Weng *et al. Environmental Sciences Europe* (2026) 38:39
https://doi.org/10.1186/s12302-026-01335-6

Environmental Sciences Europe

RESEARCH

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Changes in soil organic carbon after land-use change from primary forest to grassland

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Abstract

Forest soils hold the largest carbon on land and play a key role in global carbon balance, climate change, and the stability of terrestrial ecosystems. Consequently, fluctuations in soil organic carbon (SOC) significantly influence atmospheric CO_2 concentrations. Although carbon emissions induced by land-use change (LUC) have been extensively studied and many reports indicate SOC declines following deforestation, our analysis reveals more complex patterns. We conducted a meta-analysis of 548 observational datasets from 46 peer-reviewed studies spanning climatic gradients (semi-arid to humid, tropical to temperate) to identify global patterns and drivers of SOC changes induced by primary forest LUC to grassland. Land-use conversion increased mean SOC stocks by 3.35 Mg·ha^{-1} (13.30%), with significant regional variation: tropical systems exhibited moderate gains (2.05 Mg·ha^{-1}, 7.70%), while temperate regions showed substantial increases (5.19 Mg·ha^{-1}, 24.70%). Depth-specific analysis revealed differential accumulation across soil layers: 0–20 cm (+3.02 Mg·ha^{-1}), 0–30 cm (+3.05 Mg·ha^{-1}), and > 30 cm (+5.18 Mg·ha^{-1}). Increases in deeper layers may reflect root allocation patterns and texture-dependent stabilization mechanisms. Both mean annual temperature (MAT) and mean annual precipitation (MAP) were significantly correlated with SOC changes ($P < 0.05$), with negative associations observed between these climatic variables and changes in carbon stocks. These findings are consistent with previous studies indicating that MAT and MAP critically influence ecosystem carbon dynamics. A significant interaction effect between MAT and MAP on SOC stock changes was also identified ($P < 0.05$). Our results enhance understanding of carbon balance dynamics following LUC in primary forests and provide a scientific foundation for soil carbon management strategies under global change scenarios.

Keywords Soil organic carbon, Land-use change, Climatic factors, Primary forest, Grassland

Introduction

Soil organic carbon (SOC) plays a crucial role in maintaining soil health and ecosystem functioning by influencing soil physical, chemical, and biological properties [1, 2]. Given that soils represent the largest terrestrial carbon pool—storing approximately 1.55×10^6 Gt of carbon [3], which is twice the atmospheric pool and three times the vegetation pool [4, 5] even minor changes in SOC can substantially impact global climate change [6]. Within terrestrial ecosystems, forest soils constitute a significant carbon reservoir, storing approximately $0.93–2.78 \times 10^3$ Gt of carbon globally [7] which represents approximately

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60% of the total soil carbon in forest biomes. Forests currently cover approximately 31% of the global land surface [8]. Grassland ecosystems—including both natural and managed grasslands—cover approximately 26% of the Earth's land surface and represent another vital component of the global carbon cycle, containing about 20% of the world's soil carbon stocks [9]. SOC dynamics in grassland ecosystems are influenced by multiple factors, including climatic conditions, management practices, and land-use patterns [10]. For instance, overgrazing and improper land management can result in significant carbon losses, whereas sustainable grazing and irrigation practices can enhance carbon sequestration [11]. Moreover, grassland ecosystems are highly sensitive to climate change, which can affect their carbon storage capacity through temperature-driven decomposition rates and precipitation-mediated vegetation growth [12].

Land-use change (LUC), particularly the conversion of primary forests to other land cover types, has become a major driver of carbon stock alterations [13]. In tropical regions, LUC accounts for 12–20% of total anthropogenic greenhouse gas (GHG) emissions [8, 14], making it the second-largest source after fossil fuel combustion [15]. However, previous studies have primarily focused on vegetation biomass rather than soil organic carbon (SOC). Soils in primary forests serve as significant carbon sinks, accounting for 8–10% of total global soil carbon [16]. Historical records reveal substantial forest cover loss, with deforestation rates declining from 7.30 million ha·yr^{-1} during 1900–2010 to 3.30 million ha·yr^{-1} in 2010–2015 [17]. The conversion of primary forests to alternative land-use types generally results in SOC depletion, with reported losses ranging from 15 to 40% [18], and in some cases as high as 50% to 75% [10, 19]. Regarding LUC from primary forest to grassland, previous findings remain inconclusive. For example, Kauffman et al. [20] reported a mean loss of 1052 Mg CO_2 e·ha^{-1} from soil carbon pools following the conversion of mangroves to pasture. Similarly, Don et al. [21] found that forest conversion to grassland reduced SOC stocks by 12%. In contrast, Guo and Gifford [22] concluded that such conversion increased SOC stocks by 8%. Fujisaki et al. [23] also observed a slight increase in SOC after forest-to-grassland conversion. These inconsistent findings may stem from variations in sampling depth, baseline soil carbon pool sizes, grassland structure, and the duration of land-use change. Many conclusions were drawn from individual case studies or investigations with limited sample sizes. For example, the study by Guo and Gifford [22] had a relatively small sample size and employed an unweighted meta-analysis, which overlooked the impact of between-sample variation on outcome estimation, while the research by Don et al. [21] not only had a limited sample size but also focused primarily on tropical regions. Therefore, a comprehensive analysis based on a large dataset is essential to improve our understanding of SOC dynamics following the conversion of primary forest to grassland.

The primary aim of this study is to quantify the magnitude of SOC change following the conversion of primary forest to grassland and to identify the climatic drivers (mean annual temperature (MAT) and mean annual precipitation (MAP)) that govern these dynamics. We address three specific questions: (1) Does conversion lead to a net gain or loss in SOC stocks? (2) How does this vary across soil depths and climate zones? and (3) How do temperature and precipitation interact to influence these changes?

Materials and methods

Data collection

A comprehensive literature search has been applied using multiple electronic databases, including Centre for Agriculture and Bioscience (CAB) Abstracts, Biological Abstracts, Google Scholar, and Web of Science. The selection criteria for inclusion required that: (1) reported SOC or soil organic matter (SOM) concentrations or stocks per unit land area before and after LUC; (2) employed specific experimental designs (paired-site, time-series, or retrospective designs); and (3) provided detailed methodological information. Given that SOC may reach a new equilibrium only after several years or decades, few studies have reported time series data that trace back to the conditions prior to LUC. As such, it was assumed that, for each study, the soil conditions before LUC were comparable across sampling sites within the same land-use type. Some studies reported only ranges of soil sampling depths rather than a single specific depth. Therefore, the depth-based soil layer categories simply reflect the reporting intervals used in the original literature (*i.e.*, 0–20 cm, 0–30 cm, and > 30 cm). Since LUC is not an instantaneous or short-term process, the organic layer can be considered a relatively stable component. Moreover, in both forest and grassland ecosystems, the organic layer accounts for a substantial proportion of total soil carbon (20%–40%) [24]. Recently, researches increasingly emphasize the strong coupling and the continuous nature of SOM transformation across the interface of the organic layer and mineral soil, which treating forest-floor litter and the underlying mineral soil as an integrated system [25, 26]. Therefore, in this study, we have treated the organic layer as part of the soil layer, with its thickness included in the total soil depth, and integrate it by depth into the soil layers. Studies that explicitly stated the duration of the LUC period as being too short (*i.e.*, less than 5 years) were excluded.

Additionally, studies that reported only the magnitude of change in SOC or SOM without providing the corresponding standard deviations for these variables before and after the LUC were also excluded. Data derived from the same sites but subjected to different treatments were treated as independent observations. The screening of data for this meta-analysis followed the procedures reported by PRISMA [27] (see Supporting Information Fig. S1).

For the purposes of this study, primary forest included natural woody vegetation showing no apparent human impacts and dominated by native tree species. Grassland was defined as ecosystems dominated by herbaceous vegetation, including natural pastures and sparse grasslands, excluding intensive agricultural croplands. After applying these criteria, a total of 46 studies with 548 data sets on the conversion of primary forests to grasslands were retained (Fig. 1). The collected data across diverse geographical regions, ranging from semi-arid zones to humid tropical regions along the equator and temperate zones (Table S1).

Data processing and analysis

For studies reporting SOM reserves were converted to SOC stock by the following equation [9]:

$$SOCs = SOM_S \times 0.58 \tag{1}$$

where, $SOCs$—soil organic carbon stock (Mg/ha); $SOMs$—soil organic matter storage (Mg/ha).

For studies reporting only SOC concentrations, we calculated SOC stock using the following equation [22]:

$$SOC_S = SOC_C \times BD \times \Delta H \times 10 \tag{2}$$

here, SOC_C—soil organic carbon concentration (g/kg); BD—soil bulk density (g/cm^3); ΔH—soil layer thickness (cm).

Monte Carlo simulation approach [28] was applied to address missing soil bulk density values. We generated 10,000 simulations of bilaterally truncated normally distributed random vectors based on available BD data. Values outside the observed range were discarded to maintain data integrity. This approach allowed us to estimate the uncertainty introduced by using mean BD values while preserving the maximum amount of data. While dry combustion is the standard recommended by Intergovernmental Panel on Climate Change (IPCC), several included studies utilized the Walkley–Black method. To harmonize data, we acknowledged the associated uncertainty and, where necessary, adjusted Walkley–Black values using standard recovery factors to improve stock estimation accuracy.

We conducted the meta-analysis using two effect sizes: weighted mean difference (MD), which provides information on absolute changes, and response ratio (RR), which reflects the relative changes:

$$MD = \mu_e — \mu_c \tag{3}$$

$$RR = \ln(\mu_e/\mu_c) \tag{4}$$

where, μ_e means SOC_S after LUC; μ_c means SOC_S before LUC.

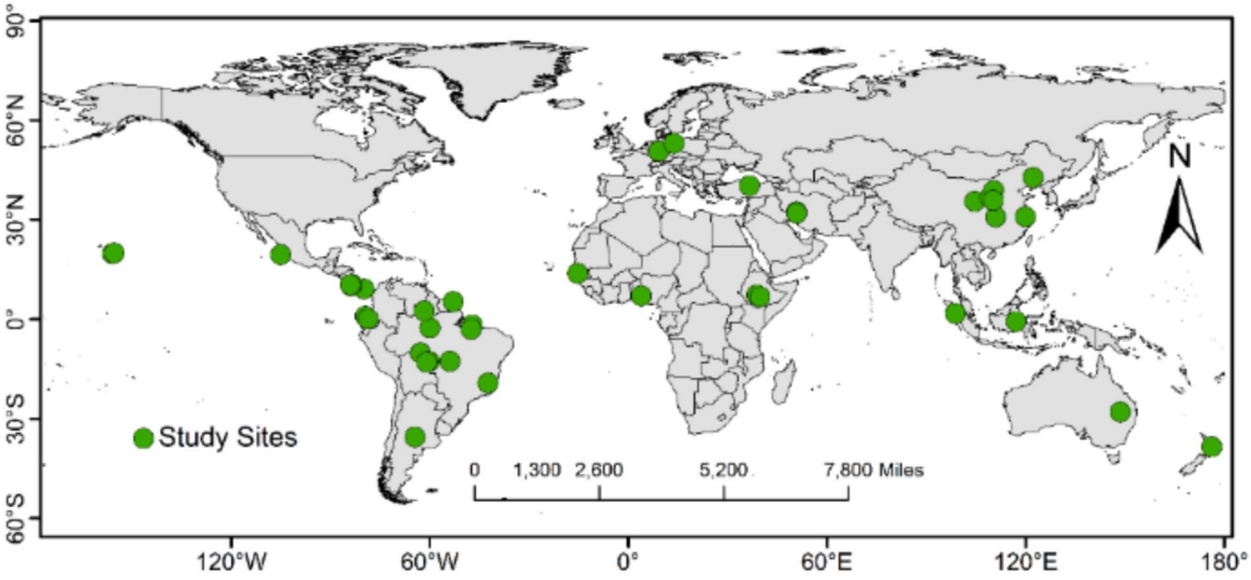

Fig. 1 Spatial distribution of the collected data

The variance (v_i) corresponding to effect size was calculated by:

$$v_i = \frac{S_e^2}{n_e \mu_e^2} + \frac{S_c^2}{n_c \mu_c^2} \quad (5)$$

where, S_e and S_c are the standard deviations of the SOC_S after and before LUC, and n_e and n_c are the corresponding sample sizes, respectively.

Random-effects model was applied to meta-analysis based on heterogeneity test (Table S2). The weighting factor (w_i) of each effect size in the random-effects model was estimated by:

$$w_i = \frac{1}{v_i + \tau^2} \quad (6)$$

where, v_i and τ^2 are within-study variance and between-study variance, respectively. The weighted effect size (ES_+) was calculated as:

$$ES_+ = \frac{\sum_{i=1}^{k} (w_i \times ES_i)}{\sum_{i=1}^{k} w_i} \quad (7)$$

where, k is the number of datasets; w_i and ES_i are the weight and the unweighted effect size corresponding to the i-th datasets, respectively.

The effect size was converted to a percentage change (PC) by Eq. (8):

$$PC = \left(e^{ES+} - 1\right) \times 100\% \quad (8)$$

Publication bias was conducted by funnel plot (Fig. S2). The general linear model (GLM) is a fundamental statistical modeling framework that extends ordinary linear regression to accommodate dependent variables that are not continuous or normally distributed, such as categorical variables. Additionally, GLM can capture nonlinear relationships between independent variables and the response variable, thereby enabling its application to a wider range of complex regression problems. To examine the effects of climatic variables on SOC changes, we developed GLM and multiple regression models [29, 30] incorporating: standardized MAT and MAP, climatic zone (tropical vs. temperate), interaction terms between climatic variables. All statistical analyses were performed using Stata (version 17.0) and R (version 4.2.1) software packages.

Results

Variations in SOC changes under LUC

The primary forest LUC to grassland resulted in a significant increase in SOC stock ($P < 0.05$). Across all studies, we observed an average increase of 3.35 Mg/ha, representing a 13.30% rise in SOC content (Fig. 2). This overall increase masks substantial regional variations, as detailed that SOC stock increased by 2.05 Mg/ha (7.70%) and 5.19 Mg/ha (24.70%) in tropical regions and temperate regions respectively. Furthermore, the differences above is significant ($P < 0.05$), suggesting that climatic conditions play a crucial role in mediating SOC dynamics following LUC.

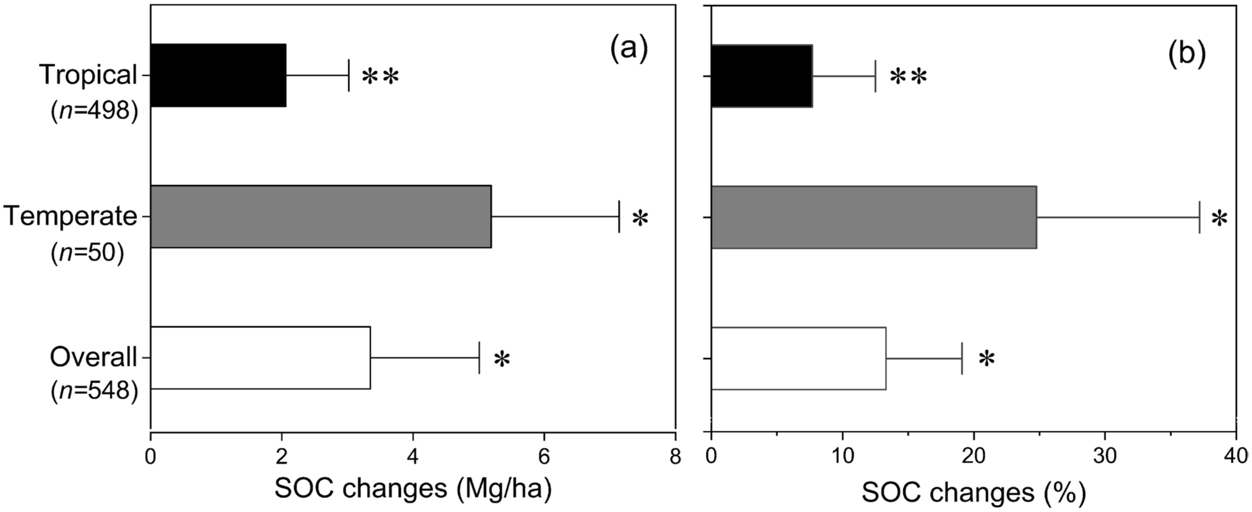

Fig. 2 Soil organic carbon changes in different climate zones after land-use change from primary forest to grassland. **a** The absolute changes (weighted mean difference), and **b** the relative changes (response ratio). *n* is sample size. The symbol **and * represent tests are significant at the level of $\alpha = 0.01$ and 0.05, respectively

SOC changes among different sampling depth

The analysis of different soil depths demonstrated varying patterns of SOC accumulation (Fig. 3). After the LUC of primary forest to grassland, SOC increased by 3.02 Mg/ha (11.90%) at a depth of 0–20 cm. In the 0–30 cm soil layer, the SOC stock increased by 3.05 Mg/ha (11.30%), while in the soil layer deeper than 30 cm, SOC increased by 5.18 Mg/ha (6.40%). These findings indicate that while surface layers show substantial SOC increases, the deeper soil layers contribute significantly to overall SOC stock changes.

SOC changes influence by climatic factors

Our analysis revealed significant effects of climatic factors on SOC alterations under primary forest LUC to grassland. SOC stock changes showed significant negative correlations with both MAT (Spearman's $r = -0.32$) and MAP ($r = -0.41$).

The relationships between SOC changes and MAT, also MAP, indicated that SOC changes after LUC from primary forest to grassland tend to be greater in regions with lower MAT and MAP (Figs. 4, 5).

According to the general linear model analysis, several important patterns emerged regarding the climatic factors influencing SOC changes (Table 1). MAT alone explained 8% of the variance in SOC changes under conversion of primary forest to grassland, while MAP accounted for 15% of the variance. Notably, the three-factor interaction model (MAT × MAP × climatic zone) explained a substantial 41% of the variance. These findings suggested that the effect of MAT on SOC changes with LUC from primary forest to grassland was more pronounced in tropical regions, whereas MAP had a stronger influence in temperate zones. Furthermore, the interaction between MAT and MAP was found to significantly affect SOC dynamics, highlighting the complex interplay of climatic factors in shaping SOC behavior across different climatic zones.

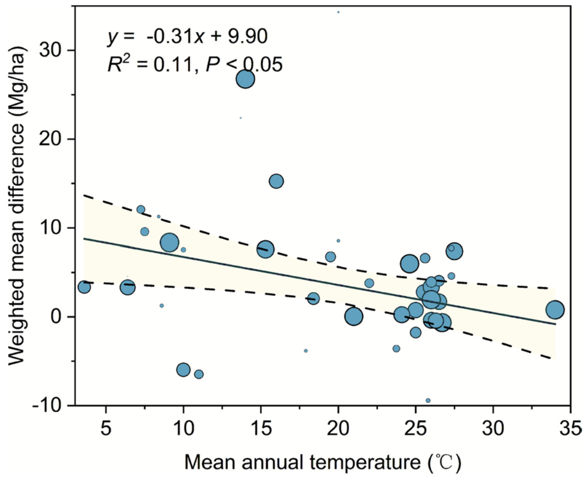

Fig. 4 The absolute changes (weighted mean difference) in SOC response to mean annual temperature with land-use change from primary forest to grassland. The size of the scatter points represents the weight

Discussion

SOC changes following conversion of primary forest to grassland.

SOC changes following the conversion of primary forest to grassland are primarily driven by alterations in carbon input–output balances, which are influenced by changes in vegetation and microbial activity. The observed increase in SOC after conversion contrasts with earlier studies that report SOC losses [10, 18], yet aligns with other studies [22, 31, 32]. This inconsistency in the literature forms the motivation for this study. Our findings suggest that these discrepancies are not merely

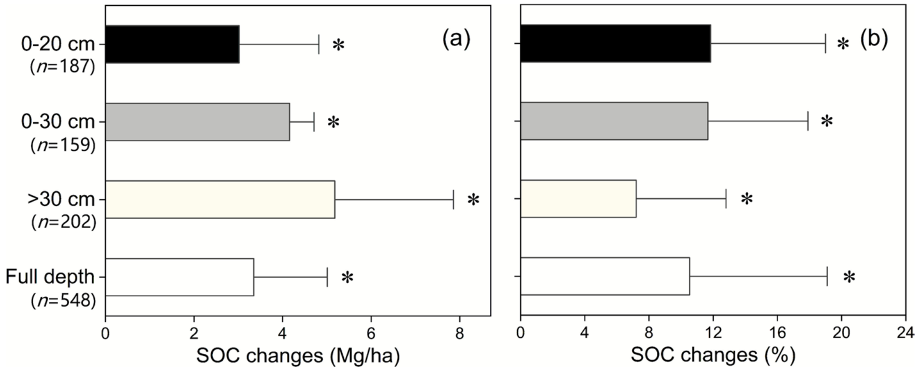

Fig. 3 Soil organic carbon changes at different soil depths after land-use change from primary forest to grassland. **a** The absolute changes (weighted mean difference), and **b** the relative changes (response ratio). *n* is sample size. The symbol **and * represent tests are significant at the level of $\alpha = 0.01$ and 0.05, respectively

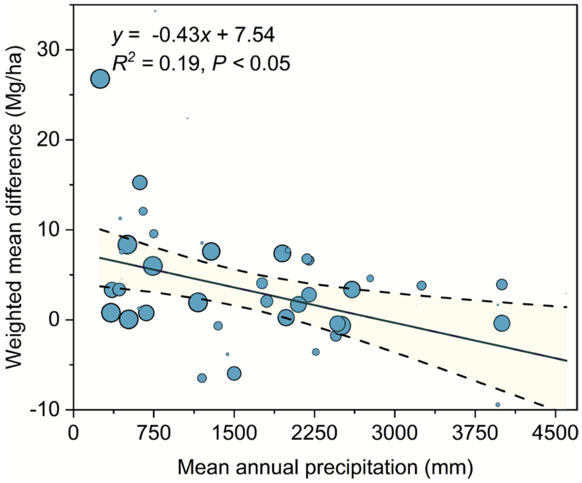

Fig. 5 The absolute changes (weighted mean difference) in SOC response to mean annual precipitation with land-use change from primary forest to grassland. The size of scatter points represents the weight

random but are systematically driven by climatic gradients. The direction and magnitude of SOC change are highly dependent on the local MAT and MAP regimes, which dictate the balance between carbon input and microbial decomposition. Several factors may attribute to the these: First, the extensive root systems characteristic of grassland ecosystems facilitate subsurface carbon storage, particularly in deeper soil layers (> 30 cm) [33]. Second, improved grassland management practices, including proper grazing and irrigation, have been shown to enhance carbon sequestration [11, 34]. Third, the continuous soil cover provided by grassland reduces erosion and temperature fluctuations, thereby promoting organic matter accumulation [21]. Additionally, the significant changes observed in deeper soil layers emphasize the importance of comprehensive soil sampling in carbon accounting [21]. These results may be related to the effects of increased carbon input and decreased decomposition. Grassland typically have deeper and denser fibrous root systems compared to forest, directly “pumping” large amounts of organic carbon into deep soils through root turnover and exudates [35, 36]. Moreover, deep soils typically exhibit low oxygen levels, stable temperatures, and consistent moisture, which significantly inhibit microbial decomposition [37]. Furthermore, organic carbon in deep soils is effectively protected both physically and chemically by binding with clay minerals or being encapsulated within soil aggregates, allowing for long-term stable accumulation [38]. Future research should focus on long-term monitoring of SOC dynamics, particularly in deeper soil layers, where we found more substantial SOC changes. Beyond ecological factors, the ‘strong argument’ for inconsistent findings in the literature may also be attributed to methodological differences in obtaining soil bulk density. As highlighted by previous meta-analyses, variations in how *BD* is calculated or estimated can lead to significant differences in reported SOC stocks, which may explain why some studies report gains while others report losses following similar land-use change [19, 22, 39]. Despite these limitations, our study aimed to include more study sites than previous meta-analyses, and we found that, on average, SOC increased significantly following the conversion of primary forest to grassland. These results demonstrate the capacity of converted grassland to store carbon, implying that proper management of these ecosystems could contribute to climate change mitigation [11]. For such converted grassland, management practices informed by ecological theory could potentially offer more carbon benefits than

Table 1 General linear model with degrees of freedom, sum of squares, *F*-values, *P*-values

Models	*Df*	Sum of squares	*F*	*P*	Explained variance (%)	AIC
SOC change ~ CZT	1	0.50	1.04	0.3125n.s		98
SOC change ~ MAT	1	2.21	5.07	< 0.000*	8	94
SOC change ~ MAP	1	3.57	8.64	< 0.000*	15	91
SOC change ~ MAP + MAT	1	3.64	4.44	< 0.000*	13	92
SOC change ~ CZT + MAT	2	3.70	4.48	< 0.000*	13	92
SOC change ~ CZT + MAP	2	3.88	4.75	< 0.000*	14	92
SOC change ~ CZT + MAT + MAP	3	5.69	5.06	< 0.000**	21	89
SOC change ~ CZT × MAT	3	5.71	5.09	< 0.000**	21	89
SOC change ~ CZT × MAP	3	4.54	3.76	< 0.000**	16	92
SOC change ~ MAT × MAP	3	3.79	3.01	< 0.000*	12	94
SOC change ~ CZT × MAT × MAP	7	10.74	5.46	< 0.000****	41	79

CZT Climate zone type, *MAT* Mean annual temperature, *MAP* Mean annual precipitation, significance codes: ‘****’ 0.001, ‘**’ 0.01, ‘*’ 0.05, ‘n.s.’ not significant afforestation. However, the findings should not be used to justify deforestation, as it leads to direct carbon emissions and biodiversity loss before SOC changes occur. Therefore, investigating the effects of specific management practices on carbon sequestration potential in converted grassland is recommended.

Regional variations in SOC changes

The results of this study reveal the regional pattern of SOC changes following the conversion of primary forest to grassland, showing that the increase in temperate regions is greater than that in tropical regions. The GLM analysis indicates that the interaction between climatic zone and temperature was a more significant predictor of SOC change in the tropics ($P < 0.05$), whereas the interaction with precipitation was more influential in temperate regions. These regional variations in SOC dynamics can be attributed to several key factors. In tropical regions, elevated temperatures accelerate the decomposition of organic matter, thereby potentially limiting SOC accumulation [40]. In contrast, temperate grasslands often exhibit higher net primary productivity, which results in greater carbon inputs into the soil [41]. Furthermore, the deeper and more developed soils typically found in temperate zones may provide a larger capacity for carbon storage [19]. The differing responses between tropical and temperate regions indicate that carbon management strategies should be tailored to local conditions [10]. Collectively, these findings underscore the importance of incorporating regional context into assessments of SOC dynamics following the conversion of primary forest to grassland.

Effects of climatic factors on SOC changes

The effects of climatic factors on SOC dynamics following the conversion of primary forest to grassland are multifaceted. Temperature and precipitation patterns significantly influence carbon accumulation and decomposition rates [40]. Our analysis demonstrates significant negative correlations between SOC changes and both MAT and MAP, indicating that SOC accumulation following conversion from primary forest to grassland is greater in cooler and drier environments. In colder regions, microbial activity and enzymatic decomposition of organic matter are generally slower [42]. Consequently, even a small increase in carbon input from grassland conversion in these regions could result in substantial net SOC gains [43], with both processes contributing to higher SOC accumulation. In drier regions, biological activity is constrained by water availability [44], leading to slower organic matter turnover and reduced leaching of dissolved organic carbon (DOC), which promotes greater SOC retention [45]. Therefore, SOC gains from grassland establishment are likely to be more significant in arid or semi-arid environments, where precipitation limits carbon loss. In contrast, in warmer and wetter climates, forest tend to have higher aboveground biomass and potentially faster carbon cycling but also higher rates of decomposition and leaching, which may limit net SOC increases upon conversion [46, 47]. Generally, warmer and wetter conditions promote greater decomposition and less stable SOC forms, whereas cooler and drier conditions favor the accumulation of more stable SOC. This climatic dependency explains why previous meta-analyses and site-specific studies have reported such divergent results. In temperate regions where MAT and MAP are lower, the establishment of grassland often results in a net carbon gain due to high root-derived inputs and slow turnover. Conversely, in tropical regions with high MAT and MAP, the rapid mineralization of organic matter can lead to minimal gains or even net losses, as observed in studies by Don et al. [21] and Kauffman et al. [20]. Consequently, the global 'average' effect of forest-to-grassland conversion is a composite of these geographically distinct responses, and failure to account for these climate-driven interactions (which explain 41% of our observed variance) can lead to misleading generalizations about the carbon sequestration potential of land-use changes.

Conclusions

This comprehensive meta-analysis provides substantial evidence regarding SOC dynamics following LUC from primary forest to grassland. In this studies, we observed a significant overall increase in SOC stocks (3.35 Mg/ha, 13.30%), highlighting the potential of properly managed grassland as carbon sinks. However, regional variations were evident, with temperate regions showing greater SOC increases (5.19 Mg/ha, 24.70%) than tropical regions (2.05 Mg/ha, 7.70%), underscoring the importance of considering regional climatic conditions in carbon management strategies. Additionally, significant SOC accumulation was observed across all soil depths, particularly in deeper layers (> 30 cm), emphasizing the need for comprehensive soil sampling in carbon accounting practices. Climatic factors, including MAT and MAP, significantly influenced SOC dynamics, with their interaction explaining 41% of the observed variance. This suggests that the positive impact of LUC on SOC is more pronounced in areas where the climate naturally supports higher SOC stability or slower turnover rates. Thus, appropriate grassland ecosystem management may provide greater carbon sequestration benefits than afforestation in certain contexts. However, these findings should not be used to justify deforestation, which degrades ecosystems in many ways beyond soil carbon. This study enhances our understanding of carbon cycle dynamics following LUC and provides a scientific basis for developing effective soil carbon management strategies. Future research should focus on long-term monitoring of SOC dynamics, particularly in deeper soil layers, and investigate the effects of specific management practices on the carbon sequestration potential of converted grasslands.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12302-026-01335-6.

Supplementary Material 1.

Acknowledgements
H. Z.-Z. was supported by the Natural Environment Research Council (NERC; NE/T011084/1) and by the Next Generation Ecosystem Experiments-Tropics project, funded by the U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research.

Author contributions
Huaikai Weng: Writing-original draft, visualization, validation, methodology, investigation, data curation, conceptualization. **Xieyu Fan:** software, visualization, validation, methodology, investigation, data curation, conceptualization. **Zekai Huang**, **Sheng Li**, **Shijie Shi**, **Kexin Lin** and **Xiaolei Pei**: Methodology, investigation, data curation. **Jingyao Chen**, **Hongwei Xie** and **Yun Ke**: Data curation, investigation. **Huanyuan Zhang-Zheng**: Writing-review & editing, supervision, investigation, conceptualization. **Zhiyuan Zhang**: Writing-review & editing, supervision, investigation, conceptualization, funding acquisition.

Funding
This study was funded by the National Natural Science Foundation of China, grant number 42207477.

Data availability
The data that support the findings of this study are available from the corresponding authors upon reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Received: 24 October 2025 Accepted: 18 January 2026

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