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A global meta-analysis of soil organic carbon response to corn stover removal

Hui Xu[1] | **Heidi Sieverding**[2] | **Hoyoung Kwon**[1] | **David Clay**[3] | **Catherine Stewart**[4] | **Jane M. F. Johnson**[5] | **Zhangcai Qin**[1,7] | **Douglas L. Karlen**[6] | **Michael Wang**[1]

[1]Systems Assessment Group, Energy Systems Division, Argonne National Laboratory, Lemont, Illinois

[2]South Dakota School of Mines & Technology, Rapid City, South Dakota

[3]South Dakota State University, Brookings, South Dakota

[4]Agricultural Research Service, United States Department of Agriculture, Fort Collins, Colorado

[5]Agricultural Research Service, United States Department of Agriculture, Morris, Minnesota

[6]Agricultural Research Service, United States Department of Agriculture, Ames, Iowa

[7]School of Atmospheric Sciences, and Guangdong Province Key Laboratory for Climate Change and Natural Disaster Studies, Sun Yat-sen University, Guangzhou, China

Correspondence
Hui Xu, Systems Assessment Group, Energy Systems Division, Argonne National Laboratory, Lemont, IL, USA.
Email: hui.xu@anl.gov

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Abstract
Corn (*Zea mays* L.) stover is a global resource used for livestock, fuel, and bioenergy feedstock, but excessive stover removal can decrease soil organic C (SOC) stocks and deteriorate soil health. Many site-specific stover removal experiments report accrual rates and SOC stock effects, but a quantitative, global synthesis is needed to provide a scientific base for long-term energy policy decisions. We used 409 data points from 74 stover harvest experiments conducted around the world for a meta-analysis and meta-regression to quantify removal rate, tillage, soil texture, and soil sampling depth effects on SOC. Changes were quantified by: (a) comparing final SOC stock differences after at least 3 years with and without stover removal and (b) calculating SOC accrual rates for both treatments. Stover removal generally reduced final SOC stocks by 8% in the upper 0–15 or 0–30 cm, compared to stover retained, irrespective of soil properties and tillage practices. A more sensitive meta-regression analysis showed that retention increased SOC stocks within the 30–150 cm depth by another 5%. Compared to baseline values, stover retention increased average SOC stocks temporally at a rate of 0.41 Mg C ha^{-1} $year^{-1}$ (statistically significant at $p < 0.01$ when averaged across all soil layers). Although SOC sequestration rates were lower with stover removal, with moderate (<50%) removal they can be positive, thus emphasizing the importance of site-specific management. Our results also showed that tillage effects on SOC stocks were inconsistent due to the high variability in practices used among the experimental sites. Finally, we conclude that research and technological efforts should continue to be given high priority because of the importance in providing science-based policy recommendations for long-term global carbon management.

KEYWORDS
carbon sequestration, corn, meta-analysis, soil organic carbon, stover removal, tillage

1 | INTRODUCTION

Globally, corn (*Zea Mays* L.) comprises roughly 13% of the world's arable land (Food and Agriculture Organization (FAO) of the United Nations, 2016; OECD (Organization for Economic Co-operation and Development) & FAO, 2018) and is expected to increase to over 190 megahectares (Mha) with yields surpassing 1.2 billion megagrams (Mg) per year by 2027 (OECD & FAO, 2018). Traditionally, residue from grain production has been harvested and used for animal forage, bedding, or household heat. Depending on the region, unharvested crop residues are sometimes burned, grazed, or left in fields to aid in soil fertility or health. In North America, corn became the dominant crop resource that supported the rise of precolonial civilizations, modern agriculture, and more recently the biofuel industry.

Bioenergy mandates have created a large global demand for crop residue. As food and feed demands for corn grain continue to rise, the proportion of corn grain used for biofuel production (17%) is projected to decrease (OECD & FAO, 2018), while the use of other perennial feedstocks, various wastes, and crop residues expands by more than 60%. The United States (US) Environmental Protection Agency (EPA) has proposed a 2019 cellulosic biofuel production target of 1.4 billion liters (EPA, 2018), which will likely be fulfilled predominantly using corn residue or corn stover (herein defined as the aboveground parts of the corn plant remaining after the corn grain is harvested; Wilhelm, Johnson, Hatfield, Voorhees, & Linden, 2004), simply because of the established stover harvest techniques and the volume of available feedstock (Moriarty et al., 2018). According to the US Department of Energy's (DOE) 2016 Billion Ton Report (DOE, 2016), corn residue was determined to be a near-term, cost-effective, and widely available biomass source, which does not require additional cultivation or dedicated land. The European Union (EU) has set a binding renewable energy target of 20% by 2020; ~27 million Mg of corn residue is expected to fulfill two-thirds of this mandate (Monforti et al., 2015; Scarlat, Martinov, & Dallemand, 2010).

While corn stover is considered to be a readily available biofuel feedstock, there is concern about the long-term viability of removal (Karlen et al., 2011). Residue (a) protects the soil surface, (b) feeds biological and microbiological processes essential in soil aggregate formation, (c) regulates soil temperature and moisture, and (d) provides C and biological material for soil aggradation (Blanco-Canqui & Lal, 2009; Johnson, Allmaras, & Reicosky, 2006). Through these processes, residue can minimize soil erosion and degradation and assist in improving the productivity of future crops. However, under very high biomass production, wet soil, or ecologically damaged areas, surface residue can negatively affect subsequent crops due to poor seed–soil contact or soil water saturation or increase the use of agrochemicals for weed and pest management. Residue management is essential to balancing soil health and with long-term cropland productivity. In cropping systems, stover removal for biofuel production or other uses needs to be managed carefully to preserve the soil resource including SOC stocks (Wilhelm et al., 2004).

Many global policies use greenhouse gas (GHG) accounting for biofuel production and feedstocks to quantify the effects of production and to allocate renewable fuel credits, such as California's low carbon fuel standard (LCFS; CARB, 2009), the US renewable fuel standard (RFS; EPA, 2010), and the European Union's renewable energy directive (European Parliament, 2009). However, the life-cycle impact of crop residues and their relationship to SOC change has not been consistently addressed (EPA, 2010). In many accounting schemas, crop residues have a minimal allocated production burden (Kim et al., 2019). However, crop residue utilization may change SOC stocks and therefore alter life-cycle GHG emissions of residue-based biofuels. Using SOC and life-cycle analysis (LCA) models, Qin et al. (2018) estimated that 30% stover removal under conventional tillage (CT) in the US can decrease SOC by 0.04 Mg C ha^{-1} year^{-1}. Based on this value, stover-based biofuel will not meet the 60% life-cycle GHG emission reduction target set by the US RFS mandate unless the tillage intensity is reduced, or additional organic matter sources are amended. Still, this analysis relied on modeling having limited field validation. Globally, momentum for action on sustaining or building SOC stocks is growing, but the lack of robust measurement is often identified as a barrier to investment in sustainable management practices (Vermeulen et al., 2019). To inform producers, industry, and other stakeholders, empirical data are needed to calibrate, validate, and refine process-based models so that SOC impacts of residue removal can be properly accounted for (Johnson et al., 2014).

In recent years, substantial research funded by a variety of sources, including the DOE, commodity groups, US Department of Agriculture (USDA), and EPA, was initiated to evaluate how corn stover harvests affect soil properties including SOC. Many of these studies reported contradicting and variable results (Johnson et al., 2014; Wilhelm et al., 2004). For instance, Blanco-Canqui, Lal, Post, Izaurralde, and Owens (2006) found that SOC decreased by more than 30% within 1 year after complete stover removal for two sites in Ohio. Wilts, Reicosky, Allmaras, and Clapp (2004) reported that stover removal decreased SOC by more than 20 Mg C ha^{-1} year^{-1}, about 20% of the initial SOC stock. In contrast, a 5 year study in Pennsylvania showed that there was no significant change in SOC due to stover removal treatment (Adler, Rau, & Roth, 2015). Similarly, Clapp, Allmaras, Layese, Linden, and Dowdy (2000) reported that 13 years of stover removal did not affect SOC in the surface soil layer. These varying results occur because soil processes are responsive to abiotic and biotic changes, agronomic management, and spatial and temporal variability. Furthermore, where, when, how, and why soil tests were conducted can affect observations and scientific conclusions (Davis et al., 2017).

Many meta-analyses show that management practices such as residue removal, fertilization, and rotational diversification and study duration will affect SOC sequestration (Anderson-Teixeira, Davis, Masters, & Delucia, 2009; Chivenge, Vanlauwe, & Six, 2011; Haddaway et al., 2017; Han, Zhang, Wang, Sun, & Huang, 2016; Liu, Lu, Cui, Li, & Fang, 2014; Qin, Dunn, Kwon, Mueller, and Wander (2016b); West & Post, 2002), but there is a lack of robust quantitative synthesis of the empirical evidence (Schmer, Stewart, & Jin, 2017; Wilhelm et al., 2004). Furthermore, previous meta-analyses have evaluated the effect of different management practices (e.g., tillage) on SOC for crop production studies, few focused on evaluating corn residue impacts. For example, Manley, Kooten, Moeltner, and Johnson (2005) reported in a global meta-analysis that no-till (NT) corn production could sequester 0.2–0.3 Mg C ha^{-1} $year^{-1}$ depending on location and NT duration; however, this study did not address residue removal. In another case, Lehtinen et al. (2014) reviewed responses of SOC to crop residue incorporation, including crop stover, in European agricultural soils and found that SOC increased by 7% on average following crop residue incorporation. However, corn was not a major crop in their database. By selecting corn residue retention and removal as key criteria, Anderson-Teixeira et al. (2009) and Qin et al. (2016b) also conducted meta-analysis primarily focused on land use change and included croplands previously cultivated with crops other than corn.

This study was undertaken to provide more empirical evidence regarding how to balance the use of corn residue to maintain SOC, promote soil health, and provide feedstock for the bioenergy industry (Johnson et al., 2014; Qin et al., 2016b). Our objectives were to: (a) assess the overall effects (direction and magnitude) of stover removal on global final experimental SOC stocks and accrual rates over time and (b) identify factors driving the observed SOC changes. Meta-analysis was used to quantitatively determine mean SOC responses to different crop residue management practices and to compute confidence limits around those means. Heterogeneity tests and meta-regression were also employed to identify the magnitude and sources of variations in the SOC responses.

2 | MATERIALS AND METHODS

2.1 | Global database

Data were collected from archived publicly available datasets or published peer-reviewed literature on corn stover management and SOC changes. To minimize publication bias, a literature review and database were compiled following four major steps: (a) collecting literature records using selected keywords, (b) screening and extracting data from qualified studies, (c) assessing data quality based on methods used and emphasis on detail provided by the authors, and (d) conducting statistical analysis (Charles et al., 2017). The review was limited to 3,380 peer-reviewed publications included in the Web of Science as of June 2018. Keywords for the review (Table 1) were developed by combining typical phrases associated with Web of Science literature searches.

First, abstracts of all papers were read to determine relevancy in a standardized manner, using a set of six criteria (Table 1). This resulted in 2,758 papers being rejected. For the remaining 622 papers, full-text screening was carried out using the same screening criteria. Eligible but duplicated studies were identified and removed from the database (Figure S1). The net result was 52 eligible studies, including two studies identified by co-authors but not returned from a Web of Science search. Multiple data sources (e.g., related publications, personal communications) were referenced to gather sufficient information for a meaningful evaluation of each study. Both corn grain (48) and corn silage studies (4) were included in the database, because the purpose of this meta-analysis was to evaluate the effect of aboveground biomass removal on SOC and the amount of dry matter of corn silage (~100% removal) is comparable to that of corn grain plus 100% stover harvest. Partial corn silage removal studies and sweet corn cultivars were excluded from this analysis.

Most studies were published between 2011 and 2018 (35) or 2001 and 2010 (12), with five published prior to 2000. Some studies reported from multiple locations, so the final database used for statistical analysis contained 74 unique experiment sites and 409 paired observations (non-removal vs. removal treatment). Unfortunately, many studies only reported SOC at the end of the experiment (hereafter, "final" SOC), so assessment of temporal SOC change was limited to 272 comparisons. All 409 observations were used for assessing the differences in final SOC stocks between removal and non-removal groups.

The 74 experiment sites included in our analysis were primarily located in the United States (40 sites) and China (17 sites) that contribute about 50% of global corn production (OECD & FAO, 2018). Furthermore, the site distribution was consistent with the spatial patterns of corn production. Most US sites were within the Corn Belt, while in China, sites were concentrated in the Northern provinces (Figure 1).

Among the 74 sites, 40 short-term (3–5 years), 26 medium-term (6–15 years), and eight long-term (>15 years) experiments were included (Figure 2a). We set a minimum duration of studies to 3 years to include as many experiments as possible and because significant SOC changes may be detected even within such a short timeframe (Blanco-Canqui et al., 2006;

TABLE 1 Keywords and criteria used in literature search

Crop keywords		Logical operator	SOC keywords		Logical operator	Farm management keywords	
	"Corn"	AND		"soil carbon"	AND		"residue"
OR	"Maize"		OR	"soil C"		OR	"stover"
OR	"*Zea mays*"		OR	"organic carbon"		OR	"straw"
			OR	"organic C"		OR	"tillage"
			OR	"soil organic matter"		OR	"manure"
			OR	"carbon sequestration"		OR	"irrigation"
			OR	"soil health"		OR	"irrigated"
			OR	"soil quality"		OR	"cover crop"

Criteria

- Corn was the predominant rotational crop (e.g., continuous corn, corn–soybean, corn–wheat, and corn–millet).
- Measurements or experiments were conducted 3 years or longer.
- The study had to be field experiments. Modeling, simulation studies, and laboratory incubations were excluded.
- Soil organic carbon was measured.
- Defined corn stover (residue) removal treatments were included in the experiment.
- The experimental design included both control (non-removal) and treatment (removal) groups.

Sindelar, Lamb, & Coulter, 2015). In terms of soil texture, medium-fine and medium soils were dominant (Figure 2b). For the 409 paired (control vs. treatment) data points, SOC sampling depth mostly fell within the range of 0–15 cm ($n = 180$) or 0–30 cm ($n = 156$) (Figure 2c), with only 73 data points sampled in a 30–150 cm soil depth. Median and maximum SOC sampling depth was 20 and 150 cm, respectively.

The most common tillage practice (Figure 2d) associated with the corn stover removal experiments was NT (208 data points), followed by conventional tillage (CT: 167) and reduced tillage (RT: 32). Tillage classification was defined based on implement type but not the number of passes. Two sites did not report tillage-specific results. Conventional tillage included moldboard plow, chisel plow, disk plowing, and rotary-till. Some studies reported CT without specifying the system. RT mainly included strip tillage and offset disking.

2.2 | Meta-analysis

Quantitative meta-analysis can help assess the overall effects and identify the sources of variation in outcomes (Gurevitch, Koricheva, Nakagawa, & Stewart, 2018), which may not be evident in individual studies because of conflicting results. Therefore, a common estimator used in meta-analysis is the magnitude of the experimental treatment mean (X_{TR}) relative to the control or reference mean (X_{CK}). Following Don, Schumacher, and Freibauer (2011) and Han et al. (2016), a logarithmic response ratio (RR) was calculated as the main effect size estimator (Equation 1):

$$\mathrm{RR} = \mathrm{Ln}\left(\frac{X_{TR}}{X_{CK}}\right) \tag{1}$$

In this study, X_{TR} and X_{CK} refer to SOC stock (Mg C/ha) of experimental treatment with and without corn stover removal practices, respectively, holding the other parameters constant. This estimator only considers SOC stocks at the end of the studies.

Differences in annualized SOC change rate (ΔSOC_R) between removal and non-removal cases were calculated because the absolute magnitude of changes in SOC stock over time is of interest:

$$\Delta\mathrm{SOC\_R} = \frac{\left(\mathrm{SOC}_{\mathrm{TR,T1}} - \mathrm{SOC}_{\mathrm{TR,T0}}\right) - \left(\mathrm{SOC}_{\mathrm{CK,T1}} - \mathrm{SOC}_{\mathrm{CK,T0}}\right)}{T} \tag{2}$$

$\mathrm{SOC}_{\mathrm{TR,T0}}$ and ~$\mathrm{SOC}_{\mathrm{TR,T1}}$ refer to the initial and final SOC stock for fields with stover removal. $\mathrm{SOC}_{\mathrm{CK,T0}}$ and $\mathrm{SOC}_{\mathrm{CK,T1}}$ represent the initial and final SOC stock under control (non-removal), and T is the duration of a study (years).

SOC change can be quantified in multiple ways, depending on the definition of baseline SOC stocks (Figure 3). Both RR and ΔSOC_R calculate SOC change relative to SOC stock with stover retention treatment as the baseline scenario (Figure 3). The two metrics are complementary to each other: RR evaluates percentage changes in final SOC stocks and ΔSOC_R assesses differences in annual SOC change rates. Note that if ΔSOC_R or RR is negative, it can be viewed as C loss relative to the baseline.

Because neither RR nor ΔSOC_R evaluated whether SOC stock in a given plot has increased or depleted since experiments initialized, average SOC accrual rates (i.e., changes in SOC relative to initial SOC levels, Mg C ha^{-1} year^{-1}) along with 95% confidence intervals

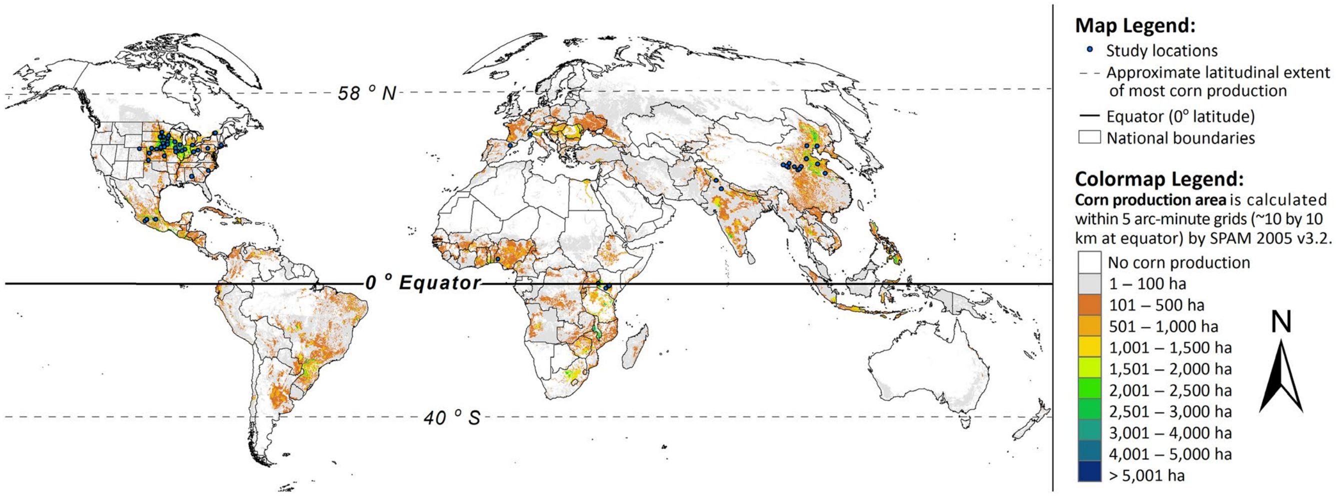


FIGURE 1 Location of experiment sites included in meta-analysis. Shaded color map shows distribution of major corn acreages worldwide. SPAM, Spatial Production Allocation Model (You et al., 2014)

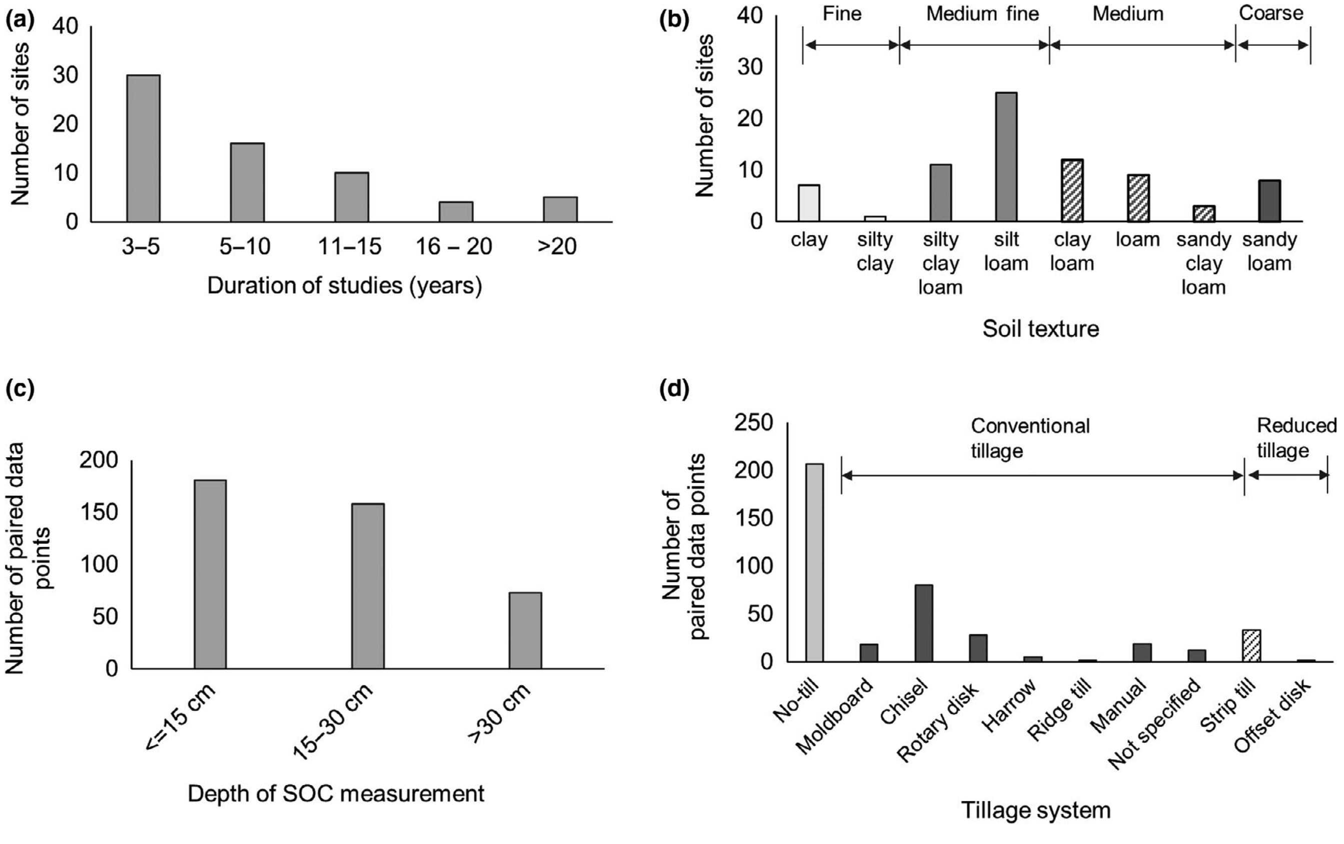


FIGURE 2 Distribution of studies by (a) duration of field experiment measurement, (b) soil texture of fields, (c) soil organic C (SOC) sampling depth, and (d) tillage system

were also calculated for various stover removal rates and tillage types. However, these descriptive statistics were not used in pairwise heterogeneity test or meta-regression analysis.

Using the two estimators defined above, a weighted meta-analysis was conducted using the Open Meta-analysis for Ecology and Evolution software (OpenMEE) (Wallace et al., 2017). In each experiment, mean, standard deviation (*SD*), and sample size (replicates) of SOC measurement were extracted to weight each study by variation (*SD*) and sample size (*n*). The *SD* of SOC stock was extracted for 62% of the studies. When it was not possible to extract *SD* or standard error (*SE*) information from a study, a *SD* equal to one-tenth of the mean was assigned, as was done

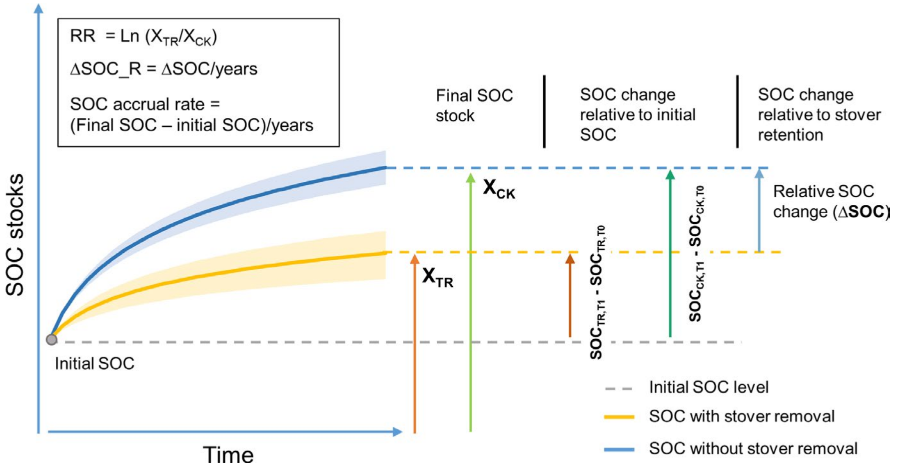


FIGURE 3 Illustration of soil organic C (SOC) change quantification based on dynamic baseline (SOC change relative to stover retention or non-removal) versus steady baseline (SOC change relative to initial SOC stock). Modified from Qin et al. (2018)

by others (Gattinger et al., 2012; Han et al., 2016; Luo, Hui, & Zhang, 2006).

To identify predominant drivers associated with the variations among observations, subgroup analysis was conducted by grouping paired observations into different groups based on biophysical (e.g., SOC sampling depth) and management practices (e.g., tillage system). The mean effect size of each group along with 95% confidence intervals (CIs) was reported. Meta-analysis generally uses either fixed-effect or random-effect models. A fixed-effect model only considers sampling variance and it assumes that effect size is the same in all studies, which is not plausible for independent corn stover experiments as site condition varies across studies. A random-effect model considers both sampling variance and heterogeneity as it assumes that the true effects are normally distributed (Gurevitch et al., 2018). "Random" here means studies can share similar but not identical true effects. In this study, the random-effect model was used because it is more general than a fixed-effect model.

Multiple factors can affect SOC dynamics simultaneously. To investigate potential drivers associated with the observed SOC differences, a random-effects meta-regression model was used. This was also run in the OpenMEE software. In addition to stover removal, a range of other factors including long-term average annual precipitation and temperature, which are known to influence SOC, were also tested.

To facilitate the interpretation of effect size, the response ratio was transformed as a percentage change ($[e^{RR} - 1] \times 100$), with zero suggesting no SOC difference between the removal and non-removal groups, and positive and negative values indicating lower and higher SOC stock in the removal groups than the no-removal groups, respectively. Differences in annualized SOC change rates (ΔSOC_R) between control and treatment groups were presented in physical units (Mg C ha^{-1} year^{-1}), with positive and negative values indicating that annual SOC sequestration rates with stover removal were higher or lower than corresponding non-removal sites.

2.3 | Data processing

For RR estimation, it was implicitly assumed that initial SOC stock was the same for both non-removal and removal plots, so that differences in final SOC stock between plots can be attributed to differences in farm management practices. We subsequently found that differences in measured initial SOC stocks of removal and non-removal sites were more than 5% for 70 comparisons (16% of total data points). To address this issue, for RR estimation, the final SOC stock for the removal group was adjusted based on differences between initial SOC stock reference values and treatment fields. For instance, if the initial SOC stock within a control plot was 5 Mg C/ha lower than the plot with stover removal treatment, 5 Mg C/ha was added to the final control plot value, so that the differences between removal and non-removal plots would not be overestimated. For subgroup analysis, data points were grouped into three intervals (0–15, 0–30, and 0–150 cm) based on each data point's sampling depth.

For ΔSOC_R, soil depth adjustment is necessary because it directly affects the absolute amount of SOC change. Among the 272 comparisons, most studies reported SOC stock for the 0–15 ($n = 83$), 0–30 ($n = 79$), or 0–60 cm ($n = 43$) depth increments. Measurements from studies with different sampling depths were adjusted to one of the three depths, which were used as standard profile segments. For observations with a sampling depth <30 cm and CT, it was assumed that SOC was uniformly distributed. For studies with NT, SOC measurements were converted to standard profiles based on vertical SOC distribution patterns. For instance, a conversion factor of 1.35, instead of 1.5, was used to convert 0–20 cm SOC stock to 0–30 cm values (Puget & Lal, 2005; Yang & Wander, 1999). This was done because C concentration in the surface layer is generally higher within NT systems. Because previous studies rarely reported vertical SOC distribution beyond the 0–100 cm interval, seven data points with a depth >100 cm were excluded from ΔSOC_R analysis to minimize uncertainties caused by depth adjustment. With that, maximum soil profile used in annual SOC change analysis was 60 cm rather than 150 cm as used in the RR analysis. More details on SOC stock adjustment can be found in the Supplementary Information.

For studies reporting fixed-depth SOC, the original SOC measurement was transformed to ESM (Ellert & Bettany, 1995) when possible. This was necessary because soil bulk density may change substantially over a monitoring period, due to differences in management practices and other factors. Among the 74 experiment sites, 23 reported SOC based on ESM. Using initial and end SOC concentration (%) and bulk density data, we adjusted the end SOC based on ESM for another 11 sites. The remaining 40 sites did not have sufficient information for ESM adjustment.

For meta-analysis, the dataset used in all calculations includes both ESM and fixed-depth measurements. This is necessary to include as many eligible studies as possible, and to test the impact of SOC calculation method on meta-analysis results.

3 | RESULTS

3.1 | Effects of corn stover removal on SOC stock

3.1.1 | Response ratios grouped by management practices and soil properties

Compared to control plots (stover retention), final SOC stocks were lower (Figure 4a) if stover was removed and RR varied by the soil profile intervals. For data points in the 0–15 and 0–30 cm profiles, plots with stover removal had an average of 7.4% and 8.4% less stored SOC than stover retention plots, respectively. Furthermore, for studies that reported SOC change over the 0–150 cm profile, there was no significant difference in SOC stock due to stover removal treatment ($p > 0.91$). Note that 150 cm is the maximum sampling depth, and all data points with a SOC sampling depth greater than 30 cm are included in the 0–150 cm profile. Note that many studies reported SOC for only one of the three profile intervals (i.e., 0–15, 0–30, 0–150 cm), so that the number of data points varied by SOC sampling depth. The database includes only 73 observations with a sampling depth >30 cm, which thus represents a relatively small fraction of the entire database. Among the 74 sites, 29 sites reported SOC for both 0–15 and 0–30 cm intervals, and 12 sites reported SOC for all three intervals. When studies reported SOC at multiple depths (e.g., 0–15 and 0–30 cm), both surface and subsurface layers were included in our analysis.

In addition to soil profile intervals, RR also varied by soil texture (Figure 4b), tillage system (Figure 4c), and stover removal rate (Figure 4d), though differences between various soil texture and tillage systems were not statistically significant. Response ratios of medium-fine (−5.6%) and medium (−5.8%) soils were close to each other. RR for fine and coarse soils was larger than 10%, but sample size of both groups was small (Figure 4b), so the results may be less robust. In terms of tillage, magnitudes of SOC change under CT (−7%) were slightly larger than NT (−6.4%), suggesting that removal may have a relatively smaller impact on SOC when NT is adopted. However, the difference in mean values was not significant ($t = -0.522$, $p = 0.602$). Results for RT were determined to be unreliable due to the small sample size ($n = 32$). RR was sensitive to the intensity of stover removal (Figure 4d). While high removal (>75%)

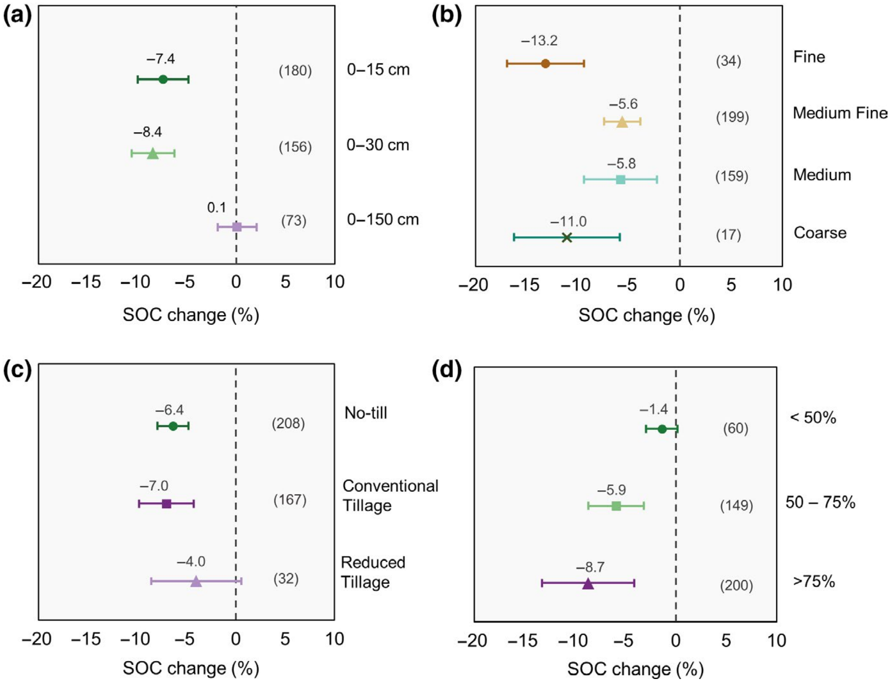


FIGURE 4 Changes in final soil organic C (SOC) stock (%) (mean with 95% confidence intervals [CIs]) by different (a) soil profile intervals, (b) soil texture, (c) tillage system, and (d) corn stover removal rate. Positive and negative values correspond to stover removal stored more and less SOC than stover retention (control) plots, respectively. Error bar represents 95% CIs, and numbers in parentheses represent number of paired comparisons in each category

reduced SOC stock by 8.7% on average, compared to stover retention, reduction in SOC was only about 1.4% for fields with moderate (<50%) removal rates. The difference between RR of moderate (<50%) and medium (50%–75%) removal groups was significant ($t = -2.913$, $p = 0.004$), but the difference between high and medium removal RR was not significant ($t = -1.532$, $p = 0.126$).

Given that NT may affect surface soil carbon concentration more than sub-surface layers, RR was also calculated by different tillage systems and SOC sampling depths (Figure 5). The results suggested that SOC change in the 0–15 cm profile was marginally smaller for fields with a NT (mean = −7.4%, *SE* = 1.11) than CT (−8.6%, *SE* = 2.94) (Figure 5), but the difference between CT and NT was not statistically significant ($t = 0.425$, $df = 157$, $p = 0.671$) because CT fields have a large variance. The response ratio calculated for the 0–30 cm profile suggested that SOC change under NT and CT was close to each other. When SOC change was reported for the 0–150 cm profile, the mean RR for NT and CT was 1.82% (*SE* = 1.51) and −1.69% (*SE* = 1.41), respectively, and the difference between NT and CT was significant at a 0.1 level ($t = -1.671$, $df = 69$, $p = 0.099$). However, due to the relatively small sample size, more research is needed.

The response of SOC to stover removal rate also varied by sampling depth (Figure 6). When SOC stock was measured for the 0–15 or 0–30 cm soil profiles, the mean SOC change was much smaller under moderate removal (<50%) than medium (50%–75%) or high (>75%) removal rates. At the 0–15 cm profile, the RR of the moderate removal (<50%) group was close to zero (mean = −1.4%, *SE* = 1.82) and not significantly different from zero, suggesting small differences in SOC stock between the removal and non-removal sites. In contrast, a much stronger SOC response (mean RR = −9.3%, *SE* = 2.33) was associated with high stover removal treatment. A *t* test showed that differences between the high and moderate removal groups were statistically different ($t = 1.915$, $df = 117$, $p = 0.058$). Differences between SOC change rates of the moderate (mean = −2.8%, *SE* = 1.82) and high removal groups (mean = −9.6%, *SE* = 1.92) were smaller in the 0–30 cm profile and marginally significant at a 0.1 level ($t = 1.642$, $df = 97$, $p = 0.102$). For SOC measurements based on the 0–150 cm profile, SOC stocks under moderate removal were higher than under high removal, but the differences were not statistically significant ($p = 0.384$).

3.1.2 | Fixed-depth versus equivalent soil mass

Because both fixed-depth and ESM results were included in the meta-analysis, effect size and variance for each method were also calculated separately to evaluate the impact of SOC calculation method on RR. The dataset was first divided into two parts based on SOC calculation method (fixed-depth or ESM), and then, a subgroup analysis based on tillage (Figure 7a) or stover removal intensity (Figure 7b) was conducted for each part of the database. Results suggest that differences due to ESM can overwhelm variations caused by tillage and removal rate (Figure 7). With respect to

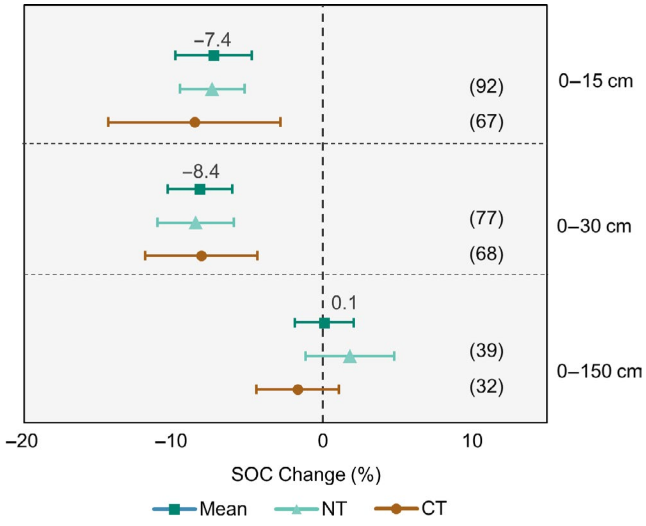


FIGURE 5 Changes in final soil organic carbon stock (%) (mean with 95% confidence intervals [CIs]) by different tillage systems and soil sampling depth. Error bar represents 95% CIs, and numbers in parentheses represent number of paired comparisons in each category. “Mean” category measures mean (with 95% CIs) response ratios for each soil organic C (SOC) sampling depth. NT and CT refer to no-till and conventional tillage

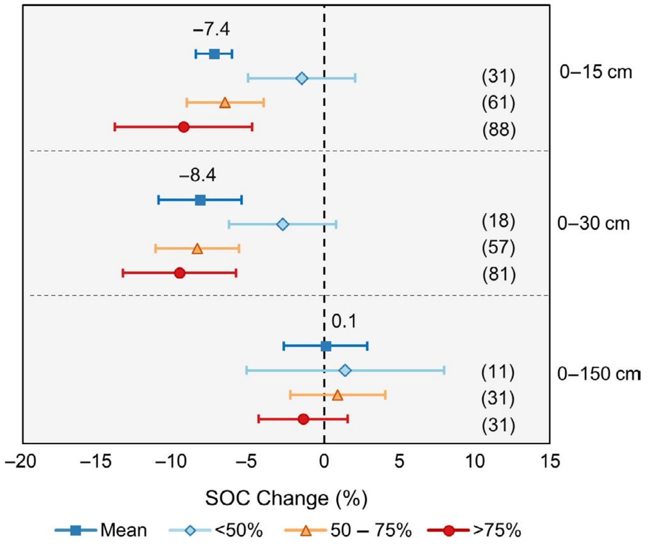


FIGURE 6 Changes in final soil organic carbon stock (%) (mean with 95% confidence intervals [CIs]) based on removal rate and soil organic C (SOC) sampling depth, compared to stover retention. Error bars represent 95% CIs. Numbers in parentheses refer to number of paired data points. For each SOC sampling depth category, mean affect size (with 95% CI) averaged across residual removal intensity was also presented (labeled as “Mean” in legend)

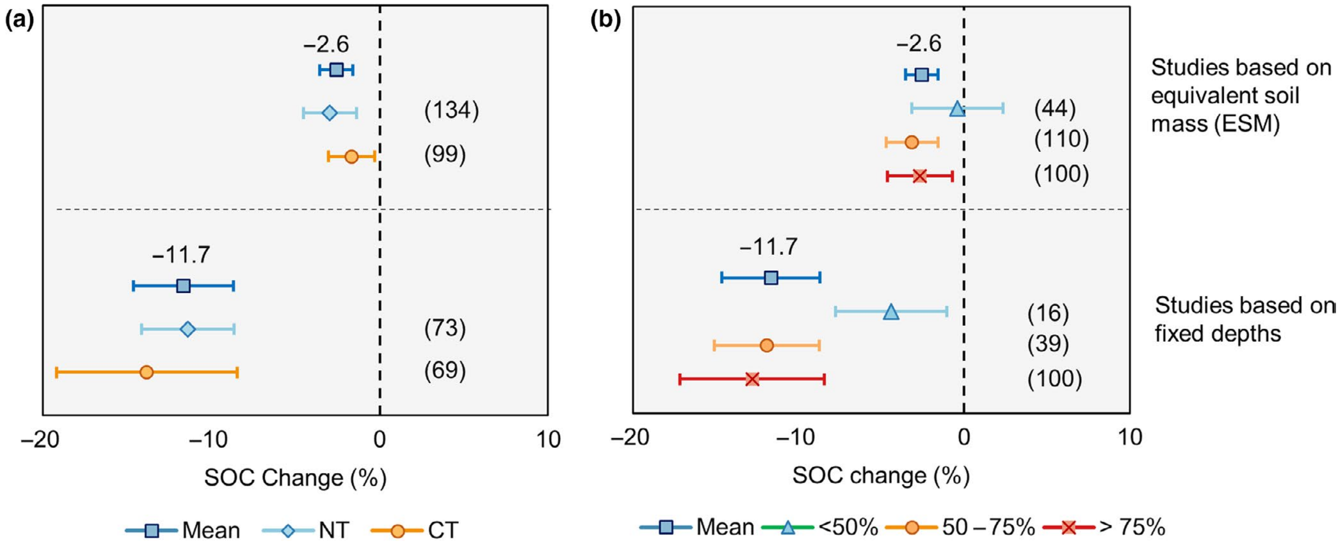


FIGURE 7 Changes in soil organic carbon stocks (%) (mean with 95% confidence intervals [CIs]) for observations with (a) different ESM status and tillage systems, and (b) different ESM status and stover removal rates. Error bars represent 95% CIs. Numbers in parentheses refer to number of paired data points. NT and CT refer to no-till and conventional tillage.

the high removal, studies reported based on ESM suggested that stover removal lowered SOC stock by 2.6%. However, observations with fixed-depth measurements indicated that stover lowered SOC stock by 11.4%. Still, one of the caveats with heterogeneity test is that it focuses on one variable at a time so that variations caused by multiple factors (e.g., crop rotation, precipitation) were not considered in the test. In this case, the impacts of ESM on RR may be overestimated in subgroup analysis. Meta-regression presented in the following section was designed to address this issue.

3.1.3 | Meta-regression analysis

Meta-regression analysis suggested that end SOC stock, SOC reporting method (ESM or fixed-depth), sampling depth, duration of studies, and crop rotation were the five most significant variables explaining the variation in response ratios (Table 2). Tillage, N fertilizer rate, irrigation status (rainfed or irrigated), and climate (mean annual precipitation and mean temperature) were not significant variables. Variance analysis suggested that 70.8% of the total variance was between studies ($I^2 = 70.7\%$), and the covariates were able to explain 44.6% of the between-study variance ($R^2 = 44.7\%$).

Consistent with subgroup analysis results, meta-regression analysis confirmed that SOC changes were sensitive to corn stover removal rate, but not tillage type. Compared to moderate removal (<50%), medium and high removal treatments may further reduce SOC stock by about 3%. Estimates of CT and RT were not statistically different from zero ($p > 0.1$), suggesting that tillage was not a significant predictor.

Estimated coefficients for end SOC stock (0.002), ESM (0.068), and corn–soybean rotation (0.077) were positive. Holding other parameters constant, a positive coefficient suggested a smaller difference in end SOC stock between removal and non-removal treatments. These results indicated that stover removal had a smaller impact on plots with higher SOC content, if other conditions were equivalent. Note that the SOC stock variable refers to the final SOC stock rather than the initial SOC stock, because approximately half of the studies did not report initial SOC values. The ESM estimated SOC losses were about 7% less than the fixed-depth measurements. Similarly, reductions in SOC stock were 7.5% smaller for plots with corn–soybean rotations than continuous corn.

Negative coefficients for duration (years) and SOC sampling depth suggested that differences in SOC stock between removal and non-removal sites increased with study duration and sampling depth. It is reasonable that differences in SOC stock tend to be larger for longer term studies than short-term studies because changes in SOC stock due to stover removal may accumulate over years. Similarly, compared to studies focusing on the 0–15 cm profile, reductions in final SOC stock were 4.2% or 9.7% larger on average, in the 0–30 and 0–150 cm profile, respectively. While subgroup analysis suggested that stover removal only affects SOC stock in the 0–30 cm profile, meta-regression results suggested that stover removal influenced SOC stock beyond the 0–30 cm profile.

3.2 | Effects of corn stover removal on SOC change rate

3.2.1 | SOC accrual rates

For plots with stover returned rather than removed, SOC accrual rate calculated from experimental baseline (initial SOC

TABLE 2 Meta-regression results for soil organic C (SOC) change response ratio (SOC stocks)

Variable	Point estimate	Standard error	p-value	95% lower	95% upper	Significance level
Intercept	−0.139	0.038	<0.001	−0.213	−0.065	***
Duration (years)	−0.003	0.001	0.005	−0.006	−0.001	**
SOC stock of treatment plot (Mg C/ha)	0.002	0	<0.001	0.001	0.002	***
N fertilizer rate[a]	−0.001	0.001	0.387	−0.002	0.001	
Mean annual precipitation[b]	0.002	0.002	0.311	−0.002	0.007	
Mean temperature (°C)	0.001	0.002	0.444	−0.002	0.004	
Irrigation applied	0.02	0.02	0.314	−0.019	0.059	
Based on ESM	0.068	0.014	<0.001	0.042	0.095	***
Soil, fine texture	−0.058	0.028	0.041	−0.113	−0.002	*
Soil, coarse texture	−0.037	0.031	0.239	−0.099	0.025	
Soil, medium texture	−0.04	0.014	0.005	−0.068	−0.012	**
Corn–millet rotation	0.028	0.054	0.607	−0.078	0.133	
Corn–soybean rotation	0.077	0.02	<0.001	0.039	0.116	***
Corn–wheat rotation	−0.027	0.026	0.305	−0.079	0.025	
SOC sampling depth (>30 cm)	−0.097	0.027	<0.001	−0.149	−0.044	***
SOC sampling depth (0–30 cm)	−0.042	0.014	0.003	−0.069	−0.014	**
Stover removal rate (>75%)	−0.033	0.017	0.047	−0.066	0	*
Stover removal rate (50%–75%)	−0.035	0.017	0.034	−0.068	−0.003	*
Conventional tillage	0.019	0.012	0.113	−0.005	0.043	
Reduced tillage	0.02	0.021	0.343	−0.021	0.062	
Test of the model						
T2 = 0.006 (*SE* = 0.001), I2 = 70.81%, R^2 = 44.62%						
Test for residual heterogeneity						
QE = 1,546.525, *df* = 387, $p < 0.001$						
Test for moderators						
QM = 208.211, *df* = 19, $p < 0.001$						

Note: Positive and negative estimates suggest smaller and larger differences between removal and non-removal groups, respectively. ESM status, soil texture, crop rotation, SOC sampling depth, stover removal rate, and tillage are categorical covariates. Their reference values were fixed-depth method, medium fine texture, continuous corn, 0–15 cm sampling depth, moderate removal group (<50%), and no-till, respectively.

Significant levels: 0 "***" 0.001 "**" 0.01 "*" 0.05.

[a] Raw N rate data were divided by 10, so one unit of change is 10 kg N/ha/year.

[b] Raw precipitation data were divided by 100, so one unit of change is 100 mm/year.

level) tended to be positive (mean = 0.41 Mg C ha^{-1} year^{-1}, CI = 0.25, 0.58) (Figure 8). While the magnitude of SOC accrual rate is relatively small, *t* test shows that it is significantly different from zero ($t = 4.796$, $df = 271$, $p < 0.01$).

Calculation of SOC change induced by stover removal depends on the definition of baseline and management practices. When reference fields (stover retention) were used as the baseline, treatments in which the stover was removed generally had lower SOC accrual rates. This difference in SOC sequestration rates can be viewed as "foregone carbon sequestration." If the baseline scenario is pretreatment or initial SOC stock, final SOC stock tends to increase over time under NT and lower removal intensity treatment, and to decrease over time under CT and high removal intensity treatment (Figure 8). For instance, for NT fields, mean SOC accrual rates under medium (50%–75%) (mean = 0.32 Mg C ha^{-1} year^{-1}, *SD* = 1.08) and low were positive and significantly greater than 0, suggesting that fields with stover removal treatment may still accumulate SOC over time, although only marginally. Wilhelm, Johnson, Karlen, and Lightle (2007) had similar results, and reported that less stover biomass input was needed to maintain SOC under NT than CT, and that stover produced beyond the amount needed to maintain SOC and address other environmental issues could be removed for other uses. For fields under CT, the mean SOC accrual rates were

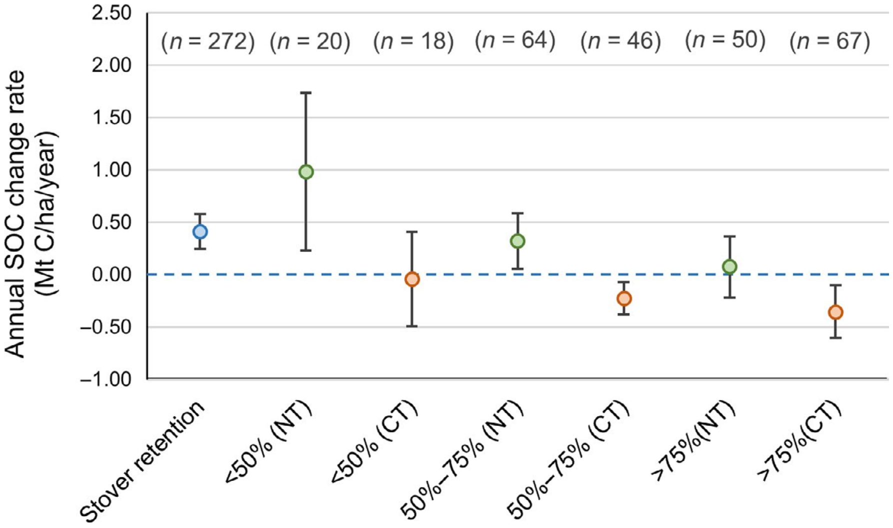


FIGURE 8 Soil organic C (SOC) accrual rate from experimental baseline (initial SOC level) (Mg C ha^{-1} year^{-1}, mean with 95% confidence intervals [CIs]) for control (stover retention, averaged for conventional tillage [CT] and no-till [NT]) and treatment cases grouped by different tillage types and removal rates from descriptive statistics. Positive values mean that SOC stock increased over time, and negative values mean that SOC stock decreased over time. Stover retention group was calculated based on all 272 control data points. Error bar represents 95% CIs. Values in parentheses represent number of data points in each treatment group

negative even under the moderate stover removal treatment (Figure 8). A t test showed that differences between SOC accrual rates of NT and CT plots were statistically significant under moderate ($t = 3.053$, $df = 36$, $p = 0.004$), medium ($t = 3.155$, $df = 108$, $p = 0.002$), and high removals ($t = -2.177$, $df = 115$, $p = 0.0315$).

It is necessary to point out that data presented in Figure 8 represent SOC accrual rates grouped by different tillage and removal treatments. These descriptive statistics are different from meta-analysis statistics because they were not pairwise heterogeneity tests. With that, although mean SOC change rate for NT with <50% treatment (0.98 Mg C ha^{-1} year^{-1}, $SD = 1.72$) was higher than 0.41 Mg C ha^{-1} year^{-1}, it does not mean that NT (<50%) treatment has the highest SOC accrual rate. This is because mean value for the retention treatment group was computed based on all 272 control data points, whereas the 0.98 value was computed for the group of data points ($n = 20$) with NT and <50% removal rates only. If mean value of stover retention treatment was calculated based on the 20 corresponding control (stover retention) data points, then there were no statistical differences between retention and NT (<50%) treatment ($t = 0.133$, $df = 38$, $p = 0.895$). Results based on pairwise meta-analysis (ΔSOC_R) were presented in the next section.

Note that mean SOC change rates were calculated from data points with varying sampling depths (0–15, 0–30, and 0–60 cm). Averaged across all crop systems, the SOC accrual rates with stover retention treatment in the 0–15 and 0–30 cm intervals were 0.39 and 0.49 Mg C ha^{-1} year^{-1}, respectively (Figure 9). The mean SOC change rate (0.29 Mg C ha^{-1} year^{-1}, $SD = 0.17$) was smaller for data points with a sampling depth >30 cm. However, most studies did not compare SOC change at both 0–30 and 0–60 cm depths, and the sample size for the 0–60 cm profile was relatively small (57). In this case, the results for the 0–60 cm profile may not be representative. Furthermore, differences in mean SOC change rates among the three groups were not statistically significant ($p > 0.5$).

For biofuel policy-making in the United States, whether domestic SOC response is consistent with the international database is relevant. Overall, SOC accrual rates in US Midwestern states (Figure S2) were similar to values in the global database (Figure 8), partly because most

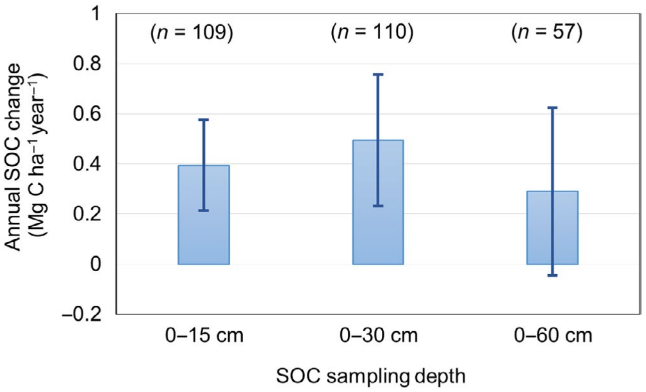


FIGURE 9 Soil organic C (SOC) accrual rate (Mg C ha^{-1} year^{-1}) (mean with 95% confidence intervals [CIs]) by SOC sampling depth for plots with stover retained in fields. Positive values mean that SOC stock increased over time, and negative values mean that SOC stock decreased over time. Error bars represent 95% CIs

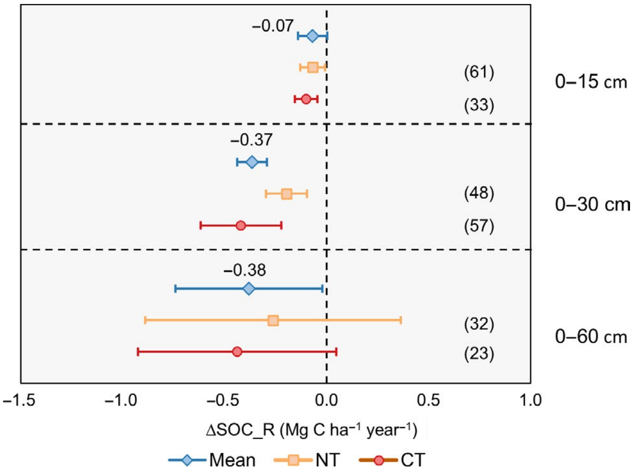


FIGURE 10 Weighted differences in annualized soil organic C change rates (ΔSOC_R) (Mg C ha^{-1} year^{-1}) for data points with different sampling depths and tillage systems (mean with 95% confidence intervals [CIs]). Error bars represent 95% CIs. Numbers in parentheses are the number of data points in each group. NT and CT refer to no-till and conventional tillage.

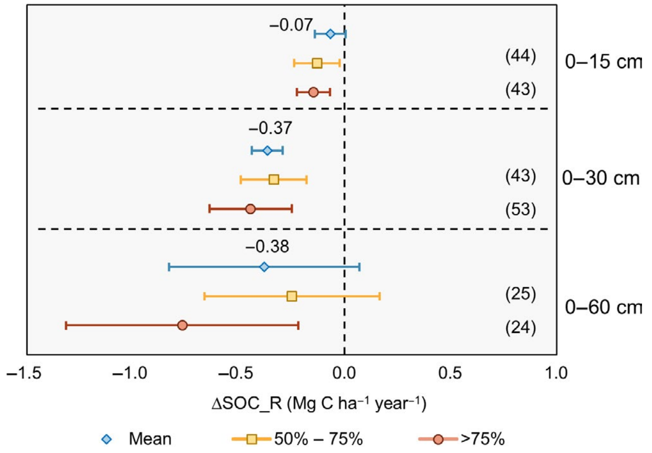


FIGURE 11 Weighted differences in annualized soil organic C change rates (ΔSOC_R) (Mg C ha^{-1} year^{-1}) for different soil depths and stover removal rates (mean with 95% confidence intervals [CIs]). Error bars represent 95% CIs. Numbers in parentheses are the number of data points in each group. 50%–75% and 75% refer to stover removal rate

comparisons (214, or 78%) were from this highly productive, corn-producing region. Most studies outside the United States did not report initial SOC content. SOC sequestration under retention treatment was relatively smaller than the group database: Midwest SOC accrual rate for the non-removal group (mean = 0.19 Mg C^{-1} ha^{-1} year^{-1}, *SD* = 1.175) was lower than that in the global database (mean = 0.41 Mg C ha^{-1} year^{-1}). Although the magnitude of C sequestration is relatively small, this positive trend was significantly different from zero ($t = 2.43$, $df = 214$, $p = 0.02$).

3.2.2 | Differences in annualized change rates

Differences in annualized SOC change rates (ΔSOC_R) between pairwise removal and non-removal plots were calculated for both tillage systems and sampling depths in the meta-analysis. The mean ΔSOC_R of NT was smaller than that of CT plots, but the difference between the two was not statistically significant for the 0–15 and 0–60 cm profiles (Figure 10). For the 0–30 cm profile, the ΔSOC_R of NT plots (mean = −0.196 Mg C ha^{-1} year^{-1}, *SD* = 0.353) were marginally smaller than those of CT plots (mean = −0.42 Mg C ha^{-1} year^{-1}, *SD* = 0.763), and the differences were statistically significant at a level of 0.1 ($t = -1.872$, $df = 103$, $p = 0.064$).

The ΔSOC_R calculated based on SOC sampling depth and stover removal rate (Figure 11) indicated that higher stover removal rates were associated with larger differences in annual SOC change rates. Compared to non-removal treatments, high removal lowered SOC accumulation rates by 0.15, 0.44, and 0.77 Mg C ha^{-1} year^{-1} on average for the 0–15, 0–30, and 0–60 cm profile intervals, respectively (Figure 11). Nonetheless, the differences between the ΔSOC_R of high and medium removal groups were not statistically significant ($p > 0.1$) at all three sampling depths. The moderate removal group was excluded from this analysis because sample size was less than 10 in most sampling depths.

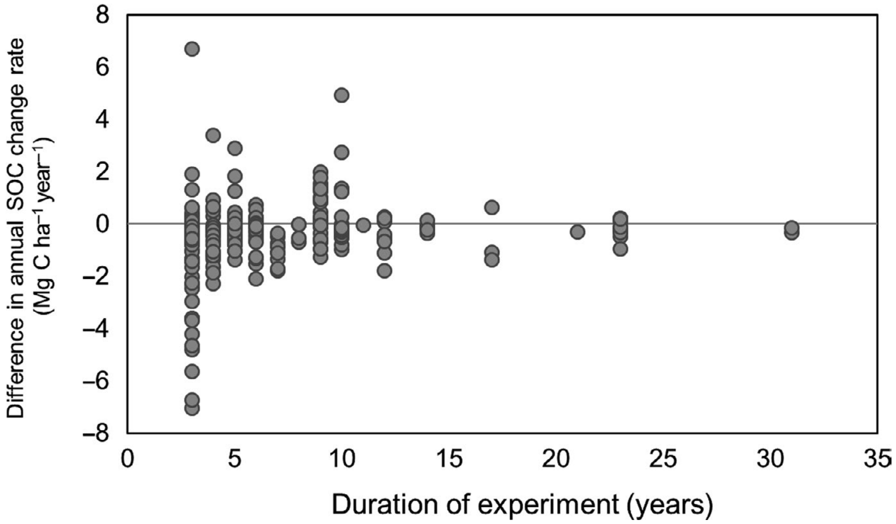
Differences in annualized SOC change rates between removal and non-removal groups depended on the field experiment duration. Overall, the magnitudes of ΔSOC_R were larger for short-term (<5 years) than longer term studies (Figure 12). On average, ΔSOC_R tended to be negative (mean = −0.63 Mg C ha^{-1} year^{-1}, *SD* = 1.63) for short-term studies, but ΔSOC_R approached zero for longer term (>10 years) studies (mean = −0.08 Mg C ha^{-1} year^{-1}, *SD* = 0.94). Even though annualized SOC change tended to decrease with time, accumulated differences in SOC stock were larger for longer term studies, as indicated by meta-regression analysis (Table 2).

4 | DISCUSSION

4.1 | Stover removal reduced SOC stocks compared to retention

Understanding how agricultural management, site characteristics, and residue removal intensity impact SOC stock changes is critical in maintaining soil fertility and health as well as determining science-based policy recommendations for carbon management. Our global synthesis of 409 data points found that stover removal generally reduced SOC stocks by about 8% in the 0–15 or 0–30 cm profile,

FIGURE 12 Differences in annualized soil organic C change rates (ΔSOC_R) plotted against the duration of field experiment measurements



compared to when stover was returned, irrespective of soil properties and tillage system. However, the magnitude of SOC stock reduction depended on the intensity of stover removal, the soil depth considered, and crop rotation with tillage having a relatively little effect. The SOC stock decreased with increasing stover removal rate, which was consistent with previous findings (Anderson-Teixeira et al., 2009; Johnson et al., 2006, 2014; Larson, Clapp, Pierre, & Morachan, 1972). On average, SOC stocks under moderate removal rate (<50%) were 1.4% lower in SOC (RR = −1.4%) than corresponding non-removal plots, and plots with high removal (>75%) had 8.7% lower SOC stocks. Note that this reduction refers to "foregone C sequestration" (Figure 3), rather than soil C change over time. A previous meta-analysis (Qin et al., 2016b) reported that stover removal did not reduce SOC stocks. In fact, SOC stocks increased by 15%–23% when stover removal rate is less than 70%. A key difference between Qin et al. (2016b) and this analysis is that response ratios were calculated differently: Qin et al. (2016b) evaluated SOC change over time in the same field, whereas RR in this study was calculated based on final SOC stocks of fields with stover removal and stover retention treatments. In addition, Qin et al. (2016b) did not evaluate additional variables (e.g., soil texture, precipitation) other than removal intensity. When additional important variables were included, meta-regression results confirm that stover removal rate was still a significant variable, but the magnitude of SOC change was relatively smaller. Holding other parameters constant, removing 50%–75% stover can further reduce SOC by about 3% when compared to moderate removal. This 3% reduction found by meta-regression was less than half the 7% difference identified in subgroup meta-analysis, due to normalization across site variables (i.e., variations caused by soil properties, tillage, and SOC stock calculation methods). These results indicated that limiting stover removal to a low level (e.g., 30%–40%) could minimize the adverse impacts of stover removal on SOC, as is currently the recommended practice. Owen et al. (2016) suggested that up to 50% of stover may be removed sustainably, if the grain yield was higher than 11 Mg ha^{-1} year^{-1} based on a synthesis of field data from the Sun Grant Regional Feedstock Partnership. It is important to remember that higher yields produce more stover and, for corn, the harvest index (grain/(grain + stover)) is approximately 0.5. Harvesting 50% of 11 Mg/ha leaves 5.5 Mg/ha of residue, which some have suggested is an appropriate maintenance requirement (Johnson et al., 2014; Owens et al., 2016).

While field experiments often included both low and high removal treatments, intensive removal is unlikely to be widely adopted because farmers recognize the need for corn residues to protect the soil and replenish soil organic matter (Obrycki & Karlen, 2018; Schmer, Brown, Jin, Mitchell, & Redfearn, 2017). In the Corn Belt, stover removal can also be limited by conservation guidelines. For instance, conservation tillage systems require 30% groundcover to meet policy requirements (e.g., commodity program conservation compliance; Tyndall, Berg, & Colletti, 2011). Because RR was only about 1.4% on average, a low removal (e.g., 30%) rate may be feasible, especially when there are additional C inputs and conservation practices (e.g., manure, cover crop; Wegner et al., 2015). On a national (United States) average basis, Qin et al. (2018) projected that SOC stock could still increase with 30% stover removed, if cover crop and manure application practices were also adopted.

Residue removal reduced SOC stocks in both the 0–15 and 0–30 cm profiles, which was consistent with observations from previous field experiments (Clay et al., 2015; Schmer, Jin, Wienhold, Varvel, & Follett, 2014). However, according to subgroup analysis (Figure 3a), this reduction in SOC stock by stover removal was close to zero when the entire 0–150 cm profile was considered. Some studies suggest that stover removal primarily influences near-surface SOC dynamics (Blanco-Canqui & Lal, 2007; Halvorson & Stewart, 2015; Stewart et al., 2015). For instance, a 5-year study in South Dakota found that residue removal influenced C cycling in the 0–15 and 15–30 cm depths, but did not affect SOC turnover in the 30–60 cm depth (Clay et al., 2015). A 10-year study in Nebraska also found that stover removal did not affect SOC beyond the 0–30 cm profile (Schmer et al., 2014). However, most studies (82% of the total data points) did not compare SOC change beyond 30 cm; more data are needed to validate whether there are stover removal effects at depths greater than 30 cm.

Agricultural management effects, such as stover removal, could be difficult to detect when SOC change was integrated over a large profile interval (Kravchenko & Robertson, 2011), but studies do detect deep SOC changes. While subgroup analysis suggested that residual removal did not affect SOC beyond the 0–30 cm profile, meta-regression analysis indicated that reduction in SOC stock was larger in the 0–150 cm interval than the 0–15 or 0–30 cm interval. In fact, some field experiments (Huang, Yang, Huang, & Ju, 2018; Stewart, Halvorson, & Delgado, 2017) found that changes in tillage and C input can affect deep SOC, probably because deep SOC can be susceptible to decomposition and priming from the addition of new labile organic C. For instance, a 13 year study found that adoption of NT reduced corn-derived C in layers deeper than 30 cm, which in turn reduced SOC (Stewart et al., 2017). Follett, Vogel, Varvel, Mitchell, and Kimble (2012) reported that more than 50% of the increase in SOC was below the 30 cm depth. Other studies also found that changes in SOC stock due to crop management practices can be more significant at the 30–100 cm depth than at the 0–30 cm depth (Fan et al., 2014; Huang et al., 2018; López-Bellido, Fontán, López-Bellido, & López-Bellido, 2010). The mechanisms of deep soil change are not well measured or understood. Possible explanations include leaching of dissolved organic carbon, changes in C input from upper soil, bioturbation caused by earthworms, and changes in root distribution (Kinoshita, Schindelbeck, & Es, 2017; Stewart et al., 2017).

Effects of tillage on response of SOC to stover removal were not consistent and small compared to other agricultural management practices. On the one hand, mean SOC accrual rates grouped by tillage (Figure 8) suggested that, averaged across studies, NT fields sequestered more C than CT fields, given similar stover removal intensity. On the other hand, tillage was not a significant predictor in the meta-analysis heterogeneity test and meta-regression, largely due to the large variability of response ratio under CT (Figure 5). Unlike NT, CT is a general term that includes many different types of tillage systems (Figure 2d) with varying tillage depths, and some sites were tilled multiple times. For this reason, although NT fields presented higher mean SOC accrual rates, benefits of NT relative to CT were highly variable at the site level. A key difference between meta-analysis and descriptive statistics (Figure 8) is that meta-analysis evaluates differences in paired-site experiments, but descriptive statistics simply compare SOC change rates among different treatment groups without considering site-level differences. These results suggest that NT fields may store slightly more SOC than CT fields (averaged values for all studies), but the benefit of NT relative to CT is highly variable in paired-site experiments.

Residue removal effects on SOC stocks are a function of the interaction of stover removal intensity and tillage (Figure 8). For instance, differences between NT and CT SOC change rates tend to diminish with higher stover removal rates (Figure 8). This is because the amount of crop residues strongly affects SOC sequestration; therefore, stover removal will reduce surface biomass input and diminish the benefits of NT (Zhang, Lal, Zhao, Xue, & Chen, 2014). A recent meta-analysis on NT and SOC (Du, Angers, Ren, Zhang, & Li, 2017) also found that the response of SOC stock to NT system was greater when residue was returned; response was not significant when residue was removed ($p = 0.099$). Because stover removal intensity appears to be a robust predictor across studies, whereas the effect of tillage on SOC is more variable, future efforts aiming to utilizing stover resource sustainably should probably focus more on identifying proper stover removal intensity.

The greater sensitivity of meta-regression allowed us to detect crop rotation effects on SOC stocks, when the subgroup analysis did not. Using meta-regression, we found that reductions in final SOC stocks due to stover removal were 7.7% lower under corn–soybean rotation compared to continuous corn fields. In other words, corn–soybean rotation was able to preserve SOC better than continuous corn. Under multicrop rotations, corn stover removal would not happen every year, so that its impact on SOC would be smaller compared to continuous corn. By synthesizing 55 studies, Ugarte, Kwon, Andrews, and Wander (2014) also found that a multicrop rotation (3 years) can increase SOC by 7%–25% compared to a continuous corn system, though crop residue removal was not considered.

4.2 | SOC change rate and baseline definition

SOC change is an important component in biofuel LCA and bioenergy policy discussions (Qin, Dunn, Kwon, Mueller, & Wander, 2016a). SOC change should be evaluated using a baseline because conclusions on SOC change can differ depending on the definition of the baseline (Qin et al., 2016a, 2016b). Two general themes: SOC change overtime and “foregone” C sequestration were included in this analysis.

Meta-analysis based on response ratio (RR) and differences in annual SOC change rate (ΔSOC_R) use SOC stocks under retention treatment as the reference or baseline scenario. With this baseline definition, both RR and ΔSOC_R-based analysis found stover removal SOC stocks were lower than non-removal plots. Because stover retention can store more C than removal, difference between retention and removal treatment SOC stocks can be viewed as "foregone" C sequestration or C debit for stover removal. If net SOC change was assessed by comparing initial and final SOC stocks overtime, this study found that stover retention generally increased SOC stock overtime, but moderate stover removal may also maintain or even increase SOC stock over time. Nonetheless, meta-analysis based on ΔSOC_R indicated that SOC accrual rates with medium and high stover removal rates were lower than non-removal plots (negative ΔSOC_R values, Figure 11). Depending on the definition of baseline scenario, corn stover as a bioenergy feedstock may either receive a C credit because moderate removal treatment may still increase initial SOC stock or carries C debit because it lowered SOC sequestration rate compared to residue retention. These results suggest that it is important to clarify the baseline used for SOC change assessment and to distinguish between absolute changes versus relative changes when evaluating the impact of stover removal on SOC.

Stover removal lowered SOC accrual rates overall, but differences in annual SOC change rates tended to decrease with time. These results are consistent with first-order kinetics (Guzman & Al-Kaisi, 2010; Janzen et al., 1998; Lal, 2004; Lugato, Berti, & Giardini, 2006; West & Post, 2002). As a result, ΔSOC_R, which was calculated by dividing the SOC change by the number of years, will be smaller for long-term studies, as changes in SOC were concentrated in the first few years.

Our findings on SOC change rate are consistent with Qin et al. (2016a) but different from Anderson-Teixeira et al. (2009). While Anderson-Teixeira et al. (2009) found that corn stover removal consistently resulted in SOC losses (3–8 Mg/ha) in the top 30 cm, Qin et al. (2016a) suggested that stover removal did not reduce SOC. Differences between Anderson-Teixeira et al. (2009) and our analysis can be attributed to multiple reasons, but the main factor might be the number of sites included in each study. Anderson-Teixeira et al. (2009) included 15 data points from five sites in their analysis, and 12 of them were from a single study (Blanco-Canqui & Lal, 2007). With a small data sample, influence of a specific study can be significant. The same study was also included in our analysis, but analysis based on a larger database (409 data points) suggested that responses of SOC could be positive or negative, depending on removal intensity and other factors. These different results confirmed that SOC responses varied by site. To estimate the overall trend, constructing a comprehensive database that covers multiple regions and farming systems is important.

4.3 | Equivalent soil mass balance

Our analysis indicated that reporting SOC change based on ESM or fixed-depth has a significant impact on the SOC change evaluation (Figure 7 and Table 2), which was consistent with previous meta-analysis studies (Du et al., 2017; Meurer, Haddaway, Bolinder, & Kätterer, 2018). Historically, SOC stock was most commonly calculated to a fixed-depth as the product of bulk density and SOC concentration and depth (Wendt & Hauser, 2013). However, the fixed-depth method may introduce substantial errors, because changes in management practices can increase or decrease soil bulk density and therefore soil volumes over time (Ellert & Bettany, 1995; Meurer et al., 2018). To address this issue, a binary variable (ESM or fixed-depth) was included in the meta-regression analysis as a control variable (Table 2). If ESM results were assumed to be closer to actual changes, regression results indicated that fixed-depth overestimated the SOC reduction by about 6.8%, after variations in other variables (e.g., tillage, crop rotation, sampling depth) were considered. Although the 6.8% difference was smaller than the 10% difference obtained via subgroup analysis, it is still significant considering the difference between moderate and medium removal intensity was only about 4% (Table 2).

4.4 | US versus international SOC responses

Overall, US Midwestern (Figure S2) SOC accrual rates were similar to the global database (Figure 8), but the magnitudes of SOC change were relatively smaller than those in the global database. By analyzing long-term samplings (n = 81,391) from fields in South Dakota, Clay et al. (2012) found that long-term (1985–2010) surface (0–15 cm), non-ESM SOC increases of 0.37 Mg C ha^{-1} $year^{-1}$ were in alignment with global means. The difference between Midwest versus international SOC change rates could largely be attributed to the fact that most Midwestern studies (83%) used in the meta-analysis reported SOC based on ESM, whereas only 59% of the studies included outside the region used ESM. As mentioned above, fixed-depth measurements did not consider changes in soil volume overtime. For this reason, meta-regression results suggested SOC change reported based on ESM method would be 6.8% smaller than fixed-depth method.

In addition, initial SOC content also impacted the results. On average, SOC content (Figure S3) of the Midwestern plots was noticeably higher than those at international experimental sites, largely because of their rich soils (e.g., Mollisols; Russell, Laird, Parkin, & Mallarino, 2005). Responses of SOC to additional biomass input can be less noticeable in fertile soils than in regions where soils are damaged or less productive. Studies have indicated that C sequestration rates can decrease if a soil is approaching saturation (Stewart, Paustian, Conant, Plante, & Six, 2007). These results indicated that the net impact of potential stover removal on SOC will vary by local soil conditions and management practices. In soils approaching C saturation, addition of stover may have lower gains. If moderate stover removal (<50%) did not reduce SOC level, then utilization of stover resource may be plausible. In fields with high C sequestration capacity, stover return may be preferred to increase SOC accrual. Still, if the overall objective of stover utilization is reducing GHG emission intensity of energy production, then a life-cycle assessment is needed to evaluate whether stover should be used as biofuel feedstock to reduce fossil fuel consumption or be returned to fields to increase SOC accrual rates.

4.5 | Limitations and future study

Since many studies considered here rarely reported how stover removal affected belowground C inputs (e.g., roots), which are critical in building and maintaining soil (Stewart et al., 2016), and rarely measured SOC changes beyond the 0–30 cm profile, it was difficult to distinguish treatment-induced SOC changes. Previous studies (Du et al., 2017; Syswerda, Corbin, Mokma, Kravchenko, & Robertson, 2011; Ugarte et al., 2014) also found similar issues related to large variations and limited sample sizes in deep depths. For a more accurate and confident SOC change assessment, more observations measuring deep (>30 cm) soil profiles are clearly needed.

To include as many eligible studies as possible, both ESM and fixed soil sampling depths were included in this analysis. In addition, how bulk density was measured also needs to be assessed. For future studies, reporting SOC changes based on a standard calculation protocol would assist in distinguishing SOC changes from soil volume changes, which would be particularly important for long-term studies. At a minimum, future experimental studies should report initial SOC and bulk density measurements. In addition, soil sampling protocols need to be designed for specific question. If the purpose is to chemically determine the impact of a treatment on the amount of organic C contained in belowground carbon pools, then grinding and sieving the samples can underestimate the reported values (Clay et al., 2015).

Once the initial SOC baseline was accounted for the analyses demonstrated that stover removal tended to slow the accrual rate, but not necessarily deplete SOC stocks. Among the biophysical and management variables examined, this study found that changes in SOC were most sensitive to the intensity of stover removal. Further analysis on the effects of stover removal along with key conservation practices like cover crop or manure addition would deepen our understanding of SOC changes in current farming practices (Palm, Blanco-Canqui, DeClerck, Gatere, & Grace, 2014; Ugarte et al., 2014). Finally, our analysis evaluated the overall impact of stover removal on SOC, but responses of soil to stover removal varied by regions and management practices. To guide sustainable utilization of crop residue resources at a relevant scale, a spatially explicit database regarding SOC and farm management practices, including stover removal, is necessary.

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DATA AVAILABILITY STATEMENT

Database constructed in this study can be downloaded from https://greet.es.anl.gov

ORCID

Hui Xu https://orcid.org/0000-0003-2994-4892
Catherine Stewart https://orcid.org/0000-0003-1216-0450
Zhangcai Qin https://orcid.org/0000-0001-9414-4854

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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