META-ANALYSIS

Soil organic carbon stock change following perennialization: a meta-analysis

Imran Ahammad Siddique[1,2] · Diego Grados[1,3] · Ji Chen[1,3] · Poul Erik Lærke[1,3,4] · Uffe Jørgensen[1,4]

Abstract

Perennial crops replacing annual crops are drawing global attention because they harbor potential for sustainable biomass production and climate change mitigation through soil carbon sequestration. At present, it remains unclear how long perennial crops can sequester carbon in the soil and how soil carbon stock dynamics are influenced by climate, soil, and plant properties across the globe. This study presents a meta-analysis synthesizing 51 publications (351 observations at 77 sites) distributed over different pedo-climatic conditions to scrutinize the effect of perennialization on organic carbon accumulation in soil compared with two annual benchmark systems (i.e., monoculture and crop rotation). Results showed that perennial crops significantly increased soil organic carbon stock by 16.6% and 23.1% at 0–30 cm depth compared with monoculture and crop rotation, respectively. Shortly after establishment (< 5 years), perennial crops revealed a negative impact on soil organic carbon stock; however, long duration (> 10 years) of perennialization had a significant positive effect on soil organic carbon stock by 30% and 36.4% at 0–30 cm depth compared with monoculture and crop rotation, respectively. Compared with both annual systems, perennial crops significantly increased soil organic carbon stock regardless of their functional photosynthetic types (C_3, C_4, or C_3-C_4 intermediates) and vegetation type (woody or herbaceous). Among other factors, pH had a significant impact on soil organic carbon; however, the effect of soil textures showed no significant impact, possibly due to a lack of observations from each textural class and mixed pedoclimatic effects. Results also showed that time effect of perennialization revealed a sigmoidal increase of soil organic carbon stock until about 20 years; thereafter, the soil carbon stocks advanced towards a steady-state level. In conclusion, perennial crops increased soil organic carbon stock compared with annual systems; however, the time since conversion from annual to perennial system decisively impacted soil organic carbon stock changes.

Keywords Perennial crop · Annual crop · Monoculture · Crop age · Carbon sequestration · Climate change

1 Introduction

Soil contains a heterogeneous dynamic pool of global terrestrial carbon (C) stocks and current estimates for global soil organic carbon (SOC) range from 1500 to 2400 PgC (Patton et al. 2019), which is two to three times the amount of C stored in the atmosphere (Paustian et al. 2016). This dynamic SOC pool varies with climatic conditions, soil physicochemical properties, soil management, land cover, and land use (Deng et al. 2014, 2016; Wiesmeier et al. 2019). For instance, land conversion from both natural and managed soils to arable agriculture has led to a decline in SOC levels (Don et al. 2011; Guo and Gifford 2002).

Although intensive agriculture has increased global food security during the past century (Godfray et al. 2010; Tilman et al. 2011), it modifies the natural ecosystems and disturbs the soil environment (Kopittke et al. 2017; Muhammed et al. 2018). The loss of SOC contributes to increasing CO_2 levels in the atmosphere, therefore worsening global warming (Le Quéré et al. 2015). On the other hand, existing agricultural land holds a great potential to become a sink sequestering C from the atmosphere and decreasing CO_2 levels (Lal 2005). The decreased SOC stock of existing agricultural systems can be restored via implementation of new land management

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techniques and adapted land use (Robertson et al. 2017; Smith 2004; Valzano 2005).

Due to continuous plant C input to the soil and minimal soil disturbance, perennial crops (PCs) may harbor a potential to maintain or sequester SOC relative to annual systems (Chimento et al. 2016; Cox et al. 2006; Emmerling et al. 2017). In addition, resource-efficient and sustainable biomass production from PCs are possible due to year-round soil cover and a long utilization period of solar radiation (Pugesgaard et al. 2015; Manevski et al. 2017). Moreover, PCs may mitigate greenhouse gas emissions (Creutzig et al. 2015), support the bio-based economy (Cherubini and Jungmeier 2010), enhance soil aggregation and aggregate stability (Stewart et al. 2015), as well as improve multiple ecosystem services (Ferrarini et al. 2017).

Perennial crops like miscanthus, poplar, willow, conventional cut grasses, and other PCs have been studied for decades to address carbon sequestration and its sustainability over time (Carvalho et al. 2017; Chimento et al. 2016; McGowan et al. 2019). A meta-analysis on soil carbon change at different soil depths and time points showed that the conversion from cropland to perennial crops increased soil carbon slightly more at 0–30 cm than at 0–100 cm depths, although with no significant difference (Qin et al. 2016). In that study, miscanthus and willow showed a positive change in soil carbon at 0–30 cm soil depth with a rate of 1.22 t C ha^{-1} year^{-1} in miscanthus and 0.29 t C ha^{-1} year^{-1} in willow. Conversion to PCs crops was also reported to show a high magnitude of soil C changes in long-term trials (Qin et al. 2016). While assessing the SOC dynamics between perennial and annual biofuel crops, McGowan et al. (2019) found increasing SOC at a rate of 0.8 and 1.3 Mg C ha^{-1} year^{-1} (0–15 cm soil depth) in perennial switchgrass and miscanthus; whereas no significant changes in SOC were detected in any of the annual crops regardless of sampling depth. Perennial grassland managed with rotational grazing accumulated SOC in a 29-year-old field experiment in the north-central United States, contributing to the accretion of more persistent mineral-associated organic matter and thus increasing SOC (18 to 29% higher) compared with both annual monoculture and crop rotation systems (Rui et al. 2022). However, examples also exist of no change in SOC accumulation using perennial crops (Ye and Hall 2020; Jung and Lal 2011).

Although much work has been conducted to enhance the understanding of how the cultivation of PCs affects SOC, it is necessary to evaluate the factors influencing SOC stocks and the temporal dynamics after PCs establishment (Figure 1). Recently, Ledo et al. (2020) provided evidence of increasing SOC at 0-30 cm after a transition from annual to perennial crops; however, they came across a large variation of the dataset—most of it unexplained. It is crucial to clarify the influence of factors (soil, climate, and plant properties) on SOC stock difference between annual and perennial crops. For example, climate conditions, namely temperature and precipitation, are key drivers of SOC stock change by
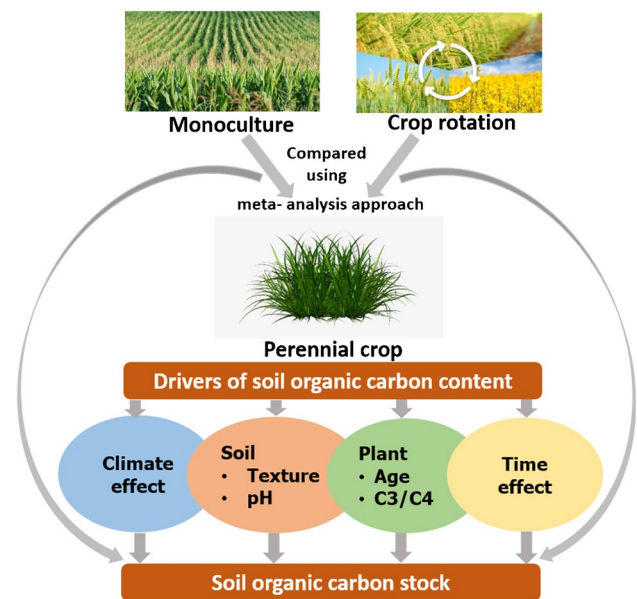
Fig. 1 Illustration of effects of perennial compared with annual systems as control (i.e., monoculture and crop rotation) on soil organic carbon stock. Influence of climate, soil, and plant properties on carbon stock changes is studied across the globe as well as the time effect of perennialization.

affecting both soil C input and decomposition (Conant et al. 2011; Doetterl et al. 2015). Besides climate, soil properties may also serve as important factor for controlling SOC stock change, for instance, soil type (Hobley et al. 2015), soil pH (Leifeld et al. 2013), and soil texture (Zinn et al. 2005). Moreover, studies at different spatial scales confirmed the effect of plant diversity and functional composition on SOC stocks (Liu et al. 2016; Gray et al. 2015).

To gain a better insight into the effect of perennialization on SOC, we here conducted a meta-analysis of SOC stocks in annual compared to perennial crops by reviewing and summarizing the existing evidence on perennialization. The specific objectives of the study were to (1) assess the performance of PCs compared with annual crops (either as monoculture or crop rotation) in terms of relative SOC stock changes; (2) explore the time effect of perennialization on SOC stock difference compared with annual crops; and (3) study the effects of soil type, climate, and plant properties on the SOC stock changes.

2 Materials and methods

2.1 Data collection

We searched peer-reviewed articles published before June 2021 using the Web of Science (http://apps.webofknowledge.com/) and Google Scholar (https://scholar.google.

com/). The reporting guidelines suggested in PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) were followed to report the data extraction process (Figure S1). We started to build our database conceptualized from a previous study on soil carbon dynamics under perennial crops (Ledo et al. 2020) where thirty-six studies were included on top of Ledo. The following combinations of keywords were used for the search: (1) "soil organic carbon" or "carbon stock" or "soil carbon sequestration" or "soil carbon"; and (2) "annual" or "annual crop"; and (3) "perennial" or "perennial crop." The database comprised of only the peer-reviewed literature and included as many studies as possible for further analysis. However, the following criteria had to be fulfilled by a study to be included in the meta-analysis: (1) soil and climatic parameters were similar for both annual and perennial cropping systems; (2) the experiment used paired-site, i.e., data on perennial and annual cropping systems were included in each study; (3) studies with duration of less than 1 year were removed to exclude short term effects (Gross and Glaser 2021). We also included several factorial experiments in our dataset to increase the number of observations. Using these criteria, we found a total of 51 studies, which allowed us to include 351 data points (effect sizes of annual monoculture, $k = 206$ and annual crop rotation, $k = 145$) obtained from 77 experimental sites worldwide. When data from literature were presented graphically, we used Grapher™ to digitize the data (http://www.goldensoftware.com/products/grapher).

We used the change of SOC in perennial as a dependent variable and two categories of control treatment to explore the potential variability sources: (1) monoculture and (2) crop rotation systems. Monoculture systems are characterized by continuous sowing of the same crop type; crop rotation included simple crop rotation (e.g., corn-wheat) and diversified crop rotations (e.g., rapeseed-wheat-corn-barley-grass clover). Perennial systems in the present study are defined as managed agricultural lands that are planted once and harvested annually (grass has several cuts per year) or after more years (willow and poplar are typically harvested every 3–6 years). Further details of the crop types, previous land use, perennial ecosystem, and usage types of perennials could be found in supplementary documents (Table S1). To better understand the factors influencing SOC stock change, we grouped data by climate zone, soil textural class, soil pH class, perennial crop age, perennial vegetation type, and functional photosynthetic types.

2.2 Climatic variables

We extracted available information on site characteristics: location, latitude, longitude, climate zone. Site coordinates (i.e., latitude and longitude) were also used to describe each experimental site into a thermal zone by agro-ecological zoning approach (Günther Fischer 2000), from the Global Agro-Ecological Zone (GAEZ) database, version 4.0. Studies included in the analysis were located in tropical, subtropical, and temperate climates.

2.3 Soil characteristics

Soil properties like pH, bulk density (BD), soil type, soil textural class, and percentage of sand, silt and clay were extracted from the literature. Unavailable data on pH, BD, and percentage of sand, silt, and clay was extracted from SoilGrids, a global soil information database (Hengl et al. 2017). Soil pH was further grouped into three classes: < 6.5 (acidic soil), 6.5–7.5 (neutral soil), > 7.5 (alkaline soil) (Gross and Glaser 2021). The soil textural class was identified using the United States Department of Agriculture soil texture calculator (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167).

2.4 Crop parameters

We included crop characteristics like perennial plant function type (PFT), vegetation type and crop age of perennials. Perennial crop species were separated into functional photosynthetic types of C_3, C_4, or C_3-C_4 in case of mixtures of prairie grasses. Vegetation types were divided into woody and herbaceous. Time since perennial crop establishment was referred to as crop age. To find soil C change patterns in time scale, crop age was categorized into three time periods (< 5 years, 5–10 years, and > 10 years) (Qin et al. 2016).

2.5 Calculation and standardization of data

Values of all soil chemical and physical properties were standardized for further analysis. Soil texture was converted to percentage if reported in original literature was given as g kg^{-1}. BD value was expressed in g cm^{-3}. Soil pH was presented based on water extracting method from SoilGrids.

The soil organic C stock of "kg m^{-2}," "g m^{-2}," "t ha^{-1}," "kg ha^{-1}," or "percent" units were transformed to "Mg ha^{-1}." Most of the soil carbon data (71%, 36 out of 51 studies) were reported in SOC stock and the rest in SOC concentration (e.g., "g kg^{-1}" or "mg g^{-1}"). Then, we converted SOC concentration (g kg^{-1}) to SOC stock (Mg C ha^{-1}) using BD value for specific soil depth (29% of the total study). Therefore, SOC stocks were calculated from the following equation (Guo and Gifford 2002):

$$SOC\ stock\ (Mg\ C\ ha^{-1}) = \frac{SOC \times BD \times D}{10}$$

where SOC is soil organic carbon concentration (g kg^{-1}), BD (g cm^{-3}), and D is soil thickness (cm).

Soil depth intervals linked to SOC stocks greatly varied across studies. To increase the comparability of SOC data derived from different studies, the methodology developed by Jobbágy and Jackson (2000) and followed by McClelland et al. (2021) was used to standardize the observed SOC measurement to a common soil depth of 0-30 cm according to the following equation:

$$SOC_{30} = \frac{1 - \beta^{30}}{1 - \beta^{d0}} \times SOC_{d0}$$

where SOC_{30} is the value of SOC in Mg C/ha in the first 30 cm of the soil profile (Jobbágy and Jackson 2000), β is the relative reduction rate of the soil carbon pool with soil depth (0.9786), d0 is the original soil depth available in individual studies (cm), and SOC_{d0} is the original SOC stocks.

2.6 Meta-analysis

All the analyses and visualization were performed with R v. 4.1.2 (R Core Team 2021). A meta-analysis approach was used to determine the significance of SOC dynamics in perennial system. Natural log of response ratio (lnRR) (Hedges et al. 1999) was used to quantify the effect of perennial system on SOC. In this study, lnRR was defined as the ratio of the mean SOC stocks of perennial systems (X_p) to the mean SOC stocks of annual systems (as monoculture or rotation) as control (X_a):

$$\text{lnRR} = \ln\left(\frac{X_p}{X_a}\right) = \ln(X_p) - \ln(X_a)$$

We used the lnRR for the following reasons. First, it stabilized the variance of the effect sizes, making them more comparable across studies. Second, it was appropriate for effect size estimation in studies where there was no a priori expectation of the direction of the effect. Third, it allowed for the use of parametric statistical methods, which assumed normality and homogeneity of variance. Fourth, it made the effect sizes more interpretable, as they represented the proportional change in the response variable (Pustejovsky 2018; Hedges et al. 1999). The variance of each study was calculated based on means, number of replications, and standard deviation (SD) of both perennial and annual (Luo et al. 2006; Hedges et al. 1999) with the following formula:

$$v = \frac{SD_p^2}{N_p X_p^2} + \frac{SD_a^2}{N_a X_a^2}$$

where SD_p and SD_a are the standard deviations of the perennial and annual systems (as monoculture or crop rotation), respectively; N_p and N_a are the sample size of the perennial

and annual systems (as monoculture or crop rotation), respectively. If a study reported standard error (SE), the corresponding SD was calculated based on the sample size (n):

$$SD = SE \times \sqrt{n}$$

The meta-analysis was weighted for each study by the inverse of variance of the effect sizes. Missing SD data (6 studies for annual monoculture and 3 for annual crop rotation comparison) was imputed using the R-package metagear (Lajeunesse 2016), following the "HotDeck" approach of Rubin and Schenker (1991) by imputing SD from data with means of similar scale. The multi-level meta-analytic mixed-effects models were fitted using the R-package "metafor" (Viechtbauer 2010). Model parameters were calculated using the restricted maximum likelihood estimator (Viechtbauer 2005). Study site and effect size were considered random factors in the meta-analysis as several study sites contributed more than one effect size. A moderator analysis (meta-regressions) was conducted to investigate the variability sources of the effect sizes linked to SOC stock change. The omnibus test of moderators (Q_M) was reported. All lookalike forest graphics are presented as orchard plot using "orchard" package in R (Nakagawa et al. 2021). "Orchard" plots, in addition to showing overall mean effects and confidence intervals from meta-analyses, also include 95% prediction intervals. Confidence intervals represent the range of the average true effect to be found, and prediction intervals show the range in which 95% of effects are anticipated to occur in future studies of a similar nature. If the effect size is larger than 0, it indicates a positive effect of perennialization, and lower than 0 indicates a negative effect of perennialization on SOC stock. Individual effect sizes were scaled by their precision; x-axis corresponds to effect size value and the y-axis was the effect size position based on quasi-random noise (Nakagawa et al. 2021). Quasi-random noise allows to visualize the data resembling a violin plot (showing the density distribution) and a scatter plot (showing the individual points). Results of meta-analysis in lnRR were back-transformed to "percentage of change" using the formula, i.e., [100 × {exp(lnRR) -1}] for easy interpretation in the results and discussion section.

Publication bias was assessed with Funnel plots and Egger's regression tests (Sterne et al. 2005; Sterne and Egger 2005). We fitted multi-level mixed meta-regression models, including the standard error and sample size as moderators. The presence of bias was identified based on the deviation of the model intercept from zero (Figure S2-3). In addition, we performed influential analysis on the model fit using the hat values (indicate which observations have high leverage). Studies with large influence were those with two times the average leverage (Habeck and Schultz 2015), whereas possible outliers were those studies with high standardized residuals (Figure S4).

A sensitivity analysis was performed to test the robustness of our results. A multi-level meta-analytic mixed-effects

model was fitted excluding those studies with imputed standard deviations (Figure S5).

A general score to assess the quality of our meta-analysis was calculated based on Fohrafellner et al. (2023). A value of 25 (out of 28) was obtained and the fulfilled specific criteria provided in the supporting information (Table S2).

2.7 Temporal analysis

A nonlinear regression was performed to analyze the temporal relationship between SOC stock change and perennial crop age. A logistic function was fitted (for monoculture and crop rotation separately) with a maximum likelihood estimation using R-package "drc" (Ritz et al. 2016). The four-parameter log-logistic function had the following parametrization:

$$f(x) = c + \frac{d - c}{1 + \exp(b(\log(x) - \log(e)))}$$

where, the coefficients c and d are the lower and upper limits or asymptotes of the response (SOC stock change) value, b is the slope (steepness) of the curve, and e is the median effective time of perennialization that produces a specific effect in 50% of the cases/population.

3 Results and discussion

To study the effect of perennials, 51 studies with total of 351 observations were included in our analysis (Figure 2, Table S3). The studies were conducted worldwide but most were located in North America and Europe with others spread across South America, Asia, and Australia (Figure 2a). Most of the studies were conducted in temperate climatic zones (83%), whereas a small number of studies (17%) took place in tropical and subtropical climatic zones. About sixty percent of the effect sizes were tested to single repetitive crop ($k=206$) as reference annual monoculture, while the other set tested the inclusion of more crop diversity referred to as annual crop rotation systems ($k=145$).

3.1 Overall effect

Perennial crops significantly increased the SOC stock at 0–30 cm soil depth relative to reference annual crop systems (Figure 3), where the intercept represents the overall change rate of the SOC. Results obtained from pairwise comparisons showed a significant increase of SOC stocks of 16.6% (95% confidence interval (CI), 10.1–23.5%; $p < 0.0001$) in PCs in comparison with the annual monoculture system (Figure 3a). For annual crop rotation as a reference, SOC stocks also showed a significant increase of 23.1% (95% CI, 14.7–32.1%; $p < 0.0001$) from pairwise comparisons (Figure 3b). For the present meta-analysis, there was no conclusive indication of publication bias based on either standard error or sample size fit (Figure S2, 3). Moreover, the sensitivity analysis showed that our results are robust, given that the effect size did not change excluding the studies with imputed standard deviations (Figure S5).
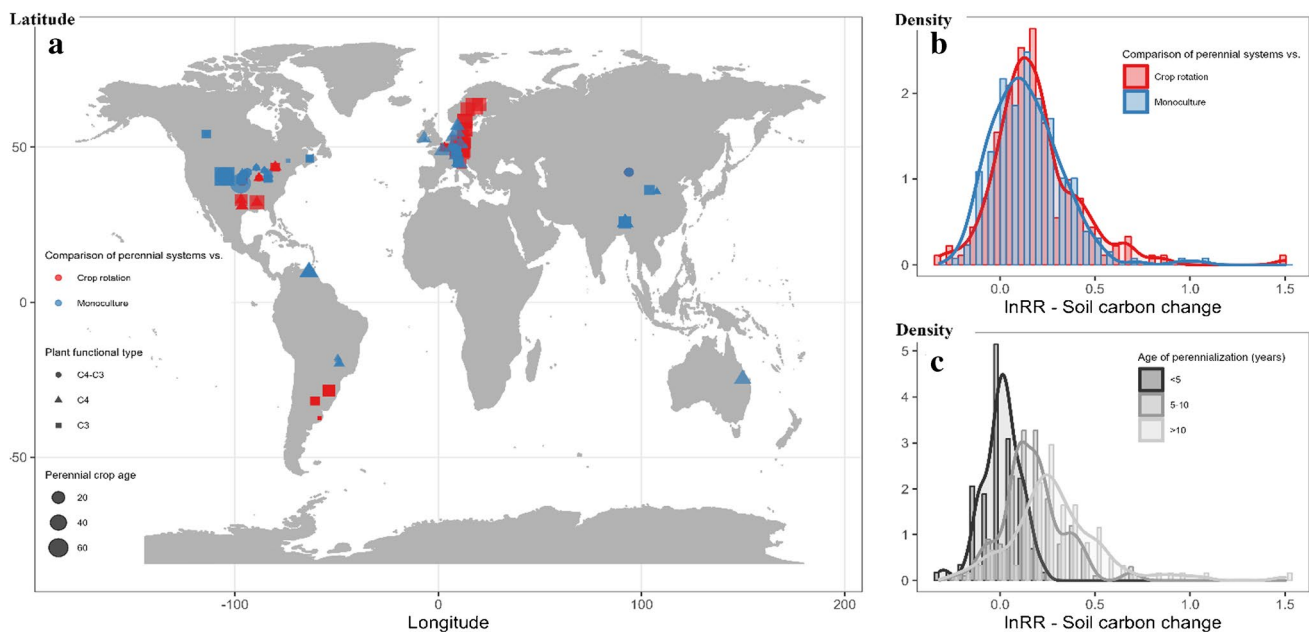
Fig. 2 a Geographical distribution of the 51 studies across 77 experimental sites included in the analysis. Colors indicate the reference annual systems to compare with perennial crops, shapes indicate the functional photosynthetic types of perennial crops (PFT; C_3, C_4, or C_3-C_4), and sizes indicate the age of perennial crops. b Distribution of the log-transformed response ratio (lnRR) of soil carbon change under reference annual systems. c Distribution of perennialization age (years).

Perennial vs monoculture

Intercept

Perennial vs crop rotation

Intercept
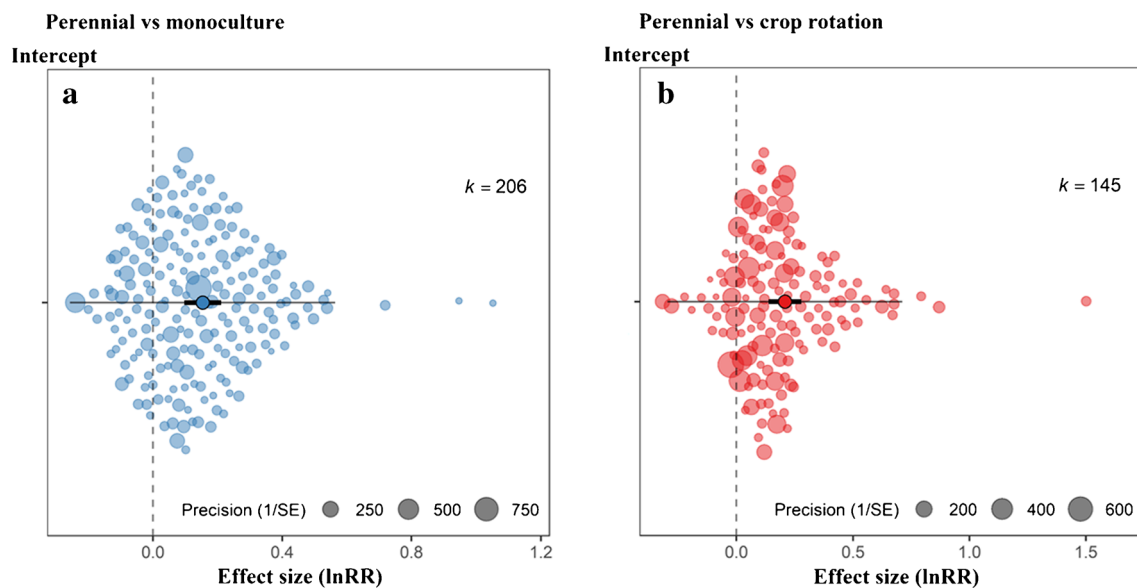
Fig. 3 Effect of perennialization on soil organic carbon stock change compared against **a** monoculture and **b** crop rotation. Meta-analytic model showing mean estimates with dark colored circles, 95% confidence interval with thick whisker, 95% prediction interval with thin whisker, and individual effect sizes scaled by their precision (i.e., inverse of the standard error) with light colored circles. k indicates the number of effect sizes. The dashed vertical line shows null log response ratio.

Several relevant features of PCs could reveal the mechanism behind; high root biomass is considered one of the most important possible explanations for the high SOC content (Lemus and Lal 2005). A recent study revealed that high amount of atmospheric C was allocated in the belowground biomass compartments and SOC after 11 years of PC establishment (Martani et al. 2021). Particularly, high turnover and exudation rate by fine roots influence SOC accumulation and stability (Shahzad et al. 2015). Another possible reason for SOC build-up by perennials is less soil disturbance. Soil cultivation disrupts soil aggregate, which exposes SOC, leading to carbon loss through erosion and accelerated microbial decomposition (Dignac et al. 2017). Perennial crops also exhibit higher levels of microbial activity than annual cropping systems, which may result in distinct aggregate formation and stability leading to higher SOC stocks (Tiemann and Grandy 2015). Increased activity of soil organisms has also been linked to gradual synthesis of complex humic chemicals and rising SOC concentration (Emmerling 2014; Hargreaves and Hofmockel 2014). Other important SOC sequestration mechanisms are chemical protection of SOC by adsorptive sites of the soil matrix like clay, silt, and metal oxides (Lützow et al. 2006) and physical protection of SOC in micro-aggregate structure ensuring inaccessibility of microbes due to limiting oxygen (Six et al. 2004; Tiemann and Grandy 2015). A study conducted by Gunina and Kuzyakov (2014) also confirmed the SOC absorption in micro-aggregates.

3.2 Crop age effect

The effect size of relative SOC stock change since PCs establishment is shown in Figure 4. The Q_M was 37 and 16 ($p < 0.0001$) for perennial vs monoculture (Figure 4a) and vs crop rotation (Figure 4b), respectively. Initialization of PCs showed a negative impact on SOC (< 5 years); however, a longer PCs duration (> 10 years) had a significant positive effect on SOC stock (Figure 4a, b).

During the crop ages of 5–10 and > 10 years, the SOC stock increased by 21.7% (95% CI, 14.9–28.8%; $p < 0.0001$) and 30% (95% CI, 21.4–39.3%; $p < 0.0001$) at 0–30 cm depth, respectively compared with annual crop monoculture (Figure 4a). When comparing with crop rotation as reference, SOC stock increased by 10.2% (95% CI, − 1.2–23.1%; $p = 0.0829$) during 5–10 years; while after 10 years, soil carbon stock was significantly higher (36.4%, 95% CI, 24.2–49.7%; $p < 0.0001$) (Figure 4b).

Similar to the findings on changes in SOC sequestration reported by Deng et al. (2014), our synthesis showed that SOC build-up started after five years of perennialization. No difference was seen in the soil C before 5 years, which is not a long time for detecting carbon accumulation (Necpálová et al. 2014). Despite initial decrease in soil C during the early stage of perennials cultivation, meta-studies and a number of field studies have reported increased content of soil C from long-term cultivation of PCs (Ledo et al. 2020; McGowan et al. 2019; Qin et al. 2016). After 11 years of perennial energy crop cultivation, at the top 0–10
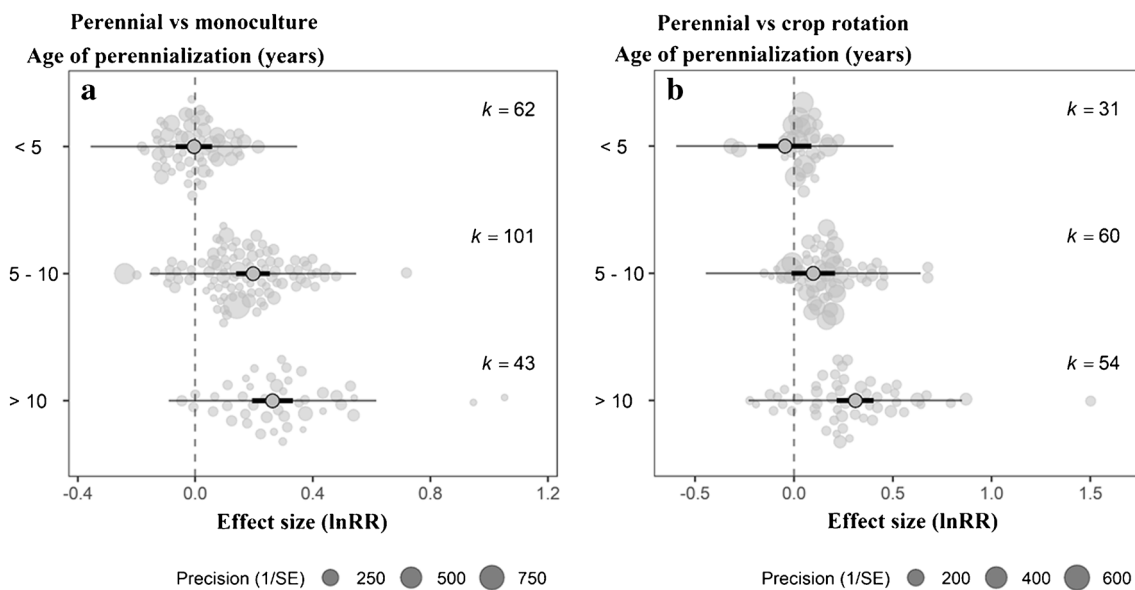
Fig. 4 Effect of perennial crop age on soil organic carbon stock change compared against **a** monoculture and **b** crop rotation. Meta-analytic model showing mean estimates with solid grey circles, 95% confidence interval with thick whisker, 95% prediction interval with thin whisker, and individual effect sizes scaled by their precision (i.e., inverse of the standard error) with transparent grey circles. Q_M was 37 and 16 ($p < 0.0001$) for perennial vs monoculture and crop rotation. k indicates the number of effect sizes. The dashed vertical line shows null log response ratio.

cm layer, all PCs (i.e., miscanthus, switchgrass, poplar, willow, giant reed and black locust) increased SOC content and SOC stock compared with arable land (Martani et al. 2021). Martani et al. (2021) also reported that all perennial crops except switchgrass increased SOC stock relative to the reference arable land by a significant amount at 0–30 cm soil depth. A recent study in central Ohio reported that perennial crops yielded a significant increase in SOC stock compared with annual crops on the surface 20 cm of soil after eight years of cultivation (Dheri et al. 2022). All these findings are in agreement with our observations, which suggest that rather long time is required after PC establishment for significant increase in SOC stock.

3.3 Crop effect

Compared to both reference annual systems, PCs increased SOC stock regardless of their functional types (Figure 5); Q_M for this moderator was 10 and 12 ($p < 0.0001$) for perennial vs monoculture (Figure 5a) and vs crop rotation (Figure 5b), respectively. SOC stock increased significantly in perennial PFT with a mean value of 14.8, 15.6, and 19.9% in C_4-C_3 ($p = 0.0136$), C_4 ($p < 0.0001$), and C_3 ($p < 0.0001$) types, respectively (Figure 5a); however, no significant difference was found between the C_3 and C_4 types. For reference annual crop rotation, perennial PFT significantly increased the SOC stocks ranges from 16.2 to 33.8% (Figure 5b).

Perennial crops with C_3 and C_4 photosynthetic pathways have shown different dynamics of SOC stock changes (Figure 5). Grass species with C_3 pathway may decrease the C accumulation, whereas C_4 grass species have a high C/N ratio (i.e., more cross-linked polymers of lignin and cellulose), which leads to increased soil C accumulation (Knops and Tilman 2000; Knops and Bradley 2009). On the contrary, Knops and Bradly (2009) showed that vegetation composition (C_3 and C_4 grasses) effects was not significant predictors for SOC, probably, because of high relative soil C pool, undetectable plant input on the deep SOC, and using only root inputs as a sole explanation for the SOC build up is insufficient. However, an incubation study from a 10-year-old field experiment showed that C derived from C_4 plants decomposed faster than C_3-derived C (Ye and Hall 2020), possibly related to decreased microbial C-use efficiency that comes along with the lower N content of C_4 plants or biochemical variations between the tissues of C_3 and C_4 plants. Moreover, on agriculturally degraded soils, increased SOC in C_3-C_4 plant mixture has been linked to high root biomass and accumulation of root biomass owing to presence of highly complementary functional groups (i.e., C_4 grasses and legumes) (Fornara and Tilman 2008).

Perennial vegetation type showed a significant positive effect in SOC stock compared with both reference annual systems (Figure 6); Q_M for this moderator was 15 and 17 ($p < 0.0001$) for perennial vs monoculture (Figure 6a) and vs crop rotation (Figure 6b), respectively. SOC stock significantly
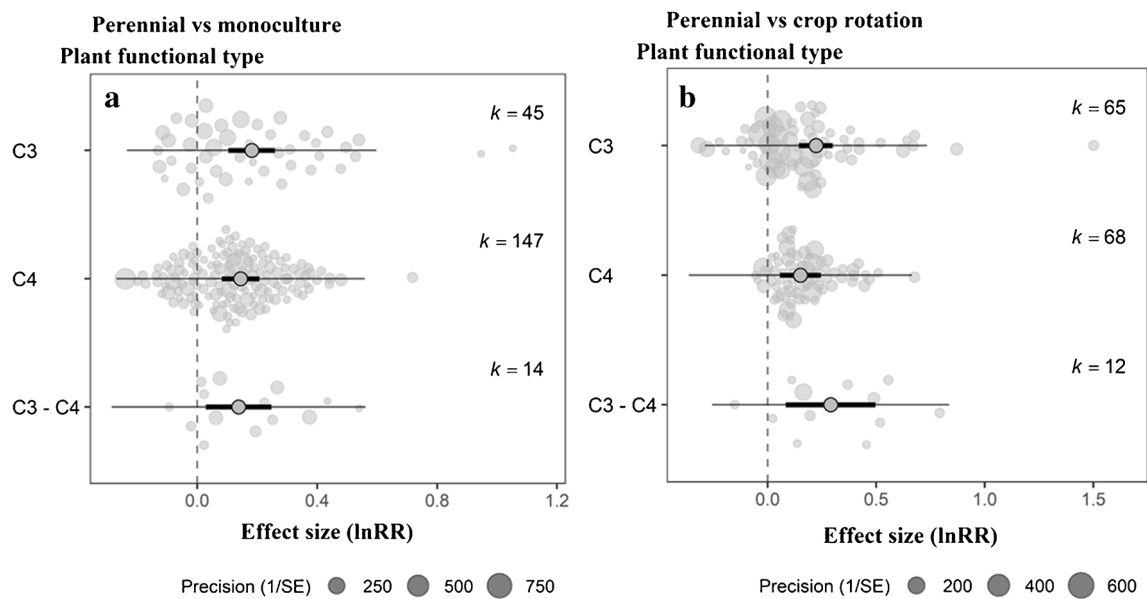
Fig. 5 Effect of functional photosynthetic type of perennial crop on soil organic carbon stock change compared with **a** monoculture and **b** crop rotation. Meta-analytic model showing mean estimates with solid grey circles, 95% confidence interval with thick whisker, 95% prediction interval with thin whisker, and individual effect sizes scaled by their precision (i.e., inverse of the standard error) with transparent grey circles. Q_M was 10 and 12 ($p < 0.0001$) for perennial vs monoculture and crop rotation. k indicates the number of effect sizes. The dashed vertical line shows null log response ratio.

increased under woody vegetation by 23% ($p < 0.0001$) followed by herbaceous vegetation with SOC stock increase of 15.8% ($p < 0.0001$) in comparison with annual monoculture. While comparing with annual crop rotation, both woody and herbaceous perennial showed significantly higher SOC stock of 21.6% and 24.1% ($p < 0.0001$), respectively. Because of the combined contribution of roots and leaf-litter C inputs, woody bioenergy crops are expected to have a higher SOC sequestration capacity than herbaceous bioenergy crops (Hangs et al. 2014); it may also be due to the high C/N ratio of woody plant organs which slows down residue mineralization and increase SOC. The C inputs to the soil come mainly from the root system in herbaceous crops because the most of aboveground biomass is removed during harvesting, whereas in woody crops, both roots and leaf-litter inputs are important contributors to SOC accumulation (Tolbert et al. 2002; Hangs et al. 2014). In contrast to woody crop roots, herbaceous crop roots contribute more than half of the total plant C (Bazrgar et al. 2020); however, SOC accumulation was not significantly different between the woody and the herbaceous systems, suggesting that perennial biomass systems may not be influenced by the vegetation type.

3.4 Soil and climatic effect

Results indicated that relative SOC stock change was influenced by both soil and climatic conditions (Figures 7, 8,

and 9). The Q_M for soil pH moderator was 13 and 11 ($p < 0.0001$) for perennial vs monoculture (Figure 7a) and crop rotation (Figure 7b), respectively. Soils in perennials with pH < 6.5 showed a significant mean response of 10.1% ($p = 0.0146$, Figure 7a). The pH neutral soils (6.5–7.5) had significant increase in SOC stock by 17.3% ($p = 0.0008$), while the alkaline (> 7.5) soils showed 37.1% ($p < 0.0001$) SOC stock changes in perennials in contrast with monoculture system (Figure 7a). Perennial crops increased SOC relative to crop rotation system regardless of the soil pH (Figure 7b); however, alkaline soil pH (> 7.5) showed a significant SOC stock change of 23.8% ($p = 0.0311$).

Increased soil pH releases more Ca^{2+} ions, which favors the formation of mineral-organic chemical complexes that eventually may retain organic carbon on their surfaces (Paradelo et al. 2015). It is widely accepted that root exudates and decomposition of fine roots result in organic acids, which lower soil pH and raise SOC (Singh 1998), but Leifeld et al. (2013) have shown that better aboveground production in alkaline soils can compensate for the observed faster SOC turnover compared to similar acidic soils. However, in principle, low soil pH values may trigger SOC accumulation by slowing down the decomposition process (Motavalli et al. 1995). Since the number of observations in the present study was limited for soil pH (Figure 7), subgroup analysis should be taken cautiously due to the large uncertainty in estimates.

Most soil textural classes were not significantly different from zero which means only a few textural classes showed
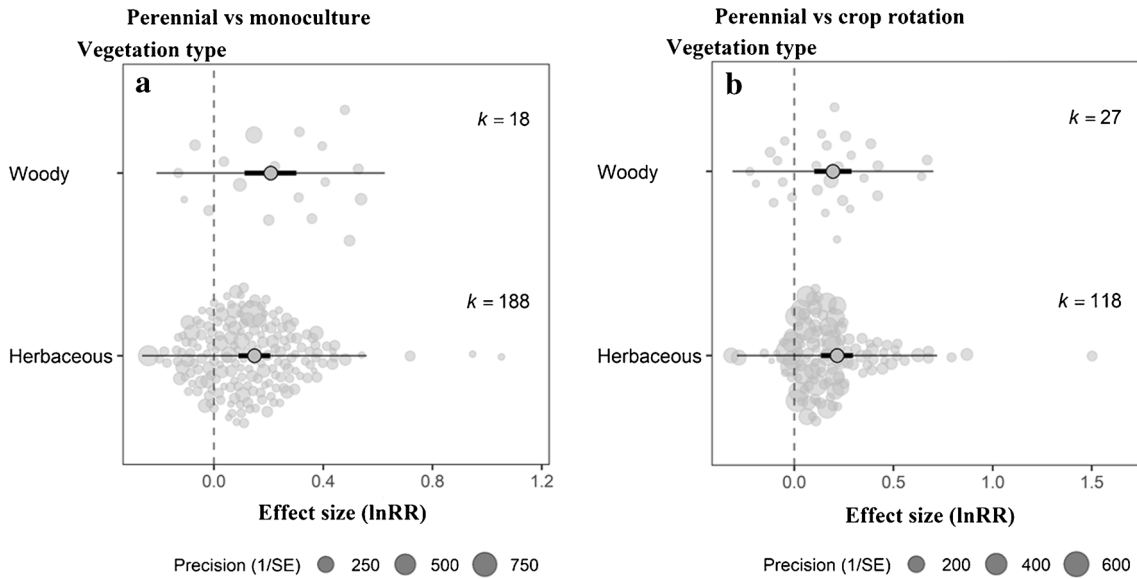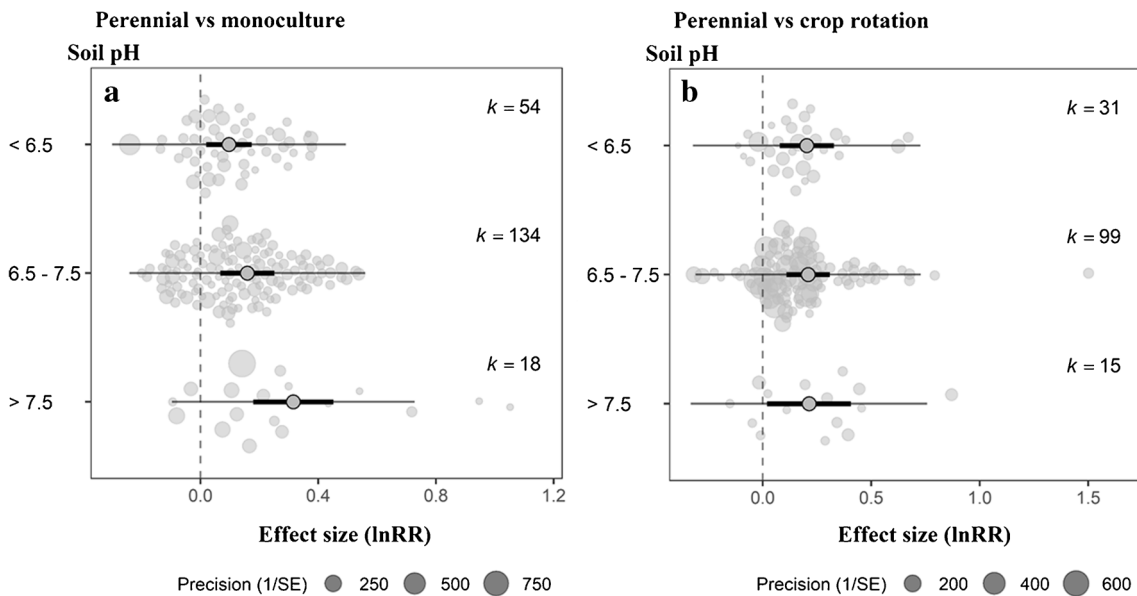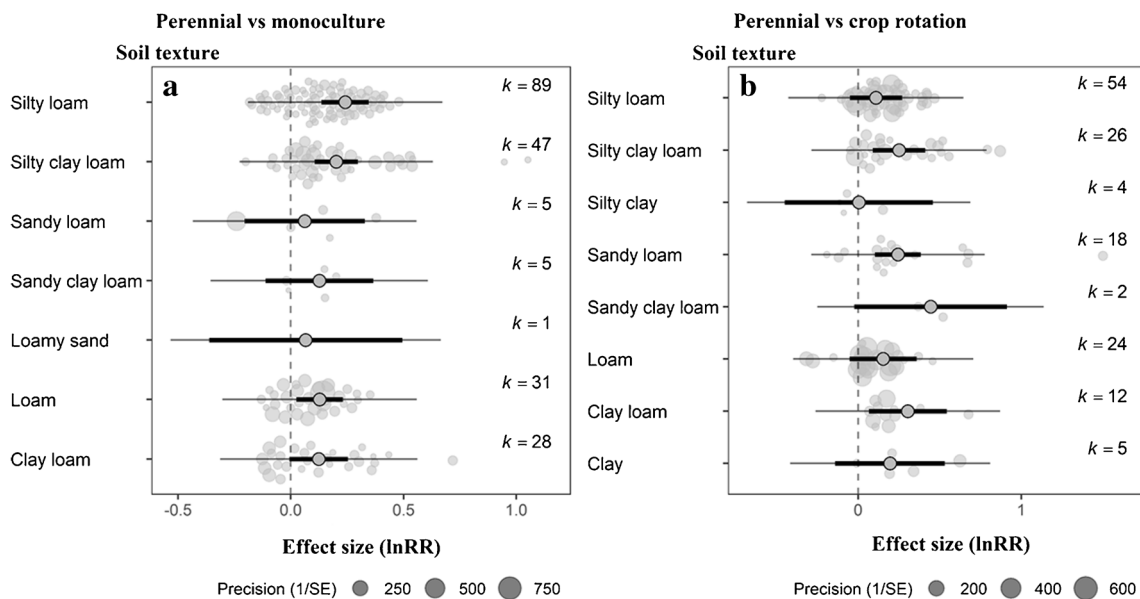
Fig. 6 Effect of vegetation type of perennial crop on soil organic carbon stock change compared against **a** monoculture and **b** crop rotation. Meta-analytic model showing mean estimates with solid grey circles, 95% confidence interval with thick whisker, 95% prediction interval with thin whisker, and individual effect sizes scaled by their precision (i.e., inverse of the standard error) with transparent grey circles. Q_M was 15 and 17 ($p < 0.0001$) for perennial vs monoculture and crop rotation. k indicates the number of effect sizes. The dashed vertical line shows null log response ratio.

significantly positive response on SOC in PCs compared with both reference annual systems (Figure 8); Q_M for soil texture was 4 and 5 ($p < 0.001$) for perennial vs monoculture (Figure 8a) and vs crop rotation (Figure 8b), respectively. Our results showed large difference in SOC stock change between the textural classes; furthermore, wide ranges of loam soils showed high relative SOC changes, suggesting that soils with fine particles are best for SOC accumulation (Figure 8). In general, the possibility of SOC accumulation is higher with increasing clay content of the soil because its greater surface

Fig. 7 Effect of soil pH on soil organic carbon stock change of perennial crops compared against **a** monoculture and **b** crop rotation. Meta-analytic model showing mean estimates with solid grey circles, 95% confidence interval with thick whisker, 95% prediction interval with thin whisker, and individual effect sizes scaled by their precision (i.e., inverse of the standard error) with transparent grey circles. Q_M was 13 and 11 ($p < 0.0001$) for perennial vs monoculture and crop rotation. k indicates the number of effect sizes. The dashed vertical line shows null log response ratio.
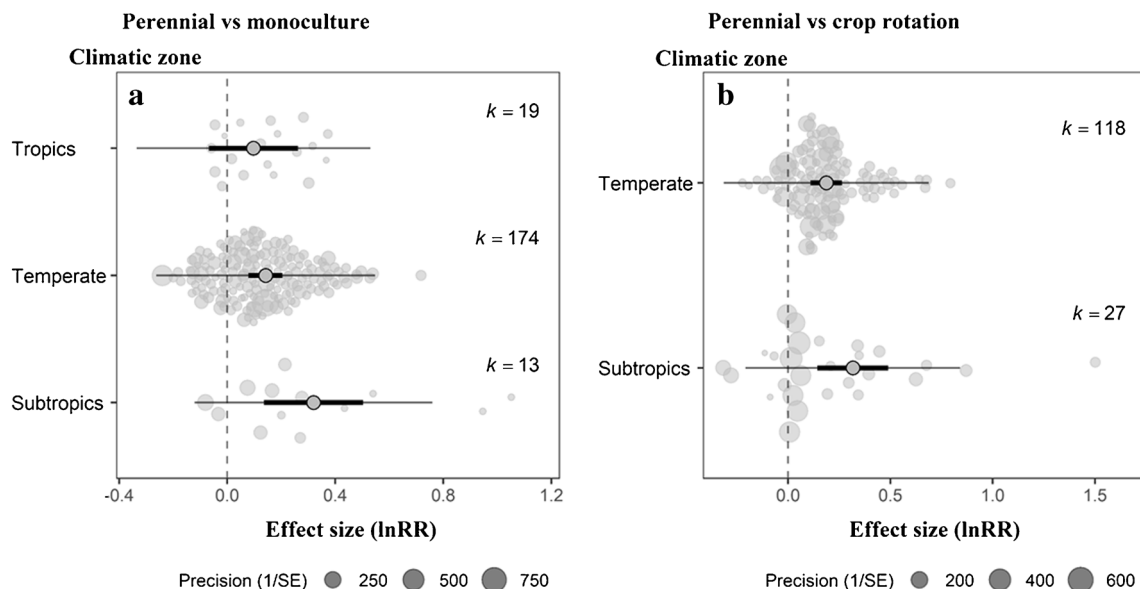
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Fig. 8 Effect of soil texture on soil organic carbon stock change of perennial crops compared against **a** monoculture and **b** crop rotation. Meta-analytic model showing mean estimates with solid grey circles, 95% confidence interval with thick whisker, 95% prediction interval with thin whisker, and individual effect sizes scaled by their precision (i.e., inverse of the standard error) with transparent grey circles. Q_M was 4 and 5 ($p < 0.001$) for perennial vs monoculture and crop rotation. k indicates the number of effect sizes. The dashed vertical line shows null log response ratio.

area leads to adsorption of organic compounds and formation of micro-aggregate (Zinn et al. 2007). Chemical protection of SOC by soil matrix, the most important SOC stabilization mechanism, can be explained by the interaction of charged organic compounds with the silt and clay particles (Lützow et al. 2006; Marschner et al. 2008). The stable complex compound between SOC and clay minerals is resistant to decomposition (Kögel-Knabner et al. 2008) and fosters aggregate

Fig. 9 Effect of climatic zone on soil organic carbon stock change of perennial crops compared against **a** monoculture and **b** crop rotation. Meta-analytic model showing mean estimates with solid grey circles, 95% confidence interval with thick whisker, 95% prediction interval with thin whisker, and individual effect sizes scaled by their precision (i.e., inverse of the standard error) with transparent grey circles. Q_M was 11 and 19 ($p < 0.0001$) for perennial vs monoculture and crop rotation. k indicates the number of effect sizes. The dashed vertical line shows null log response ratio.

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formation to protect the SOC. In our study, no significant effect of soil texture on the difference between perennial and reference systems was found because of lack of observations and mixed pedoclimatic effects.

Relative change of SOC stock showed different dynamics under different climatic conditions (Figure 9); the Q_M for climate moderator was 11 and 19 ($p < 0.0001$) for perennial vs monoculture (Figure 9a) and vs crop rotation (Figure 9b), respectively. Tropical climates had the lowest response ratio, with an average increase in SOC stock of 10.2% ($p = 0.2463$) compared with reference monoculture (Figure 9a). Relative SOC stock change in temperate climates had a significantly positive mean value of 15.2% ($p < 0.0001$), whereas subtropical climates had the largest response with 37.6% ($p < 0.0001$). Compared with reference crop rotation, SOC stock in temperate climates had a significant positive mean response of 20.5% ($p < 0.0001$), whereas, subtropical climates led to average SOC stock increase of 37.2% ($p = 0.0004$) (Figure 9b).

Climatic factors, particularly temperature and precipitation, have a strong influence on SOC stock by affecting SOC decomposition. By accelerating the weathering of the parent material and frequently causing soil acidity, humidity favors the creation of SOC-stabilizing mineral surfaces and slows down the decomposition of soil organic matter (Meier and Leuschner 2010; Doetterl et al. 2015). Furthermore, many studies have shown a decrease in SOC with rising temperature (Koven et al. 2017). In general, SOC stock might be higher in cool and humid climate than in warm and arid climate both at global and regional scale (Jobbágy and Jackson 2000; Lal 2004; de Brogniez et al. 2014). Water availability increases crop production in cool regions, limiting microbial activity, and eventually increasing SOC stock (von Lützow and Kögel-Knabner 2009); in contrast, water stress condition in arid and semi-arid sites limits the SOC input and storage by constraining crop production (Hobley et al. 2016). The abovementioned mechanism of SOC accumulation under different climatic conditions could explain the difference in relative SOC changes pattern between perennial and annual systems. Nonetheless, our findings advised that more research on perennials in the tropical and subtropical regions must be conducted to better understand the SOC stock dynamics there.

### 3.5 Changes in SOC stocks over time from perennial crop establishment

When the data were fitted to a nonlinear regression fit using a general four-parameter log-logistic function, it showed that the change of SOC stock approached equilibrium after a certain period of time (Figure 10). Initially, there seemed to be a decrease in SOC, probably due to land conversion. This drop in SOC was likely caused by increased SOC loss through soil disturbance and lower productivity of new vegetation in the early years after establishment (Laganière et al. 2010; Zhang et al. 2010). Our synthesis indicated that the increase of SOC in PCs started after approximately five years (> 5 years) when compared to both reference annual systems (Figure 4). Then, it showed a sigmoidal function of SOC stock increase slowing down around 20 years after PC establishment (Figure 10).

While summarizing the time effect of perennialization on SOC in the present meta-study, studies which were found to be outliers and could leverage the effect of perennialization are further discussed. Dou et al. (2013) found that 9-year-old switchgrass had higher increase of SOC compared to the 4-year-old switchgrass irrespective of locations (Figure 10a). These data must be interpreted with caution because high clay content influenced the SOC stock. Additionally, compared to other soils, fine-textured vertisol showed a strong capacity to store carbon in various carbon pools (Dou et al. 2013). In another long-term (75-year) investigation of perennial grassland and agricultural land, Culman et al. (2010) concluded that even after many years of annual harvest and without fertilizer, grasslands remained productive over time, supporting annual biomass production and keeping SOC levels significantly higher than cultivated agricultural land (Figure 10a). This observation advocates the fundamental differences in plant community function, nutrient cycling, and associated soil biology between perennial and annual systems. In a 52-year field experiment in Northern Sweden, the SOC stock increased in a continuous forage crop rotation, whereas a continuous annual rotation decreased the SOC stock (Bolinder et al. 2010). Due to the effect of previous land use (grassland rotated with small grain crops), and cool weather, annual system had a lower rate of SOC change, which could explain the lower effect of perennialization on SOC stock (Figure 10b). The largest effect of perennialization in Figure 10b was contributed by Fabrizzi et al. (2009), and this study has shown that irrespective of soil type, annual crops decreased carbon and nitrogen stocks in comparison to the natural grassland. Results suggested, furthermore, that continuous annual crop cultivation reduced the mass of macro-aggregates and associated C concentration (Fabrizzi et al. 2009).

3.6 Limitation and outlook

Reviewing, summarizing, and analyzing the global changes in SOC stocks after perennialization showed a significant increase in SOC stocks compared with annual crops. However, only a few other effects were found from the subgroup analysis that affected the SOC stock. Although subgroup analysis provided the confidence and prediction intervals to show the large uncertainty of the estimates, due to the limiting number of observations specific subgroup analysis

Perennial vs monoculture
Effect size (lnRR)

Perennial vs crop rotation
Effect size (lnRR)
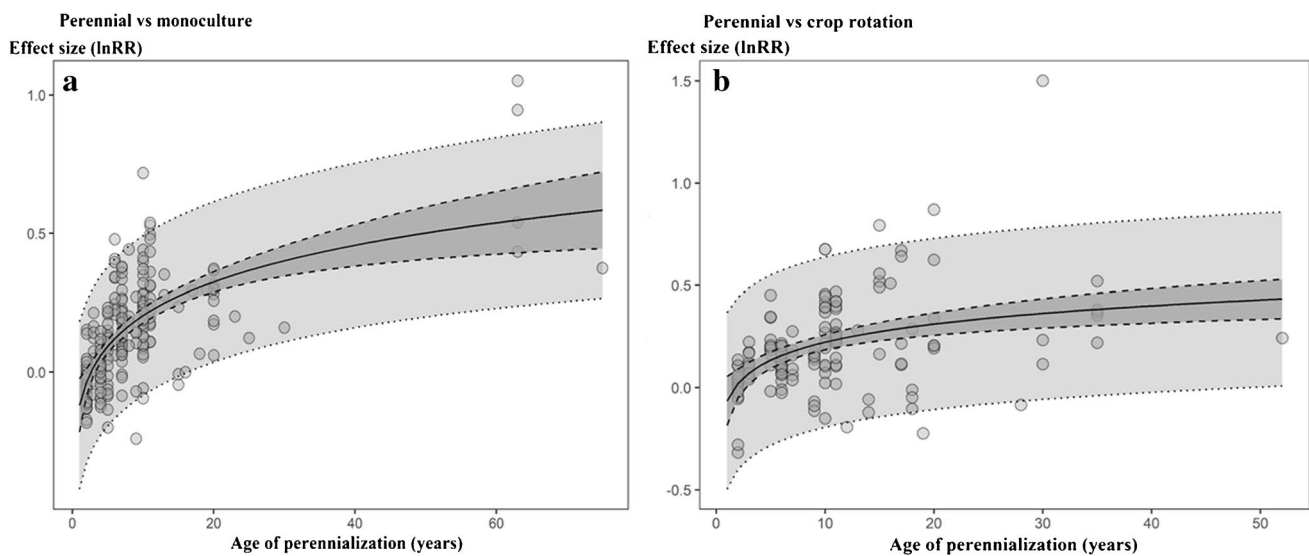
Fig. 10. Relationship between perennial crop age and log-transformed soil carbon stock change (lnRR) compared against **a** monoculture and **b** crop rotation. Dark grey range with dashed line along the logistic curve indicates 95% confidence intervals and light grey range with dotted line indicates the 95% prediction intervals.

should be taken cautiously. Results from our synthesis suggested more experimentation on perennials in the tropical and subtropical regions to unfold the SOC stock dynamics there. While the sensitivity analysis showed robust results linked to the SOC stocks and the non-existence of publication bias, some methodological procedures might induce uncertainty. First, the reported SOC stocks in this study estimated from response ratios between the annual and perennial systems provided a global overview of the perennialization effect on SOC stock. However, for future implementation of perennials, C sequestration rate estimation could be done using both SOC stock at the initial and the end of perennialization. Due to a lack of information on initial soil carbon stock in many of the studies, C sequestration analysis could not be performed from our database. Second, during the back transformation of lnRR, the convexity of the log transformation introduced a bias in the estimate of the mean response ratio. The back transformation to the percentage change of the lnRR might cause issues linked to nonlinear scaling, asymmetric error distributions, dependency on sample size, and heterogeneity (Lee 2020). However, if the number of studies and precision of their estimates are both large, and the variance of the weighted mean is low, the bias will be small (Hedges et al. 1999). Lastly, temporal synthesis assessed the relationship between SOC stock changes with perennial crop age but this was supported by very few long-term perennial studies. Further investigation exploring SOC stock dynamics using long-term studies (> 20 years) comparing annual and perennial cropping systems is paramount. In addition, we focused on 0–30 cm soil depth to quantify the SOC stock while estimating the effect of perennialization based on our existing database due to the inconsistency of reporting deeper SOC stocks and different layer discretization. We also acknowledged that different farming practices might induce short-term temporal changes in SOC. These farm management practices, including site-specific and climatic features, could increase or decrease SOC. The lack of detailed information from individual articles constrained more detailed exploration of specific farming practices. However, in our meta-analysis study, we compared the SOC stock changes at a system level controlled by the available factors (moderators) provided by the individual studies. These issues, therefore, need further attention to achieve a comprehensive system.

In the future, when turning agriculture more climate efficient, there will be a need for C crediting from specific cropping systems. Reporting the potential to sequester soil carbon requires estimation and verification in terms of tons of carbon sequestered per hectare per year. This puts significant pressure on the methodologies to be developed and their validity.

4 Conclusion

We conducted a meta-analysis on soil organic carbon stock change following perennialization and found that the change of soil organic carbon stock at 0–30 cm depth in the studied perennial crops generally increased with reference to annual crops both in monoculture and crop rotation systems. Several factors, including soil, plant, and climatic properties,

have been analyzed for their impact on the SOC stock with contrasting effects. Here we showed that the time since conversion from annual to perennial system influenced the dynamics of soil organic carbon stock changes, extending the accumulated effect after 5, 10, and 20 years. Perennialization has the potential to achieve a significant increase of soil organic carbon across biomes and pedoclimatic conditions, but the effect seems to stagnate approximately 20 years after introduction of perennial crops.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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