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RESEARCH ARTICLE

Hillside topographic pattern of tree species diversity and soil nutrients in Mount Tai, China

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Abstract
Aims Forest plant diversity, soil nutrients, and hillside terrain factors are intricately linked and serve as vital indicators for assessing the overall health and biodiversity of an ecosystem. In our study, we delved into the altitudinal patterns of soil nutrients and tree diversity in Mount Tai, exploring the relationship between topographic factors and tree diversity.
Methods We conducted field investigations along four distinct routes: Tianwaicun, Red Gate, Tianzhufeng, and Taohuayuan. Across an altitude gradient spanning from 500 to 1500 m, we established four quadrats for every 100 m of vertical ascent.
Results We found that: 1) the forest soil of Mount Tai has higher carbon, nitrogen and phosphorus nutrients, but with little soil potassium nutrients. 2) the forest soil nutrient pattern in Mount Tai is affected and restricted by herbaceous plants, but is less correlated with woody plants. 3) among the hillside terrain factors examined, slope position had the greatest impact on tree diversity, followed by slope direction, altitude, and gradient. 4) tree diversity exhibited a unique pattern along the altitudinal gradient, characterized by three distinct peaks and valleys.
Conclusions In terms of slope patterns, moderate slopes showed the highest diversity, surpassing both steep and gently sloping areas. For slope direction, westward-facing slopes were the most diverse, while northward-facing slopes were the least. Middle slope positions demonstrated greater diversity than upper and lower positions. This study provided the basis for the healthy management of forest ecosystem in this area.

Keywords Soil nutrients · Plant diversity · Slope topography · Slope direction · Slope position

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Introduction

Soil serves as the fundamental prerequisite and material foundation for forest ecosystems, as emphasized by Zhou et al. (2021). Its quality and composition significantly influence and constrain forestry production and forest vitality (Mligo and Cosmas 2016). The spatial distribution of soil nutrients plays a pivotal role in shaping, limiting, and even dictating the spatial pattern of biodiversity (Yuan 2011; Paoli et al.

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2008). Extensive research has been conducted on soil nutrient patterns across various temporal and spatial scales (Du et al. 2017; Dong et al. 2018). These studies have encompassed large-scale factors such as climate conditions and altitude, as well as smaller-scale considerations like biological components, parent material, topography, and soil formation time (Pace et al. 2017; Ahirwal and Maiti 2018). These diverse factors contribute to the regional specificity observed in soil nutrient profiles (De Deyn et al. 2008; Liptzin and Seastedt 2010).

The mountainous ecological environment, characterized by its remarkable diversity and complexity, holds the potential to function as a repository for species germplasm and resources. The study of mountain biodiversity has long captured the attention of ecologists (Wang et al. 2021). Variations in environmental factors across the Earth's surface give rise to diverse plant life and vegetation patterns (Tian et al. 2012). Scholars have systematically and enthusiastically delved into the diversity of forest plants in critical habitats, focusing particularly on plant diversity patterns in relation to environmental gradients (Yin et al. 2018). Mount Tai, as the highest mountain in Shandong province, boasts an exceptional endemism and rich plant diversity (Zang and Sun 2000; Zhou et al. 2021). This remarkable natural heritage site was recognized and inscribed by the UNESCO World Heritage Committee, on December 11, 1987. Domestic research endeavors on Mount Tai began in 1935 with Mr. Zhu Kezhen's report on the altitude of Mount Tai (Zhang 2018). From 1950 to 1960, there was a surge in small-scale investigations, primarily focusing on the vegetation of the forest fringe, in 1950,1956, and 1957 (Cui et al. 1998). Over the course of more than 80 years, research on Mount Tai has evolved, addressing topics such as soil heavy metal pollution in the scenic area (Wang et al. 2011) and the impact of tourism on soil quality (Shao et al. 2020).

To gain a deeper understanding of the current status of forest soil nutrients and the topographic pattern influencing tree species diversity in Mount Tai, a systematic approach has been undertaken. Six sample plots were strategically selected across elevations ranging from 500 to 1500 m above sea level, with a uniform interval of 100 m. Topsoil samples from these plots were collected and subjected to rigorous analysis to assess soil nutrients and plant diversity. This comprehensive study aims to provide valuable data to support forest soil nutrient management and biodiversity conservation efforts in the region. Furthermore, it seeks to establish a framework for the restoration and establishment of secondary forests and plantation forests, alongside effective forest management and protection strategies in forested areas. The ultimate goal is to holistically investigate forest plant diversity and soil nutrients on Mount Tai, unravel the correlations between plant diversity and hillside terrain factors, and evaluate the significant influence of hillside terrain on the healthy management of the forest ecosystem in this vital region.

Materials and methods

Overview of the sample plot

Located in the central part of Shandong, Mount Tai has geographic coordinates of 36°05′–36°15′N, 117°05′–117°24′ E, an area of 426 km^2, a main peak altitude of 1 545 m. Its soil type is mainly acid brown soil. Belonging to a warm temperate continental monsoon climate, it has an average annual temperature of 12.8 and an average annual rainfall of 600 mm (Zhang et al. 2011). The background data of soil nutrients were reported in our previous study (Zhou et al. 2021).

Soil sample collection and indicator testing

The study encompassed three routes: the Hongmen, Taohuayuan, and Tianzhu Peak, spanning an altitudinal range from 500 to 1,500 m. Along this gradient, treatments were established at intervals of 100 m, with each treatment comprising six sampling points. Each of these sampling points measured 5 m × 5 m. Through this meticulous setup, a total of 66 soil samples were successfully collected. For each soil sample, approximately 500 g soil samples were dug out and sealed in bags. The soil samples were transported back to the laboratory in a portable refrigerator set at 4℃. The fresh soil samples, once brought back, were air-dried at room temperature and sieved through a 1-mm mesh. The following seven characteristics were measured following Fan et al. (2006): Soil organic matter (SOM) was determined using titration according to LY/T 1237–1999; total nitrogen (TN) and hydrolyzable nitrogen (HN) were determined using

Kjeldahl method and titration according to LY/T 1228–2015; total phosphorus (TP) and available phosphorus (AP) were determined according to LY/T 1232–2015, using alkali fusion-molybdenum antimony anti-spectrophotometry and colorimetry; total potassium (TK) and rapidly available potassium (AK) were determined according to LY/T 1234–2015, using atomic absorption spectrophotometry.

Along the altitude gradient of 500 m-1 500 m, 4 quadrates were set up per100 m of vertical rise, and a total of 48 quadrates were set up in the field with quadrate size of 30 m × 20 m. All tree species with Diameter at Breast Height (*DBH*) ≥ 5 cm, number of individuals and *DBH* per tree were measured and recorded (Fang et al. 2009).

Data analysis

The concentrations of soil nutrients in different altitude gradients soil samples were tested for differences among samples using one-way ANOVA in SPSS BASE ver. 19.1 statistical software. Spearman correlation coefficients among soil nutrients were calculated using SPSS 19.1. General diversity indexes were taken for calculation and analysis (Fang et al. 2009). The following four indexes are selected herein: richness index (*S*), Shannon–Wiener diversity index (*H*), Simpson diversity index (*P*) and Pielou eveness index (*E*).

The calculation formulas are:

S the number of plant species in the quadrate;

$$H = -\sum Pi\ lnPi \quad (1)$$

$$P = 1 - \sum Pi^2 \quad (2)$$

$$E = H/lnS \quad (3)$$

where, *Pi* is the proportion of importance value of the *i*-th species in the total importance value of all species, importance value = (relative significance + relative density + relative frequency)/3. Statistical analysis was performed using SPSS 17.0 statistical software of Chinese version.

According to slope classification by the Geomorphological Survey and Geophysical Mapping Committee of the International Geographical Union on application of geomorphologic details, Mount Tai is divided into12 altitude gradients of 500 m, 600 m, 700 m, 800 m, 900 m, 1000 m, 1 100 m, 1 200 m, 1 300 m, 1 400 m, 1 500 m, 3 slope gradients of slope (> 5° ~ 15°), steep gradient (> 15° ~ 35°) and steep slope (> 35° ~ 55°), three slope position gradients of upper, middle and lower slopes, and four slope direction gradients of southward (SE ~ SW), westward (WS ~ WN), eastward (EN ~ ES) and northward (NW ~ NE).

Results

The nutrients content and grade of Mount Tai forest soil

The average contents of soil organic matter, total NPK, and available NPK in Mount Tai forest soil were found to be 41.2 $g{\cdot}kg^{-1}$, 2.29 $g{\cdot}kg^{-1}$, 1.02 $g{\cdot}kg^{-1}$, 8.49 $g{\cdot}kg^{-1}$, 198.99 $mg{\cdot}kg^{-1}$, 46.80 $mg{\cdot}kg^{-1}$, and 78.27 $mg{\cdot}kg^{-1}$, respectively. The Second National Soil Survey in China established standards (1980) for soil nutrients. In this standard, each nutrient index of the soil is divided into six levels from high to low: Grade 1 to Grade 6. When Mount Tai forest soil's nutrient content was compared to these standards, its organic matter, total NPK, and available NPK nutrients were graded as Grade 1, Grade 1, Grade 1, Grade 5, Grade 1, Grade 1, and Grade 4, respectively.

Altitude pattern of forest soil nutrients in Mount Tai

The highest levels of TN, SOM, AK, HN, and AP were found at an altitude of 1400 m on Mount Tai, indicating that the soil at this elevation is rich in various nutrients. The organic matter (SOM) content of Mount Tai forest soil approximates bimodal pattern: with content of altitude sections at 1 100 m and 1 400 m significantly higher compared to other altitude sections ($P < 0.05$), and there is no significant difference in content of other altitude sections (Fig. 1A).

The total nitrogen (TN) content of Mount Tai forest soil approximates bimodal pattern: with content of altitude sections at 1 100 m and 1 400 m significantly higher compared to other altitude sections ($P < 0.05$), and there is no significant difference in content of other altitude sections (Fig. 1B).

The total phosphorus (TP) content of Mount Tai forest soil approximates bimodal pattern: with

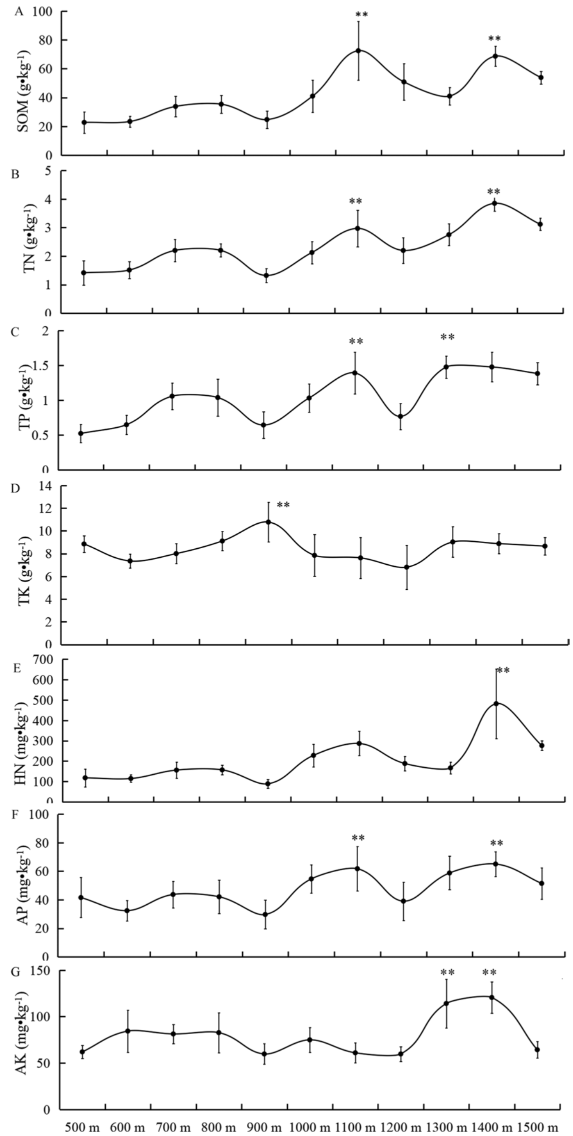

Fig. 1 Comparison of soil organic matter (**A**), total nitrogen (**B**), total phosphorus (**C**), total potassium (**D**), hydrolytic nitrogen (**E**), available phosphorus (**F**) and available potassium (**G**) contents in different altitudes of Taishan forest (mean ± standard error, n = 6), ** $P < 0.01$

content of altitude sections at 1 100 m and 1 300 m significantly higher compared to other altitude sections ($P < 0.05$), and there is no significant difference in content of other altitude sections (Fig. 1C).

The total potassium (TK) content of Mount Tai forest soil approximates unimodal pattern: with content of altitude section at 900 m significantly higher compared to other altitude sections, but there is no significant difference in content of other altitude sections (Fig. 1D).

The hydrolyzable nitrogen (HN) content of Mount Tai forest soil approximates unimodal pattern: with content of altitude section at 1400 m significantly higher compared to other altitude sections ($P < 0.05$), and there is no significant difference in content of other altitude sections (Fig. 1E).

The available phosphorus (AP) content of Mount Tai forest soil approximates bimodal pattern: with content of altitude sections at 1 100 m and 1 400 m significantly higher compared to other altitude sections ($P < 0.05$), and there is no significant difference in content of other altitude sections (Fig. 1F).

The rapidly available potassium (AK) content of Mount Tai forest soil approximates unimodal pattern: with content of altitude section at 1 300 m—1 400 m significantly higher compared to other altitude sections ($P < 0.05$), and there is no significant difference in content of other altitude sections (Fig. 1G).

Correlation between forest soil nutrients in Mount Tai

Among the seven nutrient indexes of Taishan forest soil, the five nutrient indexes of SOM, TN, TP, HN and AP show a significant positive correlation with each other; TP is significantly positively correlated with SOM, TP and AP, with no significant correlation with TN, HN and AK; AK is significantly positively correlated with TN and TP, with no significant correlation with SOM, TK, HN and AP (Table 1).

Altitude gradient pattern of tree diversity in Mount Tai forest

Tree richness index, Shannon–Wiener index, Simpson index, and Pielou index exhibit fairly consistent multi-peak and multi-valley characteristics. Richness index covered three peaks of 550 m, 850 m, and 1 150 m and three valleys of 750 m, 1 050 m, and 1 250 m (Fig. 2A); Shannon–Wiener index, Simpson index and Pielou index covered three peaks of 650 m, 850 m and 1 150 m and three valleys of 750 m, 1 050 m and 1 250 m (Fig. 2B-D). The dominant constructive species at an altitude of 400–600 m is *Platycladus orientalis*. The dominant tree species at 700–1100 m are *Platycladus orientalis, Pinus tabuliformis, Robinia pseudoacacia, Quercus acutissima,*

Table 1 Correlation of forest soil nutrients in Mount Tai

	SOM	TN	TP	TK	HN	AP	AK
SOM	1.00	0.82**	0.79**	0.12	0.72**	0.70**	0.12
TN	0.82**	1.00	0.72**	0.20	0.68**	0.66**	0.37**
TP	0.69**	0.79**	1.00	0.45**	0.55**	0.73**	0.34**
TK	0.31**	0.20	0.30**	1.00	0.08	0.45**	0.00
AN	0.72**	0.68**	0.55**	0.08	1.00	0.50**	0.21
AP	0.70**	0.66**	0.73**	0.45**	0.50**	1.00	0.16
AK	0.12	0.37**	0.34**	0.00	0.21	0.16	1.00

** ($P<0.01$)

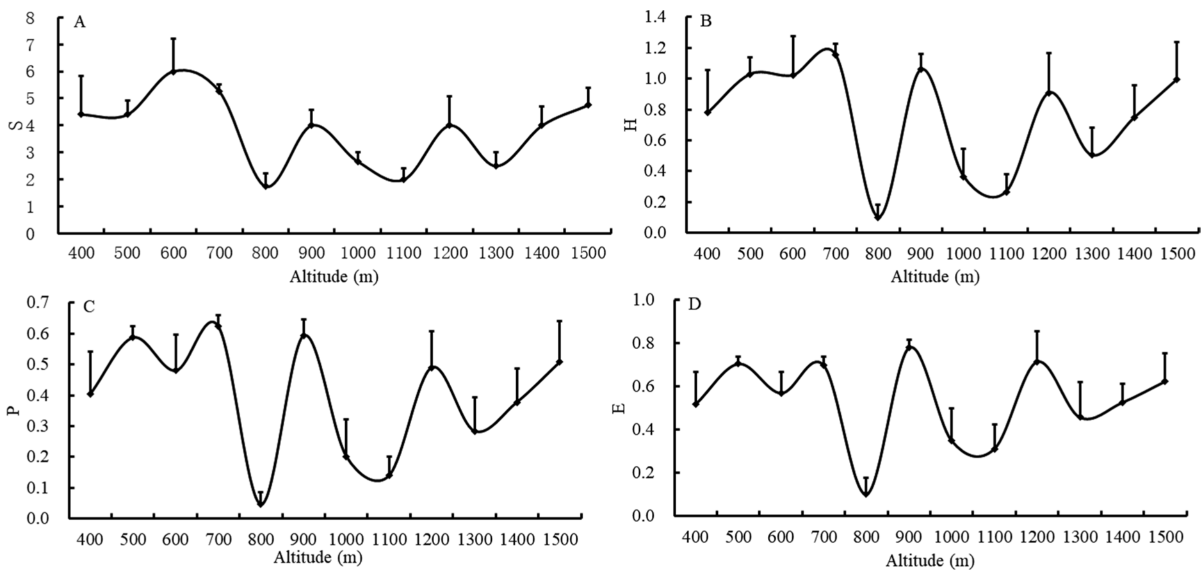

Fig. 2 Altitude gradient pattern (mean + standard error) in terms of tree richness index (*S*), Shannon–Wiener diversity index (*H*), Simpson diversity index (*P*) and Pielou evenness index (*E*) of Mount Tai forest community

Pinus armandii, and *Pinus densiflora*. The dominant tree species at 1200–1500 m are Pinaceae plants such as *Pinus tabuliformis*, *Pinus armandii*, and *Larix kaempferi*.

Slope direction gradient pattern of tree diversity in Mount Tai forest

Tree richness index appears was in the order westward > southward > eastward > northward (Fig. 3A), with that of westward extremely significantly higher than that of northward ($P<0.01$); Shannon–Wiener index, Simpson index and Pielou index appears as that of westward > eastward > southward > northward (Fig. 3B-C), with that of westward significantly higher than that of eastward ($P<0.05$) and extremely significantly higher than that of northward ($P<0.01$); Pielou index appears as that of westward > eastward > northward > southward ((Fig. 3D).

Tree layer richness index appears as that of upper slope > middle slope > lower slope (Fig. 4A); both Shannon–Wiener index and Simpson index appear as that of middle slope > upper slope > lower slope (Fig. 4B-C); Pielou index appears as that of middle slope > upper slope > lower slope (Fig. 4D).

Discussions

The altitude pattern of forest soil organic matter, total N, P, K, and available N, P, K contents in Mount Tai forest is different from the first fall and then rise

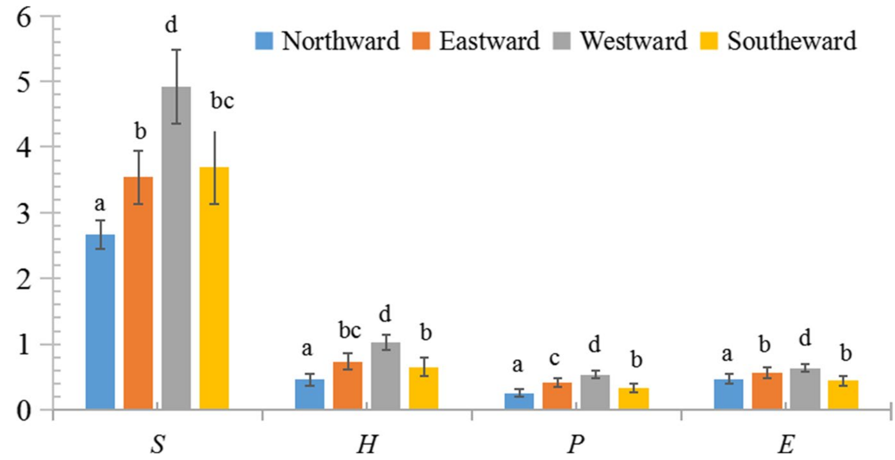

Fig. 3 Slope direction gradient pattern (mean + standard error) in terms of tree richness index (*S*), Shannon–Wiener diversity index (*H*), Simpson diversity index (*P*) and Pielou evenness index (*E*) of Mount Tai forest community

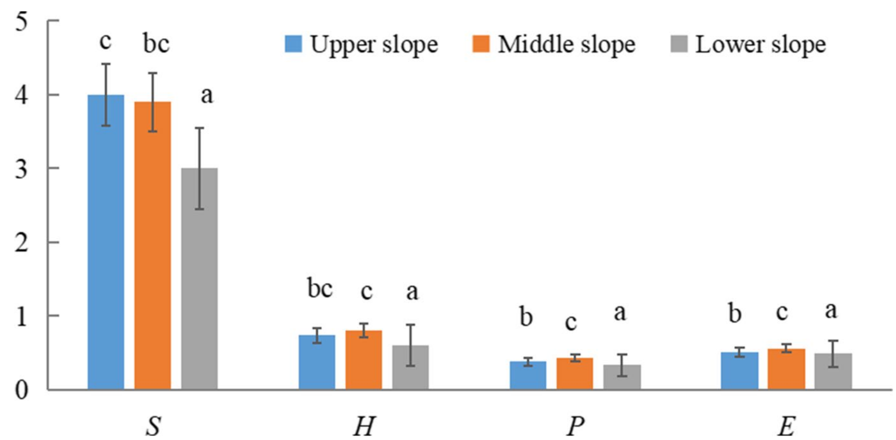

Fig. 4 Slope position gradient pattern (mean + standard error) in terms of tree richness index (*S*), Shannon–Wiener diversity index (*H*), Simpson diversity index (*P*) and Pielou evenness index (*E*) of Mount Tai forest community

pattern of Maoer Mountain forest soil nutrients along the altitude gradient (Song et al. 2016), as well as the mid-elevation prominence pattern displayed by Fanjing mountain forest soil nutrients (Yan et al. 2015) and Niubeiliang forest soil nutrient (Lv et al. 2013). Instead, it approximates the bimodal pattern of forest soil nutrient of Minjiang River in Wolong, Western Sichuan (Gong et al. 2017). Forest soil organic matter, total NPK, and available NPK nutrients in Mount Tai basically show consistent altitude pattern with herbaceous plant species diversity, which indicates that the content of carbon, nitrogen, and phosphorus nutrients in Mount Tai forest soil is mainly affected by herbaceous plants, with little impact from trees and shrubs.

The contents of forest soil organic matter, total nitrogen, total phosphorus, hydrolyzable nitrogen and available phosphorus present a significant positive correlation with each other, which is similar to the extremely significant positive correlation between soil organic matter, total nitrogen and total phosphorus content of Longli Forest Farm in Guizhou (Ni et al. 2017). Studies have shown that soil organic matter mainly comes from litter (Wesemael and Veer 2010), soil nitrogen nutrient is mainly determined by the relative intensity between organic matter accumulation and decomposition (Simfukwe et al. 2011; Sollins and Gregg 2017), soil phosphorus nutrient mainly comes from mineralization and decomposition of phosphorus nutrient in litter, so soil nitrogen and phosphorus nutrients are often positively correlated. The soil potassium nutrient content is subjected to influence of multiple factors including soil parent material, soil surface organic matter, and soil surface moisture (Mligo Cosmas 2016). This may be why TP content of Mount Tai forest soil is significantly positively correlated with the OM, TP and AP, but with no significant correlation with the content of TN, AN and AK; the content of AK is significantly positively correlated with the content of TN and TP, but with no significant correlation with the content of OM, TP, AN and AP.

The higher tree species diversity indices observed in the westward direction and the middle slope suggest that these two conditions are significant influencing factors on the vegetation distribution and ecological diversity of Mount Tai. Due to variations in environmental conditions such as light, temperature, and moisture across different aspects and slope positions on Mount Tai, changes in vegetation types and tree species diversity occur. Specifically, the westward slope (west-facing slope), possibly owing to its particular lighting conditions and soil moisture, is suitable for the growth of a wide range of plants, resulting in higher tree species diversity. On the other hand, the middle slope could be a transitional zone connecting low and high-altitude vegetation belts, thereby also exhibiting a high diversity of tree species.

Spatial distribution of plant communities in nature is a result of combined action of the three major factors of environment, space and biology at different scales. At the regional scale, climate, parent material and flora determine vegetation type (Shao et al. 2020). Studies have shown that distribution pattern of species diversity along the altitude gradient generally involves five forms: first decrease and then increase, first increase and then decrease (single peak curve), monotonous increase, monotonous decrease and no obvious pattern with the rise of altitude (Liu et al. 2005). Altitude distribution pattern differs for species diversity in different mountains and different life forms, which may be correlated to several factors such as the regional environmental conditions of the mountainous area, relative height of the mountain and geological landform (Paoli et al. 2008). Affected by the dual effects of vegetation evolution history and human activity intervention, vegetation of Mount Tai was damaged many times in the history. Most of the existing forests are artificial forests cultivated, whose zonal vegetation is broad-leaved deciduous forest. These planted forests have succeeded to natural forests after long-term hill closure and afforestation, which are subject to influence of many factors including stand density, forest edge effects, provenance, site, forest terrain and area size (Sun et al. 2009).

Due to the dual influence of human disturbance and vegetation evolution history in Mount Tai, the plant diversity belongs to a multi-peak pattern within an inconspicuous pattern. Species diversity of plant community on Mount Tai is greatly affected by human activity intervention. Strong human intervention will lead to interior thinning of the trees and apparent simplification of the community (Liu and Leung 2019). This may be a result of differentiated reproductive strategies and growth habits, shrubs are more sensitive to interference, while herbaceous have stronger buffering ability (Sarolan and Skenderolu 2016).

Conclusion

The forest soil in Mount Tai is rich in nutrients, with organic matter, total nitrogen, and total phosphorus contents all reaching the national first-level standard, while the available nutrient content is relatively low. Soil nutrient content varies with altitude, showing a certain regularity. The organic matter content exhibits an approximately bimodal distribution, while the total nitrogen, hydrolyzable nitrogen, and total potassium contents show an approximately unimodal distribution. In addition, the diversity of tree species in Mount Tai's forests is significantly affected by topographic factors, including altitude, slope, aspect, and slope position, which all influence the distribution and diversity of tree species. All the above results support that "Mount Tai is mainly affected by both human disturbance and vegetation evolution history, and its plant diversity belongs to a multi-peak pattern without obvious patterns."

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Author Contributions Gao Yuan presides over the experimental plan, conducts field investigations, and writes a paper. Wang Yun, Kong Yong and Zhou Jing participat in experimental plan, conducting field investigations, and writing papers.

Data availability All relevant data are within the paper.

Declarations

Conflicts of Interest The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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