Effect of Ecological Restoration on Carbon storage of Damaged Mountain Slope in China’s East Ussuri River Basin (#112115)

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Effect of Ecological Restoration on Carbon storage of Damaged Mountain Slope in China's East Ussuri River Basin

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Ecological restoration techniques are extensively employed in the ecological restoration of damaged mountain ecosystems via effectively restoring the plant community and improving soil functions. Aggregate spray seeding technology as an effective ecological restoration method, can quickly restore the damaged slopes to their previous status and keep the ecosystem functions. However, the lack of understanding of the characteristic of carbon storage as well as its influencing factors limits the scientific management of carbon sink function of the rehabilitated damaged mountain ecosystem.

In this study, relying on field surveys in the East Ussuri River Basin, we analyzed the carbon storage distribution and its influencing factors in damaged mountain slopes that had been restored through the spray seeding technology after an eight-year restoration phase. The results showed that the carbon storage distribution of the damaged slopes repaired by aggregate spray seeding is in the order of soil layer > tree layer > shrub layer > litter layer > herbaceous layer. Among them, the carbon storage of the vegetation layer is mainly distributed in the tree layer, and its size is similar to that of undisturbed natural slopes. Plants and soil are the main factors affecting the carbon storage of the repaired slopes, where the plant density has a significant positive correlation with carbon storage, accounting for 19% of the carbon storage variation, and the soil bulk density has a significant negative correlation with carbon storage, accounting for 23.7% of the carbon storage variation. This study reveals the mechanism of the aggregate spray seeding technology in restoring the carbon storage of damaged slopes and points out that regulating vegetation density and improving soil conditions are key to enhancing the carbon sink capacity of slopes.

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Abstract

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Key words: Ecological Restoration; Carbon Storage; Damaged Slopes; Vegetation Recovery; Soil Reconstruction

Introduction

The Ussuri River Basin, situated in northern China, represents a vital forestry region with abundant forest resources and significant forest coverage, playing a critical role in regional ecological carbon sequestration. However, rapid urbanization and associated anthropogenic activities, particularly in mountainous areas, have led to extensive slope exposure and ecosystem degradation. These changes have substantially compromised the region's carbon sequestration capacity, Li et al.(2023) reported that a 2% reduction in forest land area in the Northeast black soil region between 2000 and 2020 resulted in a 1.65% decline in forest carbon absorption. In line with the Chinese government's pledge to peak greenhouse gas emissions by 2030 and achieve carbon neutrality by 2060 (Chen et al., 2022), enhancing the carbon sink of damaged mountain ecosystems is an essential means to mitigate the increase in atmospheric CO_2 concentration and an effective way to achieve China's carbon neutrality goal. Therefore, it is of great significance to timely acquire the characteristic of the rehabilitated ecosystem and quantitatively analyze the relevant influencing factors.

Damaged mountain slopes, characterized by challenging site conditions such as shallow soils, water scarcity, and low fertility, present significant obstacles to ecological recovery. In response, extensive ecological restoration efforts have been implemented to reshape topography, rehabilitate soils, and reconstruct vegetation, ultimately aiming to restore the structure and function of these ecosystems (Aerts & Honnay, 2011; Prach, Jongepierová & Řehounková, 2013). Giupponi (2019) highlighted the role of ecological engineering in soil slope restoration, emphasizing vegetation recovery and soil conservation, while Deivaseeno and Normaniza (2021) provided a comparative analysis of bioengineering techniques for slope stabilization. Cai et al (2019) focused on the adaptability and growth characteristics of vegetation in rocky slope restoration. More recently, Li (2024) introduced aggregate spray seeding technology as an innovative approach to rehabilitate damaged mountain slopes, which rapidly promotes the growth of target plants, accelerates the formation and succession of plant communities, and ultimately achieves the restoration and self-sustenance of the damaged ecosystem.

The formation of ecosystem carbon sinks is a complex process involving the carbon allocation of plants and the sequestration of soil carbon. Vegetation, as a key factor in ecosystem carbon storage, gradually enhances its carbon sequestration capacity as plant communities are established and mature. As plants grow, they not only accumulate carbon through photosynthesis but also input organic matter into the soil through litter and roots, thereby affecting the accumulation and distribution of soil organic carbon (Shi et al., 2015; Ahirwal & K, 2018; Yang & Bai, 2021; Wu et al., 2023). Soil is another important factor affecting ecosystem carbon storage. The physical and chemical properties of soil, including the supply of water and nutrients, have an indirect impact on plant photosynthesis and respiration, thus affecting the accumulation of plant carbon. The soil's water and soil conservation capacity is a key factor in determining the soil's ability to fix organic carbon, directly influencing the long-term storage of carbon in the soil (Jia, Zhang & Yu, 2022). Ecological restoration projects are one of the main drivers of China's terrestrial ecosystem carbon sinks. Lu et al. (2019) found that ecological restoration projects contributed to 56% of the terrestrial carbon sink in the project implementation area. The unique geomorphological structure and ecological characteristics of damaged mountain slopes endow them with specific and complex carbon storage properties. However, research on carbon storage traits and influencing factors in ecologically restored slopes remains limited.

The restoration of damaged slopes using aggregate spray seeding involves the reconstruction of the soil base, the selection of plant species, seeding, and the self-replacement of plants, significantly altering the synergistic evolution process between vegetation and soil (Zhang et al., 2018; Jia, Zhang & Yu, 2022), thereby shaping the unique characteristics of vegetation and soil carbon sinks. This study focuses on a damaged mountain slope restoration project in the eastern Ussuri River Basin. Due to urban construction, the area had formed rocky, exposed slopes, which were successfully rehabilitated using "aggregate spray seeding restoration technology." The study examines the carbon storage characteristics and influencing factors in these restored slopes, providing practical recommendations and technical support for carbon sink management in ecological restoration areas.

Materials & Methods

The survey site

The survey site is located in the east of Ussuri River Basin(43°21′N, 134°19′E, 40-60 m altitude). The area is affected by monsoons, with cold and dry winters, and warm and humid summers. The annual average temperature is 3.4 ℃ and the annual average precipitation is 954.7

mm. The natural ecosystem's soil type is dark brown soil, and the community type is a secondary forest dominated by *Ulmus pumila* and *Betula platyphylla* as the primary species.

In study area, roads construction has led to the formation of damaged mountain slope. To address this environmental challenge, two restoration strategies were implemented in 2015. One method, "Aggregate spray-seeding restoration technology", was provided by Qingdao Greensum Ecology Co., Ltd., China. The spraying matrix is composed of clay, organic additives, soil amendments, and necessary slow-release fertilizers (Chen et al., 2024). The sprayed soil layer is divided into an artificial soil layer and a seed layer, with the thickness of the soil matrix formed by spraying ranging from 7 to 10 cm. The seed layer contains a variety of plants, including *Ulmus pumila*, *Betula platyphylla*, *Lespedeza davurica*, *Caragana microphylla*, *Hippophae rhamnoides Linn*, and *Amorpha fruticosa*. Another method was employed with a focus on the establishment of planted forests.

Site design

This study conducted site surveys in August 2023. Survey points were set up at different aspects of the slope, with each survey point including an aggregate spray seeding restored slope, a naturally restored slope, and an undamaged slope. Based on the restoration area and topographical characteristics of the survey points, three survey plots were set up in each type of slope. In each plot, tree survey plots were set with an area of 10×10 m², within each tree survey quadrat, shrub survey quadrats with a side length of 2×2 m², and within each shrub survey quadrat, a 1×1 m² herbaceous survey subplot was set.

The plant community survey primarily focuses on the tree layer, shrub layer, herbaceous layer, dead wood layer, and litter layer. Due to the rocky slope in the area and the thin soil layer, this study investigated the soil in the 0-10 cm depth range.

Carbon storage calculation

The carbon storage of plant tree layer, shrub layer, herb layer, dead wood layer, and litter layer is calculated using the formula:

$$C_x = B_x \times CF_x \quad (1)$$

where C is the carbon storage per unit area (kg/m²), B is the biomass (kg/m²), *CF* is the organic carbon content (g/kg), and *x* is tree, shrub, herb, dead wood, and litter.

The soil carbon storage is calculated using the formula:

$$C_s = \rho b \times CF_s \times 0.1 \quad (2)$$

where C_s is the soil carbon storage per unit area (kg/m²), ρb is the soil bulk density (g/cm³), and *CFs* is the soil organic carbon content (g/kg), focusing on a 0.1 m soil thickness in this survey.

Data Statistics

The carbon storage of aggregate spray seeding restored slopes, naturally restored slopes, and undamaged slopes is represented by the average values of three sample plots. To analyze the relative contributions of plant density and soil physicochemical properties to ecosystem carbon storage, the R language relaimpo package is utilized. T-tests or two-tailed analysis of variance (ANOVA) are employed to compare differences in various indicators among different habitat types. The Origin analysis tool is used to perform linear fitting of soil bulk density, soil total nitrogen, and plant density with ecosystem carbon storage to further reveal the underlying patterns and characteristics of the data.

Results

2.1 Current Status of Vegetation and Soil Carbon Storage

The total carbon storage of the aggregate spray seeding restored slope is 5.95 kg/m² (Table 1). Among this, the total carbon storage of the plant layer and the litter layer is 1.55 kg/m², and the carbon storage of plant roots and soil is 4.4 kg/m². Among the aboveground components, the arboreal layer has the largest carbon storage, at 1.53 kg/m², followed by the shrub layer and the litter layer, at 0.02 kg/m² and 0.013 kg/m², respectively. Among the belowground components, the soil carbon storage is 3.93 kg/m², and the root carbon storage is 0.47 kg/m².

The total carbon storage of the naturally restored slope is 1.14 kg/m². Among the aboveground components, the shrub layer has the largest carbon storage, at 0.007 kg/m², followed by the herbaceous layer and the litter layer, at 0.002 kg/m² and 0.001 kg/m², respectively. Among the belowground components, the soil carbon storage is 1.13 kg/m², and the root carbon storage is 0.002 kg/m².

The total carbon storage of the undamaged slope is 10.64 kg/m². Among the aboveground components, the arboreal layer has the largest carbon storage, at 1.59 kg/m², followed by the litter layer and the shrub layer, at 0.014 kg/m² and 0.013 kg/m², respectively. Among the belowground components, the soil carbon storage is 8.58 kg/m², and the root carbon storage is 0.45 kg/m².

The carbon storage in the herbaceous layer, litter layer, roots, and soil layer of the aggregate spray seeding restored slope is significantly higher than that of the corresponding components in the naturally restored slope. The carbon storage in the arboreal layer, shrub layer, and roots of the aggregate spray seeding restored slope shows no significant difference from the corresponding components in the undamaged control slope.

2.2 Analysis of Biological and Soil Physical and Chemical Properties in Slope Ecosystems

The vegetation growth density of the slopes is shown in Table 2. The total plant density of the aggregate spray seeding restored slope is 5.19 plants/m², the total plant density of the naturally restored slope is 2.35 plants/m², and the total plant density of the undamaged slope is 3.47 plants/m². Among them, the plant density of the arboreal layer, shrub layer, and herbaceous layer in the aggregate spray seeding restored slope is significantly higher than the vegetation density of the undamaged slope, and the diameter at breast height (DBH) of the arboreal trees is significantly lower than that of the undamaged slope's arboreal trees.

The results of the soil physicochemical properties of the slopes are shown in Table 3. The water content, total nitrogen, total phosphorus, and total potassium content of the soil in the aggregate spray seeding restored slope are significantly higher than those in the naturally restored slope and the undamaged slope, while the soil bulk density is significantly lower than that in the naturally restored slope and the undamaged slope.

2.3 Analysis of Influencing Factors on Ecosystem Carbon Storage

Plant and soil factors together account for 99.8% of the variation in carbon storage on the aggregate spray seeding restored slope (Figure 2), with plants contributing 19% relatively. Soil physicochemical properties together account for 80.8% of the variation in carbon storage, with soil bulk density explaining 23.7%, followed by soil total nitrogen, soil total potassium, soil total phosphorus, and soil water content, contributing to carbon storage by 19.2%, 14.8%, 11.7%, and 11.4%, respectively. The correlation analysis between influencing factors and carbon storage shows (Figure 3), that ecosystem carbon storage has a significant negative correlation with soil bulk density and a significant positive correlation with soil total nitrogen and plant density.

Discussion

3.1 Impact of Ecological Restoration on Slope Carbon Storage

This study takes the ecological restoration project of damaged mountain bodies in Ussuri River Basin as an example to explore the characteristics of carbon storage and its influencing factors in damaged mountain slopes after 8 years of restoration. The results reveal that the distribution of carbon storage in slopes restored by the aggregate spray seeding technology is similar to that of undamaged slopes(Table 1). This indicates that the aggregate spray seeding technology has successfully restored the original carbon storage distribution pattern of damaged slopes. The "tree, shrub, grass" plant configuration used in aggregate spray seeding can rapidly establish a stable plant community, achieving up to 95% vegetation coverage (Li et al., 2011). This study points out that the tree layer dominates (98%) the vegetation carbon storage in the aggregate spray seeding restored slopes, consistent with the results of studies where the tree layer is the main contributor to carbon storage in forest ecosystems (Wang et al.). Further analysis found that the carbon storage in the tree layer of aggregate spray seeding restored slopes is consistent with that of undamaged slopes, indicating that aggregate spray seeding technology effectively repairs the carbon sequestration function of slope vegetation by restoring the carbon storage of the arboreal layer. Nevertheless, compared with the average carbon storage of arboreal layers in Heilongjiang forests (3.3 kg/m^2) (Liu, Wang & Luan, 2011), the carbon storage of the arboreal layer in aggregate spray seeding restored slopes is lower (about 50%), which may be related to the younger age and smaller diameter at breast height of the trees (Ren & Xia, 2017). With the increase in ecological restoration years, the vegetation carbon sequestration is expected to gradually increase with plant growth (Shi et al., 2015; Ahirwal & Maiti, 2018; Yang & Bai, 2021). Therefore, aggregate spray seeding restored slopes have great potential in plant carbon sequestration but require long-term monitoring to assess their potential.

This study found that the soil carbon storage of aggregate spray seeding restored slopes is 3.5 times that of naturally restored slopes, confirming the effectiveness of ecological restoration in increasing soil carbon storage (Xu, Qu & Wang, 2020). The reasons for this are related to the aggregate spray seeding restoration technology: firstly, the technology uses a substrate rich in organic matter to construct an artificial soil layer (Li et al., 2011), significantly increasing the organic carbon content in the soil; secondly, by establishing a high-density seed bank, aggregate spray seeding promotes the input of organic matter from seed residues, plant litter, and roots into the soil, further enhancing soil carbon storage (Wu et al., 2023); finally, soil erosion is a major factor in the loss of soil organic carbon (Liu et al., 2023), and the artificial soil structure constructed by aggregate spray seeding is stable and has strong erosion resistance (Li et al., 2011), effectively promoting the fixation of soil carbon. However, compared with undamaged slopes, the soil carbon storage of aggregate spray seeding restored slopes is still lower. This may be related to the low amount of forest litter return. The results of this study show that the litter carbon storage in the sprayed restoration area is only 41% of the carbon storage of undamaged slopes, consistent with the results of a study where natural forest land was converted to artificial forest (Ran, Xu & Wan, 2022). This indicates that the reduction in the amount of litter is a key factor leading to low soil organic carbon storage. In addition, another reason for the low soil carbon storage in aggregate spray seeding areas may be related to the thin artificial soil layer in the damaged slope area. Relevant studies have pointed out that in rocky desertification ecosystems, due to high rock exposure rates and thin soil, the soil carbon storage after restoration is far below the national average (Lu, Nong & Li, 2019). A study by Lei et al. (2023) also found that the soil organic carbon pool in the spoil dump slopes of northern mining areas still has a lower content than the soil in natural areas after restoration (Lei et al., 2023).

3.2 Impact of Ecological Restoration on Plants and Soil

This study shows that the plant density of aggregate spray seeding restored slopes is significantly higher than that of naturally restored slopes and undamaged slopes (Table 2). This is related to the dense seeding method used in aggregate spray seeding. After high-density seeding, the bare slopes quickly formed a forest greening structure combined with trees, shrubs, and grass within two years, and the plant density gradually increased as the forest community succeeded from pioneer species to later species (Li et al., 2011). The aggregate spray seeding technology effectively reconstructs the soil of damaged slopes, and its soil physicochemical properties are better than those of naturally restored slopes and undamaged slopes because the artificial soil contains organic matter additives, soil conditioners, and necessary slow-release fertilizers (Greensum Ecology Co., Ltd., 2018). In addition, the root fixation of vegetation effectively protects the soil, reducing water and wind erosion. With the recovery of vegetation, the continuous accumulation of litter and the increase of root interweaving and secretions further promote the improvement of soil properties (Yang et al., 2022; Dan, 2023).

3.3 Analysis of Influencing Factors on Ecosystem Carbon Storage

This study further analyzes the influencing factors of carbon storage in aggregate spray seeding restored slopes. The results show that plant and soil factors together explain 99.8% of the variation in carbon storage (Figure 2). Plant density, as a potential influencing factor of ecosystem carbon sequestration function (Ouyang et al., 2019; Hao et al., 2022), accounts for 19% of the variation in slope carbon storage. This is because the higher the number of plants per unit area, the more sufficient the acquisition and utilization of environmental resources, thereby promoting the increase of vegetation biomass (carbon storage). This indicates that high-density seeding for vegetation restoration helps to promote resource cycling and utilization, increasing the accumulation and fixation of carbon on slopes.

Among soil factors, soil bulk density accounts for 23.7% of the variation in ecosystem carbon storage. This is because soil bulk density reflects soil aeration, infiltration performance, water-holding capacity, and solute migration potential (Chai & He, 2016). Studies have shown that excessive soil bulk density can lead to the growth of plant leaves, reducing plant photosynthetic rates or aboveground productivity (Li & Wang, 2000; Liu & Shan, 2003). This study found that carbon storage in aggregate spray seeding restored slopes is significantly negatively correlated with soil bulk density, indicating that reducing soil bulk density helps the accumulation of carbon storage on slopes.

4 Conclusion

This study confirms the effectiveness of aggregate spray seeding restoration technology in restoring the carbon storage distribution pattern of damaged slopes and identifies soil bulk density and vegetation density as important influencing factors on slope carbon storage. Future studies should further focus on the impact of litter on soil carbon storage during the process of vegetation restoration, and in conjunction with the global carbon neutrality goal, promote the restoration and enhancement of carbon sequestration functions in damaged ecosystems.

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Figure 1

Location of site

The survey site is located in the east of Ussuri River Basin(43°212N,134°192E, 40-60 m altitude).

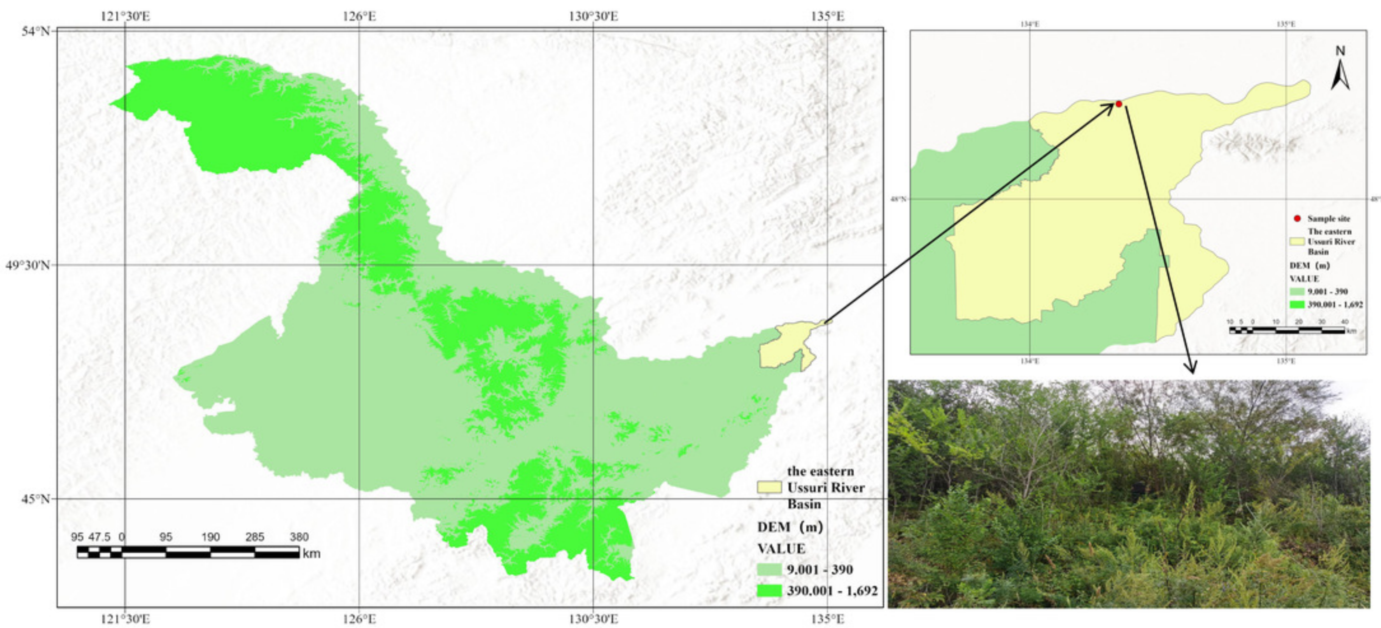

Figure 2

Relative importance of factors in the changes of ecosystem carbon storage.

Plant and soil factors together account for 99.8% of the variation in carbon storage on the aggregate spray seeding restored slope .Soil bulk density (BD) explaining 23.7%, soil water content (SWC) explaining11.4% , soil total nitrogen (N) explaining 19.2%,soil total phosphorus (P) explaining 11.7%,soil total potassium (K) explaining 14.8% and plants density (De) explaining 19% .

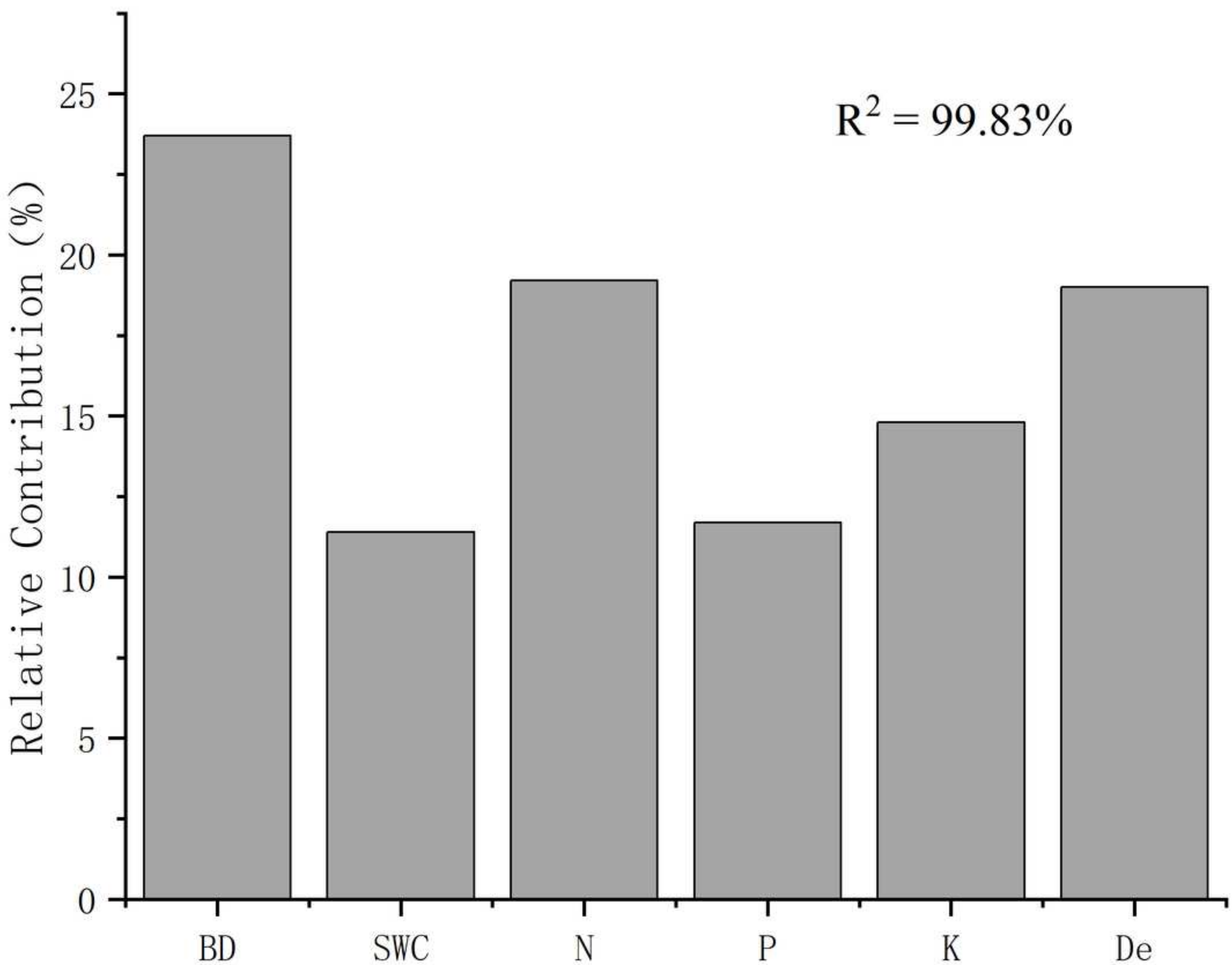

Figure 3

Influence of soil bulk density , total soil N and plant density on ecosystem carbon storage .

Ecosystem carbon storage (C) has a significant negative correlation with soil bulk density (BD) and a significant positive correlation with soil total nitrogen (N) and plant density (De) .

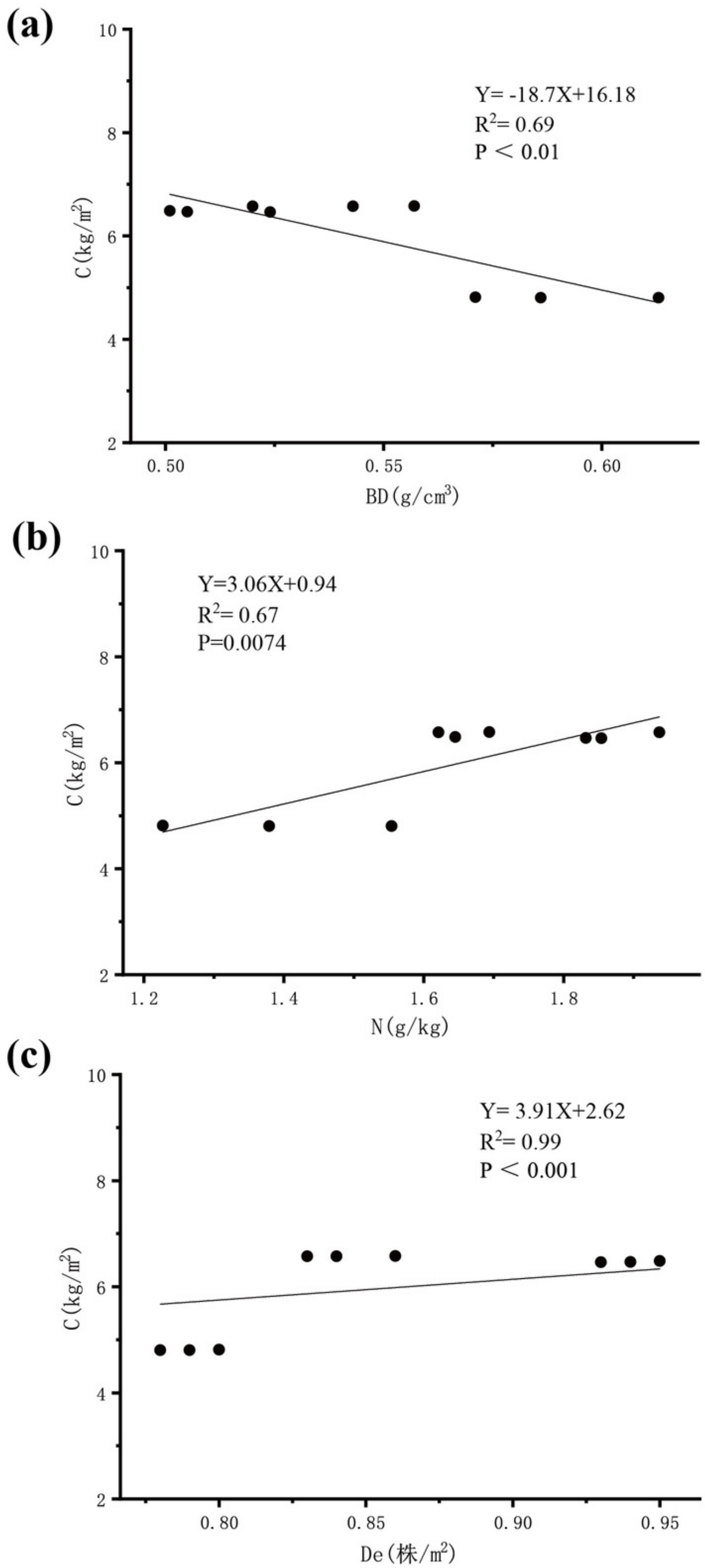
(a)
Y= -18.7X+16.18
R^2= 0.69
P < 0.01
C (kg/m²)
BD (g/cm³)
(b)
Y=3.06X+0.94
R^2= 0.67
P=0.0074
C (kg/m²)
N (g/kg)
(c)
Y= 3.91X+2.62
R^2= 0.99
P < 0.001
C (kg/m²)
De (株/m²)

Table 1 (on next page)

Slope ecosystem carbon density

Note: Mean ± SE. Different letters in the same column indicate significant differences ($P < 0.05$).

Table 1 Slope ecosystem carbon density

type	Carbon content (kg/m^2)					
	Tree Layer	Shrub Layer	Herbaceous Layer	Litter Layer	Root	Soil
Aggregate spraying repair for Slope	1.53^a±0.03	0.02^a±0.01	0.0033^a±0.0002	0.0057^b±0.0008	0.47^a±0.03	3.93^b±0.62
Natural recovery of slope		0.0073^a±0.001	0.0017^b±0.0003	0.0014^c±0.0004	0.0019^b±0.0002	1.13^c±0.009
Undamaged slope	1.59^a±0.001	0.013^a±0.0006	0.0022^b±0.0004	0.0138^a±0.0004	0.44^a±0.004	8.58^a±0.008

Note: Mean ± SE. Different letters in the same column indicate significant differences ($P < 0.05$).

Table 2(on next page)

Slope ecosystem plant status

Note: Mean ± SE. Diferent letters in the same column indicate signiûcant diûerences (P < 0.05).

Table 2 Slope ecosystem plant status

Type	Tree Layer		Shrub Layer	Herbaceous Layer
	Density(plants/m^2)	Diameter of breast height(cm)	Density(plants/m^2)	Density(plants/m^2)
Aggregate spraying repair for Slope	$0.50^{a}\pm0.03$	$5.49^{b}\pm0.20$	$0.36^{a}\pm0.02$	$4.30^{a}\pm0.38$
Natural recovery of slope			$0.08^{c}\pm0.01$	$2.27^{b}\pm0.35$
Undamaged slope	$0.05^{b}\pm0.002$	$15.00^{a}\pm0.12$	$0.15^{b}\pm0.01$	$3.27^{b}\pm0.12$

Note: Mean ± SE. Different letters in the same column indicate significant differences ($P < 0.05$).

Table 3(on next page)

Slope ecosystem soil physical and chemical properties

Note: Mean ± SE. Diferent letters in the same column indicate signifcant diferences ($P < 0.05$).

Table 3 Slope ecosystem soil physical and chemical properties

Type	Bulk Density (g/cm^3)	Soil Water Content （V/V%）	Total Nitrogen (g/kg)	Total Phosphorus (g/kg)	Total Potassium (g/kg)
Aggregate spraying repair for Slope	$0.55^{c}\pm0.01$	$33.36^{a}\pm1.53$	$1.64^{a}\pm0.08$	$0.89^{a}\pm0.05$	$18.68^{a}\pm0.30$
Natural recovery of slope	$0.75^{a}\pm0.01$	$28.94^{b}\pm0.34$	$0.50^{c}\pm0.02$	$0.55^{b}\pm0.02$	$14.12^{c}\pm0.20$
Undamaged slope	$0.71^{b}\pm0.004$	$29.69^{b}\pm0.72$	$0.91^{b}\pm0.01$	$0.59^{b}\pm0.004$	$15.78^{b}\pm0.05$

Note: Mean ± SE. Different letters in the same column indicate significant differences ($P < 0.05$).