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Restoring soil quality and root morphology of peanut under simulated topsoil erosion: effects of fertilization strategies in a controlled study

Jingyu Zhang[1,2], Xiqin Yan[1,2]✉, Lei Chen[1,2]✉, Xiaolin Xia[1,2], Yingjian Chen[1,2], Changyu Long[1,2], Bangwen Wang[1,2] & Dong Peng[1,2]

Soil erosion and deposition are critical processes affecting soil quality and crop productivity, particularly in hilly agricultural regions. Topsoil removal reduces soil fertility and degrades root development, threatening sustainable crop production. This study aimed to evaluate how different degrees of topsoil erosion and deposition, combined with different fertilization strategies,influence soil quality and peanut (Arachis hypogaea L.) root morphology. We sought to determine effective fertilization measures for restoring soil functionality and improving root growth under erosion stress. A controlled pot experiment simulated five topsoil redistribution scenarios: moderate (10 cm) and severe (20 cm) erosion and deposition, and a no-change control. Each scenario was combined with four fertilization treatments: no fertilizer, inorganic fertilizer, organic fertilizer, and combined organic-inorganic fertilizer. Soil chemical properties, soil quality index (SQI), and peanut root morphology were assessed. Topsoil erosion reduced soil organic matter, nitrogen, and phosphorus contents, with 20 cm erosion decreasing root diameter at flowering by 21.8% under inorganic fertilization and 19.3% under combined fertilization compared with the control. Erosion consistently resulted in reduced plant height, root diameter, root length, root surface area, and root volume. In contrast, deposition improved soil nutrient availability, enhancing root growth. Root length increased by 75.5% and root surface area by up to 116.7% under 20 cm deposition with combined fertilization, relative to the control. Fertilization mitigated erosion effects, with the combined organic–inorganic treatment achieving the highest SQI and best root performance. The maximum SQI value (0.417) was observed under 20 cm deposition, and combined fertilization consistently outperformed inorganic or organic fertilization alone. Organic fertilizer alone maintained more stable root morphology under erosion conditions. Topsoil redistribution profoundly alters soil quality and root morphology in peanut production. Appropriate fertilization, particularly combined organic–inorganic application, is essential for restoring soil functionality and sustaining crop productivity in erosion-affected areas.

Keywords Soil quality restoration, Fertilization strategies, Topsoil erosion and deposition, Root morphology, Soil productivity recovery

Soil erosion is widely recognized as one of the most pressing environmental threats to agricultural sustainability[1,2]. It not only degrades soil quality on-site but also contributes to significant off-site sedimentation and water pollution[3]. The removal of fertile topsoil reduces the productivity of natural, agricultural, and pasture ecosystems globally[4,5].

Erosion alters soil's physical, chemical, and biological properties[6], which directly impairs agricultural productivity[7,8]. This degradation undermines sustainable development goals and food security[7,9,10], especially given that over 99.7% of human food comes from land-based ecosystem[11].

[1]Anhui and Huaihe River Institute of Hydraulic Research, Hefei 230088, China. [2]Anhui Provincial Key Laboratory of Water Science and Intelligent Water Conservancy, Hefei 230088, China. ✉email: yxq170304@163.com; chenlei@ahwrri.org.cn

Erosion diminishes topsoil depth (TSD), soil organic carbon (SOC), and nutrient content[10]. Sloping lands are particularly susceptible to erosion due to topographic gradients[12], with approximately 90% of global farmland facing various degrees of erosion[13]. Understanding how crop productivity responds to different erosion intensities is crucial for assessing agricultural vulnerability. Yield responses are influenced by topography, crop type, soil characteristics, management practices, and climate[14,15]. Due to the redistribution of soil along slopes, both erosion and deposition vary significantly with slope position[16] (Fig. 1), with landscape position often exerting a stronger influence on yield than fertilizer application alone[17].

Soil redistribution, encompassing both erosion and deposition, is a major process affecting surface material transport and biogeochemical cycling[18,19]. The depth of topsoil has proven to be a significant parameter in determining soil quality and land productivity. Changes in topsoil depth resulting from this redistribution significantly influence soil quality and land productivity[20]. Li, et al.[21] showed that soil redistribution, including erosion and deposition under natural conditions and soil removal addition induced by anthropogenic activity.

Previous studies have used controlled soil removal or addition (desurfacing and surface accumulation) to simulate erosion–deposition processes and evaluate their effects on productivity[14]. Larney, et al.[22] established six experimental sites in Alberta to ascertain the effects of simulated erosion on soil productivity, results showed that simulated erosion drastically reduced soil productivity. Brunel, et al.[23] also showed the wheat grain yield had a proportional decreasing trend with respect to the levels of soil removed. These approaches offer a feasible way to isolate erosion effects from confounding environmental factors and reveal soil–plant interactions under disturbed topsoil conditions.

To mitigate productivity loss from erosion, fertilization has long been employed as a restoration strategy[24,25]. However, over-reliance on chemical fertilizers, particularly in China, has caused adverse environmental consequences such as soil acidification and non-point source pollution[26], which is not conducive to the sustainable development of agriculture[27].

Organic fertilizers, such as animal manure, can improve soil structure, enhance microbial activity, and reduce dependency on chemical inputs[28]. Yang, et al.[29] found animal manure is most effective in improving soil structure, while fertilizer increases aggregate penetration resistance, tensile strength, water stability, and organic matter content in the cultivated horizon (0–15 cm depth), especially at the 0–5 cm layer. Iqbal, et al.[30] carried out a pot experiment, and the results showed that higher biomass production, N-uptake, and grain yield were noted in the combined treatments relative to the CF-only fertilization at the experimental station of Guangxi University, China, in 2018.

Driven by an urgent need to both produce more food and lessen the environmental impact of agriculture[26], Chinese scientists have carried out extensive research on the prevention and control of soil erosion in sloping farmland and on fertilization management. Common approaches for monitoring and quantifying the impact of soil erosion on productivity include topsoil removal or addition[31], transect analysis, plot comparisons[32], simulation modeling[33], and erosion classification methods. For example, crop modeling has been applied to assess the effects of erosion on soybean and wheat yields in the black soil region of Northeast China[34]; pot experiments with soybean have been used to simulate gradual erosion profiles to overcome the bias of abrupt topsoil removal[31]; and erosion classification has been employed to evaluate erosion impacts on maize yields in the dry-hot valley of Southwest China[35] A global synthesis of 290 yield observations from desurfacing trials further indicated that crop sensitivity to erosion declines in the order of soybean > maize > wheat[36].

In the subtropical hilly areas of southeastern China, particularly in the middle and lower reaches of the Yangtze River, intensive cultivation and frequent heavy rainfall have led to severe soil erosion on sloping farmlands[37]. Peanut (Arachis hypogaea L.) is one of the dominant crops in this region, valued for its drought tolerance, adaptability to thin soils, and economic importance to local farming systems[38]. These characteristics make peanut an ideal model crop for evaluating how erosion and fertilization interact to influence soil quality and crop performance. However, most existing research has focused on staple crops such as maize, soybean, and wheat, using approaches such as desurfacing experiments, erosion classification, and crop modeling to assess productivity losses. While these studies have advanced our understanding of erosion–productivity relationships, the combined effects of erosion–deposition processes and fertilization regimes on peanut systems remain largely unexplored. This represents a critical research gap, and the present study was designed to address this gap by quantifying peanut responses to different erosion–deposition scenarios under contrasting fertilization strategies.

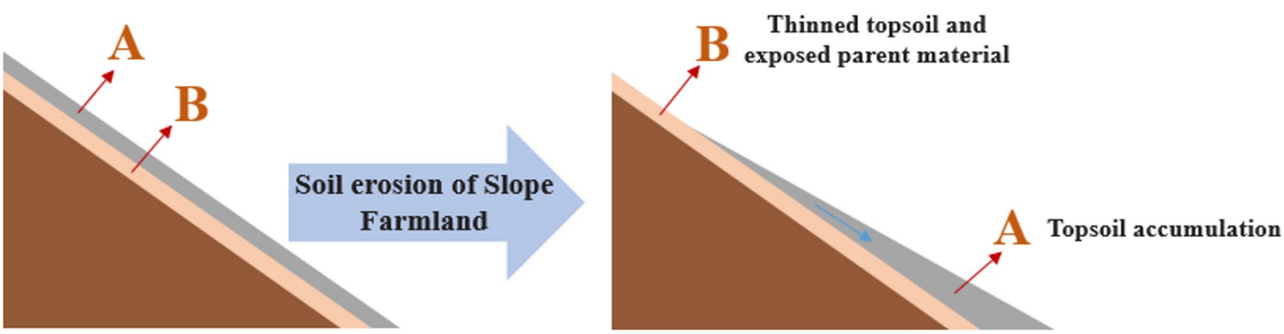

Fig. 1. Soil redistribution of slope farmland (Berhe et al., 2005; Yoo et al., 2005; Berhe et al., 2018).

In this study, we hypothesize that simulated topsoil redistribution significantly alters soil quality and peanut performance, and that fertilization can mitigate these effects. By using a controlled pot experiment to simulate different degrees of erosion and deposition, combined with four fertilization strategies, we aim to: (1) evaluate the individual and interactive effects of topsoil removal/accumulation and fertilization on soil physicochemical properties and crop root traits; (2) identify fertilization strategies that can sustain crop productivity under erosion stress; and(3) provide insights for soil quality restoration and fertilizer management in erosion-prone sloping agroecosystems.

Materials and methods

Experimental design

The experiment was conducted from May 2022 to August 2022, at the Xinmaqiao Agricultural and Water Conservation Comprehensive Experimental Station in Guzhen County, Bengbu City, Anhui Province in China (117°21′, 33°09′). The site has an average elevation of 19.7 m, with a long-term mean annual temperature of 14.3 °C, annual precipitation of 911 mm, and average annual evaporation of 917 mm.

A factorial pot experiment was established to evaluate the combined effects of topsoil redistribution and fertilization regimes on soil quality and crop performance. The experimental design consisted of 20 treatment combinations, derived from five erosion–deposition levels and four fertilization strategies (Table 1).

Experimental treatments

The study was conducted in polyethylene pots (top diameter: 55 cm; bottom diameter: 43 cm; height: 63 cm). The peanut seeds (Arachis hypogaea L.) variety ‘Luhua 8’ was used. The peanut seeds used in this study were obtained from a local agricultural supplier (Name: Guochuanhong Agricultural Materials Store, Address: West Second Road, Xinmaqiao Town, Guzhen County, Bengbu City, Anhui Province, China). Each pot was planted with four clusters (two seeds per hole, spaced 15 cm apart). Total soil depth in all pots was maintained at 50 cm.

Soil was collected from a sloped farmland in Hefei, Anhui Province (117°51′E, 31°53′N), classified as yellow-brown soil. The surface topsoil layer (0–20 cm) was designated as the A horizon, and the subsoil (below 20 cm) as the B horizon. Simulated soil erosion and deposition scenarios were implemented by adjusting A and B layer proportions (Fig. 2), enabling a controlled study of topsoil depth effects under standardized moisture, temperature, and management conditions.The following soil erosion and deposition treatments were applied (Fig. 2):

- SE20: Entire A layer removed; only 50 cm B layer used.
- SE10: 10 cm A + 40 cm B layers.

Schemes	Fertilizer Applications	Treatment	Abbreviation
1	CK	SE20	S1
2	CK	SE10	S2
3	CK	SE0	S3
4	CK	SA10	S4
5	CK	SA20	S5
6	CF	SE20	S6
7	CF	SE10	S7
8	CF	SE0	S8
9	CF	SA10	S9
10	CF	SA20	S10
11	BF	SE20	S11
12	BF	SE10	S12
13	BF	SE0	S13
14	BF	SA10	S14
15	BF	SA20	S15
16	CF + BF	SE20	S16
17	CF + BF	SE10	S17
18	CF + BF	SE0	S18
19	CF + BF	SA10	S19
20	CF + BF	SA20	S20

Table 1. Experimental scheme design. Notes: CK denotes no fertilizer (control check), CF denotes chemical fertilizer, BF denotes bio-organic fertilizer, and CF + BF denotes the combined application of chemical and bio-organic fertilizers. Soil erosion and accumulation scenarios were simulated by varying the proportions of the A and B horizons: SE20 represents 0 cm A + 50 cm B (severe erosion), SE10 represents 10 cm A + 40 cm B (moderate erosion), SE0 represents 20 cm A + 30 cm B (no erosion, control), SA10 represents 30 cm A + 20 cm B (slight accumulation), and SA20 represents 40 cm A + 10 cm B (strong accumulation). The detailed description can be found in Sect. 2.2.

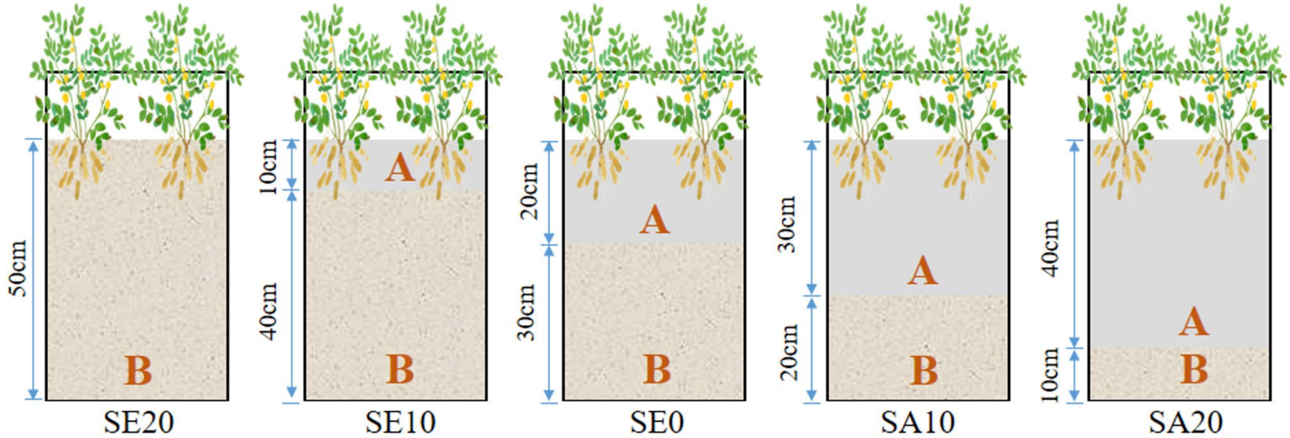

Fig. 2. The experimental layout of soil erosion and sedimentation scenarios.

- SE0: 20 cm A + 30 cm B layers (control).
- SA10: 30 cm A + 20 cm B layers.
- SA20: 40 cm A + 10 cm B layers.

Fertilizer application rates were based on regional agronomic practices and scaled to per-pot levels: CF group: N 75 kg ha^{-1} (urea, 46% N), P_2O_5 90 kg·ha^{-1} (single superphosphate, 12% P_2O_5), and K_2O 105 kg·ha^{-1} (potassium sulfate, 50% K_2O). BF group: 1500 kg·ha^{-1} of bio-organic fertilizer, supplemented with mineral N, P, and K to match the nutrient content of CF. CF + BF group: Half the dose of both CF and BF, with supplemental NPK added to match the total nutrient level of CF. All fertilizers were applied once before planting, with no top-dressing. Crop management was kept consistent across treatments. We note that the present pot experiment was conducted without biological replication due to resource limitations. All treatments were performed under highly standardized and controlled conditions (uniform soil source, pot size, moisture, temperature, and management practices) to minimize environmental variability.

Data collection

(1) Soil physical properties.

The basic soil indicators measured in this study included soil bulk density (BD), soil particle size (SPS), soil pH, and total soil porosity (TSP). Soil bulk density was determined using a stainless-steel core sampler with a volume of 100 cm³. Soil particle size distribution was measured using a Malvern MS3000 laser diffraction particle size analyzer (Malvern Instruments, UK). Prior to analysis, approximately 3 g of sieved soil was dispersed in a sodium hexametaphosphate solution and subjected to ultrasonic treatment to ensure complete dispersion. Measurements were taken both before planting and before peanut harvest. In this study, soil particles were defined as follows: 0.05–2 mm as sand, 0.002–0.05 mm as silt, and < 0.002 mm as clay[39]. Soil pH was measured using a high-precision soil pH meter. Total soil porosity was calculated using the formula (1):

$$f = (1 - \frac{\rho_b}{\rho_s}) \times 100\% \quad (1)$$

In the formula, f represents the total soil porosity; ρ_b represents soil bulk density (g/cm³); and 2.65 g/cm³ is the assumed soil particle density (ρ_s).

(2) Soil nutrient indicators.

Prior to planting, soil samples from the control treatment (no erosion, no fertilization) were collected to characterize the baseline soil properties. The initial 0–20 cm yellow-brown soil had a bulk density of 1.30 g·cm^{-3}, with pH was 6.25 (Table S1). These baseline data provide essential context for the experimental design, although subsequent analyses focused on relative differences among erosion–deposition and fertilization treatments.

Soil samples were collected from the 0–20 cm layer both before peanut planting and at maturity. After collection, small stones, root fragments, and surface debris were removed, and the samples were sealed in bags with labels recording sample ID and date. The samples were transported to the laboratory, air-dried, gently ground, sieved (2 mm), and stored for subsequent analyses.

The main function of the plow layer soil is to coordinate water, nutrients, air, and heat, ensuring that these factors meet the requirements for crop growth and development. The topsoil is considered the core of agricultural productivity. In this study, the soil nutrient indicators measured included soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), available nitrogen (AN), and available phosphorus (AP). Soil organic matter (SOM) content was determined using the potassium dichromate oxidation method, while total nitrogen and total phosphorus were measured using the Kjeldahl distillation method and acid digestion-molybdenum-antimony colorimetric method, respectively. Available nitrogen was measured using the alkaline hydrolysis diffusion method, and available phosphorus was determined using the hydrochloric acid-ammonium fluoride extraction-molybdenum-antimony colorimetric method.

(3) Crop morphological characteristics indicators.

The growth indicators of the selected peanut plants, both above and below ground, were measured at different growth stages: seedling stage (30 days after sowing, DAS), flowering stage (60 DAS), pod setting stage (90 DAS), and pod filling stage (120 DAS), to assess the crop's growth condition. The specific indicators included plant height, average root diameter, root length, root surface area, and root volume. Plant height was measured with a ruler every 10 days. Root morphological characteristics (such as average root diameter, root length, root surface area, and root volume) were measured using a CI-602 narrow root measurement instrument, with root tubes placed in advance for the measurements.

(4) Crop Biomass Indicators.

After physiological maturity, the peanut plant samples (roots, stems, leaves, and peanut fruits) were cleaned and weighed to determine the fresh biomass per pot. The peanuts were then manually threshed, placed in mesh bags, and air-dried in a shaded area until the moisture content reached about 14%. Afterward, the dry matter and yield were measured. Yield components included pod count, fruit count, and the weight distribution of different plant parts (roots, stems, leaves, pods, and fruits). In addition, seed weight and seed yield percentage were also measured. The pod count per pot was calculated based on the pods from four plants per pot. The seed weight (g/pot) was calculated by summing the weight of all mature seeds from the four plants in each pot.

Soil quality index characterization

Soil Quality Index (SQI) was established in the 1990s and is an effective tool for monitoring soil quality. The SQI, which integrates fundamental soil properties, is crucial for minimizing the harmful impacts of indiscriminate soil management and mitigating climate change[40]. Currently, various methods for assessing soil quality have been developed[41], including Reduced Regression (RR), Simplified Partial Least Squares (SIMPLS), Principal Component Regression (PCR), and Partial Least Squares Regression (PLSR)[42].

In this study, the calculation of the SQI involves three main steps. Firstly, we used the basic soil indicators and soil nutrient indicators, totaling 11 items (including soil bulk density, soil pH, total soil porosity, sand content, silt content, clay content, organic matter, total nitrogen, total phosphorus, alkaline nitrogen, and available phosphorus) to establish a total data set. Secondly, we performed principal component analysis (PCA) to identify the most representative indicators that reflect soil functions and create a minimum data set (MDS). Redundant indicators were eliminated based on Pearson's correlation coefficients of each principal component. Thirdly, we normalized the indicators in the MDS using a linear scoring function. Finally, the SQI was characterized based on the indicator scores and their respective weights[43].

$$SQI = \sum_{i=1}^{n} W_i \times S_i$$

where W_i is the weighing factor derived from the PCA (absolute value) and S_i is the score for the subscripted variable. It was assumed that higher SQI scores represented better soil quality.

Results

Effects of soil erosion and deposition on soil properties and quality

Under unfertilized conditions, varying degrees of erosion and deposition significantly affected soil physical properties, including particle composition, bulk density (BD), and total soil porosity (TSP), as well as the chemical property of soil pH (Fig. 3A–D). In terms of particle size distribution, and content increased progressively from SE20 to SA20, with SE20 (S1) exhibiting the lowest sand content (23.58%) and SA20 (S5) the highest (30.5%). Silt content showed no clear trend, though SE20 had the highest silt proportion at 58.15%. Clay content did not vary substantially among treatments, but both deposition treatments (SA10, SA20) and erosion treatments (SE10, SE20) had slightly higher clay contents than the no erosion and no deposition condition (Fig. 3A).

Bulk density ranged from 1.39 to 1.42 $g \cdot cm^{-3}$, primarily influenced by the disturbance and refilling processes during the pot experiment setup (Fig. 3B). Correspondingly, total soil porosity (TSP) was lowest in SE20 and highest in SA20, indicating that soil porosity increased with the recovery of topsoil layers and suggesting a shift toward a looser and more porous soil structure (Fig. 3D). Soil pH showed relatively small differences among treatments, fluctuating between 6.08 and 6.21, with a slight downward trend but no clear pattern (Fig. 3C).

In summary, as the A-horizon topsoil was gradually restored from SE20 to SA20, soil porosity increased, indicating that surface erosion and deposition processes play a regulatory role in shaping soil physical structure.

As shown in Fig. 4, soil nutrient contents varied significantly under the different simulated erosion and deposition treatments. The concentrations of soil organic matter (SOM), total nitrogen (TN), and total phosphorus (TP) (Fig. 4A) generally increased from the most eroded to the most depositional sites. SA20 (S5) exhibited the highest levels of SOM and TP, while SE20 (S1) showed the lowest, a pattern consistent with the enrichment of surface soils commonly observed in depositional zones due to sediment accumulation.

In contrast, an inverse trend was observed for available nitrogen (AN) (Fig. 4B), with the highest AN concentration found in the severely eroded plot (SE20, S1), decreasing progressively toward the depositional plots (SA20, S5). Available phosphorus (AP) followed a pattern similar to TP, increasing along the erosion–deposition gradient.

The first principal component (PC1) accounted for 44.32% of the total variance and was primarily associated with sand content (−0.882), silt content (0.828), and available nitrogen (AN, 0.868). The strong loadings of sand and silt highlight the central role of soil texture in determining physical structure. The antagonistic relationship between sand (negative loading) and silt (positive loading) suggests that an increase in silt content may enhance

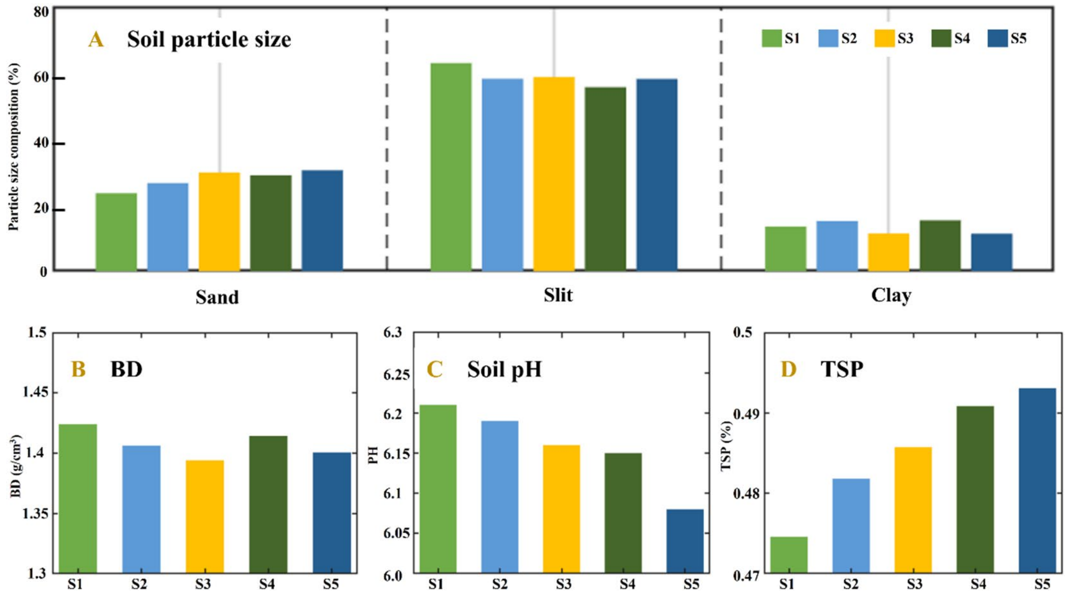

Fig. 3. Effects of different soil erosion and deposition treatments (S1–S5) on soil properties under unfertilized conditions. (**A**) Soil particle size distribution (physical indicator); (**B**) bulk density (BD, physical indicator); (**C**) soil pH (chemical indicator); (**D**) total soil porosity (TSP, physical indicator). S1 to S5 represent erosion depth of 20 cm (SE20), erosion depth of 10 cm (SE10), no erosion (SE0), surface accumulation of 10 cm (SA10), and surface accumulation of 20 cm (SA20), respectively, all under unfertilized conditions.

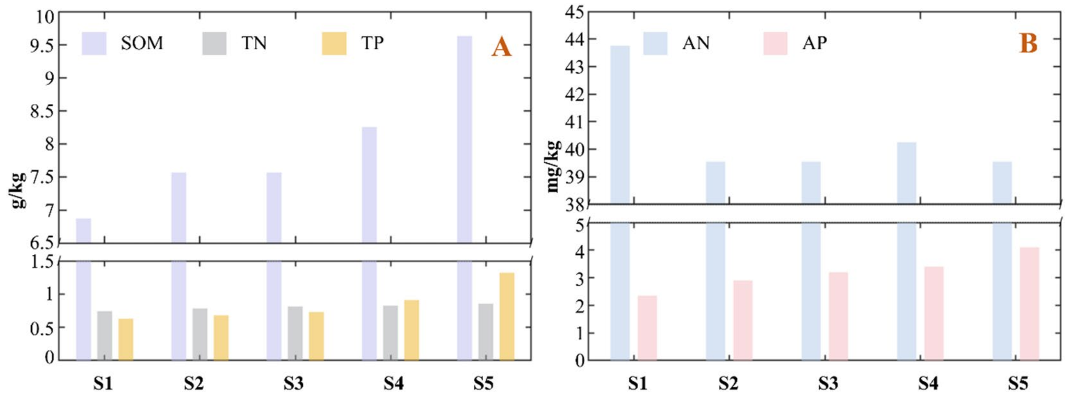

Fig. 4. Soil nutrient indicators under different simulated erosion and deposition scenarios following peanut harvest. Indicators include soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), available nitrogen (AN), and available phosphorus (AP). Treatments S1 to S5 represent erosion depth of 20 cm (SE20), erosion depth of 10 cm (SE10), no erosion (SE0), surface accumulation of 10 cm (SA10), and surface accumulation of 20 cm (SA20), respectively, all under unfertilized conditions.

aggregate stability. The high loading of AN (0.868), an important indicator of available nitrogen, underscores the critical role of nitrogen availability in soil fertility.

The second principal component (PC2), explaining 22.38% of the variance, was mainly driven by total soil porosity (TSP, 0.628), soil organic matter (SOM, 0.552), and total phosphorus (TP, 0.558). The positive association between TSP and SOM indicates that organic matter accumulation contributes to improved pore structure. The strong contribution of TP suggests that total phosphorus is an important indicator of the soil's chemical reservoir capacity.

In the third principal component (PC3), pH (0.751) and total nitrogen (TN, −0.563) showed a marked inverse relationship, reflecting the influence of soil acidity–alkalinity on nitrogen transformation processes. The high positive loading of pH (0.751) indicates that near-neutral to slightly alkaline conditions are more favorable for maintaining nutrient availability (Tables 2 and 3).

In the non-eroded condition, the soil quality index (SQI) in the Jianghuai hilly region was 0.397 (SE0), close to 0.4. Compared to this baseline, SQI values decreased by 16.1% and 19.6% at erosion depths of 10 cm and 20 cm, respectively. At a deposition depth of 10 cm, the SQI remained similar to that of SE0, while at 20 cm of

Soil quality indicators		Abbr.	PC1	PC2	PC3	Communality	Weight
Physical properties	Soil bulk density	SBD	0.736	− 0.318	− 0.247	0.704	0.081
	Sand content	Sand	− 0.882	0.405	− 0.130	0.960	0.111
	Silt content	Silt	0.828	− 0.426	0.044	0.869	0.100
	Clay content	Clay	0.703	− 0.211	0.295	0.626	0.072
	Total soil porosity	TSP	0.053	0.628	− 0.463	0.611	0.070
Chemical properties	pH value	pH	0.126	0.525	0.751	0.857	0.099
	Soil organic matter (0–10 cm)	SOM	− 0.641	0.552	0.112	0.729	0.084
	Total nitrogen	TN	0.550	0.420	− 0.563	0.796	0.092
	Total phosphorus	TP	0.659	0.558	− 0.029	0.747	0.086
	Available nitrogen	AN	0.868	0.410	− 0.027	0.921	0.106
	Available phosphorus	AP	0.675	0.582	0.262	0.863	0.099

Table 2. Principal component analysis of soil quality indicators, including rotated factor loadings, communalities, and assigned weights.

Statistical parameters	PC1	PC2	PC3
Eigenvalue	4.876	2.462	1.346
Variance (%)	44.32	22.38	12.23
Cumulative variance (%)	44.32	66.70	78.94

Table 3. Eigenvalues, explained variance, and cumulative variance contributions of the principal components.

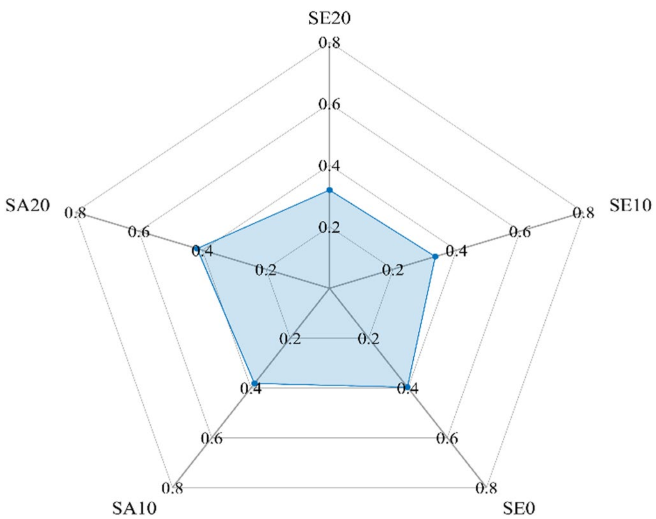

Fig. 5. Soil Quality Index (SQI) under different simulated soil erosion and deposition scenarios compared to the non-eroded condition. Treatments include erosion depths of 20 cm (SE20) and 10 cm (SE10), no erosion (SE0), and surface accumulation depths of 10 cm (SA10) and 20 cm (SA20), all under unfertilized conditions.

deposition, it increased by 5.0%. These changes in soil quality align with variations in SOM, TN, TP, and AP. As erosion severity increases, soil quality declines more sharply (Fig. 5).

Effects of soil erosion and deposition on growth characteristics of peanut

Both soil erosion and deposition had significant effects on peanut growth at various stages (Fig. 6). Erosion consistently resulted in reduced plant height, root diameter, root length, root surface area, and root volume, highlighting its detrimental impact on plant development.

In particular, the 20 cm erosion treatment (SE20, S1) led to noticeably shorter plants, especially during the seedling and maturity stages. Root diameter in SE20 was significantly smaller during the flowering and pod-filling stages, suggesting impaired root thickening under severe erosion. Likewise, root length and surface area were substantially reduced at the fruit maturity stage, indicating a less developed and less efficient root system. SE20 also exhibited the lowest root volume during early growth stages, further suggesting that erosion hampers root expansion and soil resource uptake.

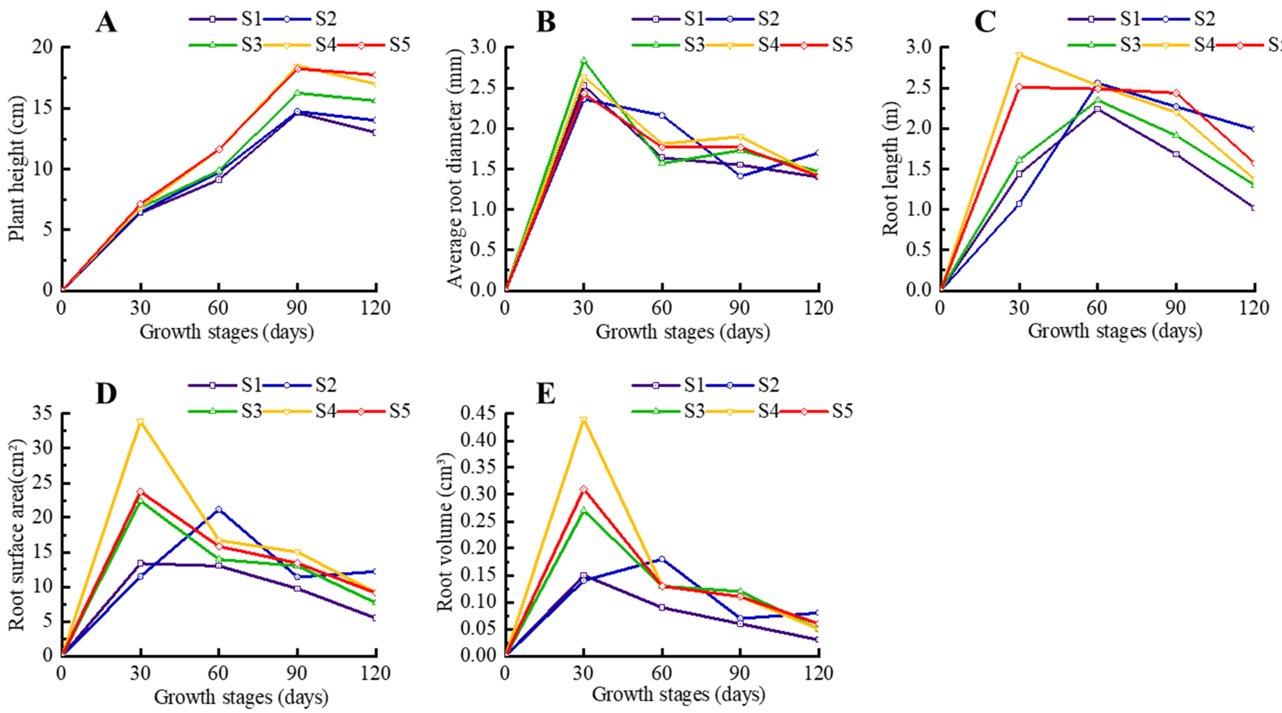

Fig. 6. Morphological responses of peanut plants to different simulated erosion and deposition treatments at various growth stages: seedling (30 days after sowing, DAS), flowering (60 DAS), pod setting (90 DAS), and pod filling (120 DAS). Treatments S1 to S5 represent erosion depth of 20 cm (SE20), erosion depth of 10 cm (SE10), no erosion (SE0), surface accumulation of 10 cm (SA10), and surface accumulation of 20 cm (SA20), respectively, all under unfertilized conditions.

In contrast, surface accumulation treatments (SA10 and SA20; S4 and S5) promoted superior root and shoot growth. These treatments consistently resulted in the tallest plants and the greatest root length, surface area, and volume across most developmental stages. While root diameter varied slightly with growth stage and treatment, S3 (no erosion) showed favorable diameter in the seedling stage, while S2 (SE10) and S4 (SA10) performed better in later stages.

Total root length was generally greater in surface coverage treatments (S4 and S5), indicating that reduced erosion or topsoil restoration encourages more extensive root systems. Additionally, root surface area and volume were highest in S5, emphasizing its role in enhancing water and nutrient uptake efficiency.

Overall, soil stability is characterized by minimal erosion and sufficient surface accumulation which plays a vital role in supporting peanut growth and root development. Severe erosion, especially at 20 cm depth, significantly impairs both shoot and root morphology. Conversely, adequate surface coverage, particularly at 20 cm (SA20, S5), yields the best overall plant performance. These findings underscore the importance of erosion control and surface management practices in improving peanut productivity.

The impact of varying erosion levels and fertilization strategies on peanut productivity

The morphological characteristics of peanut plants—including plant height, root length, average root diameter, total root surface area, and root volume, generally increased throughout the growth period (Fig. 7). These traits typically peaked at the pod-setting stage, followed by a decline during the pod-filling stage. The period between flowering and pod setting represents the most vigorous growth phase, marked by accelerated shoot and root development, pod expansion, and a sharp increase in total biomass. From seedling to flowering stages, plant height increased by 2.2 to 2.9 times under inorganic and combined fertilizer treatments. Root diameter at the pod-setting stage increased by 72.3% to 93.2% relative to the seedling stage. The application of organic fertilizer also significantly enhanced root diameter, by up to 54.5%, compared to the unfertilized treatment.

Plant height and root traits generally declined with increasing erosion depth. Under 20 cm of erosion, root diameter during the flowering stage decreased significantly by 21.8% and 19.3% under inorganic and compound fertilizer treatments, respectively. However, the variation in plant height and root size was minimal under organic fertilizer alone, indicating a more stable response. In deposition treatments, plant, and root traits generally improved with increasing accumulation depth, although the magnitude of root system changes was smaller. Notably, when only organic fertilizer was applied, plant height at the pod-filling stage increased by 27.9% compared to the non-eroded, non-deposited condition.

In unfertilized treatments, root length initially increased and then declined with increasing erosion depth. A similar pattern was observed for root surface area and total volume at the seedling and pod-filling stages. Erosion-induced nutrient loss in the topsoil prompts roots to elongate and thicken in search of nutrients;

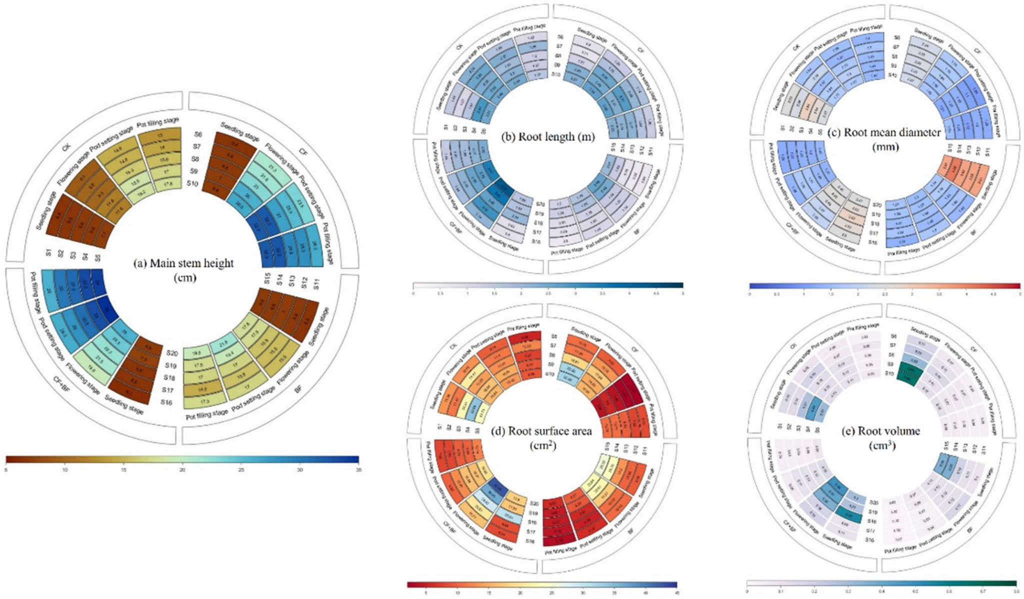

Fig. 7. Response of peanut morphological traits to different erosion–deposition levels and fertilization strategies at various growth stages.

however, at 20 cm erosion depth, nutrient depletion becomes too severe to sustain further root development. In fertilized plots, root length, surface area, and volume consistently decreased with increasing erosion severity. Among all treatments, the most pronounced reductions were observed under compound fertilizer at the pod-setting stage, with average declines of 72.3% in surface area and 83.6% in volume. Root traits in organic fertilizer treatments were less sensitive to erosion, suggesting better resilience.

Across all fertilization strategies, root length increased significantly with deeper deposition. When only organic fertilizer was applied, root length at flowering and pod-setting stages increased by 75.3% and 46.2%, respectively, compared to the control (no erosion/deposition). Under inorganic fertilization, root length at the pod-filling stage increased by 56.2% at a 10 cm deposition depth. The combined application of organic and inorganic fertilizers showed the most substantial effect, with root length at the flowering stage increasing by 75.5% under 20 cm deposition. These results suggest that nutrient-rich depositional zones, especially when coupled with fertilization, markedly enhance root elongation. Root surface area increased significantly at all growth stages with increasing deposition depth, peaking at the pod-setting stage. The largest increases in root surface area were 73.6%, 84.5%, 106.3%, and 116.7%, which were observed in the inorganic, organic, and combined fertilizer treatments, respectively. In contrast, root volume showed less sensitivity to deposition.

In unfertilized conditions, the soil quality index (SQI) exhibited the smallest shaded area, with values increasing slightly under both erosion and deposition. The highest SQI of 0.417 was observed under 20 cm of surface deposition (Fig. 8). Fertilization markedly improved SQI values across all scenarios. Among treatments, the combined application of organic and inorganic fertilizers (CF + BF) consistently resulted in the highest SQI, followed by inorganic fertilizer alone (CF), and then organic fertilizer alone (BF). These findings indicate that combined fertilization is the most effective strategy for improving soil quality under varying erosion-deposition conditions.

Discussions

Effects of erosion-deposition on soil quality

Water erosion selectively removes fine particles and nutrients, making it a key factor influencing soil degradation[44]. In our study, the increased content of available nitrogen (AN) observed in eroded soils may be attributed to the exposure of deeper soil layers (Fig. 4), which are often characterized by higher mineralization rates and lower organic matter content, leading to reduced microbial immobilization and enhanced nitrogen availability[45,46]. Additionally, erosion-induced compaction may reduce nitrogen leaching, resulting in a transient accumulation of available nitrogen in surface soils. These findings suggest that erosion alters not only the total nutrient pools but also the dynamics and bioavailability of key nutrients such as nitrogen.

Mandal, et al.[10] conducted a comparative study in the Dehradun Valley of India and reported a significant decline in total nitrogen and extractable phosphorus with increasing erosion intensity, which aligns with our findings. Soil erosion and soil quality are closely interlinked, with erosion both driving and being influenced by changes in soil properties[47]. Mandal, et al.[10] also applied a quantitative, weighted additive model to assess soil quality across different erosion phases, integrating nine key indicators—such as clay content, WHC, WSA, SOC, pH, CEC, total N, available P, and available K, by converting them to unitless scores and applying respective weights. In our study, we adopted a similar approach using 11 soil indicators, including soil bulk density, pH, total porosity, sand, silt, clay, organic matter (SOM), total nitrogen (TN), total phosphorus (TP), alkaline nitrogen

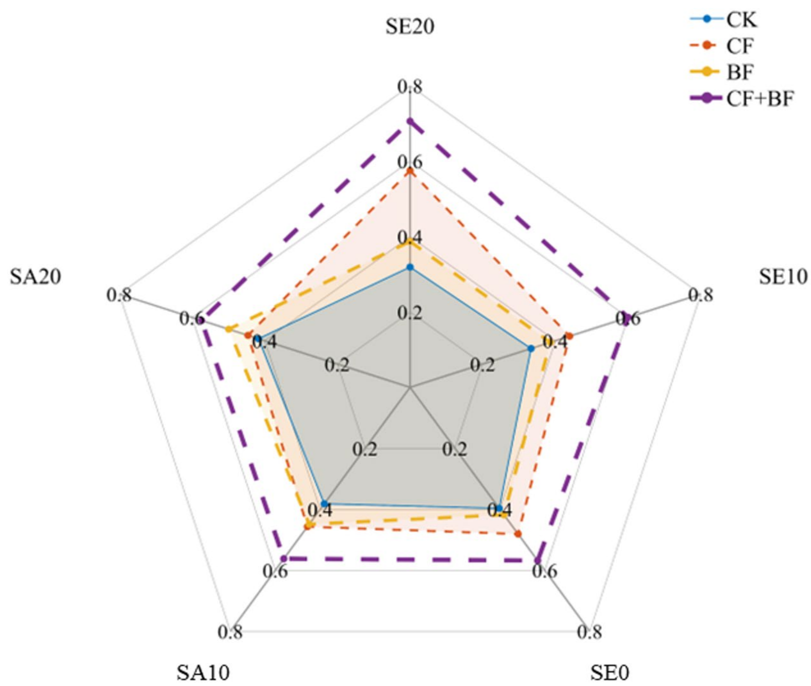

Fig. 8. Effects of fertilization strategies on soil quality index (SQI) across different soil erosion and deposition levels.

(AN), and available phosphorus (AP) to calculate the Soil Quality Index (SQI). The resulting SQI values were relatively low, approximately 0.4, indicating poor soil quality in the study area (Fig. 5).

The negative impact of erosion on soil quality is well documented[48], and our results confirm that SQI values in eroded zones were significantly lower than those in depositional areas[49]. The calculated SQI is influenced not only by the soil indicators themselves but also by their assigned weights. Mandal, et al.[10] reported SQI values of 0.7 and 0.4 for mildly and severely eroded soils, respectively, with corresponding sustainable yield indices for wheat of 0.9 and 0.6. Similarly, Fang, et al.[50] assessed erosion impacts on agricultural soils in Northeast China and reported SQI values ranging from 0.270 to 0.880, with a mean of 0.551. These findings highlight the urgent need for effective land management strategies that reduce erosion risk and improve soil quality in agroecosystems.

Fertilization is one such strategy. Singh, et al.[51] identified soil organic carbon (SOC) and exchangeable aluminum as key indicators of soil quality, emphasizing that organic matter management and pH regulation are critical for improving soil quality in intensively cultivated systems. In our study, weight analysis revealed that alkaline nitrogen (AN, 0.106), sand (0.111), and silt (0.100) were the top three contributors to the SQI (Table 2), underscoring the importance of optimizing both physical structure and available nutrients in degraded soils.

Previous studies have confirmed that soil quality is controlled by land use and associated erosion processes[52]. Demir, et al.[49] further demonstrated a negative relationship between SQI and soil loss per unit area. Our findings are consistent with these observations. Across various erosion-deposition scenarios, the application of fertilizers significantly improved soil quality compared to the unfertilized condition (Fig. 8). Among fertilization strategies, the combined application of organic and inorganic fertilizers (CF + BF) resulted in the highest SQI values, followed by inorganic (CF) and organic-only (BF) treatments. Notably, the short-term effects of organic fertilizers alone may be limited in improving physical structure and nutrient availability. However, long-term monitoring may reveal different trends and benefits over time.

Erosion and fertilization management effects on crop productivity

Soil erosion significantly alters crop productivity by modifying soil nutrient dynamics, physical structure, and moisture availability[53,54]. The removal and redistribution of topsoil lead to spatial heterogeneity in nutrient availability and soil structure across erosion–deposition landscapes. In highly eroded zones, the nutrient stock may be drastically reduced—up to 60% compared to uneroded sites[55], while depositional areas may accumulate organic matter and nutrients[56,57]. However, deposition zones often suffer from increased bulk density and compacted soil layers, which can restrict root growth and water movement, ultimately limiting crop performance[58].

In our study, we observed that fertilization strategies differentially influenced crop productivity across erosion-deposition contexts. Specifically, the application of chemical fertilizer alone (CF) resulted in higher biomass, greater root system development (root length, surface area, and volume), and pod number, especially in the erosion zone (Fig. 7). This result highlights the effectiveness of readily available nutrients in supporting plant growth under nutrient-depleted conditions where rapid nutrient uptake is essential during limited growth windows. However, reliance on inorganic fertilizers alone may degrade long-term soil health, especially in erosion-prone areas with unstable fertility status.

The combined application of organic and inorganic fertilizers (CF + BF), though less immediately effective than CF alone, has the potential to enhance long-term soil structure, nutrient retention, and biological activity, which are critical under conditions of soil degradation[59]. In contrast, organic fertilizer alone (BF) demonstrated the lowest productivity, possibly due to the slow release of nutrients that failed to meet crop demands during key growth particularly under severely eroded conditions with limited nutrient buffering capacity. These findings align with Dong, et al. [60], who reported decreasing nutrient content in macro-aggregates with increasing erosion intensity, further confirming the reduced effectiveness of organic amendments alone in degraded soils. Our results suggest that while chemical fertilizers offer short-term benefits in erosion-degraded soils, the integration of organic matter is essential for sustainable productivity restoration. This is consistent with Mandal, et al.[61], who found that the productivity index (PI) declined with increasing erosion severity, but was significantly higher under fertilized conditions compared to unfertilized ones. For instance, PI values ranged from 0.748 in slightly eroded soils to 0.651 in heavily eroded soils under fertilization, highlighting the mitigating role of nutrient inputs.

In depositional areas, productivity enhancement may depend more on improving physical conditions such as reducing bulk density and alleviating compaction[58,62]. For example, straw return with deep placement (15–30 cm) was shown to improve subsoil conditions and crop yields more effectively than surface applications. These findings suggest that tailored management strategies- chemical fertilization in erosion zones and structural improvement in deposition zones are needed to address productivity constraints shaped by erosion-deposition processes.

Overall, our study reinforces that erosion depletes fertility and impairs productivity, necessitating site-specific fertilization regimes. Integrating chemical fertilizers for immediate nutrient supply and organic inputs for long-term sustainability offers a balanced approach to restoring productivity in sloping farmland subject to soil erosion.

Implications for soil conservation and limitations

One of the most significant challenges in evaluating the erosion–productivity relationship lies in the subtle and gradual nature of productivity decline. Erosion-induced reductions in productivity often occur so slowly that they may remain unnoticed until crop yields fall below economically viable thresholds. As such, directly monitoring yield trends on eroding sites over time fails to capture the true impact of erosion. Consequently, various indirect methods have been developed to assess this relationship[14].

Among these methods, the most straightforward approach has been simulated topsoil removal (desurfacing). While effective in mimicking erosion-induced soil loss, this technique may significantly overestimate its detrimental effects on productivity due to the abruptness and completeness of soil removal, which contrasts sharply with the gradual nature of natural erosion[14,63]. Comparative studies suggest that crop yield reductions averaged 4.3% per 10 cm of soil loss in plot-based experiments, whereas transect-based and desurfacing experiments yielded higher estimates (10.9% and 26.6%, respectively), implying a potential overestimation when using simulated methods alone[14].

To better approximate real-world erosion effects, long-term field trials, comparative plot designs, or topsoil addition studies may offer more realistic insights. For instance, studies have shown that gradual topsoil restoration[64,65] produces soil conditions closer to naturally eroded sites, though complete profile reconstruction remains difficult. In addition, landscape position and erosion history must be carefully controlled when comparing productivity across fields. Paired-plot experiments with similar slopes, management history, and soil type but differing erosion intensity offer the most reliable basis for isolating erosion impacts[66].

Importantly, fertilization plays a critical role in mitigating erosion-induced productivity loss. While nutrient additions (N, P, or organic amendments) can partially restore yields on eroded soils, recovery is often incomplete and varies by erosion severity[67]. Fertilization responses may also differ in nutrient uptake efficiency and crop physiology under degraded conditions. Therefore, site-specific, erosion-aware nutrient management strategies are essential.

From a practical standpoint, we recommend that in severely eroded areas, integrated fertilization (combining organic and inorganic sources) be prioritized, along with biological conservation measures such as green manure cultivation. In depositional zones, deep tillage and soil physical improvement may be necessary to enhance root penetration and aeration. Long-term monitoring and adaptive management are crucial for sustaining productivity under ongoing erosion pressure.

Nevertheless, this study has certain limitations. First, the controlled pot experiment, while effective for isolating treatment effects, may not fully capture the complexity of natural field conditions such as micro-topography, rainfall variability, and long-term erosion dynamics. Second, a key limitation of this study is the absence of biological replicates, which restricts the statistical inference of treatment effects. Nevertheless, the consistent and clear trends observed across all treatments and measured indicators provide valuable exploratory evidence. The results should therefore be interpreted as preliminary and will be further validated in ongoing and planned field experiments with full biological replication. Finally, the simulated desurfacing and deposition approach provides valuable insights into topsoil redistribution, but its abrupt nature may differ from gradual, cumulative erosion processes in the field. These limitations should be considered when interpreting the results, and future research should focus on long-term, replicated field trials to validate and extend the findings.

Conclusion

This study comprehensively investigated the effects of simulated soil erosion and surface deposition, combined with different fertilization strategies, on soil quality and peanut (Arachis hypogaea L.) productivity in the middle and lower reaches of the Yangtze River. Severe topsoil removal impaired soil physical structure and fertility, as evidenced by lower porosity, reduced organic matter content, and declines in total nitrogen and phosphorus. In contrast, simulated deposition improved topsoil structure, enhanced nutrient retention, and yielded higher Soil Quality Index (SQI) values, indicating improved soil function. Erosion stress markedly inhibited peanut growth, particularly root morphological traits, with the 20 cm erosion treatment causing the most pronounced reductions in root length, surface area, and volume. Conversely, depositional conditions promoted robust root development and shoot biomass, emphasizing the restorative benefits of surface accumulation. Fertilization served as a critical mitigating factor. Among all treatments, the integrated application of organic and inorganic fertilizers (CF + BF) consistently yielded the highest SQI values and improved root system development, especially under deposition scenarios. Overall, our findings highlight the importance of preserving topsoil, adopting surface restoration techniques, and implementing integrated fertilization strategies to improve soil health and maintain crop productivity in erosion-prone agroecosystems.

Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Author contributions

Conceptualization, ZHANG Jingyu, CHEN Lei and YAN Xiqin; Formal analysis.ZHANG Jingyu, CHEN Lei and YAN Xiqin; Funding acquisition, ZHANG Jingyu, CHEN Lei, YAN Xiqin and PENG Dong; Investigation, CHEN Yingjian and LONGChangyu; Methodology, ZHANG Jingyu and WANG Bangwen; Project administration, XIA Xiaolin; Software, ZHANG Jingyu, CHEN Lei and YAN Xiqin; Validation, XIAXiaolin; Writing original draft, ZHANG Jingyu; Writing review and editing, YANXiqin. All authors have read and agreed to the published version of the manuscript.

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Declarations

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to X.Y. or L.C.

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