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Responses of soil carbon sequestration to climate smart agriculture practices: A meta-analysis

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Abstract

Climate-smart agriculture (CSA) management practices (e.g., conservation tillage, cover crops, and biochar applications) have been widely adopted to enhance soil organic carbon (SOC) sequestration and to reduce greenhouse gas emissions while ensuring crop productivity. However, current measurements regarding the influences of CSA management practices on SOC sequestration diverge widely, making it difficult to derive conclusions about individual and combined CSA management effects and bringing large uncertainties in quantifying the potential of the agricultural sector to mitigate climate change. We conducted a meta-analysis of 3,049 paired measurements from 417 peer-reviewed articles to examine the effects of three common CSA management practices on SOC sequestration as well as the environmental controlling factors. We found that, on average, biochar applications represented the most effective approach for increasing SOC content (39%), followed by cover crops (6%) and conservation tillage (5%). Further analysis suggested that the effects of

CSA management practices were more pronounced in areas with relatively warmer climates or lower nitrogen fertilizer inputs. Our meta-analysis demonstrated that, through adopting CSA practices, cropland could be an improved carbon sink. We also highlight the importance of considering local environmental factors (e.g., climate and soil conditions and their combination with other management practices) in identifying appropriate CSA practices for mitigating greenhouse gas emissions while ensuring crop productivity.

1. Introduction

Soil organic carbon (SOC) is a primary indicator of soil health and plays a critical role in food production, greenhouse gas balance, and climate mitigation and adaptation (Lorenz & Lal, 2016). The dynamic of agricultural SOC is regulated by the balance between carbon inputs (e.g., crop residues and organic fertilizers) and outputs (e.g., decomposition and erosion) under long-term constant environment and management conditions. However, this balance has been dramatically altered by climate change, which is expected to enhance SOC decomposition and weaken the capacity of soil to sequester carbon (Wiesmeier *et al*., 2016). Generally, agricultural soils contain considerably less SOC than soils under natural vegetation due to land conversion and cultivation (Hassink, 1997; Poeplau & Don, 2015), with a potential to sequester carbon from the atmosphere through proper management practices (Lal, 2018). Therefore, it is crucial to seek practical approaches to enhance agricultural SOC sequestration without compromising the provision of ecosystem services such as food, fiber or other agricultural products.

Climate-smart agriculture (CSA) has been promoted as a systematic approach for developing agricultural strategies to ensure sustainable food security in the context of climate change (FAO, 2013). One of the major objectives of CSA is to reduce greenhouse gas emissions and enhance soil carbon sequestration and soil health (Campbell *et al*., 2014; Lipper *et al*., 2014). The key for sequestering more carbon in soils lies in increasing carbon inputs and reducing carbon outputs. Frequently recommended approaches for SOC sequestration include adding cover crops into the crop rotation, applying biochar to soils, and minimizing soil tillage (i.e., conservation tillage). In recent decades, these management practices have been applied in major agricultural regions globally, and a large number of observations/measurements have been accumulated (e.g., Chen *et al.*, 2009; Spokas *et al.*, 2009; Clark *et al.*, 2017).

Several mechanisms have been proposed to explain the positive effects of CSA management practices on SOC sequestration. For example, conservation tillage reduces soil disturbance and the soil organic matter decomposition rate (Salinas-Garcia *et al.*, 1997) and promotes fungal and earthworm biomass (Lavelle, 1999; Briones & Schmidt, 2017), thereby improving SOC stabilization (Liang & Balser, 2012). Cover crops provide additional biomass inputs from above- and belowground (Blanco-Canqui *et al.*, 2011), increase carbon and nitrogen inputs, and enhance the biodiversity of agroecosystems (Lal, 2004). Moreover, cover crops can promote soil aggregation and structure (Sainju *et al*., 2003), therefore indirectly reduce carbon loss from soil erosion (De Baets *et al*., 2011). Biochar amendments affect SOC dynamics through two pathways: (1) improving soil aggregation and physical protection of aggregate-associated SOC against microbial attack; (2) increasing the pool of recalcitrant organic substrates resulting in a low SOC decomposition rate and substantial negative priming (Zhang *et al.*, 2012; Du *et al.*, 2017a, Weng *et al.*, 2017).

Although these CSA management practices have been widely used to enhance soil health (e.g., Thomsen & Christensen, 2004; Denef *et al.*, 2007; Fungo *et al.*, 2017; Weng *et al.*, 2017), their effects on SOC sequestration are variable and highly dependent on experiment designs and site-specific conditions such as climate and soil properties (Poeplau & Don, 2015; Abdalla *et al*., 2016; Liu *et al*., 2016; Paustian *et al.*, 2016). The potential to sequester soil carbon varies greatly among CSA practices, which has not been well addressed. Some studies even suggested negative effects of CSA management practices on SOC (e.g., Tian *et al.*, 2005; Liang *et al.*, 2007). Also, most prior quantitative research focused on the effects of a single CSA practice on SOC (e.g., Poeplau & Don, 2015; Abdalla *et al*., 2016; Liu *et al*., 2016), very few studies estimated the combined effects of diverse CSA and conventional management practices. Some recent studies reported that a combination of cover crops and conservation tillage could significantly increase SOC compared to a single management practice (Blanco-Canqui *et al.*, 2013; Ashworth *et al.*, 2014; Higashi *et al.*, 2014; Duval *et al.*, 2016). For example, Sainju *et al.* (2006) suggested that soil carbon sequestration may increase 0.267 Mg C ha^{-1} yr^{-1} under a combination of no-till and cover crop practices, where the latter was a mixed culture of hairy vetch (*Vicia villosa*) and rye (*Secale cereale*); in contrast, a carbon loss of 0.967 Mg C ha^{-1} yr^{-1} occurred when only no-till was used. Agegnehu *et al.* (2016) reported that 1.58% and 0.25% more SOC were sequestered in the mid-season and end-season, respectively, under conservation tillage when biochar was also applied. These findings highlight the importance of quantitatively evaluating the combined effects of multiple CSA management practices (including the combination of CSA and conventional management practices) on SOC sequestration under different climate and soil conditions.

This study aims to fill the above-mentioned knowledge gap through a meta-analysis to simultaneously examine the effects of three widely used CSA management practices (i.e., conservation tillage [no-till, NT; and reduced tillage, RT], cover crops, and biochar) on SOC sequestration (Fig. 1). Our scientific objectives were to: (1) evaluate and compare the effects of conservation tillage, cover crops, and biochar use on SOC; (2) examine how environmental factors (e.g., soil properties and climate) and other agronomic practices (e.g., nitrogen fertilization, residue management, irrigation, and crop rotation) influence SOC in these CSA management environments.

2. Materials and methodology

2.1. Data collection

We extracted data from 417 peer-reviewed articles (297 for conservation tillage, 64 for cover crops, and 56 for biochar) published from 1990 to May 2017 (Data S1). Among all publications, 113 for conservation tillage, 32 for cover crops, and 7 for biochar were conducted in the U.S. All articles were identified from the Web of Science. The search keywords were “soil organic carbon” and “tillage” for conservation tillage treatments; “soil organic carbon” and “cover crop” for cover crop treatments; and “soil organic carbon” and “biochar” for biochar treatments. All selected studies meet the following inclusion criteria: (1) SOC was measured in field experiments (to estimate the potential of biochar to increase soil carbon, we also included soil incubation and pot experiments with regard to biochar use); (2) observations were conducted on croplands excluding orchards and pastures; (3) ancillary information was provided, such as experiment duration, replication, and sampling depth; and (4) other agronomic management practices were included besides the three target management practices in this study. We considered conventional tillage as the control for NT and RT. Experiments that eliminated any tillage operation were grouped into the NT category, and experiments using tillage with lower frequency or shallower till-depth or less soil disturbance in comparison to the paired conventional tillage (e.g., moldboard plow and chisel plow) were grouped into the RT category. Likewise, "no cover crop" and "no biochar" were treated as control experiments relative to cover crop and biochar treatments, respectively. We only considered studies that viewed cover crops as treatments and fallow (or weeds) as controls.

Soil organic carbon data were either derived from tables or extracted from figures using the GetData Graph Digitizer software v2.26 (http://getdata-graph-digitizer.com/download.php). Other related information from the selected studies was also recorded, including location (i.e., longitude and latitude), experiment duration, climate (mean annual air temperature and precipitation), soil properties (texture, depth, and pH), and other agronomic practices (crop residues, nitrogen fertilization, irrigation, and crop rotation). The study durations were grouped into three categories: short (≤5 years), medium (6-20 years), and long term (>20 years). Climate was grouped according to the aridity index published by UNEP (1997) as either arid (≤ 0.65) or humid (> 0.65). Study sites were grouped into cool (temperate and Mediterranean climates) and warm zones (semitropical and tropical climates) (Shi *et al.*, 2010). Soil texture was grouped as silt loam, sandy loam, clay and clay loam, loam, silty clay and silty clay loam, and loamy sand according to the USDA soil texture triangle. Soil depth was grouped as 0-10 cm, 10-20 cm, 20-50 cm, and 50-100 cm. Soil pH was grouped as acidic (< 6.6), neutral (6.6-7.3), and alkaline (> 7.3). Crop residue management was grouped as "residue returned" and "residue removed." We only included those studies that used the same residue management in the control and treatment groups. Similarly, nitrogen fertilization was grouped into no addition, low (1-100 kg N ha^{-1}), medium (101-200), and high levels (> 200). Irrigation management was grouped as irrigated or rainfed. Crop sequence was grouped as rotational or continuous crops (including crop-fallow systems). We also estimated the response of SOC in the whole-soil profiles (from the soil surface to 120 cm, with an interval of 10 cm) to CSA management practices.

The standard deviation (SD) of selected variables, an important input variable to the meta-analysis, was computed as SD = SE×$\sqrt{n}$, where SE is the standard error and n is the number of observational replications. If the results of a study were reported without SD or SE, SD was calculated based on the average coefficient of variation for the known data. Publication bias was analyzed by the method of fail-safe number, which suggests that the meta-analysis can be considered robust if the fail-safe number is larger than 5*k+10 (where k is the number of observed studies) (Rothstein *et al.*, 2006).

2.2. Meta-analysis

A random-effect model of meta-analysis was used to explore environmental and management variables that might explain the response of SOC to CSA management practices. The data analysis was performed in R (R Development Core Team 2009). The response ratio (RR) was defined as the ratio between the outcome of CSA management practices and that of the control group. The logarithm of RR ($\ln RR$) was calculated as the effect size of each observation (Hedges *et al.*, 1999, Equation (1)):

$$\ln RR = \ln(\overline{X_t}/\overline{X_c}) = \ln \overline{X_t} - \ln \overline{X_c} \quad (1)$$

where $\overline{X_t}$ and $\overline{X_c}$ are SOC values in the treatment and control groups, respectively. The variance (ν) of $\ln RR$ was computed as:

$$\nu = \frac{S_t^2}{n_t \overline{X_t^2}} + \frac{S_c^2}{n_c \overline{X_c^2}} \quad (2)$$

where S_t and S_c are the standard deviations of the treatment and control groups, respectively, while n_t and n_c are the sample sizes of the treatment and control, respectively.

The weighting factor (w), as the inverse of the variance, was computed for each observation to obtain a final weighting factor (w'), which was then used to calculate the mean effect size (RR_{++}). The equations were:

$$w = 1 / v \tag{3}$$

$$w' = w / n \tag{4}$$

$$RR_{++} = \frac{\sum_i \ln RR'_i}{\sum_i w'_i} \tag{5}$$

where $\ln RR' = w' \ln RR$ is the weighted effect size, n is the total number of observations per study, and i is the ith observation.

The 95% confidence intervals (CI) of $\ln RR_{++}$ were computed to determine statistical significance. The comparison between treatment and control was considered significant if the 95% CIs did not overlap zero (vertical lines in the graphs). The percent change was transformed [($e^{RR_{++}}$-1) ×100%] to explain the response of the estimated CSA management practices.

3. Results

3.1 SOC responses to conservation tillage, cover crops, and biochar

Biochar applications enhanced SOC storage by 39% (28% in the field and 57% in incubation and pot experiments, Fig. S1), representing the most effective practice, followed by cover crops (6%) and conservation tillage (5%) (Fig. 2). Cover crop species had a pronounced positive effect on SOC sequestration (Fig. S1), ranging from 4% for non-leguminous cover crops to 9% for leguminous cover crops. When investigating different types of conservation tillage, NT and RT had similar effects on SOC (approximately 8% increase). All results were statistically significant (Fig. 2). Theoretically, the combination of CSA management practices may result in greater or lesser effects on soil sequestration compared to single CSA management practice. However, if synergistic effects were the prevalent interactions, this combination might potentially enhance carbon accumulation (e.g., over 50% increase in SOC), which is subject to further investigation in field experiments. Across the whole dataset we compiled, the SOC varied widely in each CSA treatment (Fig. S2). We calculated the distribution of the data points (the ratio of SOC of each treatment to that of the corresponding control, i.e., NT/RT vs. conventional tillage, cover crops vs. no cover crop, and biochar use vs. non-biochar; Fig. S2). Most of the studies used in this meta-analysis reported positive responses of SOC to NT, RT, cover crops, and biochar treatment (60%, 65%, 68%, and 91%, respectively). The SOC change rates were 0.38±0.71 Mg ha^{-1} yr^{-1} (n=56) and -0.29±0.79 Mg ha^{-1} yr^{-1} (n=30) in NT and RT systems, respectively (Fig. S3). We did not calculate SOC sequestration rates for other treatments (i.e., cover crops and biochar) due to the lack of some ancillary information (e.g., bulk density).

3.2 Effects of CSA management practices in different climate zones

Overall, CSA management practices sequestered more SOC in arid areas than in humid areas (Fig. 3a). Biochar and cover crops increased 12% (38% vs. 26%) and 3% (9% vs. 6%) more SOC in arid areas, respectively, compared to humid areas. In comparison, the NT-induced SOC uptake was slightly higher in arid areas than that in humid areas (9% and 8%, respectively). However, the RT-induced SOC increment in arid areas was two times greater than that in humid areas. Our further analysis suggested that CSA management practices significantly increased SOC in both cool and warm climate zones with diverse responses (Fig. 3b). For example, in warm areas, biochar applications only increased SOC by half of the enhancement observed in cool areas. Cover crops increased SOC by 15% in warm areas, three times larger than that in cool areas. In warm areas, NT increased SOC by 15% compared to 8% in cool areas. Reduced tillage increased SOC by 7% and 6% in warm and cool areas, respectively.

3.3 Effects of CSA management practices with different soil properties

The effects of CSA management practices on SOC were strongly influenced by soil texture (Fig. 4). Biochar applications increased SOC by 63, 62%, and 52% in silty clay and silty clay loam soils, loam soils, and loamy sand soils, respectively. While relatively lower soil carbon uptakes under biochar applications were found in clay loam and clay soils (32%), silt loam soils (35%), and sandy loam soils (34%). Cover crops increased SOC by 4%, 6%, 7%, and 6% in clay loam and clay soils, silt loam soils, loam soils, and sandy loam soils, respectively. No-till increased SOC by 16% in silty clay and silty clay loam soils, compared to 12% in sandy loam soils and 7% in loamy sand soils. Reduced tillage increased SOC by 21%, 7%, and 15% in silty clay and silty clay loam soils, loam soils, and loamy sand soils, respectively. Overall, cover crops sequestered more carbon in coarse-textured soils than in fine-textured soils. In contrast, NT and RT increased SOC more in fine-textured soils than in coarse-textured soils. No obvious relationship was found between biochar use and soil textures.

The positive effects of CSA management practices on SOC decreased with soil depth (Fig. 5). Biochar significantly increased SOC by 41% and 14% in the 0-10 cm and 0-30 cm soil layers, respectively (Table S1). Cover crops significantly increased SOC by 9%, 3%, and 9% in the 0-10 cm, 10-20 cm, and 20-50 cm depth ranges, respectively. Further analysis showed that cover crops could increase SOC (5%) in the entire 0-70 cm soil profile (Table S1). Both NT and RT could significantly increase SOC most at 0-10 cm depth (22% and 17%, respectively). Although reduced SOC was observed in the 10-20 cm and 20-50 cm soil layers (-4% and -10%, respectively), NT could still enhance SOC sequestration in the entire soil profile up to 120 cm (Table S1). In comparison, RT could increase SOC in the 0-70 cm soil profile (Table S1) although decreased soil carbon (not statistically significant) was observed in the 10-50 cm soil layer (Fig. 5).

All CSA management practices except RT positively influenced the SOC pool regardless of soil pH. The management-induced SOC uptake was generally higher in alkaline soils than in acid soils (Fig. 6). Biochar use increased SOC by 65%, 35%, and 28% in alkaline, neutral, and acid soils, respectively. Cover crops increased SOC by 15% in neutral soils, followed by alkaline (9%) and acid soils (6%). No-till increased SOC by 6% in acid soils and 13% in alkaline soils. The SOC increased by RT was greater in alkaline soils (9%) than acid soils (6%), but RT had no significant influence on SOC in neutral soils.

3.4 Combined effects of experiment duration and other agronomic practices

The CSA management practices are generally applied together with other agronomic practices such as residue return, nitrogen fertilizer use, and irrigation. These agronomic practices may interact with the CSA management practices with positive or negative effects on the capacity of soils to sequester carbon. In this study, we considered experiment duration and four other agronomic practices, including residue return, nitrogen fertilization, irrigation, and crop sequence, to quantify these effects.

Our results demonstrated that the influences of three CSA management practices on SOC varied with experiment duration. Biochar amendments significantly increased SOC by 45% and 36% in short-term and medium-term experiments, respectively. Cover crops significantly increased SOC by 5%, 11%, and 20% in the short-term, medium-term, and long-term experiments, respectively (Fig. 7). No-till significantly increased SOC by 13% in the long-term experiments, followed by medium-term (7%) and short-term (6%). Reduced tillage increased SOC by 12% in long-term studies, followed by medium-term (9%) and short-term experiments (3%). The average durations differed in each group (Table S2), which may influence the effect of CSA management practices on SOC. When excluding short and medium experiment durations (≤ 20 years) and shallow sampling (< 20 cm), RT significantly increased SOC by 14%, while NT had no significant effect on SOC (Fig. S4).

When crop residues were returned, conservation tillage and cover crops significantly increased SOC: 9% for NT, 6% for cover crops, and 5% for RT (Fig. 8). However, if crop residues were removed, neither cover crops nor RT had a significant effect on SOC, although there was a significant increase in SOC under NT (5%).

Our results suggested that nitrogen fertilizer use could alter the magnitude of soil carbon uptake induced by CSA management practices. Biochar boosted the most SOC among CSA management practices regardless of nitrogen fertilizer levels, with the strongest effects under the low-level nitrogen inputs, followed by the high-level (38%), medium-level (29%), and no nitrogen fertilizer use (27%) (Fig. 9). Cover crops increased SOC by 6% under both low-level and medium-level nitrogen inputs, slightly higher than that under the high-level nitrogen fertilizer use (3%). No-till tended to sequester more soil carbon when nitrogen fertilizer input was relatively lower (11%, 8%, and 6% for low-level, medium-level, and high-level nitrogen fertilization, respectively). While RT increased SOC by 13% at the medium-level nitrogen fertilizer rate, approximately two times larger than those under the low-level and high-level nitrogen fertilizer use (Fig. 9).

When investigating the irrigation effects, our results suggested that biochar markedly stimulated SOC increases in irrigated croplands (49%), three times higher than those under rainfed condition. Similarly, NT increased SOC by 15% in irrigated croplands, twice as much soil carbon as that in rainfed croplands. Cover crops increased SOC by 7% and 4% in irrigated and rainfed croplands, respectively. In contrast, the RT-induced SOC increase was 16% under the rainfed condition, 5% higher than that in irrigated croplands (Fig. 10a).

The CSA management practices significantly promoted SOC uptakes in both rotational and continuous cropping systems (Fig. 10b). Specifically, biochar amendments enhanced SOC by 52% in rotational cropping systems, much higher than that in the continuous cropping system (31%). While SOC uptakes induced by NT and RT showed no obvious differences in the rotational and continuous cropping systems (9% and 8% vs. 8% and 7%). Cover crops increased SOC by 4% in rotational cropping systems, lower than that in continuous cropping systems (8%).

3.5 Combinations of CSA management practices

Our results demonstrated that combining different CSA management practices might significantly enhance SOC sequestration. In warm regions, SOC increased by 13% with the combination of conservation tillage and cover crops (Fig. 11). In loamy sand and sandy clay loam soils, associated SOC uptakes increased to 31% and 21%, respectively. A similar effect was also observed in medium-term experiments. However, in clay soils, the combination of cover crops and conservation tillage significantly decreased SOC by 19%.

4. Discussion

4.1 Effects of CSA management practices on SOC

Common approaches for enhancing SOC focus on increasing carbon inputs, decreasing losses, or simultaneously affecting both inputs and losses. All CSA management practices discussed here, i.e., biochar, cover crops, and conservation tillage, increase soil carbon sequestration to different extents. For example, SOC enhancement by biochar applications can reach up to 40% (Liu *et al.*, 2016), while conservation tillage and cover crops increase SOC by only 3-10% (Luo *et al.*, 2010; Abdalla *et al.*, 2016; Du *et al.*, 2017b; Zhao *et al.*, 2017) and ~10% (Aguilera *et al.*, 2013), respectively. Our results agree with these earlier findings: biochar use increased SOC by 39%, followed by cover crops (6%) and conservation tillage (5%). The discrepancies among various CSA management practices in enhancing SOC fundamentally lie in their functional mechanisms. Biochar addition, with a low turnover rate, contributes directly to soil carbon storage and indirectly decreases native SOC decomposition rates by negative priming (Wang *et al.*, 2016). Cover crops are green manure that increases carbon inputs to the soil and subsequent SOC (Poeplau & Don, 2015). Conservation tillage practices may not necessarily add carbon; their contribution is primarily accomplished by protecting SOC from decomposition and erosion (Six *et al.*, 2000; Lal, 2005). Additionally, all three CSA management practices can potentially improve soil properties, thereby stimulating more carbon inputs from residue return and rhizodeposition due to promoted plant growth, and reducing carbon losses via decreasing leaching and erosion. However, the effectiveness of these practices on SOC sequestration and the mechanisms involved vary with environmental factors and other agronomic practices.

4.2 Environmental control in CSA management practices

Environmental factors such as climate and soil properties may influence carbon inputs to the soil and affect the processes that regulate carbon loss, considering that all CSA practices are implemented in site-specific climate and soil conditions. The effects of CSA management practices on SOC could be biased by environmental factors.

4.2.1 Climate variability

Climate is one of the major driving forces that regulate SOC distribution. On average, SOC accumulation is greater than decomposition in wet areas than in dry and warm regions (Jobbágy & Jackson, 2000). Soil carbon is positively related to precipitation and negatively correlated with temperature (Rusco *et al.*, 2001), with the former correlation tending to be stronger (Martin *et al.*, 2011; Meersmans *et al.*, 2011). High precipitation is usually associated with abundant growth and high rates of carbon inputs to soils (Luo *et al.*, 2017), while low temperatures may remarkably reduce microbial activity, resulting in low rates of organic matter decomposition and measurable amounts of SOC accumulation (Castro *et al.*, 1995; Garcia *et al.*, 2018). Biochar applications result in greater SOC accumulation in arid/cool areas than in humid/warm environments (Fig. 3), probably due to the porous structure and the capacity of biochar to promote greater soil water retention (Karhu *et al.*, 2011; Abel *et al.*, 2013). It is not clear why biochar has a greater impact on SOC accrual in cool regions. A possible explanation is that high soil temperatures may promote biochar decomposition and oxidation (Cheng *et al.*, 2008).

Cover crops and NT increased SOC with no significant difference between aridity conditions (Table 1), although they performed better at storing SOC in arid areas (Fig. 3a). This result suggests that arid-region soils have a high potential to store carbon when using proper management practices (Tondoh *et al.*, 2016). In addition, cover crops and NT can enhance carbon sequestration more in warm areas than in cool areas. Temperature could affect the establishment and growth of cover crops (Akemo *et al.*, 2000). In warm areas, cover crops may develop well and potentially capture more carbon dioxide (CO_2) from the atmosphere, thus providing more carbon inputs into soils after they die (e.g., Bayer *et al.*, 2009).

Tillage results in the breakdown of macroaggregates and the release of aggregate-protected SOC (Six *et al.*, 2000; Mikha & Rice, 2004). Tillage-induced SOC decomposition usually proceeds at higher rates in warm than in cool areas. Implementing NT, with minimal soil disturbance, protects SOC from decomposition. As a result, SOC increases can be more significant in warm conditions considering the relatively higher baseline of the decomposition rate compared to that in cool areas.

4.2.2 Soil properties

Soil organic carbon is strongly correlated with clay content, with an increasing trend toward more SOC in fine-textured soils (Stronkhorst & Venter, 2008; Meersmans *et al.*, 2012). The SOC mineralization rate probably diminishes as clay concentrations increase (Sainju *et al.*, 2002). Clay minerals can stabilize SOC against microbial attack through absorption of organic molecules (Ladd *et al.*, 1996). By binding organic matter, clay particles help form and stabilize soil aggregates, imposing a physical barrier between decomposer microflora and organic substrates and limiting water and oxygen available for decomposition (Dominy *et al.*, 2002).

Biochar use and cover crops promote carbon sequestration for all soil texture types. Such an enhancement of SOC does not vary significantly with soil texture (Table 1). The ability of conservation tillage to enhance SOC, however, differs with soil texture (Fig. 4). Conservation tillage merely reduces soil disturbance and normally does not add extra materials to soils. It can be inferred that the effect of conservation tillage on SOC is more texture-dependent than the other two management practices. Biochar is a carbon-rich material with a charged surface, organic functional groups, and a porous structure, which can potentially increase soil aggregation and cation exchange capacity (Jien & Wang, 2013). Similarly, cover crops directly provide carbon inputs to soils, and their root development and rhizodeposition can also benefit soil structure. These benefits are embedded in the source of biochar and cover crops *per se*. Thus, the effectiveness of biochar and cover crops in increasing SOC may depend on their properties other than soil texture.

Soil depth may potentially influence the effects of the CSA practices on SOC (Baker *et al.*, 2007). The CSA practices were most beneficial to SOC accumulation in surface soils. For example, NT increased SOC by 7% in the 0-3 cm soil layer (Abdalla *et al.*, 2016) and by 3% at the 40 cm depth (Luo *et al.*, 2010). Our findings suggested that CSA practices can enhance SOC sequestration in the entire soil profile, although the positive effects vary with soil depths (Table S1). Conventional tillage breaks soil aggregates and increases aeration and thus enhances soil organic matter mineralization (Cambardella & Elliott, 1993). Conventional tillage also incorporates residues into deeper soil layers, resulting in a more uniform distribution of SOC (albeit at lower concentrations) in the soil profile (Sainju *et al.*, 2006; Plaza-Bonilla *et al.*, 2010). In contrast, conservation tillage keeps residues at the soil surface and reduces their degree of incorporation into soil (Franzluebbers *et al.*, 1995). Nevertheless, positive effects of NT on SOC have been found in a deep soil profile (0-60 cm, Liu *et al.*, 2014). As noted, in the 10-50 cm soil layer, the effect of cover crops on SOC was found to be the greatest among all the CSA management practices we discussed (Fig. 5). This is perhaps because much of the crop and cover crop root growth occurs in the surface soil (e.g., Box & Ramsuer, 1993; Sainju *et al.*, 1998) and the generally greater contribution of roots to SOC than aboveground biomass (Balesdent & Balabane, 1996; Allmaras *et al.*, 2004).

Soil pH is recognized as a dominant factor governing the soil organic matter turnover rate, although its mode of impact is still unclear (Van Bergen *et al.*, 1998). Soil pH affects selective presentation or metabolic modification of specific components (e.g., lignin-cellulose, lipids) during decomposition (Kemmitt *et al.*, 2006) and therefore abiotic factors (e.g., carbon and nutrient availability) and biotic factors (e.g., the composition of the microbial community). Also, soil pH can change the decomposition rate of crop residues and SOC via its effect on SOC solubility and indirectly by altering microbial growth, activity, and community structure (Pietri & Brookes, 2009; Wang *et al.*, 2017). The levels of soluble organic carbon may increase with increasing acidity (Willett *et al.*, 2004; Kemmitt *et al.*, 2006). Motavalli *et al.* (1995) suggested that increased soil acidity would cause greater soil organic matter accumulation due to reduced microbial mineralization; however, this was challenged by Kemmitt *et al.* (2006) who found no significant trend in SOC in response to pH changes. In this study, most CSA management practices resulted in greater increases in SOC in neutral or alkaline soils compared to acid soils.

4.3 CSA and other agronomic practices

Crop residues provide substantial amounts of organic matter and may influence the effect of CSA practices on SOC. Residue retention changes the formation of soil macroaggregates (Benbi & Senapati, 2010), promoting SOC preservation and accumulation (Six *et al.*, 2002). Residue cover protects the soil surface from direct impact by raindrops (Blanco-Canqui *et al.*, 2014). In addition, crop residues provide organic substrates to soil microorganisms that can produce binding agents and promote soil aggregation (Guggenberger *et al.*, 1999). Conversely, residue removal reduces carbon input to the soil system and ultimately decreases SOC storage (Manna *et al.*, 2005; Koga & Tsuji, 2009). This suggests that the amount of carbon inputs predominantly controls changes in SOC stocks (Virto *et al.*, 2012). For the conditions of cover crops and NT, enhancing SOC was significantly greater with residue return than with residue removal. Our study suggests that changes in SOC did not differ with residue management in RT (Table 1), although a slightly greater increase in SOC occurred with residue retention than with residue removal (Fig. 8). This unexpected result is likely due to the limited number of observations with residue removal. Another possible reason is that the interaction between residue management and soil type may lead to various responses in SOC stocks. For example, residue removal increased SOC by 3.6% while residue retention had no effect on SOC in clay and clay loam soils. The decomposition of crop residues involves complex processes, which are controlled by multiple biogeochemical and biophysical conditions.

Nitrogen fertilization noticeably increases SOC stock but with diminishing returns. For example, Blanco-Canqui *et al.* (2014) indicate that nitrogen fertilizer increases SOC when the nitrogen fertilization rate is below 80 kg N ha^{-1}, above which it reduces aggregation and then decreases SOC stocks. Nitrogen fertilization can stimulate biological activity by altering carbon/nitrogen ratios, thereby promoting soil respiration and decreasing SOC content (Mulvaney *et al.*, 2009); however, excessive nitrogen addition may reduce soil fungi populations, inhibit soil enzyme activity, and decrease CO_2 emissions (Wilson & Al Kazi, 2008). These findings suggest that nitrogen fertilization enhances the positive effect of CSA management practices on SOC, likely through increased plant biomass production (Gregorich *et al.*, 1996). However, nitrogen addition complicates the effects of biochar on SOC (Fig. 9).

Nitrogen fertilizer may affect biochar stability and the response of native SOC decomposition to biochar addition (Jiang *et al.*, 2016). Positive (Bebber *et al.*, 2011; Jiang *et al.*, 2014) and negative (Pregitzer *et al.*, 2008) effects of nitrogen on SOC mineralization rates have been reported. These contrasting effects could be an alleviation of microbial nitrogen limitations (Jiang *et al.*, 2016) and changes in the microbial decomposer community toward more efficient carbon-users (Janssens *et al.*, 2010). A possible explanation of the various responses of nitrogen rate in biochar-modified soils is that either inadequate or excessive nitrogen addition may inhibit microbial activity to some extent, whereas medium-level nitrogen fertilization rates benefit microbes the most, which needs to be confirmed in future research.

Aridity can limit plant growth and crop residue return and ultimately compromise SOC accumulation (Moreno *et al.*, 2006). Jien and Wang (2013) suggest that CSA management practices can potentially enhance soil water retention by improving soil porosity and erosion control. Irrigation ensures sufficient water for plant growth, resulting in more biomass production than in rainfed conditions (Shipitalo *et al.*, 1990; Chan, 2004; Capowiez *et al.*, 2009; Swanepoel *et al.*, 2016). The crop root density is much higher in irrigated conditions compared to rainfed conditions (Jobbágy & Jackson, 2000), leading to higher organic matter input. Thus, CSA management practices in combination with irrigation could further increase SOC content.

Rotational cropping potentially provides high carbon input to soils. Compared to continuous cropping systems, crops in rotational cropping systems have a greater belowground allocation of biomass (Van Eerd *et al.*, 2014), resulting in more inputs of crop residue to the soil system. Enhancing rotation complexity can benefit carbon sequestration (West & Post, 2002). The present analysis suggests that all CSA practices can prominently increase SOC sequestration regardless of the crop rotation system. Biochar addition increased SOC more in rotational cropping systems than in continuous cropping systems, while cover crops increased SOC more in continuous systems (Fig. 10). This is likely because cover crops increased the diversity of the original continuous systems, resulting in larger percentage changes in SOC content compared to rotational systems. Cover crop species introduce large uncertainties because the quantity and quality of cover crop residues may vary greatly with species. Residues with a high carbon/nitrogen ratio probably increase the amount of SOC (Duong *et al.*, 2009). The growth period of legume cover crops may be longer in continuous than in rotational cropping systems, thus providing more organic matter and nitrogen input to the soil. Ultimately, these processes would increase SOC stocks.

The effect size of combined cover crops and conservation tillage was generally less than 11% (the sum of the effect size of cover crops and conservation tillage). However, in sandy clay loam and loamy sand soils, the sum of the effect size was 21% and 31%, respectively. Coarse-textured soils are not carbon-saturated and have great potential for carbon uptake. Cultivated land tends to suffer from SOC degradation, and SOC accumulation could quickly increase upon initiating farming practices due to high carbon inputs to the soil system (Vieira *et al.*, 2009). For example, in sandy loam soils, Higashi *et al.* (2014) showed that SOC increased by 22% with a combination of cover crops and NT. These results may be attributed to the stability of soil water-stable aggregates when cover crops are grown in sandy clay loam soils (McVay *et al.*, 1989), given that aggregate stability has been linked to protection of SOC from mineralization (Unger, 1997). The combination of cover crops and conservation tillage significantly decreased SOC in clay soils. The reason for this unexpected result may be due to the limited number of study sites where this combination of treatments was evaluated (few data points in our meta-analysis) but also to the diverse methods (e.g., burning) by which the cover crop biomass was managed (Tian *et al.*, 2005).

4.4 Uncertainty analysis and prospects

Our meta-analysis, based on 3,049-paired comparisons from 417 peer-reviewed articles, quantitatively analyzed SOC changes as influenced by major CSA management practices and associated environmental factors and other agronomic practices. The publication bias analysis suggested that most results in this study are robust (Table S3). The accuracy and robustness of metadata analysis depend highly on both the data quality and quantity. A detailed statement of the experimental conditions will provide more information for in-depth analysis. Future CSA research also requires standardized field management, for example, the definitions and names of different conservation tillage methods should be uniform across studies to facilitate classification research.

To the best of our knowledge, this study made the first attempt to examine synergistic effects when two or more CSA management practices are used together. Although our results present the positive effects of CSA management on soil carbon storage, especially when multiple management practices are adopted collectively, each practice may have constraints regarding enhancing soil carbon sequestration. The SOC benefit of CSA management practices strongly depends on environmental factors and other agronomic practices. Therefore, the choice of proper practices is potentially highly region-specific. Our results imply that CSA may have great potential for climate change mitigation as the combination of conservation tillage, cover crops, and biochar can theoretically enhance SOC by 50%. However, field experiments are still needed to support this claim. In addition, some CSA management practices may promote nitrous oxide or methane emissions (e.g., Six *et al.*, 2004; Spokas & Reicosky, 2009; Kessel *et al.*, 2013; Huang *et al.*, 2018), which, to some extent, would offset their benefit on climate change mitigation. Therefore, evaluating the CSA effects should also include non-CO_2 greenhouse gases such as nitrous oxide and methane. We call for field experiments that can fully examine key indicators (such as soil carbon and greenhouse gases) in response to single and combined CSA management practices.

Additionally, incorporating cover crops into current cropping systems could potentially alter conventional rotations. For example, cover crops in herbaceous crop rotations can substitute bare fallows or commercial crops. We only considered studies that treated cover crops as treatments and fallow (or weeds) as controls in this study. In comparison to bare fallows, cover crops can enhance soil health and quality (Jarecki & Lal, 2003). The benefits of cover crops include uptakes and stores of soil nutrients between seasons when they are susceptible to leaching (Doran & Smith, 1987). However, the substitution of commercial crops could reduce the productivity of the system, which has climatic implications related to the opportunity cost of the extra land required (e.g., Balmford *et al.*, 2018; Searchinger *et al.*, 2018). Thus, future studies should further address these potential side effects caused by land use change.

Materials producing biochar may have other uses or fates, and the biochar-making processes may produce CO_2 (e.g., Llorach-Massana *et al.*, 2017), although biochar addition is an effective way to sequester SOC. These uncertainties, to some extent, can offset the benefits of biochar for climate change mitigation through SOC sequestration (Powlson *et al.*, 2008). The carbon footprint of biochar production depends on production technology and the types of feedstocks (Meyer *et al.*, 2017). Mukherjee and Lal (2014) found that "carbon dioxide emissions from biochar-amended soils have been enhanced up to 61% compared with unamended soils." However, with a low carbon footprint, each ton of biochar could sequester 21 to 155 kg of equivalent CO_2 (Llorach-Massana *et al.*, 2017). Matovic (2011) also suggested that 4.8 Gt C yr^{-1} would be sequestered if 10% of the world's net primary production were converted into biochar, “at 50% yield and 30% energy from volatiles.” To fully understand the net impacts of biochar on climate mitigation, future studies should stress the carbon footprint in the lifecycle of biochar.

It is essential to realistically examine the effects of CSA management practices on SOC and greenhouse gases at multiple scales from plot and field levels to regional and global scales. Therefore, future CSA research is expected to include varied climate and geographic conditions, address more biogeochemical and hydrological processes, and apply diverse methods such as the data-model fusion approach. For example, modeling studies have attempted to investigate regional cropland SOC dynamics as influenced by multiple global environmental changes while considering more traditional and less CSA practices (e.g., Molina *et al.*, 2017; Nash *et al.*, 2018; Ren *et al.*, 2012, 2018). In the future, ecosystem models need to be improved to incorporate multiple common CSA management practices. Additional model evaluations are needed to quantify the potential of cropland carbon sequestration by adopting multiple CSA practices at broad scales as new data become available from suggested field experiments and observations.

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Table 1. Between-group variability (Q_M) of the variables controlling the effects of climate-smart agriculture management practices on soil organic carbon.

Variables	No-till		Reduced tillage		Cover crop		Biochar	
	df	Q_M	df	Q_M	df	Q_M	df	Q_M
Duration	2	12.14**	2	13.69**	2	26.19***	1	0.04
Aridity index	1	0.13	1	10.99***	1	0.04	1	5.73*
Mean annual air temperature	1	16.32***	1	0.47	1	55.99***	1	6.48*
Soil texture	5	20.98***	5	32.15***	4	3.58	5	9.65
Soil depth	3	210.69***	3	73.38***	2	17.38***	-	-
Soil pH	2	9.8**	2	3.52	2	9.05*	2	28.64***
Residue	1	6.56*	1	0.04	1	4.07*	-	-
Nitrogen fertilization	3	7.62	3	11.43*	2	0.89	2	7.22*
Irrigation	1	9.61**	1	0.92	1	0.16	1	1.7
Crop rotation	1	1.72	1	0.26	1	19.43***	1	4.53*

Statistical significance of Q_M: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Figure captions

Figure 1. Relationship between climate-smart management practices and soil processes. "+" means a positive feedback or promotion effect; "-" means a negative feedback or inhibition function; and "?" means the effect is unclear. Blue, black, and red show the effect of cover crops, conservation tillage, and biochar on the soil environment, processes, and pools, respectively. SOC: soil organic carbon.

Figure 2. Comparison of climate-smart management vs. their controls for the entire dataset. The number in parentheses represents the number of observations. Error bars represent 95% confidence intervals. SOC: soil organic carbon; NT: no-till; RT: reduced tillage.

Figure 3. Comparison of climate-smart management vs. their controls for subcategories of climate zone (a: the climate zones were divided by aridity index; b: the climate zones were divided by mean annual air temperature). The number in parentheses represents the number of observations. Error bars represent 95% confidence intervals. SOC: soil organic carbon; NT: no-till; RT: reduced tillage.

Figure 4. Comparison of climate-smart management vs. their controls for subcategories of soil textures. The number in parentheses represents the number of observations. Error bars represent 95% confidence intervals. SOC: soil organic carbon; NT: no-till; RT: reduced tillage.

Figure 5. Comparison of climate-smart management vs. their controls for subcategories of soil depth. The number in parentheses represents the number of observations. Error bars represent 95% confidence intervals. SOC: soil organic carbon; NT: no-till; RT: reduced tillage. The average depths of each categorical group were presented in supplementary files (Table S4-S7).

Figure 6. Comparison of climate-smart management vs. their controls for subcategories of soil pH. The number in parentheses represents the number of observations. Error bars represent 95% confidence intervals. SOC: soil organic carbon; NT: no-till; RT: reduced tillage.

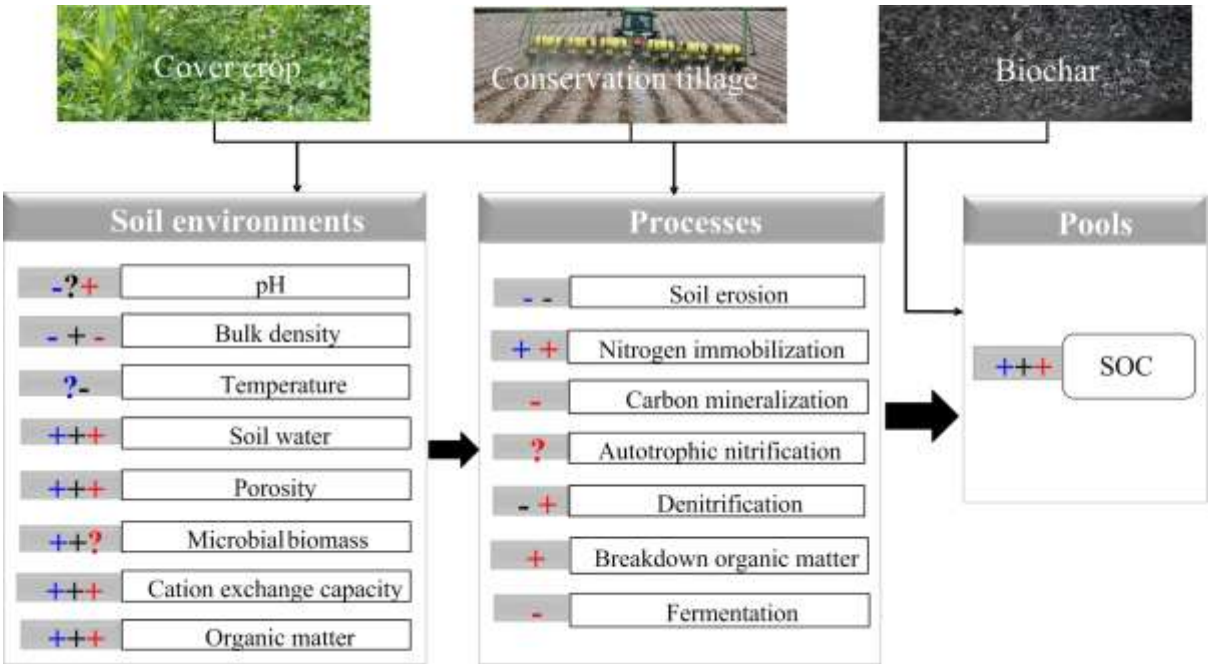
Figure 7. Comparison of climate-smart management vs. their controls for subcategories of experiment duration. The number in parentheses represents the number of observations. Error bars represent 95% confidence intervals. SOC: soil organic carbon; NT: no-till; RT: reduced tillage.

Figure 8. Comparison of climate-smart management vs. their controls for subcategories of crop residues. The number in parentheses represents the number of observations. Error bars represent 95% confidence intervals. SOC: soil organic carbon; NT: no-till; RT: reduced tillage.

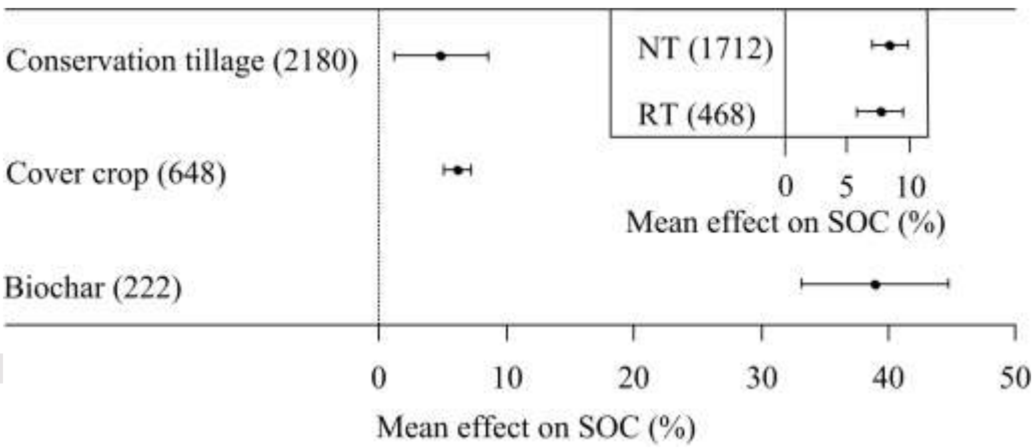
Figure 9. Comparison of climate-smart management vs. their controls for subcategories of nitrogen fertilizer use. The number in parentheses represents the number of observations. Error bars represent 95% confidence intervals. Low, medium, and high levels of nitrogen fertilizer use represent 1-100, 101-200, and >200 kg N ha^{-1}, respectively. SOC: soil organic carbon; NT: no-till; RT: reduced tillage.

Figure 10. Comparison of climate-smart management vs. their controls for subcategories of water management (a) and cropping systems (b). The number in parentheses represents the number of observations. Error bars represent 95% confidence intervals. SOC: soil organic carbon; NT: no-till; RT: reduced tillage.

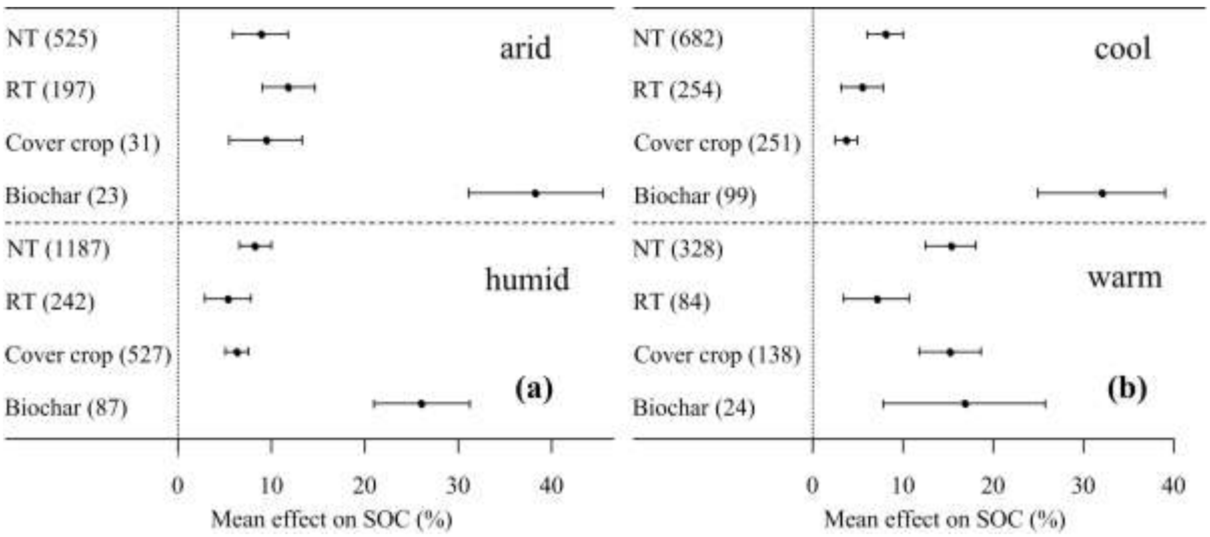
Figure 11. The effect size of combined conservation tillage and cover crops for different subcategories. The number in parentheses represents the number of observations. Error bars represent 95% confidence intervals. The vertical solid line represents 11%, which is the theoretical sum of the effect sizes of conservation tillage and cover crops. SOC: soil organic carbon.



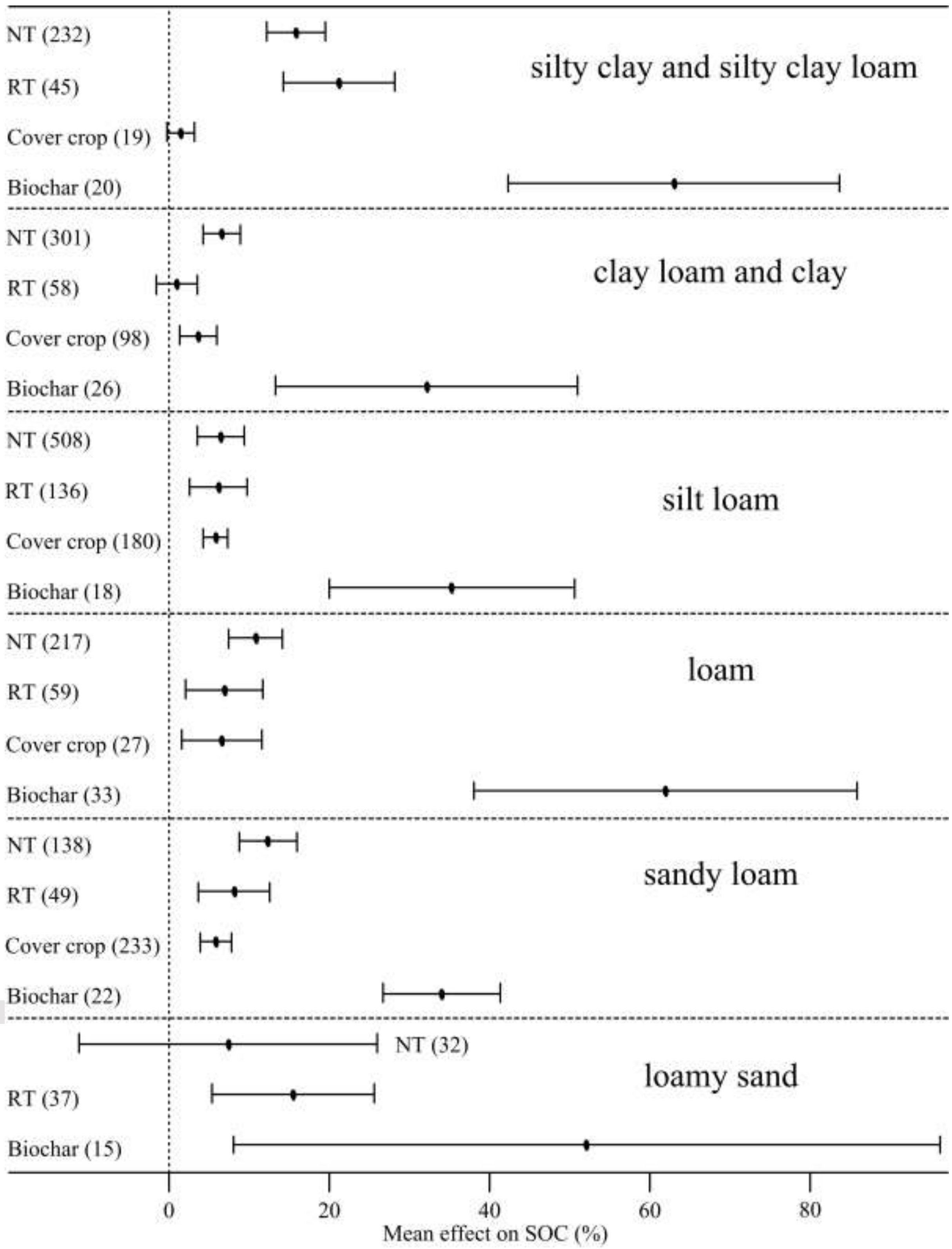
Cover crop
Conservation tillage
Biochar
Soil environments
-?+ pH
- + - Bulk density
?- Temperature
+++ Soil water
+++ Porosity
++? Microbial biomass
+++ Cation exchange capacity
+++ Organic matter
Processes
- - Soil erosion
+ + Nitrogen immobilization
- Carbon mineralization
? Autotrophic nitrification
- + Denitrification
+ Breakdown organic matter
- Fermentation
Pools
+++ SOC

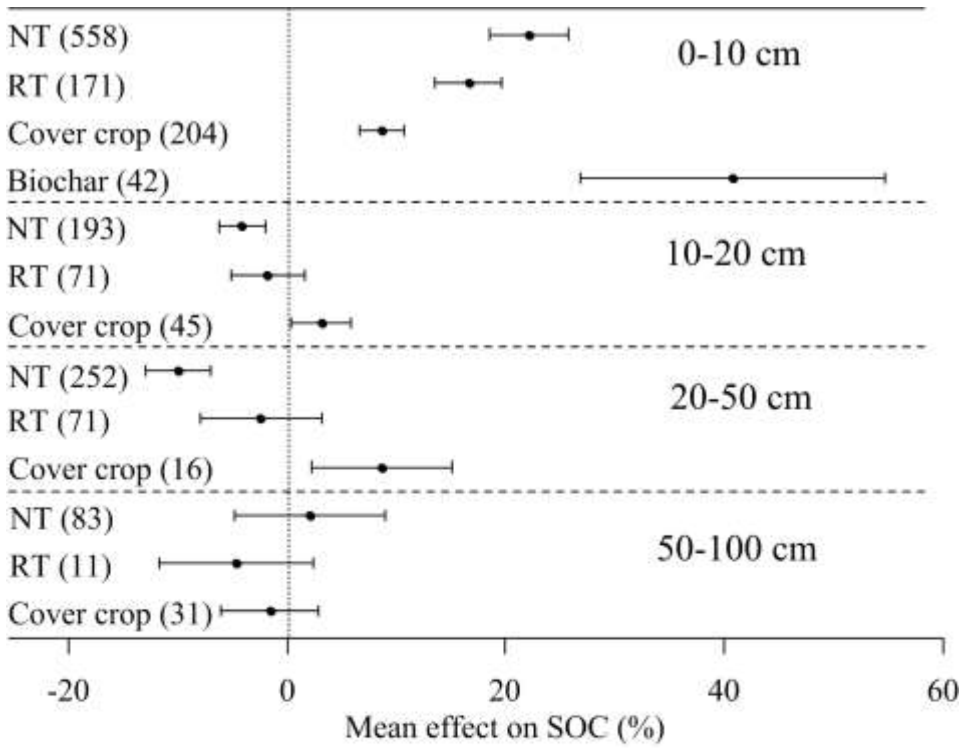


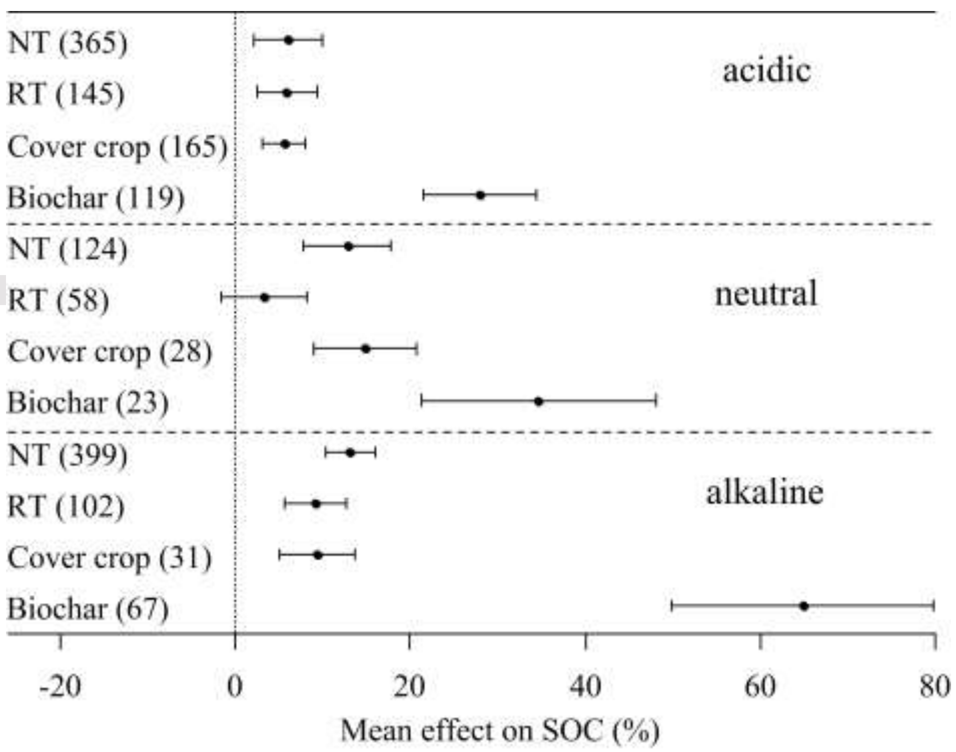
Conservation tillage (2180)
Cover crop (648)
Biochar (222)
NT (1712)
RT (468)
0 5 10
Mean effect on SOC (%)
0 10 20 30 40 50
Mean effect on SOC (%)

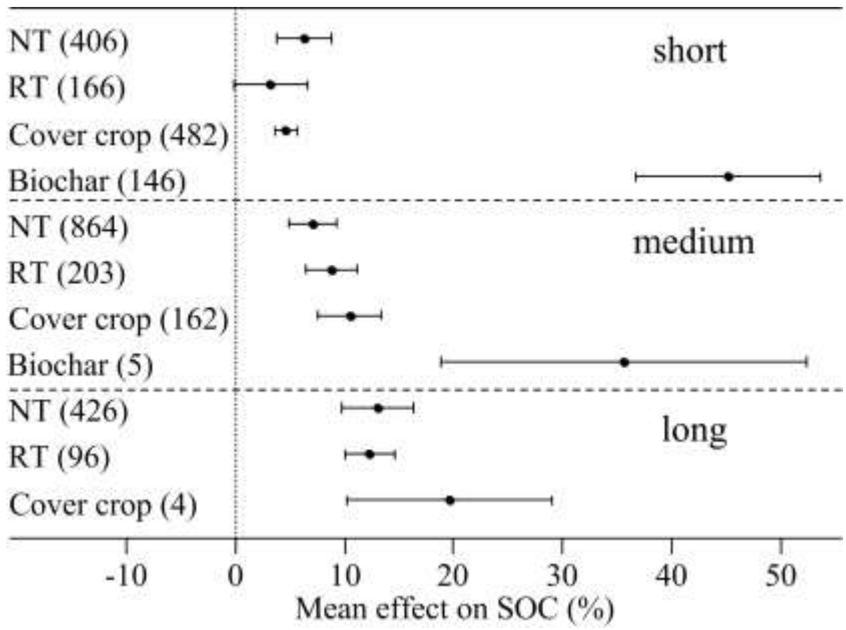


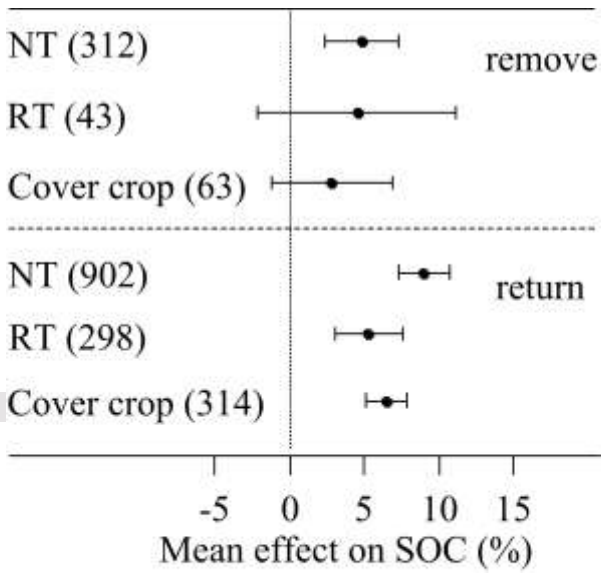
NT (525)
RT (197)
Cover crop (31)
Biochar (23)
arid
NT (1187)
RT (242)
Cover crop (527)
Biochar (87)
humid
(a)
0
10
20
30
40
Mean effect on SOC (%)
NT (682)
RT (254)
Cover crop (251)
Biochar (99)
cool
NT (328)
RT (84)
Cover crop (138)
Biochar (24)
warm
(b)
0
10
20
30
40
Mean effect on SOC (%)

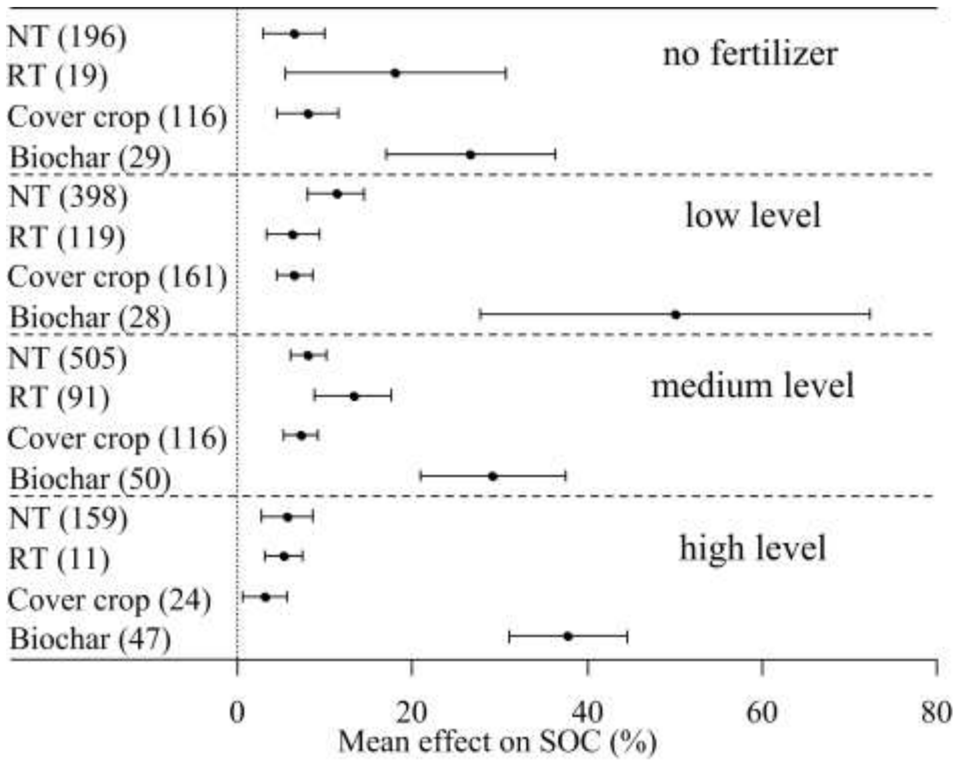

NT (232)
RT (45)
Cover crop (19)
Biochar (20)
silty clay and silty clay loam
NT (301)
RT (58)
Cover crop (98)
Biochar (26)
clay loam and clay
NT (508)
RT (136)
Cover crop (180)
Biochar (18)
silt loam
NT (217)
RT (59)
Cover crop (27)
Biochar (33)
loam
NT (138)
RT (49)
Cover crop (233)
Biochar (22)
sandy loam
NT (32)
RT (37)
Biochar (15)
loamy sand
0
20
40
60
80
Mean effect on SOC (%)

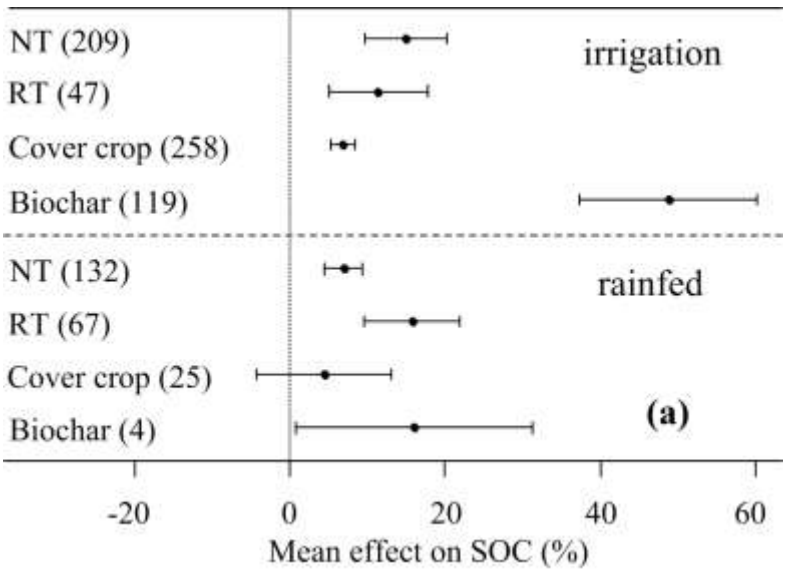

NT (558)
RT (171)
Cover crop (204)
Biochar (42)
0-10 cm
NT (193)
RT (71)
Cover crop (45)
10-20 cm
NT (252)
RT (71)
Cover crop (16)
20-50 cm
NT (83)
RT (11)
Cover crop (31)
50-100 cm
-20
0
20
40
60
Mean effect on SOC (%)

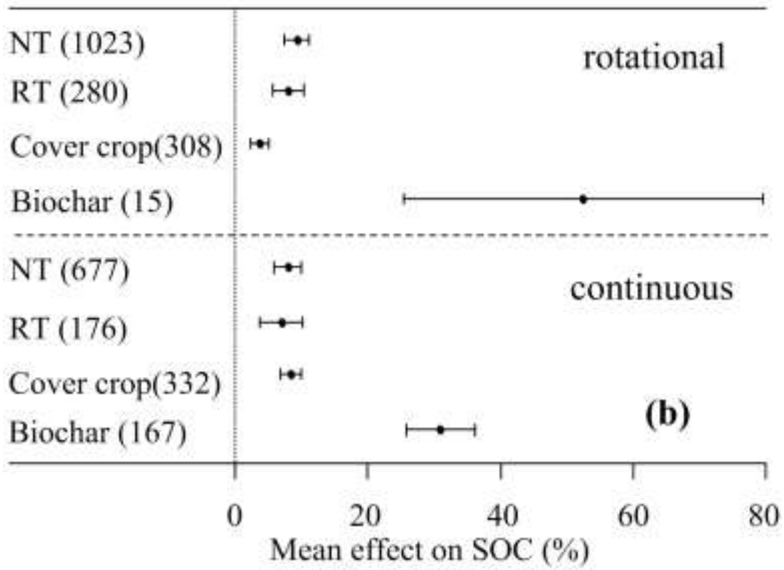

NT (365)
RT (145)
Cover crop (165)
Biochar (119)
acidic
NT (124)
RT (58)
Cover crop (28)
Biochar (23)
neutral
NT (399)
RT (102)
Cover crop (31)
Biochar (67)
alkaline
-20
0
20
40
60
80
Mean effect on SOC (%)

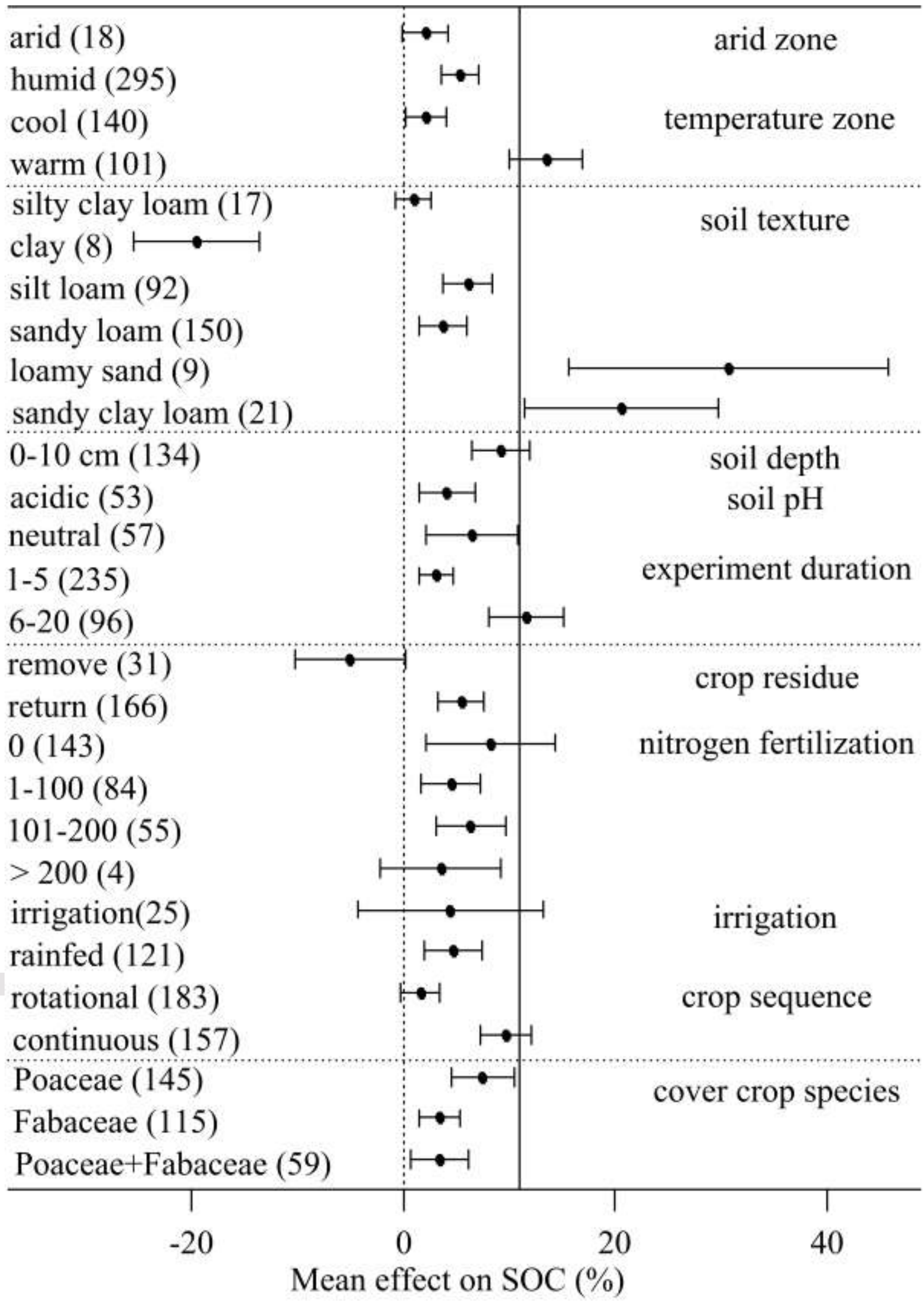

NT (406)
RT (166)
Cover crop (482)
Biochar (146)
short
NT (864)
RT (203)
Cover crop (162)
Biochar (5)
medium
NT (426)
RT (96)
Cover crop (4)
long
-10
0
10
20
30
40
50
Mean effect on SOC (%)


NT (312)
RT (43)
Cover crop (63)
remove
NT (902)
RT (298)
Cover crop (314)
return
-5
0
5
10
15
Mean effect on SOC (%)


NT (196)
RT (19)
Cover crop (116)
Biochar (29)
no fertilizer
NT (398)
RT (119)
Cover crop (161)
Biochar (28)
low level
NT (505)
RT (91)
Cover crop (116)
Biochar (50)
medium level
NT (159)
RT (11)
Cover crop (24)
Biochar (47)
high level
0
20
40
60
80
Mean effect on SOC (%)


NT (209)
RT (47)
Cover crop (258)
Biochar (119)
irrigation
NT (132)
RT (67)
Cover crop (25)
Biochar (4)
rainfed
(a)
-20
0
20
40
60
Mean effect on SOC (%)


NT (1023)
RT (280)
Cover crop(308)
Biochar (15)
rotational
NT (677)
RT (176)
Cover crop(332)
Biochar (167)
continuous
(b)
0
20
40
60
80
Mean effect on SOC (%)



arid (18)
humid (295)
cool (140)
warm (101)
silty clay loam (17)
clay (8)
silt loam (92)
sandy loam (150)
loamy sand (9)
sandy clay loam (21)
0-10 cm (134)
acidic (53)
neutral (57)
1-5 (235)
6-20 (96)
remove (31)
return (166)
0 (143)
1-100 (84)
101-200 (55)
> 200 (4)
irrigation(25)
rainfed (121)
rotational (183)
continuous (157)
Poaceae (145)
Fabaceae (115)
Poaceae+Fabaceae (59)
arid zone
temperature zone
soil texture
soil depth
soil pH
experiment duration
crop residue
nitrogen fertilization
irrigation
crop sequence
cover crop species
-20
0
20
40
Mean effect on SOC (%)