

Accelerated warming and soil erosion drive topsoil carbon decline across the Tibetan Plateau: A 40-year resampling analysis

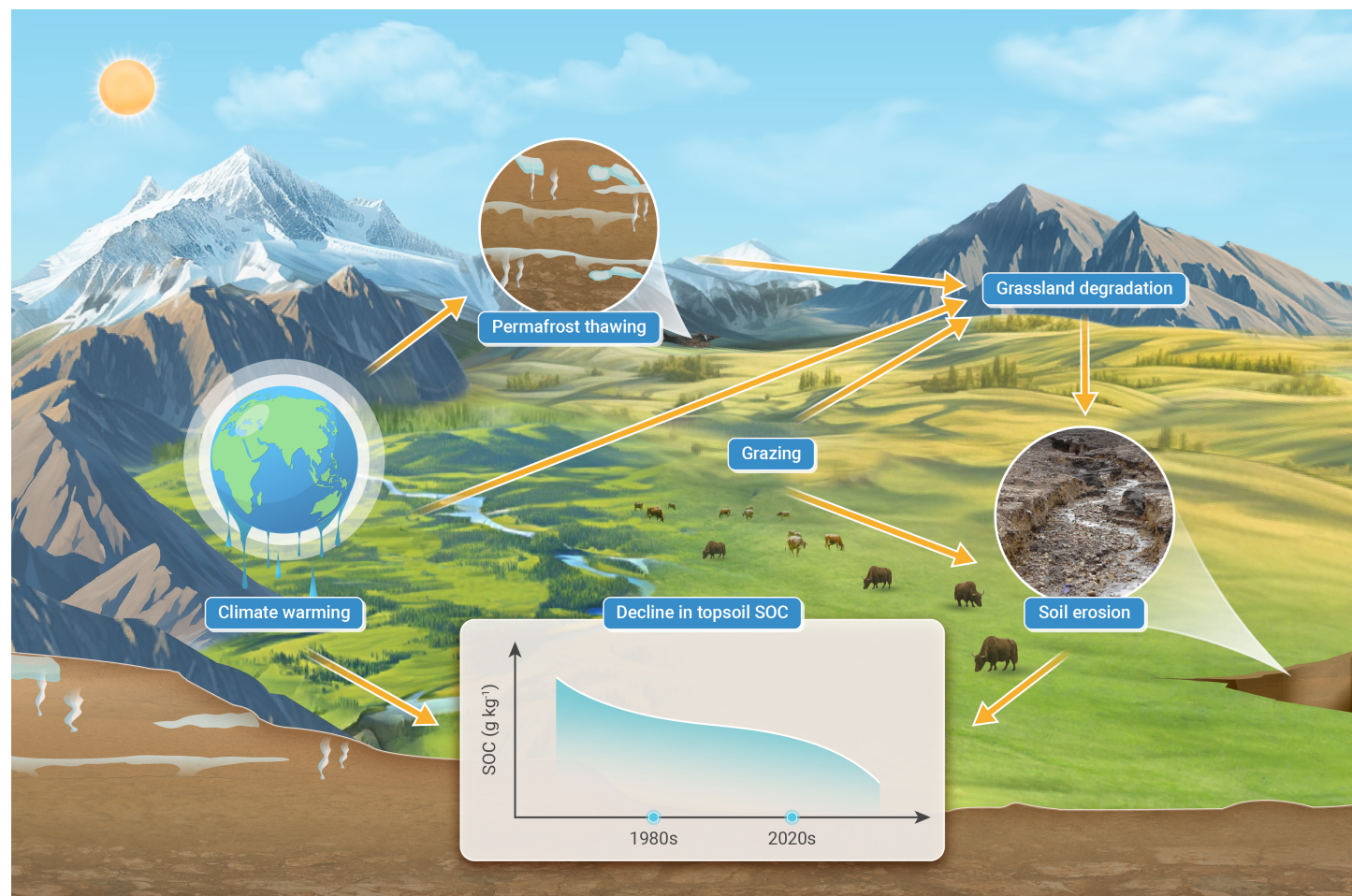
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Topsoil carbon declined by 8.9 g kg^{-1} in 40 years on the Tibetan Plateau, while subsoil remained stable.
- Erosion surpassed warming in driving SOC loss, revealing overlooked risks in Earth system models.
- Erosion-focused land management is vital to protect high-altitude carbon under climate change.

Accelerated warming and soil erosion drive topsoil carbon decline across the Tibetan Plateau: A 40-year resampling analysis

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Soil organic carbon (SOC) is a critical component of global carbon cycling, especially in climate-sensitive high-altitude ecosystems like the Tibetan Plateau. Despite its ecological significance, the decadal-scale response of alpine SOC to interactive warming-erosion pressures remains poorly quantified in Earth system models. Through systematic resampling of 261 sites spanning four decades (1980s–2020s), we quantified the combined impacts of climate warming, soil erosion, and geographic controls on SOC dynamics across the Tibetan Plateau. Our results reveal a significant decline in topsoil SOC ($p < 0.0001$), with an average reduction of 8.9 g kg^{-1} , while subsoil SOC remained relatively stable ($p = 0.13$), underscoring the heightened sensitivity of topsoil to environmental shifts. Spatiotemporal patterns show geographic divergence: severe SOC depletion occurred in southeastern valleys through erosion-geography synergies, while western plateau regions exhibited modest gains. Variance partitioning attributes 9.1% of SOC variation to erosion (exceeding climate's 5.7% and environmental variables' 6.0%), with 22.9% explained by their three-way interactions. Warming enhances carbon mineralization, but erosion is the dominant mechanism of carbon loss in steep valleys, leading to greater carbon depletion than warming alone and challenging prevailing assumptions about SOC dynamics in alpine systems. These findings provide critical insights for global climate models and underscore the urgency for targeted land management interventions to mitigate SOC loss and protect these vulnerable high-altitude ecosystems amidst ongoing environmental changes.

INTRODUCTION

The soil-atmosphere interface is a critical component of Earth's carbon cycle, with soil organic carbon (SOC) dynamics playing a pivotal role in regulating CO_2 fluxes.^{1,2} Environmental shifts, such as climate warming and land degradation, can destabilize SOC, triggering feedback loops that influence global climate stability.^{3,4} This reality elevates understanding of SOC responses to combined environmental stresses from a scientific priority to an operational requirement for achieving net-zero climate targets.⁵

Central to this challenge is the dual role of climate warming in regulating SOC dynamics—simultaneously accelerating microbial decomposition while variably modulating biomass production.⁶ These competing processes create complex land-atmosphere feedbacks, where shifts in vegetation productivity and microbial activity may either amplify or mitigate CO_2 fluxes under warming.^{7,8} While empirical studies emphasize warming-induced carbon loss via enhanced decomposition,⁶ SOC stocks ultimately reflect a balance between respiratory losses and plant-derived carbon retention.⁹ Short-term warming experiments (< 10 years) often show minimal net SOC changes, as increased biomass production temporarily offsets decomposition.¹⁰ However, their limited duration obscures long-term trends.¹¹ Synthesis studies now identify a pivotal threshold: Initial SOC accumulation under warming transitions to net losses after 5–10 years, as sustained decomposition overtakes carbon inputs.¹² This temporal divergence highlights a fundamental limitation in current approaches and underscores the urgent need for decadal-scale observational data to unravel warming's cumulative impacts on SOC persistence.

Beyond reducing carbon inputs, soil erosion—the planet's most extensive

land degradation process—emerges as a pivotal yet under quantified modulator of SOC stability. This dual-force mechanism not only diminishes biomass-derived carbon inputs but also laterally redistributes SOC across topographical gradients, thereby compromising vertical stabilization processes while amplifying microbial decomposition.^{13,14} While studies at plot or hillslope scales consistently show erosion-induced SOC loss via aggregate disruption and accelerated mineralization,¹⁵ the net regional impact remains unresolved due to contradictory carbon retention signals in depositional zones.^{16,17} This scale-dependent discrepancy between localized carbon loss and landscape-scale redistribution continues to drive debate on erosion's role as a regional carbon source versus sink.¹³ Systematic, field-based studies are needed to better understand erosion's role in SOC dynamics.

The Tibetan Plateau, often termed the “Third Pole,” uniquely influences Earth's climate and water cycles through its atmospheric, hydrological, cryospheric, and geological interactions.¹⁸ SOC stocks on the Tibetan Plateau represent a critical part of the global carbon cycle, and understanding potential changes in these stocks under climate warming is essential for refining climate models and strategies. Mirroring Arctic permafrost systems, the plateau stores approximately 28 Pg of SOC within its upper 2 m,¹⁹ forming a frozen reservoir now undergoing rapid thermal destabilization.²⁰ Over recent decades, the plateau has experienced accelerated climate change and land degradation, with temperatures rising at a rate of approximately 0.46°C per decade, nearly twice the global average rate,^{21,22} and over half of the alpine grasslands now show signs of severe degradation.^{23,24} Thawing permafrost and intensified soil erosion further compromise SOC persistence, creating potential shifts in the overall soil carbon stock.³ The Tibetan Plateau's ecological and geomorphological distinctiveness amplifies its scientific importance. Its combination of vast high-altitude grasslands, steep terrain, cryogenic processes (e.g., freeze–thaw cycles), and fragile soils makes it particularly susceptible to erosion. Moreover, the region serves as a climate change hotspot and water tower for much of Asia, linking local SOC dynamics to downstream hydrological and biogeochemical processes. Unlike temperate systems, where SOC responses are moderated by deeper soils and stable vegetation cover, the Plateau's shallow soils and variable vegetation heighten its sensitivity to surface disturbance and environmental forcing. These unique attributes position the Tibetan Plateau as a critical but under-represented region for understanding high-elevation carbon–climate feedbacks.

This study assesses soil organic carbon (SOC) dynamics across the Tibetan Plateau over four decades (1980s–2020s) and identifies the dominant drivers of observed changes, revealing that soil erosion plays a stronger independent role than climate warming in SOC decline — Contrary to long-standing assumptions. By resurveying 261 historically sampled sites, we directly quantify SOC changes at consistent soil depths (0–50 cm) and analyze their linkages to climatic, erosional, and geographic factors. Our analysis clarifies two unresolved questions: (1) The relative contributions of climate warming versus soil erosion to SOC loss in high-altitude ecosystems, and (2) how geomorphic controls mediate these processes at landscape scales. These insights refine predictions of alpine carbon–climate feedbacks while informing targeted strategies to conserve vulnerable SOC stocks under accelerating environmental change.

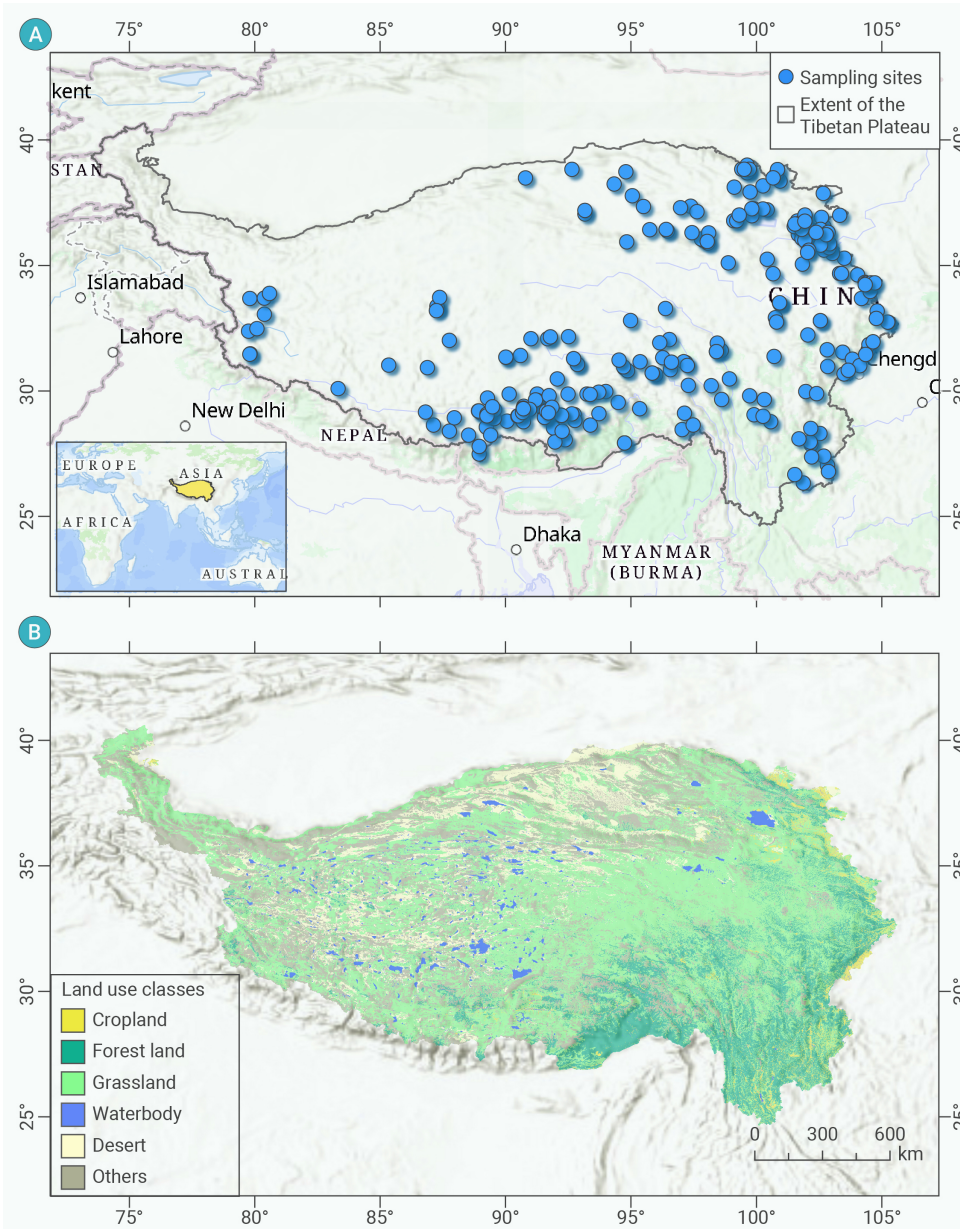


Figure 1. Sampling site distribution and land use in the Tibetan Plateau (A) Spatial distribution of sampling sites across the Tibetan Plateau; (B) Land use classification in the Tibetan Plateau, highlighting cropland, forest, and grassland areas.

These combined factors, along with the rugged terrain, exacerbate the vulnerability of SOC to erosion, particularly in the context of intensified land use and environmental changes (Figure 1).

Field surveys

SOC changes were assessed through two field surveys conducted in the 1980s and 2020s on the Tibetan Plateau.

Original field survey. A comprehensive soil survey was conducted across China from 1979 to 1989, focusing on the Tibetan Plateau around 1984.²⁵ This survey recorded the geographical location, surrounding topography, and land use/cover types for representative soil profiles. Soil samples were collected by horizon to determine key properties, including SOC.

Resurvey and laboratory measurements. To evaluate SOC changes, a resampling campaign was conducted from 2020 to 2021. Historical sampling locations were first identified based on-site information from the original 1980s survey. Specific sampling points were then selected according to previously recorded soil types, topographic positions, slope aspects, slope gradients, land use, soil depth, and gravel content. A total of 261 well-matched sites were resampled, including 120 grassland, 120 cropland, and 21 forest sites to ensure broad ecosystem coverage. At each site, soil samples were collected from the top three horizons, with three replicates at the same depths as in the original survey. In total, 261 topsoil samples (0–20 cm) and 408 subsoil samples (20–50 cm) were gathered. These samples were transported to the laboratory in Kunming, air-dried, cleaned of debris, and sieved through a 0.149-mm mesh. SOC and granulometric composition

were determined using the same methods as the original survey: SOC was analyzed with the Walkley-Black method,²⁶ and granulometric composition was measured using the pipette method.²⁷

Environmental data collection

To characterize environmental changes from the 1980s to 2020s, meteorological data, remotely sensed vegetation data, and land use/cover data were collected. Observed average annual temperatures and precipitation totals from 106 stations in the study area, covering approximately 1951–2020, were used to analyze climate change. Considering the region's complex topography and the limited number of stations, gridded meteorological data from the China Meteorological Forcing Dataset (1979–2018), with a spatial resolution of 0.1° and a temporal resolution of 1 day, were also used.²⁸ These datasets, including temperature and precipitation records, were found to be strongly correlated with observations from the meteorological stations (Figure S2). Normalized Difference Vegetation Index (NDVI) data were utilized for the periods 1990–2000 and 2005–2020, at five-year intervals. NDVI data for 1990–2000 were extracted from the 250 m resolution Vegetation Index and Phenology datasets (VIP15; <https://lpdaac.usgs.gov>), while data for 2005–2020 were obtained from the MODIS reflectance data products (MOD13Q1; <https://earthdata.nasa.gov/>). Changes in land use/cover from 1990 to 2020 (five-year intervals) were analyzed using data from the National

MATERIALS AND METHODS

Study area

The Tibetan Plateau, the world's largest alpine landscape, spans approximately 5 million km² and has an average elevation exceeding 4,000 m asl.¹⁸ This high-altitude region plays a critical role in global carbon cycling due to its large stores of SOC, particularly in permafrost and alpine grassland ecosystems. The plateau experiences a cold and dry climate, with mean annual temperatures ranging from -5.4 to 21.0°C and annual precipitation between 17 and 1,196 mm (Figure S1). These harsh conditions limit organic matter decomposition, facilitating long-term SOC accumulation. However, they also render the region highly sensitive to climate change, as warming could accelerate SOC loss through enhanced decomposition and soil respiration. Vegetation is dominated by alpine grasslands, covering approximately 46.6% of the area, with key species like *Stipa* spp. and *Kobresia*, which significantly contribute to SOC input through biomass. Forests, which make up 19.3% of the area, include species such as *Abies fabri*, *Picea asperata*, *Pinus densata*, and *Platycladus orientalis*. Cropland and desert occupy 2.0% and 6.8% of the plateau, respectively. The soils of the plateau are typically shallow, poorly developed, and coarse-textured, with types like Cambisols, Calcisols, Chernozems, and Kastanozems (as classified by the World Reference Base for Soil Resources). Livestock grazing, particularly yak herding, is the dominant land use in the region, influencing both vegetation cover and soil structure.

Land-Use/Cover Database of China (<http://www.resdc.cn>) with a spatial resolution of 30 m.

Characterization of climate change

Climate change was assessed at both sampling sites and meteorological stations. Sampling sites allowed analysis of the relationship between SOC changes and climate variation, while meteorological stations provided a broader climate characterization for the study area. Rates of change in climate variables were determined by linear regression over time, following the equation:

$$y = ax + b \quad (1)$$

where y is the value of climate variables for year x , a is the rate of change in variable y , and b is the intercept.

For each sampling site, daily temperature and precipitation values were extracted from gridded data layers, and rates of change were calculated by applying the linear fit. For meteorological stations, this fitting was applied directly to station data.

Indicators for evaluating soil erosion

Soil erodibility and radionuclides, specifically cesium-137 (^{137}Cs) and lead-210 (^{210}Pb), were used as indicators to characterize the intensity of soil erosion and analyze its relationship with changes in SOC.

Soil erodibility factor. The soil erodibility factor (K) was calculated based on soil sampling data. When soil organic matter content (SOM) was below 12%, we used the nomograph method (Eq. 2);²⁹ otherwise, the EPIC model (Eq. 3) was applied:³⁰

$$K = \frac{2.1 \times 10^{-4} M^{1.14} (12 - \text{SOM}) + 3.25 (S_c - 2) + 2.5 (P_c - 3)}{759.3} \quad (2)$$

$$K = \left[0.2 + 0.3 \exp \left(-0.0256 \text{ sand} \left(1 - \frac{\text{silt}}{100} \right) \right) \right] \left(\frac{\text{silt}}{\text{clay} + \text{silt}} \right)^{0.3} \times \left(1.0 - \frac{0.25 \text{SOC}}{\text{SOC} + \exp(3.72 - 2.95 \text{SOC})} \right) \times \left(1.0 - \frac{0.7 \text{SN1}}{\text{SN1} + \exp(-5.51 + 22.9 \text{SN1})} \right) \times 0.1317 \quad (3)$$

where K is the erodibility factor for water erosion ($\text{t ha h MJ}^{-1} \text{mm}^{-1}$), $M = \text{SVF} \times (100 - \text{Clay})$, SVF is the content of particle fractions of 0.002–0.1 mm (%), S is the structural class ranging from 1 for very fine soils to 4 for massive soils, P is the permeability class for a soil profile ranging from 1 for rapid drainage to 6 for very slow; and clay, silt, and sand are fractions of less than 0.002 mm, 0.002–0.05 mm, and 0.05–0.2 mm, respectively, %; while $\text{SN1} = (1 - \text{sand})/100$.

Radionuclides ^{137}Cs and ^{210}Pb . ^{137}Cs and ^{210}Pb were used to estimate soil erosion intensity. These radionuclides are well-established indicators of soil movement, as their redistribution patterns within the soil profile provide critical insights into the rates and extent of soil erosion. Higher concentrations of ^{137}Cs and ^{210}Pb in the soil typically indicate areas with lower erosion rates, as these radionuclides tend to accumulate in less disturbed soils. Conversely, lower concentrations suggest more intense erosion, where soil and its associated organic carbon have been lost.^{31–33}

Empirical Bayesian Kriging interpolation

To model the spatial distribution of SOC changes on the Tibetan Plateau from the 1980s to the 2020s, we employed Empirical Bayesian Kriging (EBK) due to its suitability for spatial heterogeneity and semivariogram uncertainty in complex landscapes. Unlike traditional kriging methods, EBK generates multiple semivariograms from data subsets, capturing local variability and reducing prediction errors, which is critical in the Plateau's diverse topography and environmental gradients.^{34,35}

We performed separate spatial interpolations for the 1980s and 2020s data and derived the SOC change map by subtracting the 1980s results from those of the 2020s. Based on cross-validation, we applied the Empirical transformation and selected the K-Bessel semivariogram model to represent spatial structure. To enhance predictive accuracy, explanatory variables—

including mean annual precipitation (MAP), mean annual temperature (MAT), NDVI, and Digital Elevation Model (DEM) data—were integrated into the EBK model. The 261 resampled sites were divided into overlapping subsets (100 points each) to simulate semivariogram uncertainty, allowing SOC predictions at unsampled locations across the plateau.

We validated the EBK predictions using cross-validation metrics such as Mean Error, Root Mean Square Error (RMSE), and Mean Standardized Error. Additional accuracy metrics, including Continuous Ranked Probability Score (CRPS) and the 90% and 95% prediction interval coverage, provided further probabilistic insights. Detailed formulas and methodologies are included in the supplementary file.

Statistical analyses

To assess temporal changes in SOC at each site from the 1980s to the 2020s, we performed paired t-tests to determine statistical significance. Using EBK interpolation in ArcGIS Pro 3.0.2 (ESRI, USA), we created spatial predictions to map SOC dynamics across the study area. Relationships between SOC changes and environmental variables—such as geographic, climatic, and soil erosion factors—were analyzed using linear regression to examine individual correlations. Additionally, a multiple regression model evaluated the combined effects of these variables on SOC changes, providing a comprehensive view of the drivers of SOC dynamics across the plateau.

To quantify the independent and synergistic contributions of climate change, soil erosion, and geographic controls, we conducted variance partitioning analysis (VPA) using the *varpart* function in the *vegan* package (v2.6-4). Three predictor sets were defined:

(1) *Climate change*: Rates of temperature (ΔT) and precipitation (ΔP) changes

(2) *Soil erosion*: Cesium-137 activity, lead-210 activity, and soil erodibility (K)

(3) *Geographic factors*: Mean annual precipitation (MAP), elevation, NDVI, and mean annual temperature (MAT)

Adjusted R^2 values were calculated via 999 permutations to correct for multicollinearity. Significance of individual fractions ($\alpha = 0.05$) was tested using redundancy analysis (RDA) with Benjamini-Hochberg false discovery rate control.

All analyses were conducted using R software (version 4.4.0).

RESULTS

Environmental changes on the Tibetan Plateau over the past four decades

Over the past four decades, the Tibetan Plateau has experienced substantial environmental changes. The mean annual temperature has increased significantly, at an average rate of 0.46°C per decade ($R^2 = 0.75$, $p < 0.001$; Figure 2A), while mean annual precipitation has remained relatively stable, showing no significant trend ($R^2 < 0.01$, $p = 0.658$; Figure 2B). Vegetation cover, as measured by the NDVI, has also shown a positive trend, increasing by 0.01 per decade since 1990 ($R^2 = 0.91$, $p < 0.001$; Figure 2C). However, this greening effect contrasts with ongoing land degradation: the area of grassland, which is the dominant land cover, has decreased from 57.0% to 47.4%, whereas desert, bare land, and rocky terrain have expanded by 3.6%, 2.4%, and 2.3%, respectively (Figure 2D). These environmental transformations likely have significant implications for SOC dynamics across the plateau.

Changes in SOC across the Tibetan Plateau during the 1980s–2020s

Topsoil SOC exhibited a significant decline from the 1980s to the 2020s ($p < 0.0001$), with an overall reduction averaging 8.9 g kg^{-1} (95% confidence interval (CI): 6.2 to 11.8 g kg^{-1}). In contrast, SOC levels in the subsoil remained statistically unchanged over the same period ($p = 0.13$). By land type, topsoil SOC in grasslands, forests, and croplands decreased by averages of 9.9 g kg^{-1} (95% CI: 5.9 to 14.5 g kg^{-1}), 44.0 (95% CI: 27.2 to 60.0 g kg^{-1}), and 2.0 g kg^{-1} (95% CI: 0.4 to 4.0 g kg^{-1}), respectively (Figure 3).

Cross-validation demonstrated that K-Bessel semivariograms effectively fitted both topsoil and subsoil SOC data (Figure 4). Consequently, the predicted SOC densities closely aligned with the measured values, with a mean error ranging from -0.03 to -0.08 g kg^{-1} .

SOC changes exhibited substantial spatial heterogeneity across the

plateau. The EBK regression predictions revealed the most significant reductions in topsoil SOC in the southeastern alpine valley regions, where intensified soil erosion and climate warming exert a strong influence. Conversely, topsoil SOC levels showed a clear increasing trend in the western regions, likely due to improved vegetation conditions associated with increased precipitation in these typically arid areas (Figure 5A). Subsoil SOC changes, however, were more muted across the plateau, indicating lower sensitivity to environmental shifts (Figure 5B).

Linking changes in SOC to environmental changes

The changes in SOC across the Tibetan Plateau were closely associated with several key environmental variables. Our analysis identified a significant positive correlation between SOC and both mean annual precipitation (MAP; Figure 6A) and elevation (Figure 6C), suggesting that increased precipitation

and higher altitudes support greater SOC retention. Conversely, SOC showed a significant negative correlation with the rate of change in temperature (ΔT ; Figure 6D) and in precipitation (ΔP ; Figure 6E), indicating that warming and changing precipitation patterns over time contributed to SOC reductions. Furthermore, SOC was positively correlated with changes in NDVI (Figure 6F), highlighting that vegetation greening is associated with SOC gains.

In terms of erosion-related factors, SOC exhibited a strong negative correlation with soil erodibility (Figure 6G), underscoring the detrimental effect of erosion potential on SOC stability. Additionally, SOC was positively correlated with cesium-137 (^{137}Cs ; Figure 6H) and lead-210 (^{210}Pb ; Figure 6I), both indicators of soil erosion, with higher concentrations generally indicating areas with lower erosion rates. These findings reinforce that more intense erosion is linked to SOC loss, while less disturbed soils retain higher SOC levels.

The multiple regression analysis revealed that geographic factors, climate

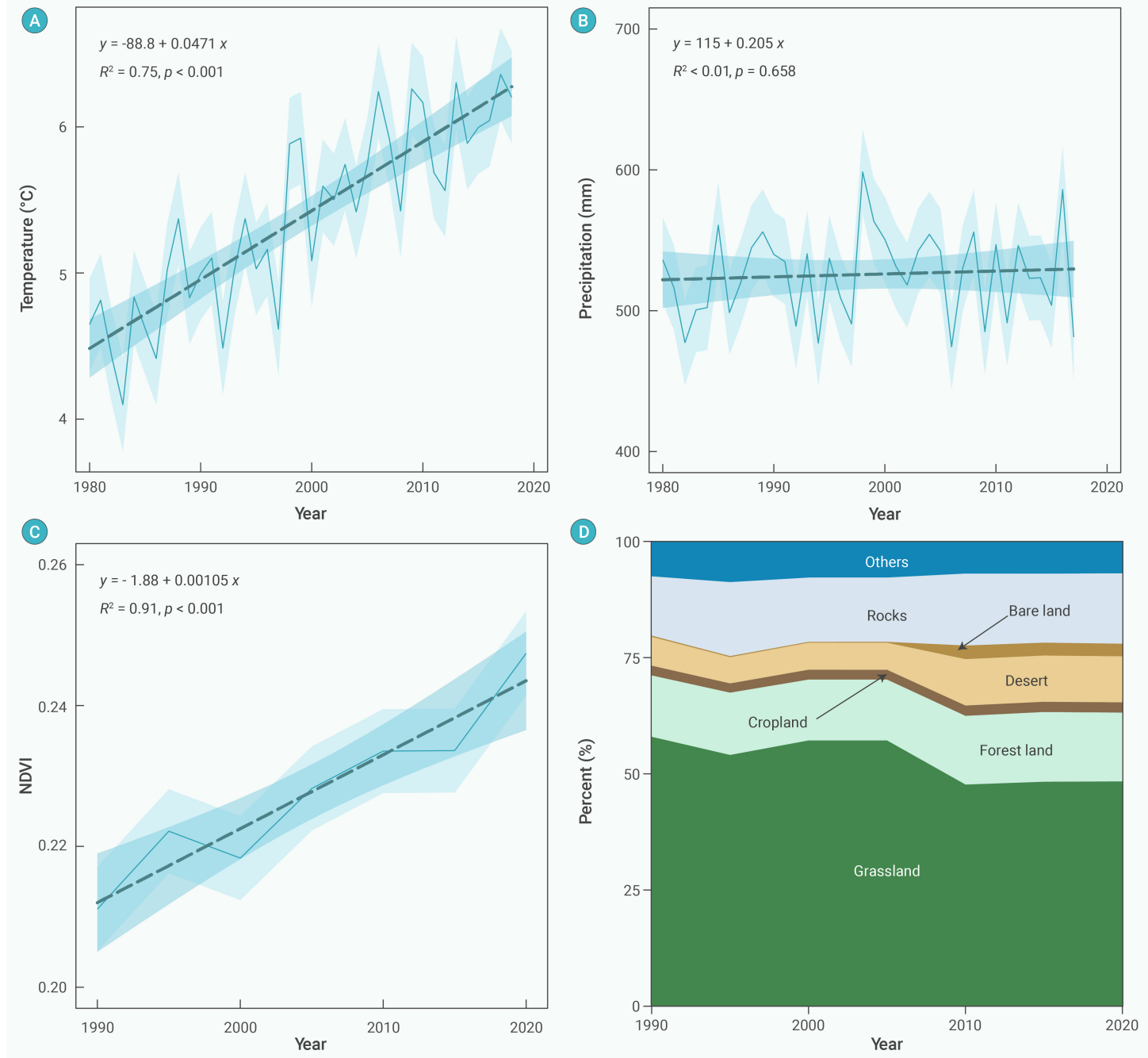


Figure 2. Temporal trends in environmental factors and land cover composition on the Tibetan Plateau from the 1980s to the 2020s (A) Increase in average annual temperature, showing a significant upward trend. (B) Stability in average annual precipitation, with no significant trend. (C) Positive trend in vegetation cover as measured by NDVI, with an increase of 0.01 per decade since 1990. (D) Changes in land cover composition, with a decline in grassland area from 57.0% to 47.4%, and corresponding increases in desert, bare land, and rocky terrain. Shaded areas represent 95% confidence intervals.



Figure 3. Changes in soil organic carbon (ΔSOC) between the 1980s and 2020s across different land-use types on the Tibetan Plateau (A) Topsoil (0–20 cm); (B) Subsoil (20–50 cm). Points represent mean SOC change values, with error bars indicating 95% confidence intervals. Asterisks denote statistical significance of mean changes based on paired t-tests: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; **** $p < 0.0001$. Note: Larger uncertainty in the forest group is partly due to its smaller sample size ($n = 21$), leading to wider confidence intervals. Positive ΔSOC values indicate net accumulation, while negative values indicate net loss over the 40-year period.

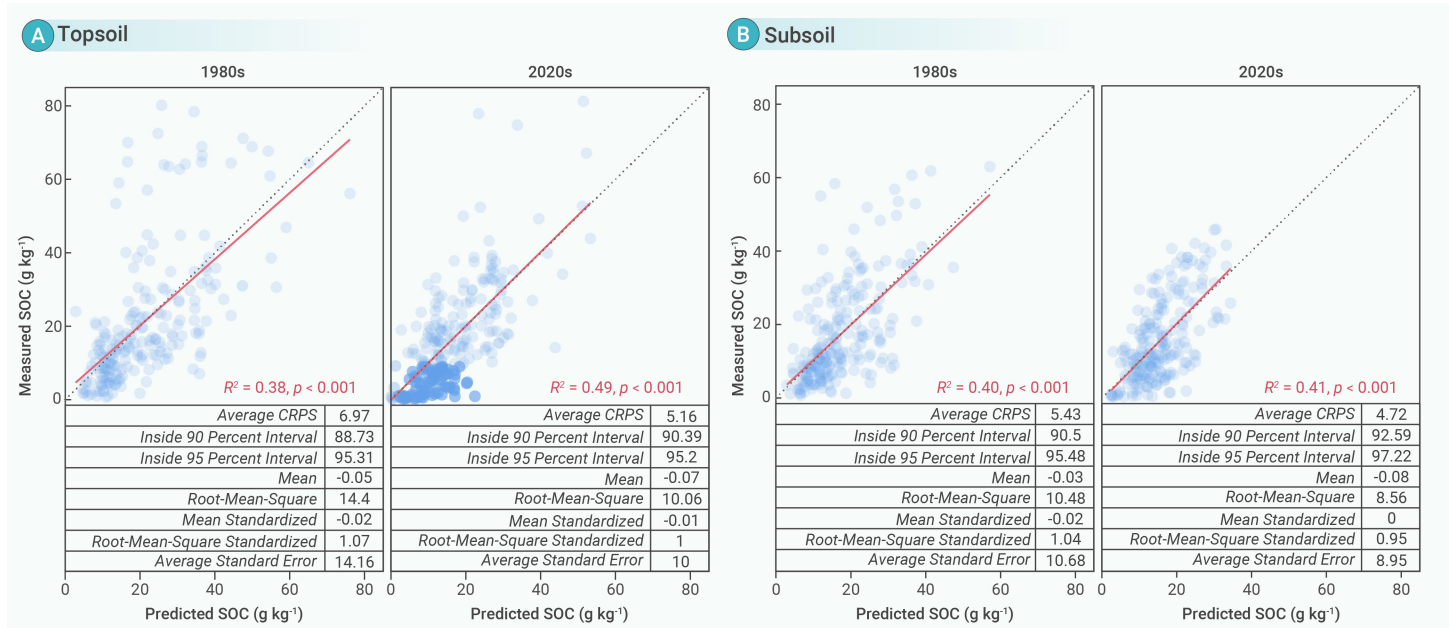


Figure 4. Prediction accuracy of Empirical Bayesian Kriging (EBK) interpolation for topsoil and subsoil SOC across the Tibetan Plateau in the 1980s and 2020s (A) Topsoil SOC; (B) Subsoil SOC. Each panel shows predicted versus measured SOC for the 1980s (left) and 2020s (right). Dashed lines indicate the 1:1 reference, and solid red lines show linear regression fits. Summary metrics including CRPS, RMSE, and prediction interval coverage are presented below each plot. Detailed metric calculations are provided in the Supplementary Information.

change, and soil erosion collectively account for 44% of the variance in SOC changes (Figure 7). Among these variables, geographic factors—including mean annual precipitation (MAP), elevation, NDVI changes, and mean annual temperature (MAT)—were the most influential, explaining 41.7% of the variance in SOC changes. Notably, MAP and elevation exhibited strong positive correlations with SOC, underscoring their pivotal roles in supporting SOC stability.

Climate change factors, specifically the rates of change in temperature

(ΔT) and precipitation (ΔP), also had significant effects. Temperature change (ΔT) showed a pronounced negative impact on SOC, while precipitation change (ΔP) had a weaker but still negative influence, indicating that warming trends are particularly critical in driving SOC reductions.

Soil erosion indicators further contributed to SOC dynamics, with soil erodibility displaying a strong negative association with SOC, underscoring the detrimental effects of erosion. Conversely, ¹³⁷Cs levels were positively associated with SOC, suggesting that areas with less erosion tend to retain

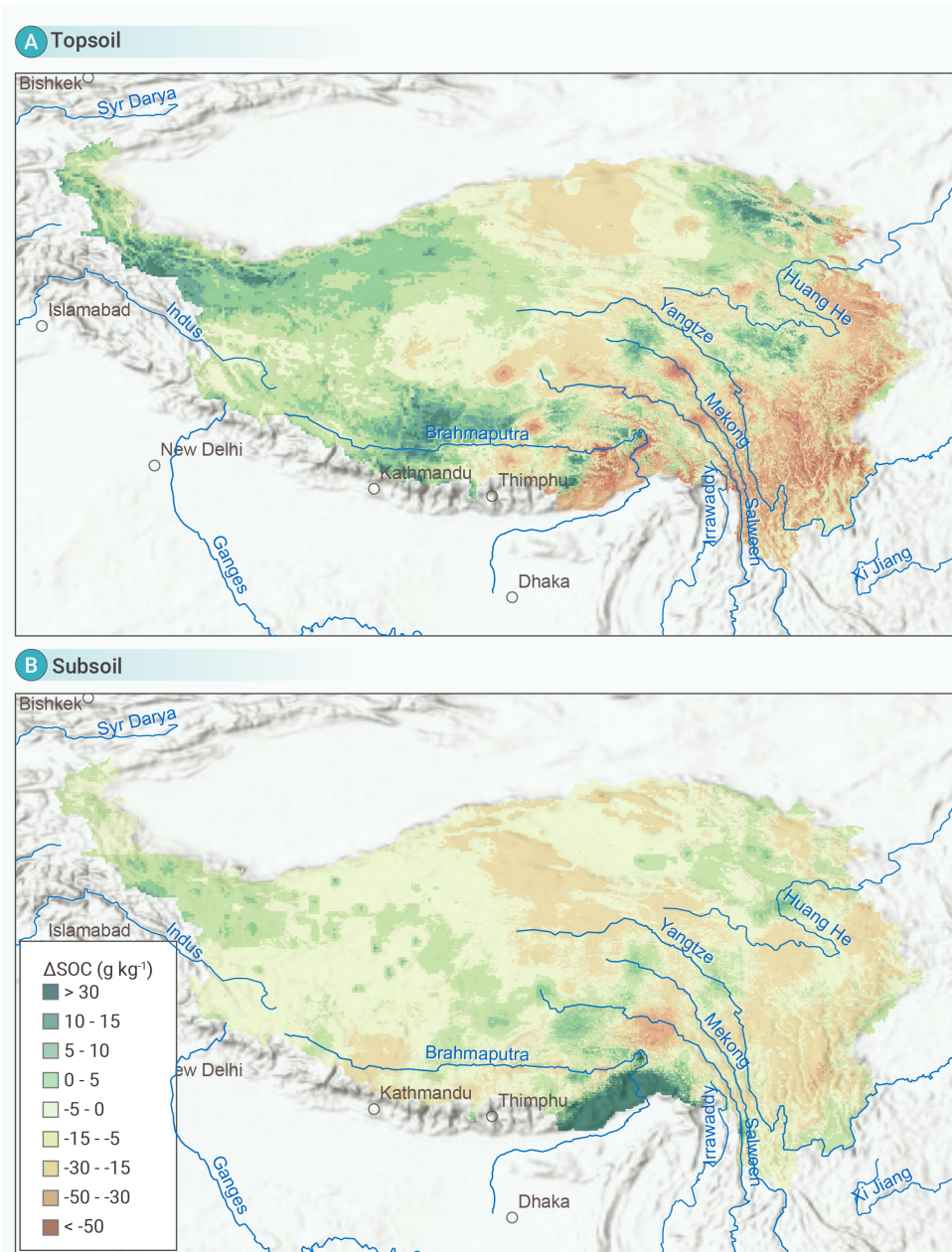


Figure 5. Spatial distribution of changes in soil organic carbon (Δ SOC) across the Tibetan Plateau from the 1980s to the 2020s, estimated using Empirical Bayesian Kriging interpolation based on field sampling data (A) Δ SOC distribution in topsoil; (B) Δ SOC distribution in subsoil. The color gradient represents Δ SOC (g kg^{-1}), with green areas indicating SOC gains and red areas indicating SOC losses.

thereby confirming the warming-SOC feedback mechanism. This aligns with observations in Northeast China's permafrost regions where short-term warming reduced SOC stocks, although those systems exhibited partial recovery through vegetation succession over longer timescales.³⁸ Importantly, while our data do not preclude compensatory processes in alpine ecosystems, they demonstrate that over decadal scales such compensation remains insufficient to offset warming-induced SOC losses, suggesting the persistence of net carbon release under current warming trajectories.

While these findings align with global research identifying warming as a critical threat to SOC stability, they diverge from some earlier studies on the Tibetan Plateau, such as Chen et al.³⁹ and Ding et al.⁴⁰, which reported SOC increases during the early 2000s. Three factors explain this divergence: (1) Temporal scope differences (our 1980s–2020s vs. their 2000s–2010s), (2) their focus on localized vegetation restoration hotspots versus our basin-scale sampling, and (3) the time-dependent efficacy of restoration measures—early-stage (< 10 years) soil carbon gains may mask subsequent warming-driven losses. The discrepancy between earlier decadal studies and our four-decade dataset likely reflects the nonlinear trajectory of SOC under environmental change. Restoration programs or short-term vegetation increases may initially elevate SOC levels, but our long-term resurvey data indicate that such early-stage gains are insufficient to compensate for persistent erosion and warming effects. This time-scale sensitivity reinforces the importance of multi-decadal monitoring frameworks,

higher SOC levels. The effect of ^{210}Pb was minimal in comparison.

Variance partitioning analysis revealed distinct driver contributions to SOC variation (Figure 8). Soil erosion exhibited the strongest independent explanatory power (9.1%), followed by climate change (5.7%) and geographic factors (5.9%). Notably, the synergistic interaction between soil erosion and geographic factors accounted for 18.4% of variance – the largest interaction component – demonstrating their compounding effects on SOC depletion.

DISCUSSION

This study provided a comprehensive assessment of SOC dynamics in alpine soils across the Tibetan Plateau over the past four decades, based on two repeated field surveys. The results revealed significant declines in SOC within the topsoil, while subsoil SOC remained relatively stable, highlighting the pronounced sensitivity of surface soils to environmental changes. These findings contributed critical observational evidence to the ongoing discourse on SOC responses to climate change and soil erosion.

Numerous global studies predict SOC loss under climate warming due to accelerated decomposition processes,^{6,36,37} yet high-altitude ecosystems like the Tibetan Plateau may exhibit distinct responses stemming from their unique environmental legacy of cold-adapted carbon accumulation.¹⁹ Our results substantiated a temperature-dependent SOC decline (Figure 6E),

which are necessary to detect delayed or masked losses and to provide a more accurate basis for evaluating SOC resilience and informing land management policies.

Notably, while temperature increases exerted a pronounced negative effect on SOC, changes in precipitation (ΔP) also reduced SOC stocks, albeit with spatially divergent impacts (Figure 7). Consistent with global patterns,⁴¹ warming emerged as the dominant driver of SOC loss across the plateau, particularly in permafrost-affected regions where accelerated thaw exacerbated carbon mineralization. In contrast, precipitation effects exhibited ecosystem-specific thresholds: increased rainfall partially offset SOC losses in arid western grasslands, but intensified erosion in humid southeastern valleys amplified carbon depletion. This dual control underscores the need for geographically tailored mitigation strategies. Building on Wang et al.'s framework,⁴¹ we recommend prioritizing temperature-driven SOC conservation in permafrost zones while implementing precipitation-sensitive interventions elsewhere – such as erosion barriers in high-rainfall valleys and vegetation-assisted water retention in arid grasslands. A holistic approach integrating thermal and hydrological management will be critical to preserving SOC in these climate-sensitive alpine ecosystems.

Importantly, the impacts of climate change and erosion do not operate in isolation but interact in regionally specific ways. In humid alpine valleys,

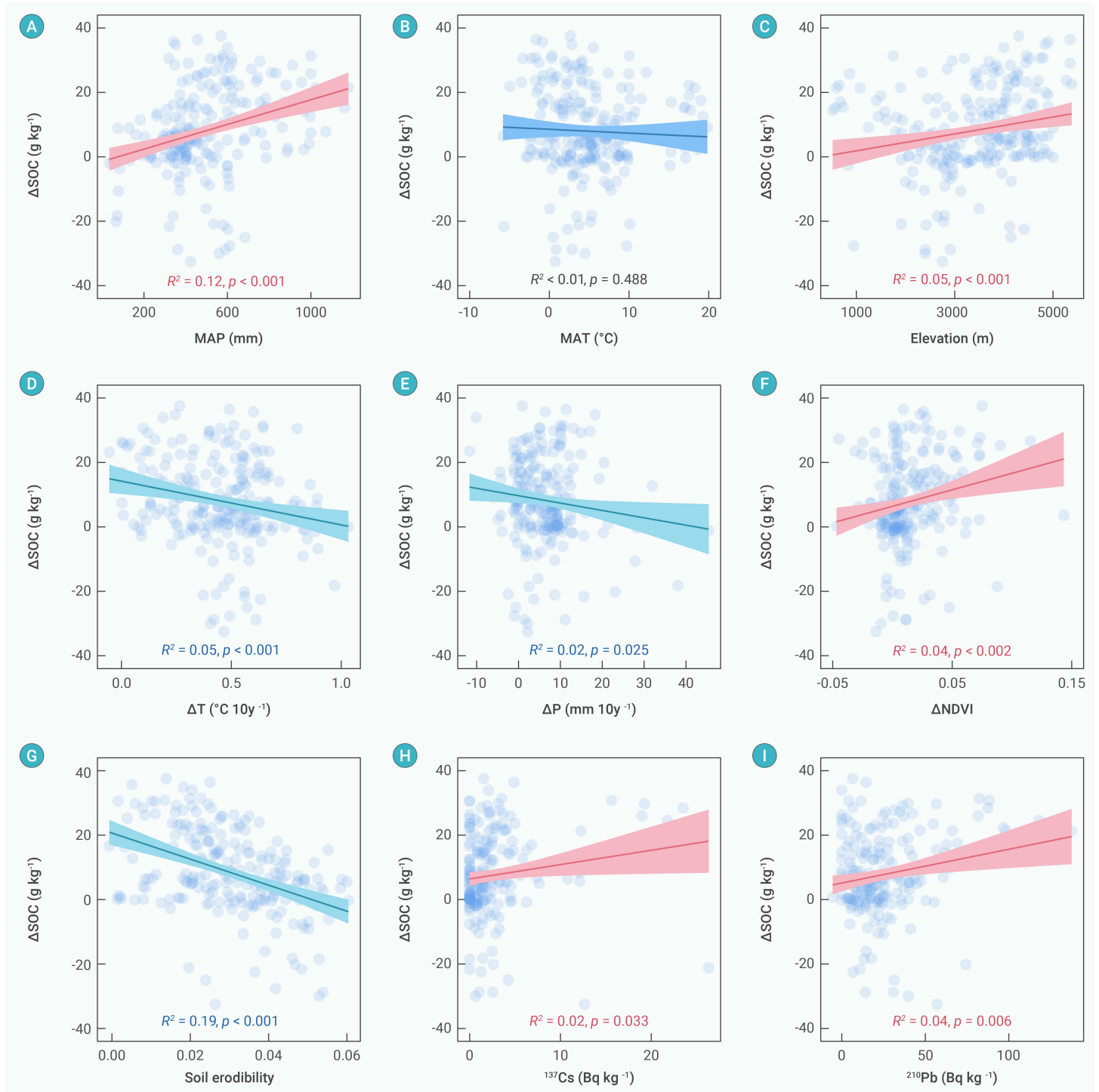


Figure 6. Relationships between changes in soil organic carbon (ΔSOC) and various environmental factors across the Tibetan Plateau Panels show correlations of ΔSOC with (A) Mean annual precipitation (MAP), (B) mean annual temperature (MAT), (C) elevation, (D) temperature change rate (ΔT), (E) precipitation change rate (ΔP), (F) changes in NDVI (ΔNDVI), (G) soil erodibility, (H) cesium-137 (¹³⁷Cs) activity, and (I) lead-210 (²¹⁰Pb) activity. Regression lines, R^2 values, and p-values indicate the significance of each relationship.

increased precipitation and warming jointly enhance vegetation decomposition and slope instability, intensifying surface erosion and carbon loss. In contrast, in semi-arid western regions, modest precipitation gains can stimulate plant growth, partially compensating for warming-driven carbon losses and even improving topsoil stability. These contrasting responses highlight the importance of ecological zoning in SOC conservation planning. Our findings suggest that in erosion-prone zones, climate variability can amplify the erosive redistribution of labile SOC, whereas in drier systems, the same variability may reinforce vegetation-mediated SOC retention. Such interaction patterns are critical for regionally optimizing land management and should be incorporated into future ecosystem-specific carbon models.

In addition to climate warming, soil erosion emerged as a significant driver of SOC loss, and notably, it plays an even more substantial role than warming in this context (Figure 7). Global evidence suggests that practices such as agroforestry and organic amendments can restore degraded SOC,⁴² highlighting the need for targeted erosion control in vulnerable alpine valleys to mitigate SOC depletion. Our study found that areas with higher soil erodibility experienced greater SOC depletion (Figure 2), particularly in the topsoil, which is more vulnerable to erosional processes. Erosion may exacerbate SOC loss by disrupting mineral-organic associations, which are critical for stabilizing SOC through adsorption and aggregation.⁴³ This relationship is further supported by the positive correlation between SOC and ¹³⁷Cs activity

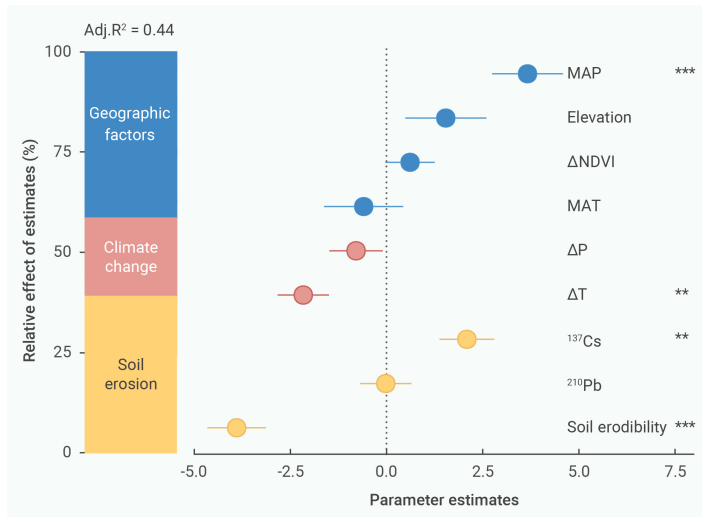


Figure 7. Relative contributions of geographic factors, climate change, and soil erosion to soil organic carbon (SOC) changes across the Tibetan Plateau Parameter estimates are shown for mean annual precipitation (MAP), elevation, changes in NDVI (Δ NDVI), mean annual temperature (MAT), precipitation change rate (Δ P), temperature change rate (Δ T), cesium-137 (^{137}Cs), lead-210 (^{210}Pb), and soil erodibility. Error bars represent standard errors, with significance levels denoted by * ($p < 0.05$), ** ($p < 0.01$), and *** ($p < 0.001$). Adjusted R^2 value indicates the explanatory power of the model.

(Figures 6H–I), indicating that regions with lower erosion rates tend to retain more SOC. The erosion-induced loss of labile SOC fractions aligns with Liu et al.'s⁴⁴ global synthesis, where conventional tillage and heavy grazing reduced particulate organic carbon in managed ecosystems. The net effect of soil erosion on SOC at a large scale is still a topic of debate. However, it is well-established that erosion leads to local SOC reductions,⁴⁵ particularly through the preferential loss of dynamic SOC fractions such as fine particulate organic carbon.⁴⁶ In China, large-scale ecological restoration projects have demonstrated that reducing erosion through vegetation restoration can simultaneously enhance carbon sequestration. Lu et al.⁴⁷ estimated that historical reforestation efforts contributed 247 Tg $\text{CO}_2 \text{ yr}^{-1}$ of carbon sequestration during 2000–2020, highlighting the dual benefits of erosion control and climate mitigation. In sensitive ecosystems like the grasslands of the Tibetan Plateau, which are highly vulnerable to both natural and anthropogenic disturbances, erosion may exacerbate SOC depletion by removing the labile SOC pool that responds rapidly to environmental changes. The Plateau's ecosystems are subject to diverse erosional forces, including rainfall, wind, and freeze-thaw cycles.⁴⁸ Once vegetation cover is lost, erosion intensifies, as corroborated by multiple studies.^{24,49,50} The shallow soils on the plateau, coupled with limited water retention capacity, make the impacts of erosion even more pronounced.⁵¹ Our findings highlight the urgent need for targeted soil erosion control measures to preserve SOC and maintain ecosystem stability in these fragile alpine environments. The dominant erosion-geography synergy (18.4%) reflects how valley morphology (steep slopes, high rainfall) amplifies erosion-mediated carbon loss — a mechanism requiring integration into Earth system models via hillslope sediment transport modules. As climate change continues to intensify, addressing soil erosion will be essential for safeguarding the SOC reservoirs that are vital to both local and global carbon cycles. Various erosion control strategies have shown effectiveness in stabilizing SOC in alpine and sloped landscapes. In particular, contour farming and terracing have been widely implemented in mountainous agricultural regions to reduce surface runoff and soil loss. Afforestation and grazing exclusion zones, such as those established under China's "Grain for Green" program, have also been proven effective in enhancing vegetation cover and protecting topsoil carbon. In the context of the Tibetan Plateau, check dams, silt fences, and bioengineering methods may offer additional co-benefits by reinforcing slopes and facilitating long-term SOC accumulation. Selecting site-specific combinations of these interventions will be critical for erosion-prone valleys where warming and precipitation amplify carbon loss.

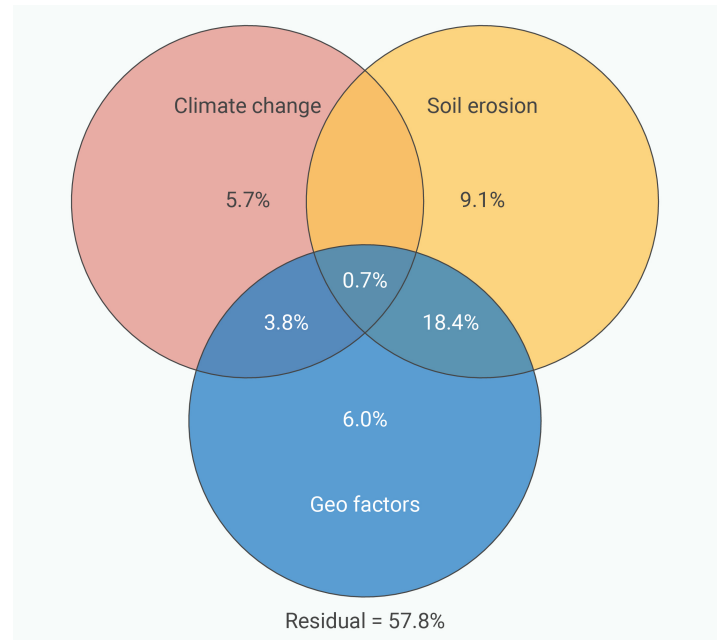


Figure 8. Variance partitioning of soil organic carbon (SOC) changes across the Tibetan Plateau (1980s–2020s) Triple Venn diagram quantifies independent and interactive contributions of climate change, soil erosion, and geographic factors. Geographic factors, as defined in our modeling framework, include mean annual precipitation (MAP), mean annual temperature (MAT), elevation, and NDVI change (Δ NDVI), which together reflect spatial and environmental heterogeneity across the region.

Geographic factors, particularly mean annual precipitation and elevation, were also identified as significant determinants of SOC changes across the plateau. Higher precipitation levels facilitate increased vegetation productivity, which in turn boosts organic matter inputs to the soil, thereby promoting SOC accumulation.⁵² Similarly, the positive correlation between SOC and elevation likely reflects the cooler temperatures and reduced decomposition rates found at higher altitudes, conditions that are conducive to SOC preservation. These geographic controls suggest that regions with favorable environmental conditions — Characterized by higher precipitation and elevation — Should be prioritized for SOC conservation efforts.

Our findings also have important implications for improving global carbon cycle models. Most Earth system and land surface models currently lack explicit representation of erosion-mediated carbon loss, particularly in complex alpine terrains. The observed dominance of erosion as a driver of SOC change suggests that conventional grid-based frameworks may underestimate carbon losses in mountainous landscapes. To address this gap, we recommend incorporating hillslope-scale sediment transport schemes and terrain-sensitive erosion algorithms into SOC modeling frameworks. Furthermore, our regionally validated estimates of topsoil SOC decline and erosion-geography interactions provide valuable empirical benchmarks for model calibration in erosion-prone highland systems.

While this study advances understanding of SOC drivers, three limitations merit consideration. First, the spatial resolution of our dataset, while regionally representative, might obscure microhabitat-scale SOC heterogeneity in landscapes with pronounced topographic variability. Future work incorporating UAV-based hyperspectral imaging could better resolve these fine-scale patterns. Second, although we quantified climate-geomorphic controls, anthropogenic drivers (e.g., grazing intensity fluctuations, land-use legacies) were not systematically addressed due to data granularity constraints. Third, the 40-year observational timeframe — While capturing interdecadal trends — May inadequately resolve century-scale SOC turnover dynamics, particularly in slow-cycling mineral-associated pools. We recommend complementing remote sensing with eddy covariance flux measurements and controlled grazing exclusion experiments to disentangle these temporal and anthropogenic effects. Such integrated approaches would strengthen predictions of SOC trajectories under coupled climate-human perturbations.

CONCLUSION

This study advances the understanding of SOC dynamics in high-altitude ecosystems, offering a comprehensive spatiotemporal analysis of SOC changes across the Tibetan Plateau over four decades. Key findings reveal a marked decline in topsoil SOC (averaging -8.9 g kg^{-1}), while subsoil SOC levels remained stable. Spatial heterogeneity emerged as a critical feature: southeastern alpine valleys experienced the most severe SOC losses due to compounded warming and erosion pressures, while western regions exhibited SOC increases, likely driven by a combination of precipitation-induced vegetation recovery and localized ecological restoration measures such as grazing exclusion.

Our analysis quantitatively differentiated control mechanisms, identifying soil erosion as the dominant independent driver — Surpassing both climate change and geographic factors. Crucially, erosion interacted with geographic controls to amplify SOC depletion in southeastern valleys, substantiating our hypothesis that landscape-mediated erosion accelerates carbon loss beyond direct warming effects. These results underscore the need for a paradigm shift in alpine ecosystem management, where erosion control should receive equal priority to climate mitigation in vulnerable geomorphic settings.

We recommend targeted actions to mitigate SOC loss and protect these carbon stocks. Site-specific erosion control measures, including reforestation, sustainable grazing, and erosion barriers, should be prioritized, especially in the southeastern valleys. Vegetation restoration programs are essential in areas with declining SOC to enhance biomass and stabilize soils. Additionally, climate adaptation policies should include continuous SOC monitoring to safeguard vulnerable topsoils in high-altitude ecosystems.

In summary, this study underscores the critical need for regionally tailored land management strategies — particularly erosion control and adaptive vegetation restoration — to mitigate SOC loss and enhance ecosystem resilience across the Tibetan Plateau. These findings also offer valuable insights for improving global climate models. Understanding the interactions between climate change, erosion, and geographic factors in such unique ecosystems is essential for effective SOC conservation and broader climate mitigation. Future research should prioritize long-term SOC monitoring and scalable conservation practices for stressed high-altitude regions.

The results provide guidance for both regional ecosystem management and global land-based climate mitigation strategies. The observed erosion-induced SOC losses and spatially divergent responses highlight the need to integrate soil conservation into nature-based climate solutions, as emphasized in IPCC land-sector mitigation pathways. Protecting vulnerable SOC pools in alpine regions aligns with global carbon neutrality targets by maintaining natural carbon sinks and preventing irreversible carbon release. Therefore, targeted SOC conservation in the Tibetan Plateau should be recognized as a critical component of nature-based strategies for achieving long-term climate goals.

REFERENCES

- Hansen P.M., Even R., King A.E., et al. (2024). Distinct, direct and climate-mediated environmental controls on global particulate and mineral-associated organic carbon storage. *Glob. Chang. Biol.* **30**:e17080. DOI:10.1111/gcb.17080
- Hicks Pries C.E., Castanha C., Porras R.C., et al. (2017). The whole-soil carbon flux in response to warming. *Science* **355**:1420–1423. DOI:10.1126/science.aal1319
- Wieder W.R., Sulman B.N., Hartman G.D., et al. (2019). Arctic soil governs whether climate change drives global losses or gains in soil carbon. *Geophys. Res. Lett.* **46**:14486–14495. DOI:10.1029/2019GL085543
- Wang M., Guo X., Zhang S., et al. (2022). Global soil profiles indicate depth-dependent soil carbon losses under a warmer climate. *Nat. Commun.* **13**:5514. DOI:10.1038/s41467-022-33278-w
- Loisel J. and Walenta J. (2022). Carbon parks could secure essential ecosystems for climate stabilization. *Ecol. Evol.* **6**:486–488. DOI:10.1038/s41559-022-01695-1
- Bradford M.A., Wieder W.R., Bonan G.B., et al. (2016). Managing uncertainty in soil carbon feedbacks to climate change. *Nat. Clim. Chang.* **6**:751–758. DOI:10.1038/nclimate3071
- Heimann M. and Reichstein M. (2008). Terrestrial ecosystem carbon dynamics and climate feedbacks. *Nature* **451**:289–292. DOI:10.1038/nature06591
- Don A., Seidel F., Leifeld J., et al. (2024). Carbon sequestration in soils and climate change mitigation—Definitions and pitfalls. *Glob. Chang. Biol.* **30**:e16983. DOI:10.1111/gcb.16983
- Barracough D., Smith P., Worrall F., et al. (2015). Is there an impact of climate change on soil carbon contents in England and Wales. *Eur. J. Soil Sci.* **66**:451–462. DOI:10.1111/ejss.12253
- Lu M., Zhou X., Yang Q., et al. (2013). Responses of ecosystem carbon cycle to experimental warming: A meta-analysis. *Ecology* **94**:726–738. DOI:10.1890/12-0279.1
- Sistla S.A., Moore J.C., Simpson R.T., et al. (2013). Long-term warming restructures Arctic tundra without changing net soil carbon storage. *Nature* **497**:615–618. DOI:10.1038/nature12129
- Xu H., Huang L. and Wang S. (2025). Effects of warming on change rate of soil organic carbon content in forest soils. *Forests* **16**:59. DOI:10.3390/f16010059
- Lal R. (2022). Fate of soil carbon transported by erosional processes. *Appl. Sci.* **12**:48. DOI:10.3390/app12010048
- Lin H., Duan X., Li Y., et al. (2022). Simulating the effects of erosion on organic carbon dynamics in agricultural soils. *Catena* **208**:105753. DOI:10.1016/j.catena.2021.105753
- Doetterl S., Berhe A.A., Nadeu E., et al. (2016). Erosion, deposition and soil carbon: A review of process-level controls, experimental tools and models to address C cycling in dynamic landscapes. *Earth-Sci. Rev.* **154**:102–122. DOI:10.1016/j.earscirev.2015.12.005
- Berhe A.A., Barnes R.T., Six J., et al. (2018). Role of soil erosion in biogeochemical cycling of essential elements: Carbon, nitrogen, and phosphorus. *Annu. Rev. Earth Planet. Sci.* **46**:521–548. DOI:10.1146/annurev-earth-082517-010018
- Tan Z., Leung L.R., Li H.Y., et al. (2020). A substantial role of soil erosion in the land carbon sink and its future changes. *Glob. Chang. Biol.* **26**:2642–2655. DOI:10.1111/gcb.14982
- Yao T., Thompson L.G., Mosbrugger V., et al. (2012). Third Pole Environment (TPE). *Environ. Dev.* **3**:52–64. DOI:10.1016/j.envdev.2012.04.002
- Mu C., Zhang T., Wu Q., et al. (2015). Editorial: Organic carbon pools in permafrost regions on the Qinghai–Xizang (Tibetan) Plateau. *Cryosphere* **9**:479–486. DOI:10.5194/tc-9-479-2015
- Dutta K., Schuur E.A.G., Neff J.C., et al. (2006). Potential carbon release from permafrost soils of Northeastern Siberia. *Glob. Chang. Biol.* **12**:2336–2351. DOI:10.1111/j.1365-2486.2006.01259.x
- Li D., Lu X., Overeem I., et al. (2021). Exceptional increases in fluvial sediment fluxes in a warmer and wetter High Mountain Asia. *Science* **374**:599–603. DOI:10.1126/science.abi9649
- Xu Z.X., Gong T.L. and Li J.Y. (2008). Decadal trend of climate in the Tibetan Plateau—Regional temperature and precipitation. *Hydrol. Process.* **22**:3056–3065. DOI:10.1002/hyp.6892
- Dong S., Zhang J., Li Y., et al. (2020). Effect of grassland degradation on aggregate-associated soil organic carbon of alpine grassland ecosystems in the Qinghai–Tibetan Plateau. *Eur. J. Soil Sci.* **71**:69–79. DOI:10.1111/ejss.12835
- Fayiah M., Dong S., Khomera S.W., et al. (2020). Status and challenges of Qinghai–Tibet Plateau's grasslands: An analysis of causes, mitigation measures, and way forward. *Sustainability* **12**:1099. DOI:10.3390/su12031099
- National Soil Survey Office (1993). State soil survey service of China. *China Soil Service*.
- Reeuwijk L. (2002). Procedures for soil analysis. *Int. Soil Ref. Inf. Cent.* DOI: 10.1016/0196-0709(89)90091-4.
- Nelson D.W. and Sommers L.E. (2018). Total carbon, organic carbon, and organic matter. *Methods of Soil Analysis*. **9**: 539–579. DOI: 10.2136/sssabookser5.3.c34.
- Yang K. and He J. (2019). China meteorological forcing dataset (1979–2018). *Natl. Tibetan Plateau Data Center*. DOI: 10.11888/AtmosphericPhysics.tpe.249369.file.
- Wischmeier W.H., Johnson C.B. and Cross B.V. (1971). A soil erodibility nomograph for farmland and construction sites. *J. Soil Water Conserv.* **26**:189–193.
- Williams J.R., Jones C.A. and Dyke P.T. (1984). A modelling approach to determining the relationship between erosion and soil productivity. *Trans. ASAE* **27**:129–144. DOI:10.13031/2013.32748
- Walling D. E., He Q. and Quine T. A. (1995). Use of caesium-137 and lead-210 as tracers in soil erosion investigations. Tracer technologies for hydrological systems. Proc. International Symposium, Colorado. pp:163–172.
- Walling D.E., Porto P., Zhang Y., et al. (2014). Upscaling the use of fallout radionuclides in soil erosion and sediment budget investigations: Addressing the challenge. *Int. Soil Water Conserv. Res.* **2**:1–21. DOI:10.1016/S2095-6339(15)30019-8
- Zhang X.J. (2023). Evaluating and improving ^{137}Cs technology for estimating soil erosion using soil loss data measured during 1954–2015. *Earth-Sci. Rev.* **247**:104619. DOI:10.1016/j.earscirev.2023.104619
- Samsonova V.P., Blagoveshchenskii Yu.N. and Meshalkina Yu.L. (2017). Use of empirical Bayesian kriging for revealing heterogeneities in the distribution of organic carbon on agricultural lands. *Eur. Soil Sci.* **50**:305–311. DOI:10.1134/S1064229317030103
- Krivoruchko K. and Gribov A. (2019). Evaluation of empirical Bayesian kriging. *Spat. Stat.* **32**:100368. DOI:10.1016/j.spasta.2019.100368
- Dorrepaal E., Toet S., van Logtestijn R.S.P., et al. (2009). Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. *Nature* **460**:616–619. DOI:10.1038/nature08216
- Ofiti N.O.E., Schmidt M.W.I., Abiven S., et al. (2023). Climate warming and elevated CO_2 alter peatland soil carbon sources and stability. *Nat. Commun.* **14**:7533. DOI:10.1038/s41467-023-45111-1

- 1038/s41467-023-43410-z
38. Song Y., Huang S., Zhang H., et al. (2024). The impact of permafrost change on soil organic carbon stocks in Northeast China. *Forests* **15**:14. DOI:10.3390/f15010014
 39. Chen L., Jing X., Flynn D.F.B., et al. (2017). Changes of carbon stocks in alpine grassland soils from 2002 to 2011 on the Tibetan Plateau and their climatic causes. *Geoderma* **288**:166–174. DOI:10.1016/j.geoderma.2016.11.016
 40. Ding J., Chen L., Ji C., et al. (2017). Decadal soil carbon accumulation across Tibetan permafrost regions. *Nat. Geosci.* **10**:420–424. DOI:10.1038/ngeo2945
 41. Wang M., Zhang S., Guo X., et al. (2025). Whole-profile soil carbon responses to concurrent warming and precipitation changes across global biomes. *Glob. Chang. Biol.* **31**:e70105. DOI:10.1111/gcb.70105
 42. Beillouin D., Corbeels M., Demenois J., et al. (2023). A global meta-analysis of soil organic carbon in the Anthropocene. *Nat. Commun.* **14**:3700. DOI:10.1038/s41467-023-39338-z
 43. Gu J., Li D., Yang F., et al. (2025). Mineral, molecular composition and ecosystem type jointly determine the stability of soil organic carbon on the Qinghai-Tibetan Plateau. *Catena* **249**:108638. DOI:10.1016/j.catena.2024.108638
 44. Liu M., Zheng S., Pendall E., et al. (2025). Unprotected carbon dominates decadal soil carbon increase. *Nat. Commun.* **16**:2008. DOI:10.1038/s41467-025-57354-z
 45. Lal R. (2019). Accelerated soil erosion as a source of atmospheric CO₂. *Soil Tillage Res.* **188**:35–40. DOI:10.1016/j.still.2018.02.001
 46. Schiedung M., Barré P. and Poeplau C. (2025). Separating fast from slow cycling soil organic carbon – A multi-method comparison on land use change sites. *Geoderma* **453**:117154. DOI:10.1016/j.geoderma.2024.117154
 47. Lu N., Tian H., Fu B., et al. (2022). Biophysical and economic constraints on China's natural climate solutions. *Nat. Clim. Chang.* **12**:847–853. DOI:10.1038/s41558-022-01432-3
 48. Li Y., Li J., Are K.S., et al. (2019). Livestock grazing significantly accelerates soil erosion more than climate change in Qinghai-Tibet Plateau: Evidenced from 137Cs and 210Pbex measurements. *Agric. Ecosyst. Environ.* **285**:106643. DOI:10.1016/j.agee.2019.106643
 49. Miehle G., Schleuss P.-M., Seeber E., et al. (2019). The *Kobresia pygmaea* ecosystem of the Tibetan highlands – Origin, functioning and degradation of the world's largest pastoral alpine ecosystem. *Sci. Total Environ.* **648**:754–771. DOI:10.1016/j.scitotenv.2018.08.164
 50. Dong S., Shang Z., Gao J., et al. (2020). Enhancing sustainability of grassland ecosystems through ecological restoration and grazing management in an era of climate change on Qinghai-Tibetan Plateau. *Agric. Ecosyst. Environ.* **287**:106684. DOI:10.1016/j.agee.2019.106684
 51. Zhang F., Shi X., Zeng C., et al. (2020). Recent stepwise sediment flux increase with climate change in the Tuotuo River in the central Tibetan Plateau. *Sci. Bull.* **65**:410–418. DOI:10.1016/j.scib.2019.12.017
 52. Xu C., McDowell N.G., Fisher R.A., et al. (2019). Increasing impacts of extreme droughts on vegetation productivity under climate change. *Nat. Clim. Chang.* **9**:948–953. DOI:10.1038/s41558-019-0630-6

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AUTHOR CONTRIBUTIONS

Xingwu Duan and Honghong Lin conceptualized and designed the research. Fieldwork and data collection were carried out by Honghong Lin, Yifan Dong, Ronghua Zhong, Li Rong, and Jiangcheng Huang. Writing was primarily done by Honghong Lin, Haijuan Zhao, and Xingwu Duan, with contributions from all co-authors. Damia Barcelo and Hua Zheng provided critical review and editing assistance. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

Data are available from the corresponding author upon reasonable request.

SUPPLEMENTAL INFORMATION

It can be found online at <https://doi.org/10.59717/j.xinn-geo.2025.100165>