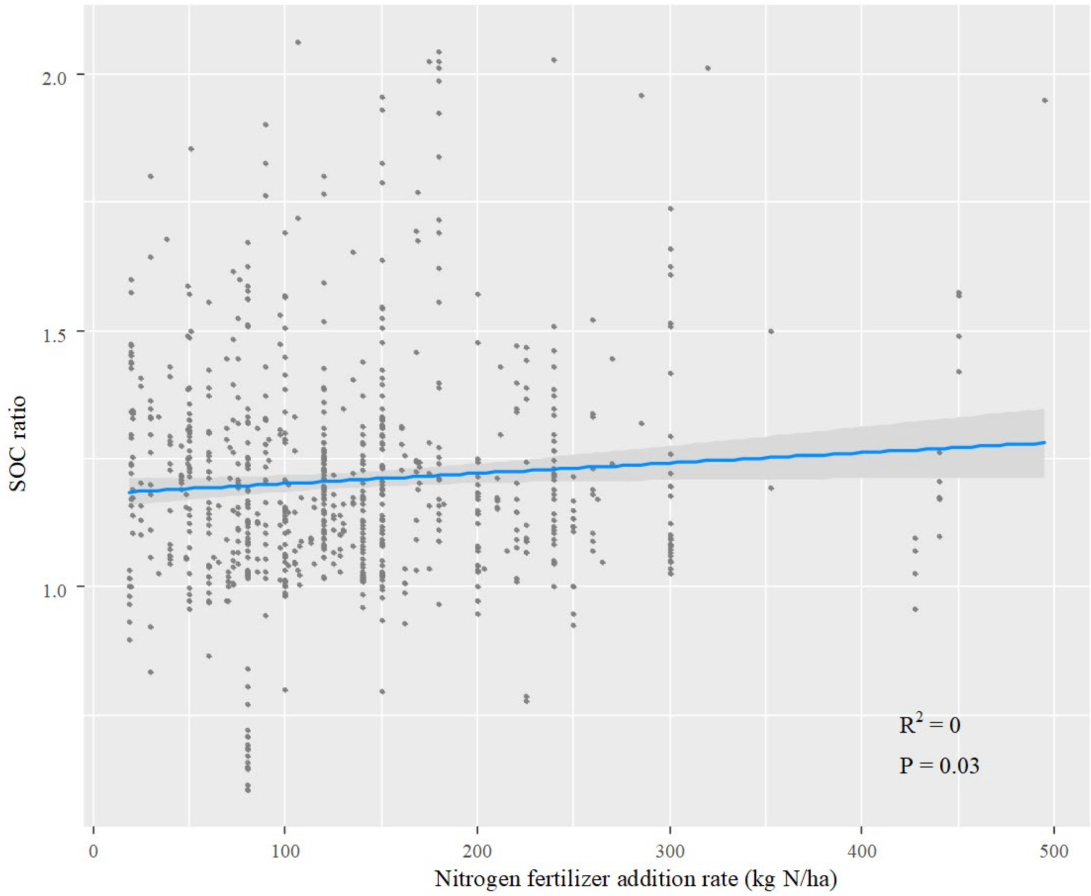


Fig. B.3 Irrigation and rainfed effect on soil organic carbon (SOC) increased by organic amendments in arid and humid regions, respectively. Numbers in second column are observations; p value shows between-group heterogeneity.

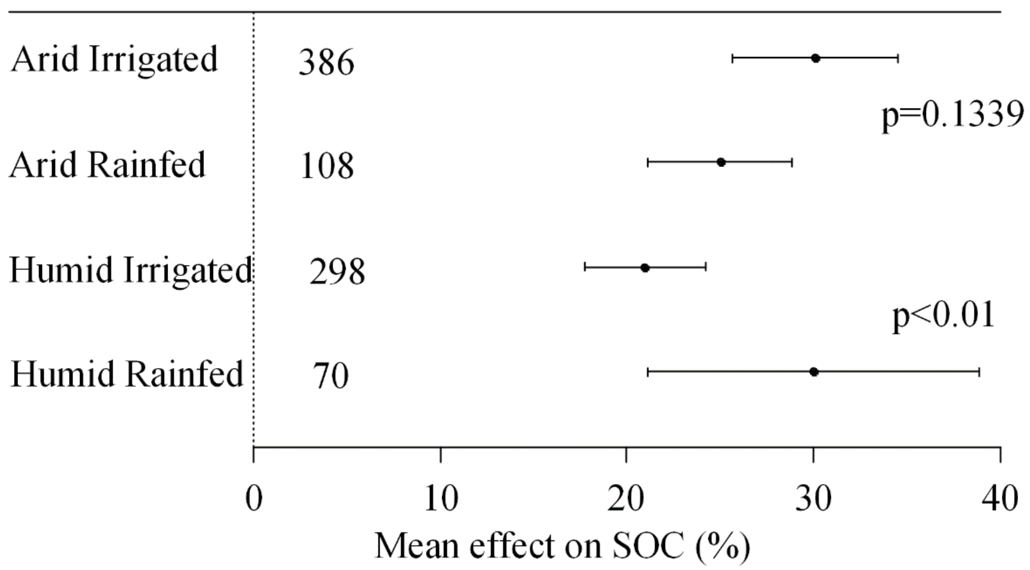
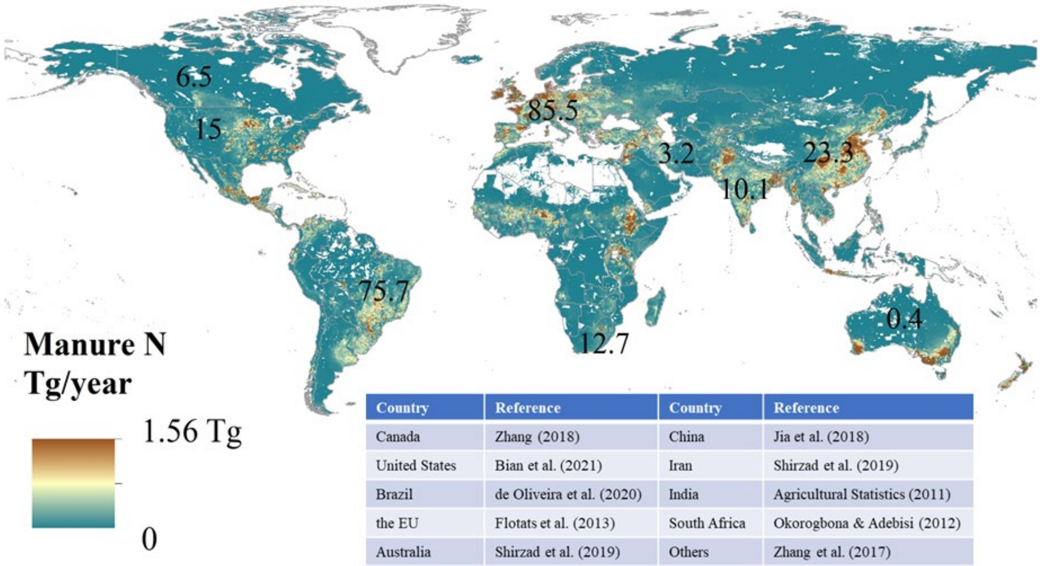


Fig. B.4 Global manure application (Tg N year^{-1}) in cropland and rangeland. The numbers were the total potential of soil carbon sequestration (Tg C year^{-1}) in several countries or regions (see inserted table). Carbon (C) sequestration potential = manure production × application rate × C sequestration rate. Application rate was offered by Zhang et al. (2017) and C sequestration rate was in our study. Manure production was offered by references shown in inserted table. N is nitrogen.



Country	Reference	Country	Reference
Canada	Zhang (2018)	China	Jia et al. (2018)
United States	Bian et al. (2021)	Iran	Shirzad et al. (2019)
Brazil	de Oliveira et al. (2020)	India	Agricultural Statistics (2011)
the EU	Flotats et al. (2013)	South Africa	Okorogbona & Adebisi (2012)
Australia	Shirzad et al. (2019)	Others	Zhang et al. (2017)

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Data S1. A list of 424 papers included in this meta-analysis

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