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Reduced Erosion Augments Soil Carbon Storage Under Cover Crops

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ABSTRACT

Cover crops, a promising strategy to increase soil organic carbon (SOC) storage in croplands and mitigate climate change, have typically been shown to benefit soil carbon (C) storage from increased plant C inputs. However, input-driven C benefits may be augmented by the reduction of C outputs induced by cover crops, a process that has been tested by individual studies but has not yet been synthesized. Here we quantified the impact of cover crops on organic C loss via soil erosion (SOC erosion) and revealed the geographical variability at the global scale. We analyzed the field data from 152 paired control and cover crop treatments from 57 published studies worldwide using meta-analysis and machine learning. The meta-analysis results showed that cover crops widely reduced SOC erosion by an average of 68% on an annual basis, while they increased SOC stock by 14% (0–15 cm). The absolute SOC erosion reduction ranged from 0 to 18.0 $\mathrm{Mg\,C^{-1}\,ha^{-1}\,year^{-1}}$ and showed no correlation with the SOC stock change that varied from −8.07 to 22.6 $\mathrm{Mg\,C^{-1}\,ha^{-1}\,year^{-1}}$ at 0–15 cm depth, indicating the latter more likely related to plant C inputs. The magnitude of SOC erosion reduction was dominantly determined by topographic slope. The global map generated by machine learning showed the relative effectiveness of SOC erosion reduction mainly occurred in temperate regions, including central Europe, central-east China, and Southern South America. Our results highlight that cover crop-induced erosion reduction can augment SOC stock to provide additive C benefits, especially in sloping and temperate croplands, for mitigating climate change.

1 | Introduction

Agriculture development has resulted in substantial losses of soil organic carbon (SOC) (Sanderman et al. 2017), which diminishes soil health and exacerbates climate change (Jayaraman et al. 2021). Regenerative farming aimed at increasing SOC sequestration has been widely applied to rebuild SOC and mitigate greenhouse gas emissions. Of all the regenerative farming practices, planting cover crops to cover the soil during fallow periods to provide year-round C inputs is considered one of the most promising strategies (Schlesinger 2022). However, the benefits from the adoption of cover crops on SOC remain uncertain and contentious (Chaplot and Smith 2023; Poeplau et al. 2024). Numerous studies have emphasized that cover crops enhance SOC stock via increasing plant C inputs to soils (McDaniel et al. 2014; Poeplau and Don 2015; Schlesinger 2022), a process which is intuitive and straightforward. Yet, another critical C-related process, organic C loss through soil erosion (hereafter termed SOC erosion), could potentially contribute to the uncertainties related to input-driven C credits, which are often overlooked.

Reducing soil erosion is one of the primary motivations for growing cover crops, as they extend the time of soil covered by living plants or plant residues (Kaspar and Singer 2015). Cover crops have been widely recognized for their effectiveness in reducing soil erosion (Haruna et al. 2020). For example, a recent meta-analysis study has showed that cover crops significantly reduced soil erosion by ~90% across the globe (Du et al. 2022). At a regional scale, soil erosion may induce a net C loss despite dynamic C replacement (Sanderman and Berhe 2017; Van Oost and Six 2023). Cover crop-induced SOC erosion reduction may deserve attention as "additive C credits". Although numerous research efforts have examined SOC erosion under cover crops, a synthesized quantitative evaluation of the effects is still lacking.

Consideration of SOC erosion reduction can also enhance our understanding of SOC gains through additional plant C inputs from cover crops that remain a topic of ongoing debate (Chaplot and Smith 2023; Poeplau et al. 2024). Many meta-analyses have reported positive effects of cover crops on SOC stocks or concentrations, with an average effect size often $<16\%$ in the topsoil (≤ 30 cm) (Jian et al. 2020; McClelland et al. 2021; Poeplau and Don 2015; Prairie et al. 2023; Wooliver and Jagadamma 2023). Reduction in soil erosion through cover crops in comparison to the control can decrease SOC output, which may have partially explained the observed increase in SOC under cover crops (Jian et al. 2020). This implies that the lack of consideration of SOC erosion reduction may lead to overestimation of SOC gains contributed by plant C inputs from cover crops. This is because the control plots, which experience more extensive erosion, end up with more exposed deeper soil layers that naturally have lower SOC levels (Lal 2005; Xiao et al. 2018). As a result, when comparing the control and cover crop plots, it might appear that SOC is higher in the cover crop plots, which is at least partly due to erosion. The observed increase in SOC stocks induced by cover crops could be highly linked to SOC erosion reduction if SOC erosion is the dominant contributing factor. Thus, elucidating the relationship between SOC erosion reduction and SOC changes under cover crops can help draw more sound conclusions about the efficiency of cover crops on C sequestration. However, we still lack a clear understanding of the extent to which cover crop-induced SOC erosion reduction can impact SOC accrual across global croplands.

As many studies on cover crops were conducted under specific climate, soil, geographic, and agronomic conditions, we have yet to synthesize them and develop a generalizable framework to provide insights into effective cover crop implementation in mitigating C loss via erosion. Site-specific individual studies found that cover crops had inconsistent impacts on SOC changes (Kuo et al. 1997; Oelbermann 2009; Tautges et al. 2019), which hinder the widespread adoption of effective cover crop practices. However, cover crops consistently reduce soil erosion (Du et al. 2022), which consequently influences soil C. This process of SOC erosion reduction could be significant, yet often underappreciated, in areas where plant C input-driven SOC increase is quite limited. Thus, the variable outcomes on SOC changes and the importance of soil erosion reduction highlight the need to identify the key factors and reveal geographical variability for SOC erosion reduction under cover crops that may contribute to SOC changes at the global scale. A synthesis of how SOC erosion reduction vs. SOC stock changes vary across different environments and practices with cover crops can have important implications for optimizing C benefits from adopting cover crops.

The objectives of this study were to quantitatively investigate the magnitude of SOC erosion reduction under cover crops using meta-analysis and to reveal geographical variability and potential hotspots for SOC erosion reduction by cover crops at a global scale using a machine learning method. We also compared SOC erosion reduction with SOC stock change and examined their drivers to better understand input-driven C sequestration by cover crops and their variabilities. We hypothesized that cover crops can reduce SOC erosion to a greater extent than they can increase SOC stock, given the substantial positive effects on soil erosion.

2 | Materials and Methods

Here, we first quantified the magnitude of SOC erosion reduction under cover crops at the global scale using meta-analysis. SOC erosion reduction by cover crops was then compared with SOC stock changes within the same collected database, considering both the effect sizes and absolute change rates. We also explored the effects of topography, climate, soil properties, and management practices and their relative importance in predicting the effect sizes of SOC erosion reduction and SOC stock change using machine learning. Finally, we generated a global map of the potential magnitude of SOC erosion reduction under cover crops in agricultural lands to reveal the spatial distributions of their effectiveness in mitigating SOC loss through erosion worldwide.

2.1 | Data Collection

To construct a comprehensive dataset of the experimentally examined effects of cover crops on SOC erosion, we collected as many studies as possible that met our criteria (described below). Data were collected by searching the peer-reviewed research articles published prior to September 2023 using Web of Science (https://apps.webofknowledge.com), and the combinations of keywords used for searching included ("cover crop*" OR "green manure" OR "cover cropping") AND ("carbon erosion" OR "erosion" OR "runoff" OR "carbon loss"). In addition, we also searched the literature in Chinese using China National Knowledge Infrastructure (CNKI, https://www.cnki.net/). The total number of articles initially searched based on the keywords included 4158 from the Web of Science and 2095 from the CNKI.

We used the following criteria to determine whether a study should be included in our database. (1) Experiments were conducted in the field or at a research station with a pairwise design, including cover crop and control treatments under identical environmental conditions and management practices (e.g., no tillage, conservation tillage and conventional tillage). We specifically restricted the data to studies performed with the same tillage intensity for both the control and cover crop treatments, as the tillage can substantially affect soil erosion (Mhazo et al. 2016). (2) SOC erosion rates could be directly and indirectly retrieved from the experiments (as described below). (3) When the data were reported in the same experiments but in different publications, the data were only included once. For the studies that measured SOC erosion at multiple time points, only the most recent measurement was used to keep the statistical independence between individual observations. If multiple fertilization rates were applied to crops, mean values across these treatments were calculated and used for this study. Although numerous studies measured SOC concentration or stock changes under cover crops vs. control, they often did not assess soil erosion, thereby hindering our estimation of SOC erosion. After subsequent screening of the papers initially retrieved via keyword searches, we retained a total of 87 papers that investigated SOC erosion under cover crops. We further excluded some studies (32% of the 87 papers) either because tillage was present in the control but not the cover crop treatments or because the experimental measurements did not meet the aforementioned criteria. In total, we collected data from 152 experiments reported in 57 publications between 1994 and 2023 (Table S1; Data Sources; Huang et al. 2025) for this meta-analysis.

In the selected publications, we manually extracted the mean values, replicates, and standard deviation (or standard errors where available) for SOC erosion, soil erosion, SOC concentrations (or SOC stocks) and organic C concentration in sediments as much as possible, along with the related information from tables and texts, or indirectly extracted data from figures using the online tool WebPlotDigitizer (https://apps.automeris.io/wpd/). The SOC erosion was measured or calculated in $\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$. The related information included climate variables (mean annual air temperature, MAT and mean annual precipitation, MAP), site characteristics, and experimental details, which were used to assess their relationships with the response ratio of SOC erosion under cover crop treatments relative to controls. Site characteristics included experiment location (latitude and longitude), topographic conditions (slope and altitude), soil properties (SOC concentrations, total nitrogen (N), available phosphorus (P), bulk density, and soil texture) and sampling depth. Experimental details included cover crop type (legume and non-legume), tillage intensity, and experimental duration.

2.2 | Data Preparation

The means of SOC erosions ($\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$) under the control and cover crop treatments were either directly extracted from the published studies or indirectly calculated. The measurement of SOC erosion in the collected studies commonly involved the runoff plot method (McDonald et al. 2002), which collected direct runoff and eroded soil from a defined plot area into a collector for soil erosion assessment and organic C analysis. If there was no direct measurement of SOC erosion, the value was calculated by multiplying soil erosion by organic C concentration in the sediments or by SOC concentration in the topsoil, given that soil erosion predominately leads to SOC loss in the topsoil layer. For those studies that only reported initial SOC concentration under the control, we assumed that SOC concentration in the sediments under the cover crop treatment was equal to the value at the time of initial sampling. The estimation (or calculation) method that accounted for SOC erosion using organic C concentration in sediments was consistent with the principle of direct measurement. However, applying SOC concentration from the topsoil as a substitute for organic C in sediments could induce some uncertainties in SOC erosion. The estimation method of the latter was likely to underestimate SOC erosion reduction, as the eroded soil organic C concentration in the control may be even higher than the SOC that remained due to its more loss of C-rich topsoil than the cover crop treatments.

When standard error (SE) was provided, SD was calculated using the following equation:

$$\mathrm{SD} = \mathrm{SE}\sqrt{n} \quad (1)$$

In those cases where neither SD nor SE was reported, we estimated the missing SD by multiplying the reported mean by the average coefficient of variance of our complete dataset for the control and cover crop treatments, separately. If the sample size was unspecified, we used the median sample size of our complete dataset for the control and cover crop treatments, separately.

We also calculated SOC stock change rates ($\mathrm{Mg\,C\,ha^{-1}\,year^{-1}}$) under cover crops. As the majority of the collected studies provided SOC concentrations, we converted SOC concentrations into SOC stock ($\mathrm{SOC_{stock}}$, $\mathrm{Mg\,C\,ha^{-1}}$) by multiplying SOC concentration ($\mathrm{SOC_{conc}}$, g/kg) by bulk density (BD, g $\mathrm{cm^{-3}}$) and soil depth (D, cm) according to the following equation (Jian et al. 2020; Poeplau and Don 2015):

$$\mathrm{SOC_{stock}} = \frac{\mathrm{SOC_{conc}} \times \mathrm{BD} \times D}{10} \quad (2)$$

Not all the collected studies (61% of the collected data) reported bulk density data for both the control and cover crop treatments or SOC concentration for the cover crop treatments. We filled the missing values of bulk density and SOC concentration by leveraging the extensive dataset of SOC concentration and bulk density published in a meta-analysis on the cover cropping effects on SOC changes by Jian et al. (2020). We acknowledged that bulk density data can be obtained from other databases (e.g., SoilGrids250m database); however, the dataset provided by Jian et al. (2020) included the effects of cover crops on bulk density, which helped reduce potential bias associated with ignoring bulk density changes. Firstly, based on the significantly negative relationship between bulk density and SOC concentration observed in the dataset from Jian et al. (2020) ($R^2 = 0.14$; $p < 0.01$; Figure S1a), regardless of the treatments, we approximated bulk density under the control using this relationship (Figure S1a). Secondly, we estimated SOC concentration under the cover crop treatment by extrapolating from the relationship between the response ratio of SOC concentration under cover crops to the control and experimental durations (Figure S1b). Finally, we estimated bulk density under cover crops by employing the relationship between bulk density and SOC concentration (Figure S1a).

To improve the comparability of SOC erosion and SOC stock changes, we normalized the SOC stock data to the top 15 cm using the depth distribution method proposed by Jobbágy and Jackson (2000).

$$\mathrm{SOC}_{15} = \frac{\left(1-\beta^{15}\right)}{\left(1-\beta^{d0}\right)} \times \mathrm{SOC}_{d_o} \tag{3}$$

where β is the relative rate of decrease in SOC stock with soil depth, equal to 0.9786, SOC_{15} is SOC stock in the upper 15 cm depth, d_o is the original soil depth available in individual studies (cm), and SOC_{do} is the original SOC stock.

For studies where the latitude and longitude of the experiment were not provided, we approximated these coordinates by geocoding the location names in Google Earth (the free version). Similarly, if MAT, MAP, altitude, or slope was not reported, we obtained the values of MAT, MAP, and altitude from WorldClim, and calculated slope with elevation data from SRTM using the geographic coordinates (latitude and longitude) of the study sites. The aridity index (AI) for each site was acquired from the Global Aridity Index and Potential Evapotranspiration Database (version 3) (Zomer and Trabucco 2019). Whenever soil texture was not reported in the original studies, we extracted the data from the Global Land Data Assimilation System 2 Noah Land Surface Model (https://ldas.gsfc.nasa.gov/gldas/soils).

We categorized the data by climate zone, aridity index, altitude, slope, tillage type, cover crop type, and experimental duration. Experiments were grouped by absolute latitude into three climatic regions, including tropic (23.5° N–23.5° S), subtropic (23.5° N–35° N or 23.5° S–35° S), and temperate (> 66.5° N or > 66.5° S). Data were grouped into humid (> 0.5) or arid (≤ 0.5) regions based on site aridity level. Altitude was categorized into low altitude (≤ 500 m) and high altitude (> 500 m). Tillage types were classified as no tillage, reduced tillage (or conservation tillage, less intensive than conventional tillage) and conventional tillage. Slope was divided into level (≤ 3%), sloping (3%–12%) and steep (> 12%). Experimental duration included very short-term (≤ 2 years), short-term (2–5 years), and long-term (> 5 years) as cover crops often started to increase SOC after 5 years (Blanco-Canqui 2022) and could reduce soil loss within a very short term (i.e., ~2 years) to compensate for lack of immediate SOC increase (Jacobs et al. 2022).

2.3 | Meta-Analysis

The effects of cover crops on SOC erosion at the global scale and in different groups in terms of climate zone, aridity, altitude, slope, tillage type, cover crop type, and experimental duration were quantified by weighting the natural logarithm of response ratio (LnRR) with the inverse variance and a random-effects model. To do this, we first calculated LnRR for each observation as follows:

$$\mathrm{LnRR} = \mathrm{Ln}\frac{\overline{X_t}}{\overline{X_c}} = \mathrm{Ln}\left(\overline{X_t}\right) - \mathrm{Ln}\left(\overline{X_c}\right) \tag{4}$$

where $\overline{X_t}$ and $\overline{X_c}$ are mean values under the cover crop treatment and the control, respectively.

We then estimated the variance (v_i) of each individual LnRR using the following equation:

$$v_i = \frac{\mathrm{S}_t^2}{\mathrm{n}_t\overline{X}_t^2} + \frac{\mathrm{S}_c^2}{\mathrm{n}_c\overline{X}_c^2} \tag{5}$$

where S_t and S_c are the SDs of the cover crop treatment and the control, respectively; n_t and n_c are the sample sizes for the cover crop treatment and the control, respectively.

Then, the weighted mean response ratio (LnRR_+) was calculated to assign more weight to the studies that yield a more precise estimate of the effects as follows:

$$\mathrm{LnRR}_+ = \frac{\sum_{i=1}^{m}\left(w_i^* \times \mathrm{LnRR}_i\right)}{\sum_{i=1}^{m} w_i^*} \tag{6}$$

where w_i^* is the weighting factor of the ith observation in the group, and m is the number of observations in the group. The w_i^* was calculated as:

$$w_i^* = \frac{1}{v_i + T^2} \tag{7}$$

where T^2 is the between-studies variance, and the details of computing can be seen in Borenstein et al. (2010).

The standard error of LnRR_+, $\mathrm{s}(\mathrm{LnRR}_+)$, and the 95% confidence interval (CI) for the LnRR_+ were used to test significant differences in the response ratios, which were calculated as follows:

$$\mathrm{s}\left(\mathrm{LnRR}_+\right) = \sqrt{\frac{1}{\sum_{i=1}^{m} w_i^*}} \tag{8}$$

$$95\,\%\,\mathrm{CI} = \mathrm{LnRR}_+ + 1.96 \times \mathrm{s}\left(\mathrm{LnRR}_+\right) \tag{9}$$

If the 95% CI did not overlap with zero, the effects of cover crops were considered significant. A negative value denotes that cover crops significantly reduced SOC erosion, whereas a positive value indicates the opposite effect. The percentage decrease in SOC erosion by cover crops (i.e., the effect size) in a group was calculated as follows:

$$\text{Effect size}\,(\%) = \left(1 - \mathrm{e}^{\mathrm{LnRR}_+}\right) \times 100 \tag{10}$$

To compare the impacts of cover crops on SOC erosion with those on SOC stock changes, we also calculated the effect size of cover crops on SOC stock changes using the method described above. To express the percentage increase in SOC stock induced by cover crops and enable comparison between SOC erosion decreases and SOC stock increases, the effect size of SOC stock was calculated as follows:

$$\text{Effect size}_{\mathrm{SOC_{stock}}}\,(\%) = \left(\mathrm{e}^{\mathrm{LnRR}_+} - 1\right) \times 100 \tag{11}$$

The meta-analyses were performed using "meta" package in R version 4.3.1. We also conducted two sensitivity tests (Figure S2): a leave-one-out meta-analysis using the "*metainf*" function and a cumulative meta-analysis using a random-effects model in the "*metacum*" function. The cumulative meta-analysis was repeated 1000 times with random orders of experiments. We statistically tested for the possible publication bias using the "*metabias*" function and explored the relationships between the LnRR and the slope, altitude, aridity, and experimental duration using the "*metareg*" function.

2.4 | Boosted Regression Tree Analysis

We used the Boosted Regression Tree (BRT) analyses to identify important predictors for the response ratio of SOC erosion and SOC stocks. We included the above-mentioned climate (MAT and MAP), geography (slope and altitude), soil properties (silt+clay and SOC concentration) and agricultural management (cover crop species, tillage intensity and experimental duration) in the models. Soil properties such as soil pH and total N and available P concentrations were not included due to extensive missing data. The relative importance of each predictor was expressed as a percentage of the total variation explained by the model. The BRT analyses were conducted using the "gbm" package version 2.1.9 (Greg and GBM Developers 2024), with custom code provided by Elith et al. (2008). Gaussian distribution of errors was chosen since the response ratio is a continuous numerical variable. Some of the parameter values used in the BRT model were based on the recommendations from a previous study (Elith et al. 2008), with a bag fraction of 0.75 and 10-fold cross-validation (CV). We assumed up to two-way interactions between the predictors affecting the response values, setting the tree complexity (tc) to 2. We identified an optimal combination of parameters for the BRT models, including learning rate (lr) and number of trees (nt), to minimize predictive error when applied to independent samples (Elith et al. 2008). The CV was used to address the potential risks of overfitting and estimate optimal nt, where the predictive error stabilized at its minimum, and any further increase indicated overfitting. We fitted the BRT models with varying lr values of 0.01, 0.005, and 0.001. Based on the CV results, we found that an lr value of 0.005 fitted the model with more than 1000 trees (as recommended by the rule of thumb for fitting models with sufficient complexity) (Elith et al. 2008) without signs of overfitting, while the smallest lr value of 0.001 gained little predictive power with thousands of trees as indicated by the similar minimum predictive deviance (Figure S3). Thus, we opted for a learning rate of 0.005 to include a large number (>1000) of regression trees in the models. The Moran's I test was used to check spatial autocorrelation using the "spdep" package (Pebesma and Bivand 2023). The Moran I test showed no significant autocorrelation for the response ratios of either SOC erosion (Moran I statistic $=0.011$, $p=0.405$) or SOC stocks (Moran I statistic $=-0.113$, $p=0.930$).

2.5 | Spatial Map Extrapolation for the Effect Size of SOC Erosion Reduction Under Cover Crops

After identifying the importance of the predictors for the effect size of SOC erosion reduction under cover crops by BRT, we estimated the effect size for the global croplands if adopting cover crops by inputting grid-based spatial data of climate, topography, and soil properties from multiple sources into the trained BRT model. For the agricultural management practices in the trained BRT model, we assumed no tillage, the use of a mixture of legume and non-legume cover crops, and a cover crop treatment duration of 2.5 years, as these practices had the most conservative effects on SOC erosion reduction, and the response did not change much after 2.5 years (Figure S4). The data on climate, topography, and soil texture (silt + clay) were extracted as described above, and SOC concentration data were obtained from the SoilGrids250m database (version 2.0). The map of worldwide croplands was downloaded from the USGS website (https://www.usgs.gov/media/images/map-worldwide-croplands). A small percentage (14.7%) of grids showed positive effects of cover crops on SOC erosion, indicating increased SOC erosion under cover crops. This outcome likely reflected the inclusion of a limited number of positive-effect cases (4.6%) in the trained BRT model, as well as uncertainties arising from the extrapolation of the BRT model. We retained data points with positive effects in the trained BRT model to avoid introducing biases or increasing the uncertainty of the model. Overall, the positive effects occurred in the grids with a relatively small average slope of 0.76%. The global averaged effect size of SOC erosion reduction under cover crops was only reduced by $<2\%$ even when all the positive effects were included. As shown in our collected data (Figure 1), cover crops typically either reduce soil erosion or have no effect, with occasional negligible increases in soil erosion likely due to sampling variability, errors, or other unaccounted factors. Therefore, we set the positive-effect size of SOC erosion induced by cover crops to zero when generating the global distribution of the effect size, which may be partially associated with model uncertainties. The map of the global distribution of the effect size of SOC erosion reduction under cover crops is generated at a 0.25° spatial resolution. To demonstrate the validity and parsimony of using this resolution, we compared the results with maps at 1-km and 30-m resolutions in Eastern-Central China and the Central U.S. (Figure S5). The results from 1-km were similar to those from the 0.25° resolution, whereas the 30-m resolution yielded relatively higher effect sizes. The differences from the 30-m resolution may be due to steeper areas contributing more significantly to the effect sizes. However, the data used for model training was primarily concentrated in areas with relatively gentle slopes (63% data points with a slope $\leq 15\%$), which were more suitable for cultivation. It was more likely to introduce higher uncertainties by using 30-m resolution though the finer resolution could allow increasing slope gradient. Thus, to balance model uncertainty, study objectives, data availability, and computational cost, we selected to use the 0.25° spatial resolution to generate the global map.

3 | Results

3.1 | Reduced SOC Erosion Under Cover Crops

Our synthesis showed that cover crops significantly and consistently reduced SOC erosion relative to controls. Globally, 145 out of the 152 experiments (95% of all experiments) showed a decrease in SOC erosion under cover crops relative to the control (Figure 1), and the magnitude of SOC erosion reduction varied

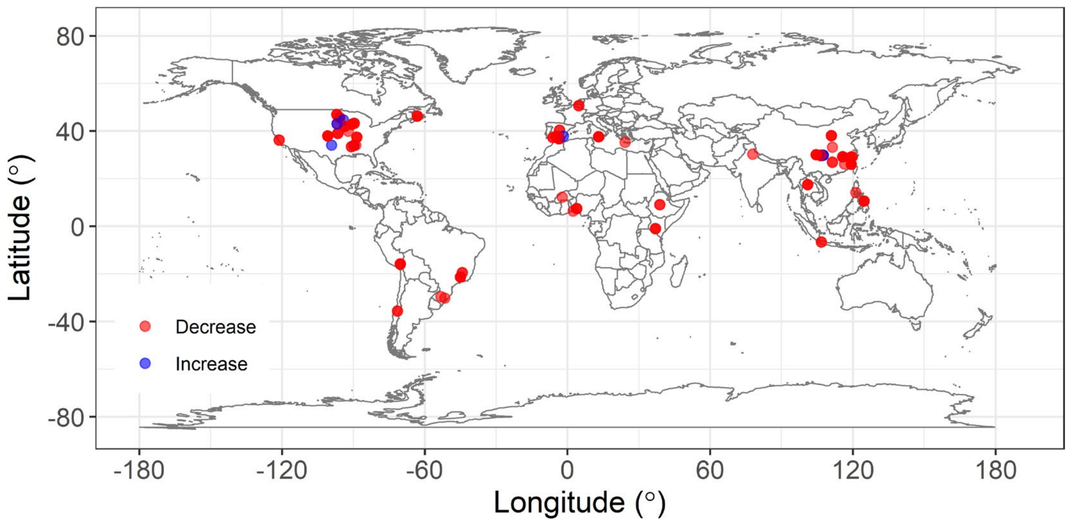

FIGURE 1 | Locations of the 152 experiments in which the effect of cover crops on SOC erosion was assessed. The red point indicates decreased SOC erosion under cover crops relative to the control, while the blue point indicates increased SOC erosion. Please note that only 7 out of 152 points showed an increase in SOC erosion under cover crops, with minimal absolute differences in SOC erosion between control and cover crop treatments ($<2\,kg\,ha^{-1}\,year^{-1}$), likely due to sampling variability or errors. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

greatly among experiments, ranging from 1.1% to 99.6% (nearly complete reduction). Overall, cover crops reduced SOC erosion over control by an average of 68%, with a 95% confidence interval of 62%–73% ($N=152$; Figure 2). Our estimates were robust, as indicated by no significant publication bias in the asymmetry tests ($p=0.11$) and insensitivity to outliers in the sensitivity analyses (Figure S2).

The meta-regression analysis showed that the effect size of SOC erosion reduction under cover crops varied with the topographic conditions (i.e., altitude and slope) and some management practices (i.e., cover crop type and duration), but not with climate zone, aridity, and tillage intensity (Figure 2). Specifically, lower altitude significantly increased the effect size of SOC erosion reduction under cover crops ($p<0.05$), with an averaged reduction of 70% at the low-altitude (≤ 500 m a.s.l.) experimental sites compared to 60% at the high-altitude ones (> 500 a.s.l.; Figure 2). The magnitude of SOC erosion reduction significantly increased with steeper slopes ($p<0.01$), from an average reduction of 44% at the level sites to 65% at the sloping sites, and up to 79% at the steep sites. When separating the data into different cover crop types, the non-legume showed a significantly higher magnitude of SOC erosion reduction (an average of 77%) than the legume (an average of 57%). The longer experimental duration also significantly increased the effect size of SOC erosion reduction ($p<0.05$), reaching an average of 81% in the experiments lasting more than 5 years.

3.2 | SOC Stock Change and Its Relationship With SOC Erosion Reduction

We further analyzed the effects of cover crops on SOC stocks at 0–15 cm from these experiments and compared them with the magnitude of SOC erosion reduction. We found that cover crops significantly increased SOC stocks, consistent with previous meta-analysis studies (Hu et al. 2023; Jian et al. 2020; Wooliver and Jagadamma 2023). However, the response ratio of SOC stock change was considerably smaller than that of SOC erosion reduction (Figure 2). Overall, cover crops increased SOC stocks by an average of 14%, with a 95% confidence interval of 10%–18%. Even based on a smaller dataset ($n=59$) excluding the estimated data due to the lack of bulk density or SOC concentration, the overall effects of cover crops on SOC stock change remained consistent, showing an average increase of 13% and a 95% confidence interval of 6%–22% (Figure S6). Different from the effects of SOC erosion reduction, the SOC stock increase under cover crops was only significantly affected by experimental duration and cover crop types. The longer experimental duration significantly enhanced the effect size of the SOC stock increase ($p<0.01$; Figure 2). The mixtures of legumes and non-legumes had a lower effect size of SOC increase (7%) than the legumes (16%; $p<0.05$; Figure 2).

We also estimated the absolute SOC stock increase rate at 0–15 cm and compared it with the SOC erosion reduction rate under cover crops. The SOC stock increase rate at 0–15 cm varied considerably across experiments, ranging from −8.07 to $22.6\,Mg\,C\,ha^{-1}\,year^{-1}$, with a median value of $0.75\,Mg\,C\,ha^{-1}\,year^{-1}$. In comparison, the SOC erosion reduction rate ranged from 0.0 to $18.0\,Mg\,C\,ha^{-1}\,year^{-1}$, with the median value at $0.04\,Mg\,C\,ha^{-1}\,year.^{-1}$. Moreover, there was no significant relationship between the SOC erosion reduction rate and the SOC stock increase rate under cover crops (Figure S7; $p>0.05$).

3.3 | Predictions of the Magnitude of SOC Erosion Reduction and SOC Stock Increase

We used the BRT analyses to identify the most important climatic, topographic, and soil geochemical factors as well as

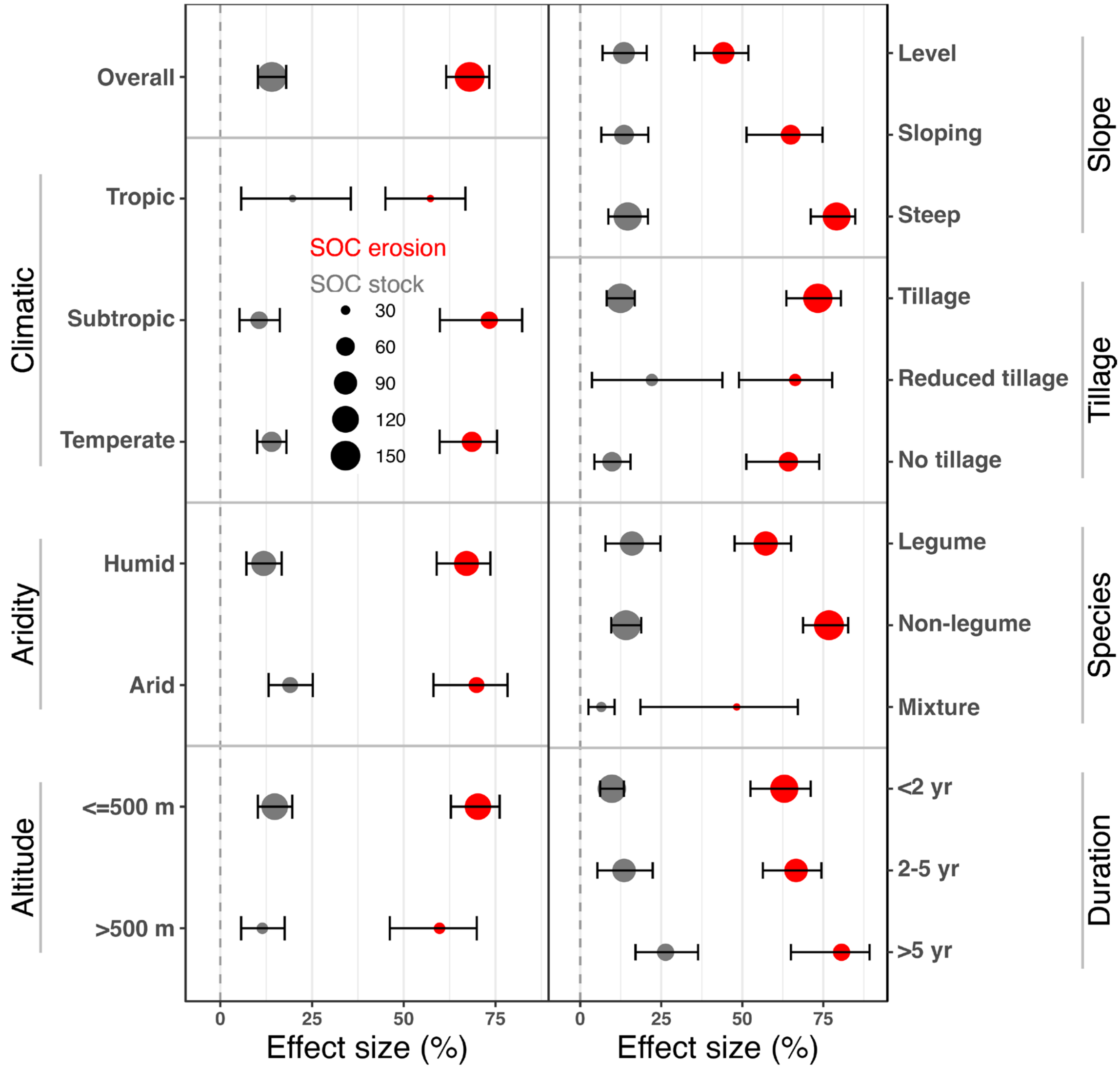

FIGURE 2 | Effect sizes of SOC erosion reduction and SOC stock increase under cover crops relative to the control. The points in red and gray indicate SOC erosion reduction and SOC stock increase, respectively. The error bars represent the 95% confidence interval (scaled to %). The point size indicates the sample size.

management practices regulating SOC erosion reduction and SOC stock increase. The topography (slope and altitude) explained a larger percentage (36.1% for slope and 21.6% for altitude) of the variations in the response ratio of SOC erosion ($R^2=0.75$; Figure 3). The greater SOC erosion reduction tended to occur at the sites with steeper slopes and lower altitudes (Figure S4). In contrast, the variation in the response ratio of SOC stock was mainly regulated by climate (MAT and MAP) and SOC concentration at the control, explaining nearly 60% of the total variations in the response ratio (21.0% for MAT, 19.6% for MAP, and 19.5% for SOC; $R^2=0.86$). Greater SOC stock increase occurred at the sites with lower SOC concentration and MAP but higher MAT (Figure S8).

3.4 | Global Distribution of Effect Sizes of SOC Erosion Reduction Under Cover Crops

We further predicted the global distribution of the magnitude (i.e., effect size) of SOC erosion reduction under cover crops in croplands by integrating the knowledge of SOC erosion reduction with above-mentioned factors from the BRT analysis (Figure 4). For the scenario of global croplands with cover crops of a mixture of legume and non-legume and no tillage for 2.5 years, the estimated effect size of SOC erosion reduction in the global croplands averaged 25%, ranging from 0% to 89% at a 0.25° resolution. Over croplands, the mid-latitude (or temperate) regions tended to have higher effect sizes of SOC erosion reduction. Specifically, central Europe, central-east China, and southern South America showed relatively higher effect sizes of SOC erosion reduction (> 70%). These hotspots of high effect sizes were mainly associated with the relatively steeper slopes and/or lower altitudes in the croplands. For example, when comparing the regions with the steeper vs. gentler slopes (i.e., the central-east China vs. the central U.S.; Figure S5), the effect size in central-east China averaged 47%, whereas it averaged 20% in central U.S. The more than twofold difference between the two regions was partially attributed to variations in slope, which ranged from 0% to 45% in central-east China and from 0% to 17% in central U.S.

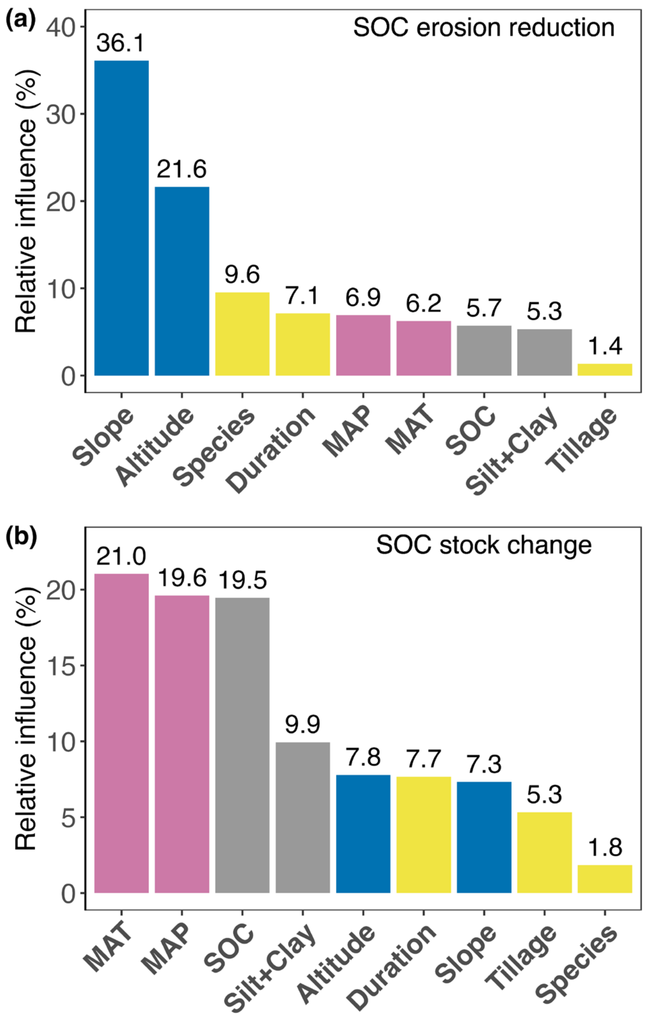

FIGURE 3 | Relative influence of climate (purple), topography (blue), soil properties (gray), and management (yellow) on the magnitude of SOC erosion reduction (a) and SOC stock change (b) under crop crops relative to the control. The number on the top of the bar indicates relative influence.

4 | Discussion

Overall, our global synthesis provided quantitative evidence that cover crops can reduce SOC erosion by 68% on average (Figure 2). This protective effectiveness of cover crops on SOC consistently far exceeded its responsiveness for promoting SOC sequestration, which showed an average effect size of 14% at 0–15 cm. The results collectively supported our hypothesis and emphasized the effectiveness of cover crops on preventing C loss by erosion. The absolute amount of SOC erosion rate was on average smaller than the SOC stock change rate, while it might involve uncertainty due to estimation methods. The SOC erosion reduction rate can, however, occasionally be higher, especially in the sloping areas. The two weakly related processes of SOC erosion reduction and SOC increases and their distinct predictors reinforced the overall importance of plant C inputs but also highlighted the need to consider SOC erosion when studying cover crop impacts on SOC storage with limited plant C input contributions, particularly over a short period (e.g., ~2 years) and in sloping areas. Finally, results from the estimation of global SOC erosion reduction under cover crops by the machine learning identified potential hotspots, mainly occurring in the temperate regions (i.e., central Europe, eastern China, and southern South America), where cover crops can be a highly effective practice for reducing SOC erosion in croplands.

4.1 | Greater Responsiveness and Variability of SOC Erosion Reduction Than SOC Stock Change Under Cover Crops

To our knowledge, this study is the first meta-analysis to synthesize the degree of the beneficial effect of cover crops on preventing SOC erosion, highlighting their highly responsive role in mitigating soil C loss. Previous meta-analysis studies have synthesized the benefits of cover crops on SOC stocks and/or related C fractions, including particulate organic C, mineral-associated organic C, dissolved organic C, and microbial biomass C, and typically reported

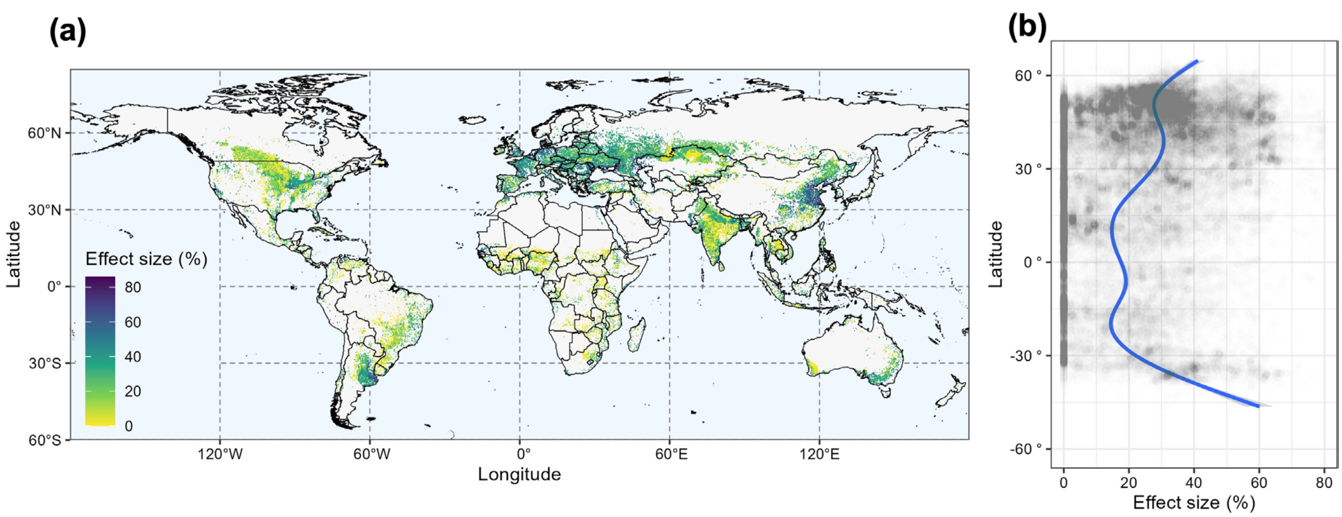

FIGURE 4 | The global distribution of effect size (%) of SOC erosion reduction under cover crops at a 0.25° spatial resolution. (a) The global map of effect sizes; (b) the latitudinal patterns of effect sizes. Each grey point in the panel B indicates 1 cell (0.25° × 0.25°). The grey shaded area for the blue line represents a 95% confidence interval. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

an average increase of less than 20% in SOC stock or concentration and up to 33% in the most sensitive microbial biomass C in the topsoil at the global scale (Hu et al. 2023; Jian et al. 2020; Muhammad et al. 2021; Prairie et al. 2023; Wooliver and Jagadamma 2023). Our results of SOC stock change (13%–14% increase in the topsoil under cover crop) based on both the complete ($n=152$) and smaller ($n=59$) datasets fell within the credible range reported by previous studies (Hu et al. 2023; Jian et al. 2020; Prairie et al. 2023; Wooliver and Jagadamma 2023), despite being based on relatively smaller datasets due to the exclusion of many studies lacking SOC erosion data. However, compared to changes in SOC and other C fractions, SOC erosion showed greater sensitivity and variability in response to cover crops, indicating that SOC erosion reduction should not be overlooked, especially when cover crops had larger impacts on this process (> 70% decrease) in some areas (i.e., steep slope and low altitude) and under certain practices (i.e., non-legume and longer experimental duration).

The BRT revealed that the slope was the dominant factor controlling SOC erosion. This is consistent with the notion that the slope is the main driver of soil erosion (Wang et al. 2018) as steeper slopes can increase flow velocity and connectivity (Chaplot and Le Bissonnais 2000; Chaplot and Poesen 2012). Correspondingly, the effectiveness of soil erosion reduction induced by conservation practices often increased with the slope gradient, as also evidenced by no-tillage management practices (Mhazo et al. 2016). An overall negative relationship of altitude with the effect size of SOC erosion reductionmight reflect multiple climate and soil chemical factors that co-vary with altitude. The greater efficiency of SOC erosion reduction induced by non-legumes compared to legumes might be related to the generally fine and fibrous root systems of non-legumes that are well adapted for improving soil structure to reduce soil erosion (Daryanto et al. 2018; Koudahe et al. 2022). On the other hand, the effect size of SOC stock change was primarily controlled by climate (MAT and MAP). Other studies have shown the dominant role of cover crop biomass on SOC change (Blanco-Canqui 2022; Wooliver and Jagadamma 2023). The importance of climate in our study may be a result of its close relationship with plant productivity (Chaplot et al. 2010; Nemani et al. 2003; Wiesmeier et al. 2019), although we did not investigate cover crop biomass due to limited observations. The negative relationship between initial SOC concentration and the effect size of SOC stock increase may reflect that SOC-rich soils are closer to saturation and thus have less capacity to store additional C than SOC-poor soils (Georgiou et al. 2022; Stewart et al. 2007), while this pattern may be partly attributed to the normalization artifacts (Slessarev et al. 2023). Thus, their distinct driving factors indicate that, in addition to considering the vertical input of C from plants into soil, it is also important to account for the lateral loss of soil C through erosion, which enables a better assessment of the impact of cover crops on site-level soil C accumulation.

4.2 | Influence of SOC Erosion Reduction on SOC Stock Change Under Cover Crops

Our results added another line of evidence for the potential overestimation of the ability of cover crops to improve soil C sequestration through increasing plant C inputs. In addition to some bias related to the difference in soil bulk density between treatments (Chaplot and Smith 2023; von Haden et al. 2020), input-driven SOC stock changes estimated by the fixed depth approach in our study, as was typically done in many studies, may be systematically overestimated when soil erosion occurred. This overestimation occurs particularly in the sloping areas because the control and cover crop treatments are no longer an apples-to-apples comparison at a fixed depth: after erosion, soils previously present in subsoils become a larger proportion of the topsoil in the control compared to the cover crop treatment. Moreover, even if SOC erosion reduction was significant, cover crops did not always lead to the observed greater SOC storage. For example, a meta-analysis of cover crops in temperate climates revealed that 21% of cases observed no change or an even decrease in SOC stocks (McClelland et al. 2021). This suggests that besides the direct impact of reduced SOC erosion, other mechanisms may also regulate SOC change. Indeed, the fresh C or root inputs may stimulate microorganisms and accelerate SOC decomposition to acquire key nutrients for their demand (Dijkstra et al. 2021; Yi et al. 2025). A recent modeling study on the effects of growing cover crops on SOC in German croplands showed that while cover crops alone might not lead to net SOC sequestration within 50 years, they did reduce erosion-induced SOC losses (Seitz et al. 2023). Thus, no detected increase in SOC storage due to positive effects on C decomposition further emphasized C credits from soil erosion that would be otherwise easily dismissed. Next, we asked to what extent SOC stock change under cover crops could be explained by SOC erosion reduction at the global scale.

No relationship between absolute SOC erosion reduction rate and SOC stock increase rate, along with their disparate driving factors, indicated the independence of SOC erosion and input-driven change. If SOC stock changes were mainly due to SOC erosion reduction, we would expect a closely positive relationship between them. Instead, no relationship implied other processes related to plant C inputs, rather than SOC erosion reduction, may mainly drive SOC stock changes at the global scale. However, the lack of an overall relationship did not exclude the possibility of a substantial contribution of SOC erosion reduction to SOC change under certain environmental conditions as the absolute SOC erosion reduction rate did occasionally surpass the SOC stock change rate (Figure S7). In addition, we should note that the SOC erosion reduction rate appeared to be underestimated in our study. This underestimation may be attributed to the use of a relatively conservative estimation approach that applied surface soil (≤ 30 cm) C concentrations to sediments due to the lack of direct SOC erosion measurements. Soil erosion, primarily from SOC-enriched topsoil, often led to SOC enrichment in the eroded sediments (Müller-Müller-Nedebock and Chaplot 2015). Given the higher soil erosion in the control, the estimation method using surface SOC underestimated its SOC erosion to a greater extent than that under the cover crop treatment. In the future, more field data on SOC erosion and/or alternative approaches using C isotopes to disentangle this independent process (Guillaume et al. 2015) may help accurately quantify soil C sequestration under cover crops.

4.3 | Global Implications for SOC Erosion Reduction Under Cover Crops

We generated the first global-scale, grid-based atlas of effect sizes of SOC erosion reduction under cover crops, offering insights into cover crop adoption incentives based on local climate conditions, geographic position, soil properties, and agricultural management practices. Despite some limitations, our global extrapolation revealed substantial geographic variability (the effect size of 0%–89% across the globe) and identified the hotspots in the effectiveness of SOC erosion reduction under cover crops. This underscores the importance of considering the varying responses of SOC erosion reduction under cover crops, in addition to their capacity to build up SOC through additional plant C input, when supporting C sequestration efforts across different regions. Our findings also help pinpoint regions where cover crop adoption is most effective in retaining soil C, despite the fact that the efficiency of cover crops for sequestering additional C may vary depending on other factors regulating the balance of plant C inputs and decomposition outputs. The relatively higher efficiency of cover crops in reducing SOC erosion occurred concurrently with larger soil erosion in temperate climates (Mhazo et al. 2016), where the soils were more vulnerable to erosion due to a coarse texture of lower aggregation capacity than the tropical soils (Six et al. 2002). In addition, the warmer and wetter tropical regions often experience intense and highly erosive storms, which may increase the ability of rainfall to cause erosion and diminish the contributions of cover crops to reducing erosion (Burt et al. 2016; Wei et al. 2024).

Moreover, the global estimation of SOC erosion reduction under cover crops was 25% on average. This was consistent with a simple calculation based on an estimation of SOC displaced by soil erosion at 0.36 Pg C $year^{-1}$ for cropland (Doetterl et al. 2012): if applying the median cover crop-induced SOC erosion reduction rate (0.04 Mg C ha^{-1} $year^{-1}$) across 1.874 billion hectares of global croplands (https://www.usgs.gov/media/images/map-worldwide-croplands), total SOC reduction rate under cover crops was estimated at 0.075 Pg C $year^{-1}$, which accounted for 21% of the aforementioned SOC erosion rate of 0.36 Pg C $year^{-1}$. It should be noted that a portion of eroded SOC would be redistributed within the terrestrial ecosystems or sequestered in other reservoirs. These processes could potentially diminish the expected C benefits from cover crop-induced SOC erosion at a broader landscape scale, where the buried C with longer residence time may compensate for the partial decomposition of eroded soil C during transport (Berhe et al. 2007; Xiao et al. 2018). However, for a field whose boundary is close to the edge of the cover crop system, reduced soil erosion would more likely reduce net C loss (Sanderman and Berhe 2017), thus sustaining C benefits from SOC sequestration within the field. Moreover, reduced topsoil erosion under cover crops can help bring many other ecosystem services, such as enhanced soil water holding capacity and retaining soil essential nutrients. Together, all these insights highlight the critical role of cover crops in reducing SOC erosion improving soil health, and contributing to sustainable agriculture.

5 | Conclusions

Our meta-analysis found that SOC erosion reduction by cover crops was widespread, and its effect size was much larger than that of SOC stock increase at the global scale. Variations in the effect size of SOC erosion reduction under cover crops were primarily related to topographic features, differing from those for SOC stock change. The strong responsiveness of SOC erosion reduction to cover crops provided another plausible explanation for the view that cover crops may not increase SOC stocks through added C input as much as has been claimed, particularly in the sloping areas. While substantial research has focused on C credits from the added C input provided by cover crops, our results demonstrate a critical need to account for SOC erosion reduction facilitated by cover crops at the field level, particularly in the sloping areas and over long-term experiments. This process is an independent, additive process relative to plant C inputs, not to mention its additional benefits for soil quality and the provision of ecosystem services. Further research from long-term trials by considering the combined effects of SOC erosion reduction on SOC sequestration at varying spatial scales and/or seeking a more powerful tool (e.g., C isotope) to separate SOC erosion could improve regional estimates of SOC sequestration potential and actual impacts of cover crops on climate change mitigation.

Author Contributions

Wenjuan Huang: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, visualization, writing – original draft, writing – review and editing. **Lifen Jiang:** conceptualization, project administration, writing – original draft, writing – review and editing. **Jian Zhou:** writing – original draft, writing – review and editing. **Hyung-Sub Kim:** data curation, formal analysis, writing – original draft, writing – review and editing. **Jingfeng Xiao:** funding acquisition, writing – original draft, writing – review and editing. **Yiqi Luo:** conceptualization, funding acquisition, supervision, writing – original draft, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Environmental Data Initiative at https://doi.org/10.6073/pasta/3ddee90c1630f0931770fce806846726.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.