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EDITED BY
Zhiguang Liu,
Shandong Agricultural University, China

REVIEWED BY
Praeploy Kongsurakan,
Hokkaido University, Japan
Delei Kong,
Zhejiang A&F University, China
Dianqing Gong,
Institute of Geographic Sciences and Natural Resources Research, China

*CORRESPONDENCE
Wei Zhang,
zhangdaw007@163.com

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# Effect of off-road vehicle activity on vegetation community and soil properties in the Otindag Sandy Land, China

Xuanxuan Wang[1], Jinghua Long[1,2], Wei Zhang[1,2]*, Xinrui Cao[1], Shuang Liang[1], Hui Gao[1] and Jintian Yang[1]

[1]School of Public Administration, Hebei University of Economics and Business, Shijiazhuang, China, [2]Hebei Collaborative Innovation Center for Urban-rural Integrated Development, Shijiazhuang, China

Off-road vehicle (ORV) activity has emerged as a growing ecological disturbance in arid and semi-arid grasslands, yet its combined impact with topographic factors such as slope remains poorly understood. A 4-year field compaction test was conducted in Otindag Sandy Land to explore changes in the vegetation community and soil properties under different degrees of off-road vehicle compaction and different slope conditions and investigate the effect of ORV activity on grassland vegetation and soil. The results showed that ORV activity caused a marked reduction ($P < 0.05$) in plant community species diversity, and the Shannon–Wiener (SWI), Margalef's (MI), Simpson dominance (SDI), and Pielou evenness (PEI) indices decreased by 58.62%–81.31%, 24.44%–48.78%, 52.22%–77.78% and 50.00%–75.68%, respectively, in ORV treatments compared to that in the control treatments. Additionally, ORV activity caused a significant increase in soil bulk density and a notable decrease in soil organic matter, water and clay contents, available phosphorus and potassium, and soil enzyme activity. Redundancy analysis showed that the species diversity of the plant community was closely related to soil factors. MI, SWI, SDI, and PEI were positively correlated with pH, available phosphorus and potassium, alkali-hydrolyzable nitrogen, soil organic matter, and soil water, silt, and clay contents and negatively correlated with bulk density and sand content. The slope and ORV activity interacted significantly with the Simpson dominance index, soil particle composition, pH, total nitrogen, alkali-hydrolyzable nitrogen, soil sucrase activity, and solid-urease activity. The impact of ORV activity on the vegetation community and soil properties became more severe with an increase in the slope. Assessing the impact of ORV activity on soil and vegetation can provide a scientific basis for the sustainable development and management of outdoor cross-country activities.

KEYWORDS

**off-road vehicle, soil properties, sandy land, vegetation community, redundancy analysis**

## 1 Introduction

Outdoor off-road activities typically encompass long-distance hiking, running, cycling, and off-road vehicle (ORV) driving in natural environments. With the rapid proliferation of these activities, the substantial influx of tourists into natural areas has exerted both direct and indirect effects on the ecosystem (Navas et al., 2019). Land trampling associated with off-road activities can lead to soil erosion and vegetation destruction (Schlacher and

Thompson, 2008; Gill et al., 2023). In fragile ecosystems, such as nature reserves, these activities may irreversibly damage plant and soil quality. Thus, investigating changes in vegetation and soil during off-road activities is of significant importance for a deeper understanding of grassland degradation processes and for scientifically guiding the development and management of off-road activities.

Recently, numerous scholars have investigated the impact of ORV activity on the structure and function of ecosystems in the context of outdoor activities. ORV activity has been identified to exert potential adverse effects on soil, plants, and animals (Navas et al., 2019 Yu et al., 2017). Wilshire and Nakata (1976) demonstrated that ORV activity induce physical damage to the soil in the Mojave Desert, which may subsequently reduce soil permeability, through wheel compaction. Westcott and Andrew (2015) found that ORV activity influenced the growth of plant seedlings, thereby altering species diversity. In lowland areas, trails formed by ORV tracks can cause localized impacts, such as the melting of permafrost and changes in the drainage density of river wetlands. These changes can, in turn, affect hydrological conditions and aquatic habitats downstream (Arp and Simmons, 2012). ORV activity can modify animal habitats by altering soil physicochemical properties, reducing vegetation cover, and altering plant communities. Wildlife concentrated in coastal, desert, and forested areas were also directly affected (Schlacher and Thompson, 2008).

Researchers use various methods, including field surveys, remote sensing image analyses, and site experiments, to investigate the ecological impacts of ORV activities (Yeh et al., 2021; Dewidar et al., 2016). Westcott and Andrew (2015) used high-precision MaxEnt models to predict the distribution of ORV tracks and analyzed the correlation between off-road activities and the environment. Dewidar et al. (2016) quantified the impact of ORV activity on vegetation and soil in central Saudi Arabia using field surveys and image analysis. Arp and simmons (2012) used outdoor mapping and aerial photography to monitor and analyze the soil and river basins of ORV trails in Alaska's Wrangell-St. Elias National Park found that ORV trails can alter watershed processes, potentially increasing drainage density and changing river water quality and aquatic habitats. In addition, some researchers have conducted studies from a microscopic perspective using field surveys and site experiments. Robert and Douglas (1978) quantified soil bulk density, soil moisture, and other indicators to study the impact of ORV activity and explore the challenges of vegetation restoration. Rickard et al. (1994) monitored changes in vegetation height and cover under different vehicle compaction and pedestrian trampling intensities to assess the vegetation recovery status in South African dune shrublands. These studies provide valuable data and insights into the environmental impacts of off-road activities.

The Otindag Sandy Land is one of China's five major sandy lands and is characterized by strong winds, abundant sand, low annual precipitation, and fragile habitats. Numerous studies on the ecological impacts of degraded grassland restoration and grazing utilization have been conducted in this region (Zhang et al., 2023; Zhao et al., 2023). However, studies of the effects of ORV activity on grassland ecosystems are limited. Therefore, we used the Otindag Sandy Land as the research area and explored the effects of ORV activity on grassland vegetation and soil under different slope gradient conditions using site experiments. The aim of this study was to understand the relationship between vegetation and soil during the degradation of grasslands in the Otindag Sandy Land and to provide scientific evidence for maintaining the stability of sandy grassland ecosystems and promoting sustainable development and management of off-road activities.

# 2 Materials and methods

## 2.1 Study area and experiment design

The Otindag Sandy Land (41°56′–44°26′N, 112°22′–117°57′E) is located in the eastern part of the Inner Mongolia Plateau, China. It is bordered by the Yin Mountains and Yan Mountains to the south, the Xilingol Prairie to the north, and the Greater Khingan Range to the east. The terrain of this area slopes gently from southeast to northwest, with minor undulations and a total area of approximately 29,500 $km^2$. It is one of China's well-known sandy areas with abundant water resources. The region has a temperate continental climate, with an annual average temperature ranging from 0 °C to 3 °C and an annual evaporation rate of 1,455.4–2,116.4 mm. It features mobile, semi-fixed, and fixed dunes, inter-dune depressions, and wetlands. The vegetation is dominated by sandy grassland herbaceous plants, including *Cynodon dactylon* L., *Caragana microphylla*, *Salix gordejevii*, and *Amygdalus pedunculata*, etc. The zonal soils are primarily chestnut and brown calcic soils, whereas the azonal soils are mainly aeolian sands.

The Otindag Sandy Land is a crucial component of the ecological barrier in northern China and plays an irreplaceable role in protecting the ecological environment and biodiversity. In addition, this region has become a popular destination for ORV activities, with a total loop distance of over 2,700 km for self-driving and off-road routes. More than 12,000 ORVs visit the area annually to participate in these activities.

An experimental strip plot (length 500 m, width 60 m) was selected in Saiyin Huda Gacha, Zhenglan Banner, in the southern part of the Otindag Sandy Land. Three parallel off-road routes spaced 30 m apart were established. A compaction experiment was conducted on grassland using three different compaction frequencies (HS: high-intensity disturbance, 100 passes per year, LS:low-intensity disturbance, 10 passes per year; CK: control, no ORV activity) from June 2020 to October 2023. Off-road routes traversed flat terrain and two areas with different slopes (S0: 0.0°–2.5°; S1: 8.5°–10.5°; S2: 16.0°–17.5°). A Toyota Prado off-road vehicle (Automatic TX, 2018) was used as the experimental vehicle (weight: 2,300 kg, Tire width: 265 mm), and the speed was 40 km $h^{-1}$. In each treatment–slope combination, four replicate plots were established. This replication level follows common practice in long-term grassland ecology and soil disturbance experiments conducted under comparable field conditions, where logistical constraints (e.g., site accessibility, protection of surrounding habitats) limit the feasible number of experimental units. Four replicates represent a balance between ensuring adequate statistical analysis and minimizing cumulative disturbance to the study area caused by repeated ORV passes and sampling. Preliminary field surveys prior to the experiment indicated

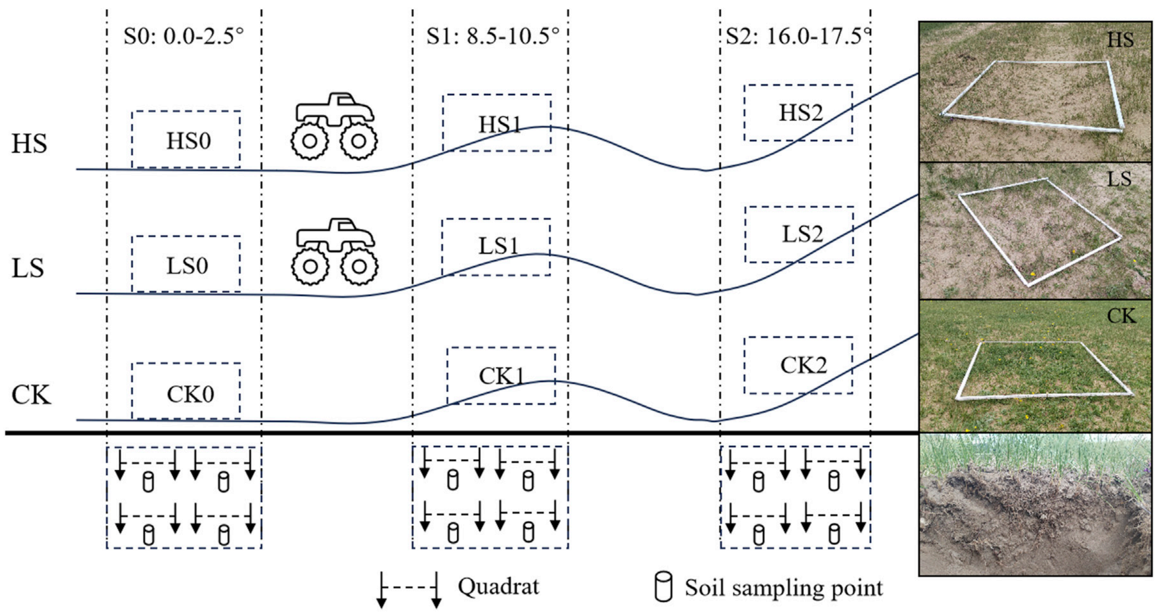


FIGURE 1
Details of the experiment design.

relatively homogeneous vegetation and soil conditions within each slope category, which supported the use of this replication level. The details of the experimental design and sampling process are shown in Figure 1.

A survey of the diversity of herbaceous plants was conducted in 36 quadrats (1 m × 1 m) in June 2024 to measure plant height, density, and coverage. Concurrently, soil samples from the 0–15 cm layer were collected from each quadrat. These samples were taken back to the laboratory, air-dried, passed through a 2 mm sieve after removing plant roots and gravel, and analyzed for soil properties.

## 2.2 Analysis of plant community species diversity

Margalef's (MI), Simpson dominance (SDI), Shannon–Wiener (SWI), and Pielou evenness (PEI) indices were used to reflect plant community species diversity using the following formulas:

$$RC = (\text{Total basal area of the species}/\text{Total basal area of all the species}) \times 100\%$$

$$RH = (\text{Average height of the species}/\text{Sum of the average height of all species}) \times 100\%$$

$$RD = (\text{No. of individuals of the species}/\text{No. of individuals of all species}) \times 100\%$$

$$P_i = (RC + RH + RD)/3$$

$$MI = (S - 1)/\ln N$$

$$SDI = 1 - \sum_{i=1}^{s} P_i^2$$

$$SWI = -\sum_{i=1}^{s} P_i \ln(P_i)$$

$$PEI = -\sum_{i=1}^{s} P_i \ln(P_i)/\ln(S)$$

where RC represents the relative coverage, RH denotes the relative height, RD denotes the relative density, $P_i$ denotes the species importance value of i, and S represents the number of species.

## 2.3 Soil properties analysis

The soil properties included soil bulk density (BD), soil porosity (SP), soil water content (SWC), pH, soil particle size distribution, soil organic matter (SOM), total nitrogen (TN), total potassium (TK), total phosphorus (TP), available potassium (AK), alkali-hydrolyzable nitrogen (AN), available phosphorus (AP), soil sucrase activity (S-SC), soil urease activity (S-UE), and alkaline phosphatase activity (ALP). The selected soil physical, chemical, and biochemical indicators comprehensively represent the structural, hydrological, nutritional, and biological dimensions of soil function, which are essential for capturing the mechanisms through which ORV activity and slope gradient affect grassland ecosystem dynamics. Table 1 provided the corresponding analysis methods for these properties. All measurements were conducted in duplicate for each composite field sample, and the coefficient of variation (CV) ≤ 5%.

## 2.4 Statistical analysis

Data were analyzed using SPSS 22.0, with all data presented as mean ± standard deviation (Mean ± SD). Prior to analysis, all data were tested for normality test and homogeneity of variance. A two-way analysis of variance (ANOVA) was used to evaluate the main

**TABLE 1** Measuring methods for soil properties.

| Properties | Measuring method |
|---|---|
| Bulk density | Cutting-ring method |
| Soil porosity | Cutting-ring method |
| Soil water content | Oven drying method |
| pH | pH meter (soil-to-water ratio of 2.5:1) |
| Soil particle composition | laser particle analyzer (Messing et al., 2024) |
| Soil organic matter | Potassium dichromate volumetric method with a UV–Vis spectrophotometer (Shamrikova et al., 2022) |
| Total Nitrogen | Elemental analyzer (Vario EL-III, Elementar United Kingdom Ltd., Germany) |
| Total Potassium | Flame photometry (Zhang et al., 2017) |
| Total Phosphorus | Molybdenum-antimony resistance colorimetric method (Ku et al., 2023) |
| Alkali-hydrolyzable nitrogen | Alkali diffusion method (Zhang and Gong, 2012) |
| Available phosphorus | Molybdenum-antimony resistance colorimetric method (Ku et al., 2023) |
| Available potassium | Flame photometry (Zhang et al., 2017) |
| Soil sucrase activity | Spectrophotometry (Gao et al., 2013) |
| Solid-Urease activity | Spectrophotometry (Gao et al., 2013) |
| Alkaline phosphatase activity | Spectrophotometry (Gao et al., 2013) |

and interactive effects of slope gradient and ORV activity intensity on vegetation community diversity, soil physicochemical properties, and enzymatic activities. Multiple comparisons were conducted using Bonferroni-adjusted post-hoc tests to control the familywise error rate. For each significant result, the corresponding effect size (Cohen's $d$) was also reported.

Detrended correspondence analysis (DCA) was performed on the plant community characteristics and soil properties using Canoco 5.0, and redundancy analysis (RDA) was used to determine the relationships between plant community characteristics and soil properties. GraphPad Prism software was used for data visualization and graphing.

# 3 Results

## 3.1 Changes in plant community species diversity

ORV activity caused a marked reduction in plant community species diversity (Figure 2). The SWI, MI, SDI, and PEI in the LS and HS treatments decreased by 58.62%–81.31% ($P < 0.01$; Cohen's $d$ = 6.52–10.11), 24.44%–48.78% ($P < 0.01$; Cohen's $d$ = 3.85–6.79), 52.22%–77.78% ($P < 0.01$; Cohen's $d$ = 4.26–7.93), and 50.00%–75.68% ($P < 0.01$; Cohen's $d$ = 6.48–10.14), respectively, compared to that in the control treatments. Specifically, these indices showed consistent declines in the LS0 vs. CK0, LS1 vs. CK1, and LS2 vs. CK2 comparisons, as well as in the HS0 vs. CK0, HS1 vs. CK1, and HS2 vs. CK2 comparisons. The magnitude of the decrease varied slightly among the indices and conditions; however, the overall trend was a notable reduction in species diversity measures due to ORV activity.

The SWI and PEI demonstrated a significant decline with an increasing slope gradient. SWI and PEI in CK2 exhibited a reduction of 0.11 and 0.05, respectively, when compared to that in CK0. A significant interaction effect on SDI ($F = 4.46$, $P < 0.01$) was observed between the slope gradient ORV activity (Supplementary Table S1).

## 3.2 Changes in soil physicochemical properties and enzymatic activities

### 3.2.1 Soil physical properties

Figure 3 shows that as the ORV disturbance intensity increased, the BD significantly increased, and the soil water content decreased. BD in treated plots (LS0, HS0, LS1, HS1, LS2, and HS2) increased by 0.08–0.26 g $cm^{-3}$ compared to that in the respective controls (CK0, CK1, CK2) ($P < 0.05$, Cohen's $d$ = 1.50–4.13). The soil water content in these plots decreased by 2.47%–4.37% compared to that in the controls ($P < 0.01$, Cohen's $d$ = 2.43–4.29). ORV activity also notably changed soil particle composition, with clay content in treated plots decreasing by 0.20%–1.39% compared to that in the controls ($P <$ 0.05, Cohen's $d$ = 2.01–12.09). The interaction between slope and ORV activity significantly affected soil particle composition, including clay ($F = 4.19$, $P < 0.01$), silt ($F = 3.79$, $P < 0.01$), and sand contents ($F = 5.62$, $P < 0.01$) (Supplementary Table S1).

### 3.2.2 Soil chemical properties

As shown in Figure 4, ORV activity caused a significant decrease in SOM ($P < 0.01$; Cohen's $d$ = 2.57–5.29), TN ($P < 0.05$; Cohen's $d$ = 1.37–4.57), AN ($P < 0.05$; Cohen's $d$ = 1.59–5.63), TP ($P < 0.05$; Cohen's $d$ = 1.62–2.43), AP ($P < 0.05$; Cohen's $d$ = 1.86–3.62), and AK ($P < 0.01$; Cohen's $d$ = 3.61–5.93). SOM content declined by 1.10–2.20 g $kg^{-1}$, TN by 0.06–0.15 g $kg^{-1}$, AN by 4.53–16.04 mg $kg^{-1}$, TP by 0.02–0.04 g $kg^{-1}$, AP by 2.35–4.58 mg $kg^{-1}$, and AK by 22.53–71.23 mg $kg^{-1}$ in ORV-affected plots compared to that in the respective controls. Specifically, soil pH in highland areas (CK1 and CK2) decreased by 0.27–0.38 units compared to that in the lowland control (CK0), with further reductions in ORV-affected plots (LS0, HS0, LS1, and HS1). Additionally, soil pH, TN, and AK significantly decreased with increasing slope gradient, and the interaction between slope gradient and ORV activity had a significant effect on pH ($F = 6.37$, $P < 0.01$), TN ($F = 3.03$, $P < 0.05$), and AN ($F = 4.73$, $P < 0.01$) (Supplementary Table S1).

### 3.2.3 Soil enzyme activities

ORV activity and slope gradient significantly affected soil enzyme activity (Figure 5). Sucrase activity decreased by 3.30–8.63 mg $g^{-1}$ $d^{-1}$ in ORV-affected plots (LS0, HS0, LS1, HS1, LS2, and HS2) compared to that in the respective controls (CK0, CK1, and CK2), with the largest reduction observed in HS2. ALP activity declined by 0.06–0.12 mg $g^{-1}$ $d^{-1}$ in HS plots relative to that in the controls. Solid-urease activity decreased by 0.06–0.15 mg $g^{-1}$ $d^{-1}$ in specific ORV-affected plots (HS1, LS2, and HS2) compared to that in the control plots. The interaction between slope and ORV

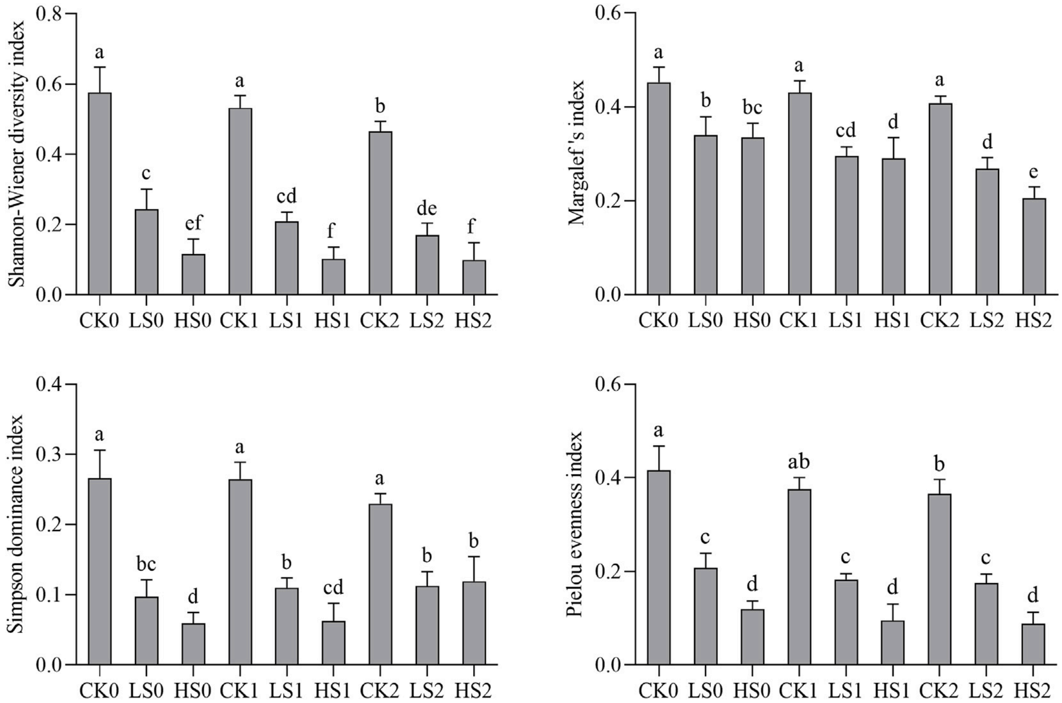


FIGURE 2
Plant community species diversity in different treatments. Mean values ± S.D. are shown. Different letters denotes significant difference ($P$ < 0.05).

activity significantly affected sucrase ($F$ = 2.92, $P$ < 0.05) and solid-urease activity ($F$ = 7.15, $P$ < 0.01) (Supplementary Table S1).

## 3.3 RDA of vegetation community and soil properties

The results of RDA are shown in Figure 6. The first two ordination axes of the RDA accounted for 89.99% of the relationship between vegetation community characteristics and soil properties. This indicated that the first and second axes can effectively reflect the relationship between grassland vegetation community characteristics and soil properties under ORV activity. Among them, MI, SWI, SDI, and PEI were positively correlated with pH (r = 0.56–0.74, $P$ < 0.05), AP (r = 0.75–0.81, $P$ < 0.05), AK (r = 0.76–0.86, $P$ < 0.05), AN (r = 0.50–0.81, $P$ < 0.05), SWC (r = 0.75–0.83, $P$ < 0.05), SOM (r = 0.67–0.85, $P$ < 0.05), and clay content (r = 0.56–0.74, $P$ < 0.05) and negatively correlated with BD (r = −0.73 to −0.84) and sand content (r = −0.73 to −0.88, $P$ < 0.05) (Supplementary Figure S1).

# 4 Discussion

## 4.1 Effect of ORV activity on plant community characteristics and soil properties

ORV activity significantly affected the growth and community structure of grassland vegetation. We found that species diversity within the grassland community significantly declined as ORV activity intensified, which is consistent with previous research results (Yang et al., 2009). This decline can be attributed to the mechanical damage inflicted on plants by ORV activity, which reduces plant height and cover. Additionally, soil compaction and destruction of root systems by ORV activity impede plant growth and reproductive capabilities, thereby diminishing plant abundance (Schlacher and Thompson, 2008). In this study, the Shannon–Wiener index exhibited a 40.30%–81.13% reduction as the ORV disturbance increased, indicates that grasslands reached the threshold for moderate (30%–50%) to severe (>50%) degradation (Magurran, 2021; Luo et al., 2022). As disturbance levels increase, plant community structures tend to simplify, with species composition shifting towards those more tolerant to disturbance. Perennial plants predominated in the study area of the Otindag Sandy Land, and their root systems survived, even when the aboveground parts were damaged. However, the diversity of perennial vegetation significantly decreased following ORV disturbance, with species such as *Cynodon dactylon* L. and *Aster pilosus* demonstrating relatively strong survival capabilities. In addition, ORV activity causes physical damage to the soil and affects vegetation communities by limiting water and nutrient availability.

ORV activity significantly alters the physical and chemical properties of soil, which are closely related to vegetation community characteristics (Ploughe et al., 2022). In this study, ORV activity increased soil bulk density (BD) by 14.00%–19.54% and reduced clay content by more than 40%. According to the Parameters for Degradation, Sandification and Salinization of

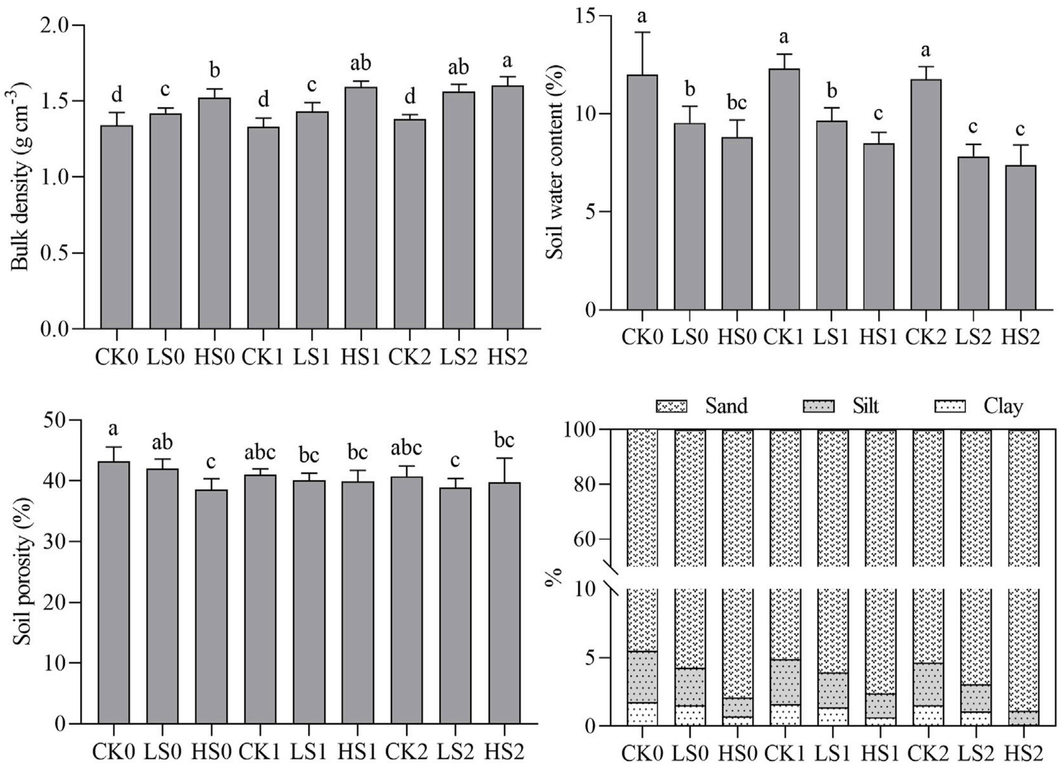


FIGURE 3
Soil physical properties in different treatments. Mean values ± S.D. are shown. Different letters denotes significant difference ($P$ < 0.05).

Rangelands (GB 19377–2003), such a substantial reduction in fine particles places the grassland within the category of severe sandification. This increase in BD can be attributed to soil compaction caused by ORV. Moreover, the destruction of surface vegetation exposes finer soil particles to wind erosion, increasing the coarse sand content and BD (Goossens and Buck, 2009). RDA indicated that the first two ordination axes together accounted for 89.99% of the relationship between vegetation community characteristics and soil properties, and that key vegetation diversity indices were positively associated with SWC, SOM, and available nutrients (AP, AK, AN). These findings were consistent with those reported by Amrein et al. (2005). Vegetation in sandy grasslands stabilizes sand and reduces water evaporation. When vegetation is disturbed, the reduction in root systems significantly diminishes the water-retention capacity of the soil. As the physical structure of the soil changes, precipitation is less likely to be retained in the surface soil with a reduction in fine sand and silt content. Additionally, the lack of vegetation cover leads to rapid surface warming, further exacerbating soil water evaporation.

Additionally, our results demonstrated that ORV activity markedly reduced soil organic matter (SOM) by 17.90%–41.60%. Based on GB 19377–2003, this magnitude of SOM loss indicates that grasslands in the LS treatment reached the threshold for light to moderate degradation, whereas those in the HS treatment corresponded to moderate to severe degradation. We found a close relationship between soil particles and soil nutrients, with clay content positively correlated with SOM, AP, AK, and AN, these findings align with those of Arocena et al. (2006) and Jiang et al. (2016). Fine soil particles contain high levels of C, N, P, and K nutrients (Sujatha and Jaidhar, 2024). These fine particles were more easily blown away by the wind after ORV disturbances, leading to a decline in SOM content and nutrient loss (Wei et al., 2018). In contrast, a reduction in fine particles decreases the soil adsorption capacity, thereby reducing the ability of the soil to retain nutrients. Under severe disturbance, a significant reduction in surface vegetation leads to a decrease in organic matter entering the soil (Ning et al., 2019).

Soil enzyme activity is an important biological indicator of changes in soil quality. The RDA revealed positive correlations between soil enzyme activity and SOM, AN, AK, and clay content. Soil enzyme activity was the lowest in severely disturbed areas due to reduced plant litter and the consequent decrease in organic matter input into the soil. This reduced the availability of substrates and energy for soil microorganisms, thereby affecting the microbial activity. Additionally, ORV activity altered the soil texture and disrupted the living environment of soil enzymes, leading to a decline in their activity (Zhu et al., 2021).

## 4.2 Interactive effects of slope gradient and ORV activity on soil and vegetation

The impacts of human disturbances on grassland soil physicochemical properties and vegetation community characteristics vary significantly under different site conditions (Yuan et al., 2019). Previous research reported that the vegetation

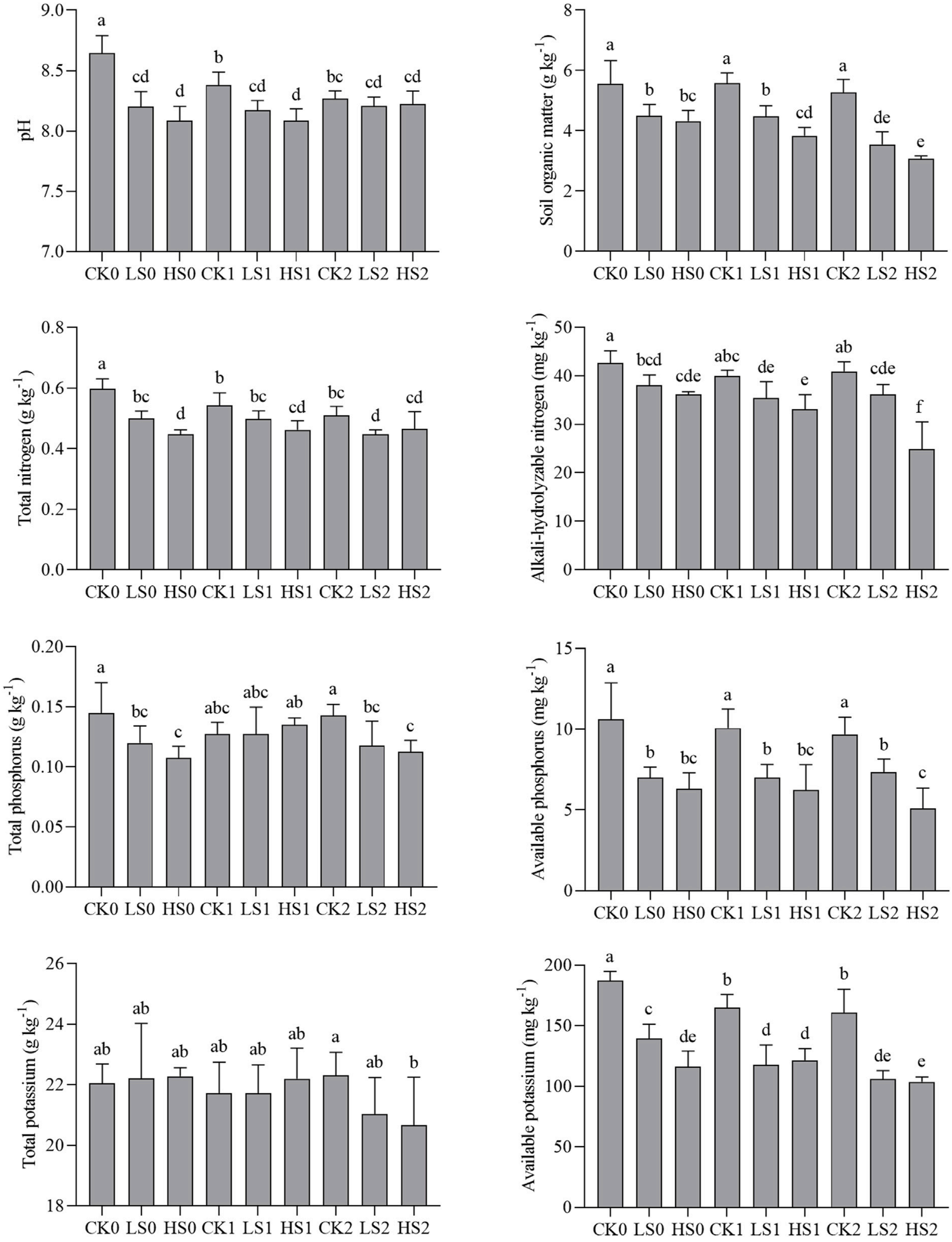


FIGURE 4
Soil chemical properties in different treatments. Mean values ± S.D. are shown. Different letters denotes significant difference ($P < 0.05$).

community was significant differences in different slopes and directions (Timothy et al., 2008). Slope influences hydrological processes; as slope increases, surface runoff is more likely to occur, thereby intensifying water erosion (Gerhardus et al., 2012). We observed significant interactive effects of the slope gradient and ORV intensity on the SDI ($F = 4.46$, $P < 0.01$), clay content ($F = 4.19$,

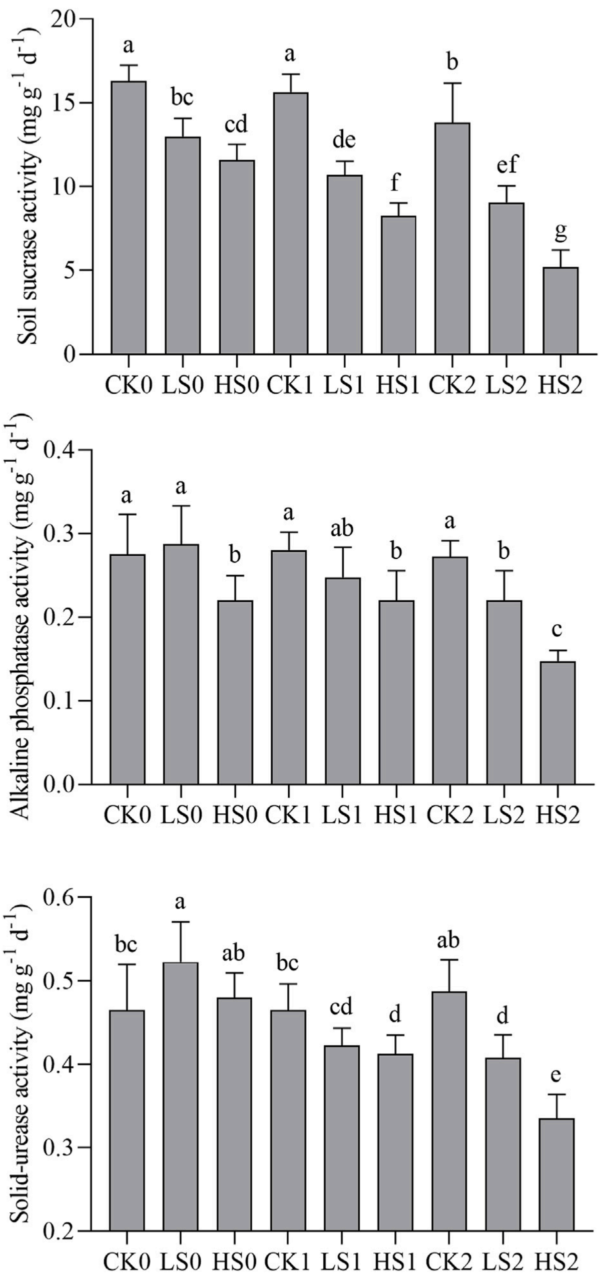


FIGURE 5
Soil enzyme activities in different treatments. Mean values ± S.D. are shown. Different letters denotes significant difference ($P$ < 0.05).

$P$ < 0.01), TN ($F$ = 3.03, $P$ < 0.05), AN ($F$ = 4.73, $P$ < 0.01), soil sucrase activity ($F$ = 2.92, $P$ < 0.05), and solid-urease activity ($F$ = 7.15, $P$ < 0.01) in this study. This indicated that the impact of ORV activity on vegetation and soil became more pronounced as the slope gradient increased. Under sloped conditions, ORV activity can lead to soil slippage or shear failure. Steep-slope areas, characterized by shallow topsoil and poor nutrient content, are inherently ecologically fragile, making them more susceptible to structural damage caused by trampling. Additionally, the ORV activity disrupted the soil surface structure more readily in these areas, reducing the resistance of the soil to erosion. Once the soil surface was compacted or damaged, soil sandification by rainfall or wind becomes more likely, with steeper slopes posing a higher risk of soil sandification.

Therefore, it is essential to consider the combined effects of these factors when managing and protecting grasslands. Effective measures should be implemented to regulate ORV activity and mitigate the damage caused by vehicle traffic, particularly in areas with high slopes.

### 4.3 Future research and management implications

While our statistical analyses indicated significant responses of multiple vegetation and soil indicators to ORV disturbance, these results should be interpreted with caution when generalizing to broader landscapes or different environmental contexts. In natural grassland systems, spatial variability in vegetation composition and soil properties can be substantial even within short distances, incorporating hierarchical sampling across multiple sites could improve the representativeness.

Future research should focus on several key directions. First, identifying disturbance thresholds at which ORV activity causes irreversible degradation to vegetation communities and soil functions is essential. The thresholds could inform the definition of safe carrying capacities and usage limits. Second, consider conducting field experiments under various environmental conditions (site conditions, seasons, vehicle types, and tires, etc.). Third, long-term and multi-seasonal monitoring would help capture inter-annual variability and delayed ecological responses, including vegetation succession and soil recovery dynamics. Finally, optimize the spatial distribution of ORV activities and explicit management strategies, such as restricting ORV use to high-slope areas, establishing buffer zones.

## 5 Conclusion

With the intensification of ORV activity, the species diversity of grassland vegetation communities decreased significantly. ORV activity led to a significant increase in soil bulk density and a notable decrease in soil organic matter, water and clay contents, available phosphorus and potassium, and soil enzyme activity. Plant community species diversity (MI, SWI, SDI, and PEI) was positively correlated with pH, AP, AK, AN, soil water content, SOM, silt content, and clay content and negatively correlated with soil BD and sand content. The slope gradient and ORV activity significantly interacted with the SDI, soil particle composition, TN, AN, soil sucrase activity, and solid-urease activity. The impact of ORV activity on vegetation and soil in the sandy grasslands became more pronounced as the slope gradient increased.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

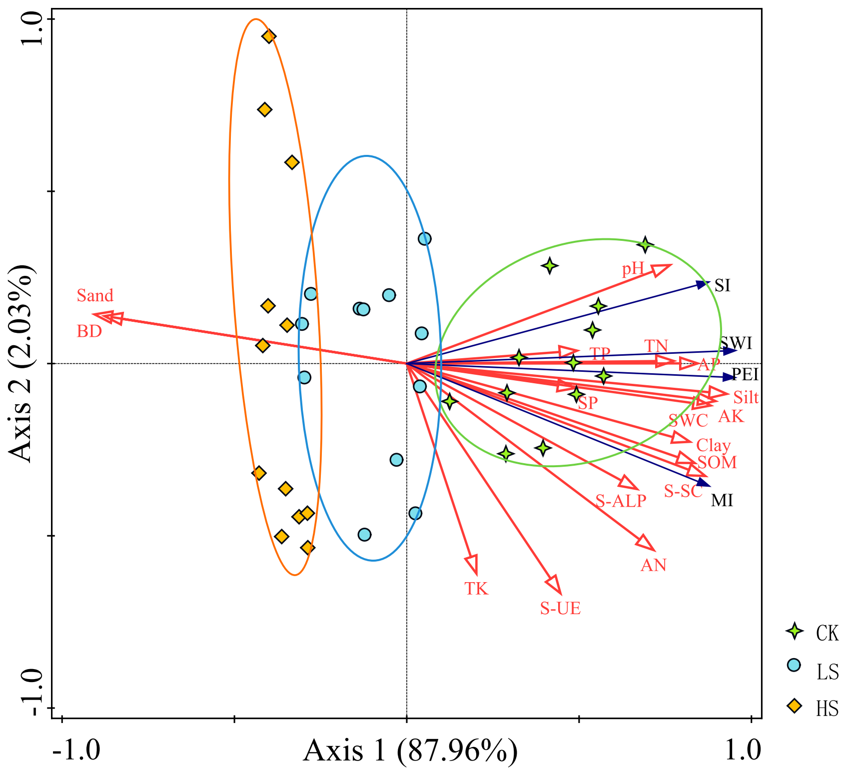


FIGURE 6
RDA two-dimensional ordination of vegetation community characteristics and soil. MI, Margalef's richness index; SWI, Shannon−Wiener index; SDI, Simpson dominance index; PEI, Pielou evenness index; BD, bulk density; SWC, soil water content; SP, soil porosity; TN, total nitrogen; AN, alkali-hydrolyzable nitrogen; TP, total phosphorus; AP, available phosphorus; TK, total potassium; AK, available potassium; SOM, soil organic matte; S-SC, soil sucrase activity; S-UE, soil urease activity; S-ALP, alkaline phosphatase activity.

## Author contributions

XW: Investigation, Methodology, Writing – original draft, Formal Analysis. JL: Writing – original draft, Formal Analysis, Conceptualization, Funding acquisition. WZ: Supervision, Writing – review and editing. XC: Methodology, Investigation, Writing – original draft. SL: Investigation, Writing – original draft. HG: Investigation, Writing – original draft. JY: Funding acquisition, Writing – original draft, Project administration.

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## Conflict of interest

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## Supplementary material

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# References


Amrein, D., Rusterholz, H. P., and Baur, B. (2005). Disturbance of suburban Fagus forests by recreational activities: effects on soil characteristics, above-ground vegetation and seed bank. *Appl. Veg. Sci.* 8, 175–182. doi:10.1111/j.1654-109X.2005.tb00643.x

Arocena, J. M., Nepal, S. K., and Rutherford, M. (2006). Visitor-induced changes in the chemical composition of soils in backcountry areas of Mt Robson Provincial Park, British Columbia, Canada. *J. Environ. Manage.* 79, 10–19. doi:10.1016/j.jenvman.2005.05.008

Arp, C. D., and Simmons, T. (2012). Analyzing the impacts of off-road vehicle (ORV) trails on watershed processes in Wrangell-St. Elias National Park and Preserve, Alaska. *Environ. Manage.* 49 (3), 751–766. doi:10.1007/s00267-012-9811-z

Dewidar, K., Thomas, J., and Bayoumi, S. (2016). Detecting the environmental impact of off-road vehicles on Rawdat Al Shams in central Saudi Arabia by remote sensing. *Environ. Monit. Assess.* 188 (7), 396. doi:10.1007/s10661-016-5400-6

Gao, M. L., Song, W. H., Zhou, Q., Ma, X. J., and Chen, X. Y. (2013). Interactive effect of oxytetracycline and lead on soil enzymatic activity and microbial biomass. *Environ. Toxicol. Phar.* 36 (2), 667–674. doi:10.1016/j.etap.2013.07.003

Gerhardus, N. P., van Hoven, W., and Laker, M. C. (2012). Factors affecting the impact of off-road driving on soils in an area in the Kruger National Park, South Africa. *Environ. Manage.* 50 (6), 1164–1176. doi:10.1007/s00267-012-9954-y

Gill, A. L., Grinder, R. M., See, C. R., Chapin, F. S., DeLancey, L. C., Fisk, M. C., et al. (2023). Soil carbon availability decouples net nitrogen mineralization and net nitrification across United States Long Term Ecological Research sites. *Biogeochemistry* 162 (1), 13–24. doi:10.1007/s10533-022-01011-w

Goossens, D., and Buck, B. (2009). Dust emission by off-road driving: experiments on 17 arid soil types, Nevada, USA. *Geomorphology* 107 (3-4), 118–138. doi:10.1016/j.geomorph.2008.12.001

Jiang, S. L., Hu, Y. F., Pu, Q., Shu, X. Y., Yuan, C. M., and Yu Qian, 余. (2016). Changes in soil nitrogen characteristics during grassland desertification in Northwest Sichuan. *Acta Ecol. Sin.* 36 (15), 4644–4653. doi:10.5846/stxb201501140111

Ku, Y. L., Han, X. T., Lei, Y. T., Zhang, M., and Zhao, Z. (2023). Different sensitivities and assembly mechanisms of the root-associated microbial communities of Robinia pseudoacacia to spatial variation at the regional scale. *Plant Soil* 486, 621–637. doi:10.1007/s11104-023-05897-9

Luo, F. L., Zhang, F. W., Wang, C. Y., Zhang, G. R., and Li, Y. N. (2022). Response of community characteristics and representative plant living state to grassland degradation in alpine meadow of Qinghai-Tibet Plateau. *Chin. J. Ecol.* 41 (1), 18–24. doi:10.13292/i.1000-4890.202201.004

Magurran, A. E. (2021). Measuring biological diversity. *Curr. Biol.* 31 (19), 1174–1177. doi:10.1016/j.cub.2021.07.049

Messing, I., Soriano, A. M. M., Svensson, D. N., and Barron, J. (2024). Variability and compatibility in determining soil particle size distribution by sieving, sedimentation and laser diffraction methods. *Soil till. Res.* 238, 105987. doi:10.1016/j.still.2023.105987

Navas, R. A. L., Herrera, M. M. A., Dalmasso, A. D., and Barros, A. (2019). Quad bike impacts on vegetation and soil physicochemical properties in an arid ecosystem. *Acta Oecl* 97, 14–22. doi:10.1016/j.actao.2019.04.007

Ning, Z. Y., Li, Y. L., Yang, H. L., Zhang, Z. Q., and Zhang, J. P. (2019). Stoichiometry and effects of carbon, nitrogen,and phosphorus in soil of desertified grasslands on community productivity and species diversity. *Acta Ecol. Sin.* 39 (10), 3537–3546. doi:10.5846/stxb201711242094

Ploughe, L. W., Jacobs, E. M., Frank, G. S., Greenler, S. M., Smith, M. D., and Dukes, J. S. (2019). Community response to extreme drought (CRED): a framework for drought-induced shifts in plant-plant interactions. *N. Phytol.* 222 (1), 52–69. doi:10.1111/nph.15595

Rickard, C. A., McLachlan, A., and Kerley, G. I. H. (1994). The Effects of vehicular and pedestrian traffic on dune vegetation in South Africa. *Ocean. Coast. Manage.* 23 (3), 225–247. doi:10.1016/0964-5691(94)90021-3

Robert, H. M., and Douglas, M. L. (1978). *Distribution of Illinois vascular plants.* America: Southern lllinois University. doi:10.2307/2484346

Schlacher, T. A., and Thompson, L. M. C. (2008). Physical impacts caused by off-road vehicles to sandy beaches: spatial quantification of car tracks on an Australian barrier island. *J. Coast. Res.* 24, 234–242. doi:10.2112/06-0691.1

Shamrikova, E. V., Kondratenok, B. M., Tumanova, E. A., Vanchikova, E. V., Lapteva, E. M., Zonova, T., et al. (2022). Transferability between soil organic matter measurement methods for database harmonization. *Geoderma* 412, 115547. doi:10.1016/j.geoderma.2021.115547

Sujatha, M., and Jaidhar, C. D. (2024). Machine learning-based approaches to enhance the soil fertility-A review. *Expert Syst. Appl.* 240, 122557. doi:10.1016/j.eswa.2023.122557

Timothy, M. M. S. T., Jeffery, J. B., Jim, B. I., Charlotte, E. O., Wiliam, O., O'Brien, W., et al. (2008). Vegetation change during the mesolithic and neolithic on the mizen peninsula, Co. Cork, south-west Ireland. *Veg. Hist. Archaeobot.* 17 (6), 617–628. doi:10.1007/s00334-007-0136-4

Wei, W. D., Liu, Y. H., Ma, H., and Li, J. L. (2018). Relationships between soil factors and grassland degradation on an alpine grassland based on redundancy analysis. *Pratacultural Sci.* 35 (3), 472–481. doi:10.11829/i.issn.1001-0629.2017-0324

Westcott, F., and Andrew, E. M. (2015). Spatial and environmental patterns of off-road vehicle recreation in a semi-arid wood land. *Appl. Geogr.* 62, 97–106. doi:10.1016/j.apgeog.2015.04.011

Wilshire, H. G., and Nakata, J. K. (1976). Off-road vehicle effects on California's Mojave Desert: calif. *Geology* 29, 123–132. doi:10.1007/BF01866102

Yang, M. Y., Hens, L., Xiao, K. O., and Wulf, R. D. (2009). Impacts of recreational trampling on sub-alpine vegetation and soils in Northwest Yunnan, China. *Acta Phys. Sin-Ch* 29, 171–175. doi:10.1016/j.chnaes.2009.07.005

Yeh, C. C., Lin, C. J. Y., Hsiao, J. P. H., and Huang, C. H. (2021). Landscape damage effect impacts on natural environment and recreational benefits in bikeway. *Diversity* 13, 52. doi:10.3390/d13020052

Yu, C., Pang, X., Wang, Q., Jin, S., Shu, C., and Guo, Z. G. (2017). Soil nutrient changes induced by the presence and intensity of plateau pika (Ochotona curzoniae) disturbances in the Qinghai-Tibet plateau, China. *Ecol. Eng.* 106, 1–9. doi:10.1016/j.ecoleng.2017.05.029

Yuan, Z. Q., Jiang, X. J., Liu, G. J., Jin, H. J., Chen, J., and Wu, Q. B. (2019). Responses of soil organic carbon and nutrient stocks to human-induced grassland degradation in a Tibetan alpine meadow. *Catena* 178, 40–48. doi:10.1016/j.catena.2019.03.001

Zhang, G. L., and Gong, Z. T. (2012). *Soil survey laboratory methods*. Beijing: Science Press.

Zhang, Y. L., Nachimuthu, G., Mason, S., McLaughlin, M. J., McNeill, A., and Bell, M. J. (2017). Comparison of soil analytical methods for estimating wheat potassium fertilizer requirements in response to contrasting plant K demand in the glasshouse. *Sci. Rep.* 7, 11391. doi:10.1038/s41598-017-11681-4

Zhang, M., Delgado-Baquerizo, M., Li, G., Lsbell, F., Wang, Y., Hautier, Y., et al. (2023). Experimental impacts of grazing on grassland biodiversity and function are explained by aridity. *Nat. Commun.* 14, 5040. doi:10.1038/s41467-023-40809-6

Zhao, X., Han, D., Lu, Q., Li, Y. P., and Zhang, F. M. (2023). Spatiotemporal variations in ecological quality of Otindag Sandy Land based on a new modified remote sensing ecological index. *Arid. Land* 15, 920–939. doi:10.1007/s40333-023-0065-9

Zhu, L., Li, Y., Yang, W. Q., and Gao, Y. H. (2021). Effect of desertification on soil carbon and nitrogen, enzyme activity and bacterial diversity in alpine grassland. *J. Soil Water Conserv.* 35, 3. doi:10.13870/j.cnki.stbcxb.2021.03.048