Vertical Zonality of Soil Physical Properties in Sejila Mountain, Tibet: Postprint

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Date: 2018-02-01T00:00:00+00:00

Abstract

Soil erosion in the plateau mountainous regions of southeastern Tibet, represented by Sejila Mountain, has become a significant issue for the regional ecological environment. Analysis of soil physical properties across different altitude gradients in Sejila Mountain reveals the following results: (1) Except at altitudes of 3600 m and 4200 m, soil bulk density increases with soil depth; total porosity and capillary porosity decrease with soil depth; non-capillary porosity shows no discernible pattern with soil depth variation; saturated water content, capillary water content, and field water capacity all decrease with increasing soil depth. (2) Across different altitude gradients, the ranges of overall mean soil bulk density, total porosity, capillary porosity, and non-capillary porosity are 0.58-1.10 g/cm^3, 57.00%-72.47%, 53.33%-67.59%, and 3.20%-4.87%, respectively. Saturated water content, capillary water content, and permeability exhibit identical patterns, being maximal at 3800 m and 3400 m, minimal at 3200 m and 3600 m, and intermediate at 4000-4600 m; field water capacity displays an M-shaped fluctuation trend with altitude gradient variation. (3) Soil physical properties demonstrate pronounced spatial heterogeneity, with evident spatial autocorrelation among various indicators. The indicators of soil physical properties exhibit significant differences across different soil layers and altitudes, and anthropogenic disturbance constitutes another important factor contributing to the spatial heterogeneity of soil physical properties. (4) Overall, the physical structure of surface soil (0-10 cm) in Sejila Mountain is superior to that of deeper soil layers (>10-30 cm); conditions are poorest at 3200 m and 3600 m, intermediate at 4000-4600 m, and optimal at 3400-3800 m. The research findings indicate that in the primary forest zones of southeastern Tibet represented by Sejila Mountain, the soil structure is fragile, and to conserve soil and water, over-exploitation from tourism and forest production and management activities should be prevented.

Full Text

Preamble

ACTA ECOLOGICA SINICA
ChinaXiv Partner Journal
Vol. 38, No. 3, Feb., 2018
DOI: 10.5846/stxb201611282429

Research on Vertical Zonation of Soil Physical Properties in Sygera Mountain, Tibet

Wan D, Liang B, Nie X G, Yu W, Zhang B. Research on vertical zonation of soil physical properties in Sygera Mountain, Tibet. *Acta Ecologica Sinica*, 2018, 38(3): 1065-1074.

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Abstract

Soil erosion in the southeastern Tibetan plateau, particularly in Sygera Mountain, has become a critical regional ecological and environmental issue. This study analyzed soil physical properties across different altitude gradients in Sygera Mountain. The results demonstrated that: (1) Soil bulk density increased with soil depth at all elevations except at 3600 m and 4200 m, while total porosity and capillary porosity decreased with soil depth across all elevations. Non-capillary porosity showed no significant relationship with soil layer depth. Saturated water content, capillary water content, and field capacity all decreased with increasing soil depth at different elevations. (2) Across different elevations, soil bulk density, total porosity, capillary porosity, and non-capillary porosity ranged from 0.58-1.10 g/cm^3, 57.00%-72.47%, 53.33%-67.59%, and 3.20%-4.87%, respectively. Saturated water content, capillary water content, and permeability followed similar trends, with maximum values at 3800 m and 3400 m, minimum values at 3200 m and 3600 m, and intermediate values in the summit area (4000-4600 m). Field capacity plotted against altitude revealed an M-shaped trend. (3) Soil physical properties exhibited strong spatial heterogeneity across different elevations, with indices showing spatial autocorrelation. Significant differences in soil physical properties were present among different soil layers and elevations, and human disturbance was an important factor underlying this spatial heterogeneity. (4) Overall, surface soil (0-10 cm) physical properties in Sygera Mountain were better than those of deeper soil layers (>10-

30 cm). However, surface soil properties at the mountain foot (3200 m) and at 3600 m were the worst, those in the summit area (4000–4600 m) were intermediate, and those in the hillside areas (3400 m, 3800 m) were the best. This study indicates that soil structure is vulnerable in the virgin forest areas of Sygera Mountain, southeastern Tibet. Therefore, tourism and forest industrial production and management should be better regulated to maintain the forest' s water and soil conservation capacity.

Keywords: Sygera Mountain; soil physical property; altitude gradient; water and soil conservation

Introduction

Soil serves as a crucial ecological factor in ecosystems, with its physical properties exhibiting pronounced spatial heterogeneity due to varying environmental influences along both horizontal and vertical gradients. These influencing factors—climate, vegetation, topography, and regional differences—cause soils to develop into various types and largely govern their vertical distribution patterns, which in turn create differences in water storage capacity and erosion resistance across different altitudes. Numerous studies have demonstrated that soil physical properties show distinct vertical distribution characteristics along altitude gradients. For instance, Tang et al. [?] investigated the vertical zonation of mountain soils in the Zhagana area of Diebu, finding that soil physical properties exhibited clear vertical differentiation, with mountain soil characteristics being particularly pronounced. He et al. [?] studied soil physical properties of *Abies faxoniana* virgin forests along an altitude gradient, concluding that soil physical properties varied significantly with elevation. Similarly, Chen et al. [?] analyzed the effects of altitude on soil physical properties and water characteristics of moso bamboo forests, also finding certain differences among different altitude gradients. However, due to the inherent heterogeneity of soil physical properties, the patterns and trends of environmental and anthropogenic influences remain unclear [?].

With advances in computer technology and enhanced computational capacity, the widespread application of models has increased attention to soil spatial heterogeneity issues. Sygera Mountain in southeastern Tibet hosts vast tracts of undeveloped virgin forest that serve as a natural barrier for China's ecosystem, playing a major regulatory role in atmospheric circulation, climate change, and ecological balance across the entire Qinghai-Tibet Plateau. The region features interlaced alpine valleys and complex topography that make it highly prone to soil erosion, severely affecting ecosystem stability and dominating the formation of forest climate in southeastern Tibet [?]. This leads to uneven distribution and unstable soil texture conditions. While Chinese scholars have conducted extensive research on the ecology of Sygera Mountain [?], studies on the vertical zonation patterns of soil physical properties remain scarce. This paper attempts to analyze soil physical properties across different altitude gradients and soil depths in Sygera Mountain, aiming to provide fundamental data for ecological and hydrological research in the southeastern Tibetan plateau high mountain region, particularly for establishing predictive models of soil erosion in plateau mountain areas, and to provide a scientific theoretical basis for soil and water conservation efforts in this region.

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1. Study Area Overview

Sygera Mountain is located in Linzhi County, southeastern Tibet, on the northwest side of the Yarlung Tsangpo River' s great bend, and belongs to the Nyenchen Tanglha Mountain range. Geographical coordinates are 94°12 -95°35 E, 29°10 -30°15 N, with a large altitude distribution ranging from 2200–5300 m. The area is significantly influenced by the warm and humid monsoon from the Indian Ocean, featuring a subalpine temperate semi-humid climate with cool summers and mild winters. The region has distinct wet and dry seasons, with an average annual precipitation of 1134.1 mm (48.0% concentrated in July, accounting for 22.9% of annual precipitation), average annual relative humidity of 75.0%-82.0%, average annual temperature of -0.7°C, extreme maximum temperature of 24.0°C, extreme minimum temperature of -31.6°C, average annual sunshine duration of 1150.6 h, and sunshine percentage of 40.0%. The current vegetation consists of virgin forests, with dominant species including *Abies georgei* var. *smithii*, *Pinus densata*, *Picea likiangensis* var. *linzhiensis*, and *Sabina saltuaria*. Understory shrubs include *Fargesia setosa*, *Rhododendron simsii*, and *Lonicera japonica*, with a well-developed moss layer. Soils are predominantly acidic brown earth.

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1. Sampling Scheme

On the western slope of Sygera Mountain, sampling sites were established at 200 m altitude intervals from 3200 m to 4600 m, with three replicates at each elevation. At each sampling point, soil samples were collected at three depths: 0–10 cm, >10–20 cm, and >20–30 cm. Aluminum box samples were used to determine water-holding capacity, capillary water content, capillary porosity, non-capillary porosity, saturated water content, and permeability, while ring knife samples were used to measure various physical indices.

Figure 1 [Figure 1: see original paper] Sampling roadmap

Table 1 Basic information of the research sites

Altitude (m)	Longitude and Latitude	Slope Gradient (°)	Aspect	Main Plant Types	Vegetation Coverage	Human Disturbance Degree
3200	29°33 58.23 N, 94°32 20.26 E	-	-	Artificial spruce forest, etc.	-	-
3400	29°34 03.33 N, 94°33 38.37 E	-	-	*Quercus aquifolioides*	-	-
3600	29°33 26.61 N, 94°33 31.67 E	-	-	*Picea likiangensis*, etc.	-	-
3800	29°33 45.01 N, 94°34 13.03 E	-	-	*Picea likiangensis*, etc.	-	-
4000	29°34 41.61 N, 94°35 19.17 E	-	-	*Abies georgei* var. *smithii*	-	-
4200	29°36 40.66 N, 94°37 02.76 E	-	-	*Abies georgei* var. *smithii*	-	-
4400	29°37 39.66 N, 94°38 07.55 E	-	-	*Abies georgei* var. *smithii*	-	-
4600	29°36 08.38 N, 94°39 00.27 E	-	-	*Picea likiangensis*, etc.	-	-

2. Test Methods and Data Processing

Soil bulk density was determined using the ring knife method. Capillary water content was measured using the ring knife method and water immersion method. Determination and calculation of physical properties followed the Forestry Industry Standard of the People' s Republic of China—Forest Soil Analysis Methods. The ring knife volume was 100 cm^3. Field capacity was measured using the ring knife method. Soil permeability was determined using the constant-head double ring method. Statistical processing employed classical statistical methods to calculate mean values, minima, and standard deviations of soil physical properties. Correlation analysis was performed using bivariate Pearson correlation analysis. Data statistics and processing were completed using Excel 2010 and SPSS 17.0 statistical software. Chart production and significance analysis used ANOVA.

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1. Soil Bulk Density

Soil bulk density is one of the most fundamental physical properties of soil, significantly influencing soil aeration, vegetation growth, solute migration characteristics, and soil erosion capacity [?, ?]. The results showed that soil bulk density tended to increase with soil depth, except at 3600 m and 4200 m where the opposite pattern was observed. At the same soil depth across different altitudes, bulk density at 3200 m and 3600 m was significantly greater than at other elevations ($P < 0.05$). In the 0–10 cm layer, bulk density at 3800 m was significantly smaller than at 3200 m and 3600 m ($P < 0.05$), but showed no significant difference from 3400 m and 3800 m ($P > 0.05$). In the >10–20 cm layer, bulk density at 3200 m, 3600 m, and 4400 m was significantly greater than at 3800 m and 4000 m ($P < 0.05$), while other elevations showed no significant differences ($P > 0.05$). In the >20–30 cm layer, bulk density at 3200 m, 3600 m, and 4400 m was significantly greater than at 3400 m and 3800 m ($P < 0.05$), while 4200 m and 4600 m showed no significant difference but were both significantly greater than 4000 m ($P < 0.05$).

The overall mean bulk density varied significantly with altitude, ranging from 0.58-1.10 g/cm^3. The ranking from largest to smallest was: 3200 m, 3600 m, 4400 m, 4000 m, 4200 m, 4600 m, 3400 m, and 3800 m. Bulk density at 3200 m and 3600 m was at the same level ($P > 0.05$) but significantly greater than at 3400 m and 3800 m ($P < 0.05$). The 3400–3800 m range, with minimal human disturbance, showed significantly different bulk density compared to the 4000–4600 m range.

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2. Soil Porosity

Soil porosity directly affects soil aeration, water retention and movement, and root penetration, reflecting the soil' s potential water storage and precipitation regulation capacity [?, ?]. Total porosity and capillary porosity decreased with soil depth, showing the opposite pattern to bulk density. Non-capillary porosity showed no clear pattern with soil depth changes. At 3600 m, total porosity and capillary porosity in the 0–10 cm layer were greater than in deeper layers (>10–30 cm), decreasing significantly with depth ($P < 0.05$). Non-capillary porosity at 3600 m increased with depth.

Capillary porosity at 3200 m, 3600 m, and 4400 m was significantly smaller than at 3400 m, 3800 m, and 4000 m ($P < 0.05$), while other elevations showed no significant differences. Total porosity and capillary porosity at 3200 m and 3600 m were significantly greater than at 3800 m ($P < 0.05$), with no significant differences among other elevations ($P > 0.05$). In the >20–30 cm layer, capillary porosity at 4000 m and 4200 m was significantly smaller than at 3400 m, 3800 m, and 4600 m ($P < 0.05$), while other elevations showed no significant differences ($P > 0.05$).

Overall means for total porosity, capillary porosity, and non-capillary porosity ranged from 57.00%–72.47%, 53.33%–67.59%, and 3.20%–4.87%, respectively. Total porosity and capillary porosity values ranked from largest to smallest as: 3800 m, 3400 m, 4200 m, 4600 m, 4000 m, 4400 m, 3600 m, and 3200 m. Non-capillary porosity ranked as: 3800 m, 4400 m, 4600 m, 3400 m, 3200 m, 4200 m, 4000 m, and 3600 m.

Stepwise regression analysis of soil bulk density, total porosity, and capillary porosity across altitude gradients yielded the following equations:
Capillary water content = 0.822 - 0.250 × (capillary porosity), $R^2 = 0.724$, $P < 0.01$;
Capillary water content = 0.874 - 0.265 × (bulk density), $R^2 = 0.774$, $P < 0.01$.
Both total porosity and capillary porosity were negatively correlated with bulk density.

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3. Soil Water Content

Soil water content reflects the soil' s ability to regulate and control various forms of water, directly influencing soil water erosion resistance.

1. Saturated Water Content and Capillary Water Content

Both saturated and capillary water content decreased with soil depth at all altitudes. Except at 3600 m and 3200 m, all other elevations showed significant decreases ($P < 0.05$). In the 0–10 cm and >10–20 cm layers, minimum values occurred at 3600 m for saturated water content and at 3200 m and 4400 m for capillary water content. Saturated water content in surface soil (0–10 cm) ranged from 50.77%–205.08%, while in deeper soil (>10–30 cm) it ranged from 45.81%–110.75%. Capillary water content ranged from 48.21%–187.70% in surface soil and 41.47%–103.31% in deeper layers. Surface soil (0–10 cm) clearly outperformed deeper soil (>10–30 cm) in water-holding capacity.

At 3400 m and 3800 m, both saturated and capillary water content were significantly greater than at 3200 m and 3600 m ($P < 0.05$), with no significant differences among other elevations ($P > 0.05$). Overall means ranked from largest to smallest as: 3800 m, 3400 m, 4000 m, 4600 m, 4200 m, 4400 m, 3600 m, and 3200 m. Both saturated and capillary water content showed clear vertical zonation patterns.

Stepwise regression analysis yielded:
Saturated water content = 2.142 - 1.567 × (bulk density), $R^2 = 0.895$, $P < 0.01$;
Capillary water content = 3.340 - 1.996 × (bulk density) - 1.279 × (capillary porosity), $R^2 = 0.890$, $P < 0.01$.
These results indicate that saturated water content is most affected by bulk density, followed by soil porosity.

2. Field Capacity

Field capacity is related to soil structure, organic matter content, and land use conditions [?]. Except at 4600 m, field capacity decreased significantly with soil depth ($P < 0.05$), with more pronounced reduction in the >20–30 cm layer than in the >10–20 cm layer. Field capacity in the 0–10 cm layer ranged from 42.15%–136.72%, while in deeper soil (>10–30 cm) it ranged from 29.21%–75.37%. The greater variation in surface soil reflects rapid renewal and good soil structure influenced by surface vegetation, resulting in high porosity and strong water-holding capacity.

In the 0–10 cm layer, field capacity at 3800 m was significantly greater than at 3200 m and 4600 m ($P < 0.05$), while other elevations showed no significant differences ($P > 0.05$). In the >10–20 cm layer, field capacity at 3800 m was significantly greater than at 3200 m and 4600 m ($P < 0.05$), with no significant differences among other elevations ($P > 0.05$). Overall means showed an M-shaped fluctuating trend with altitude, increasing from 3200 m to 3800 m, then decreasing sharply at 4000 m. The ranking was: 3800 m, 3600 m, 3400 m, 4200 m, 4000 m, 4400 m, 4600 m, and 3200 m.

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4. Soil Permeability

Soil permeability is a crucial water-physical property and an important indicator of soil water conservation and erosion resistance. Permeability directly relates to surface runoff generation—better permeability reduces surface runoff and soil erosion [?]. As permeability describes the vertical physical structure of soil, we averaged permeability values across soil layers for holistic comparison.

Initial infiltration rate, stable infiltration rate, and average infiltration rate all showed clear vertical zonation patterns with altitude: 3400–3800 m > 4000–4600 m > 3200 m. Minimum values occurred at 3200 m and 3600 m, while maximum values appeared at 3800 m, 3400 m, and 4000–4600 m. Maximum values exceeded minimum values by 95.91%, 93.45%, and 94.34% for initial, stable, and average infiltration rates, respectively.

At 3800 m, initial infiltration rate was significantly greater than at 3200 m, 3600 m, 4200 m, 4400 m, and 4600 m ($P < 0.05$), with no significant differences among other elevations ($P > 0.05$). Stable infiltration rate at 3400–3800 m was significantly greater than at 3200 m, 3600 m, 4200 m, 4400 m, and 4600 m ($P < 0.05$), but showed no significant difference from 4000 m ($P > 0.05$). This pattern allows surface runoff generated at high elevations to be effectively intercepted at mid-slope areas, reducing soil and water loss.

Figure 2 [**Figure 2: see original paper**] Characteristics of soil permeability (0–30 cm) at different altitudes

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5. Correlations Among Soil Physical Properties

To investigate vertical differentiation characteristics of soil physical indices along altitude gradients and their interrelationships, correlation analysis was performed. Among the correlation relationships, 60% reached significant or highly significant levels, consistent with the high frequency of interconnections reported by Zhang et al. [**?**] for soil quality indicator datasets. This demonstrates that the studied soil physical properties are interrelated and can provide a basis for selecting soil quality evaluation indicators.

Capillary porosity was highly significantly negatively correlated with bulk density ($P < 0.01$), while non-capillary porosity was significantly negatively correlated with bulk density ($P < 0.05$), consistent with most previous studies [**?**, **?**]. Bulk density showed a non-significant correlation with altitude ($r = 0.156$, $P > 0.05$). Total porosity and capillary porosity were significantly positively correlated with altitude ($P < 0.05$). Saturated water content and capillary water content were highly significantly negatively correlated with bulk density, indicating that looser soil texture can store more water. Field capacity was positively correlated with altitude and highly significantly negatively correlated with soil layer, demonstrating that shallow soil has better water retention than deep soil.

Initial infiltration rate and stable infiltration rate were both highly significantly negatively correlated with bulk density ($P < 0.01$), while average infiltration rate was negatively correlated with bulk density ($P > 0.05$). Initial infiltration rate was non-significantly negatively correlated with altitude ($P > 0.05$). Stable infiltration rate and average infiltration rate were positively correlated with total porosity and capillary porosity, while initial infiltration rate was significantly positively correlated with non-capillary porosity, indicating that permeability is strongly influenced by non-capillary porosity. Along altitude gradients, total porosity and capillary porosity showed the strongest vertical differentiation, while other indices also exhibited strong differentiation except for non-capillary porosity.

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4. Discussion and Conclusions

1. Discussion

Due to large vertical altitude changes in plateau mountains, the results show that surface soil (0-10 cm) physical properties are better than deep soil (>10-30 cm), with clear vertical distribution patterns of basic physical indices along slopes. This occurs because surface soil has abundant vegetation roots, high microbial activity, and more decomposed litter, making it looser with higher porosity and stronger water retention—consistent with most previous studies [**?**]. However, at 3200 m and 3600 m, intense and frequent human activities have compacted surface soil through repeated trampling, leading to conversion to single-species forests, increased bulk density, and poor soil structure.

At 4000–4600 m, vegetation consists mainly of shrubs and grasses receiving enhanced solar radiation with large diurnal temperature variations, promoting physical weathering. The soil surface is covered with numerous gravel particles, microbial activity is weak, and the thin humus layer results in smaller saturated and capillary water content. As altitude increases, soil physical indices in the summit area are weaker than in mid-slope areas. The mid-slope areas (3400 m, 3800 m) experience minimal human disturbance and contain dense *Picea* and *Abies* forests. Large amounts of litter decompose into humus under microbial action, and slope runoff carries soil particles and organic matter to mid-slope areas, effectively improving soil structure and intercepting water and soil for conservation. At 3200 m and 3600 m, soil physical indices are poor due to obvious high-intensity human impacts. These results realistically reflect the combined effects of natural environmental factors and human activities on soil structure and properties.

Human activity is an important factor affecting soil physical properties. In the forest zones of southeastern Tibet represented by Sygera Mountain, soil structure is extremely fragile. Therefore, special attention should be paid to protecting surface cover and reducing disturbance intensity during tourism development and forest production management.

2. Conclusions

(1) With increasing soil depth, bulk density showed an increasing trend, while total porosity and capillary porosity showed decreasing trends. Non-capillary porosity showed no significant pattern with depth. Except at 3600 m and 4400 m, all other altitudes showed significant differences among soil layers ($P < 0.05$).

(2) Across altitudes, bulk density, total porosity, capillary porosity, and non-capillary porosity ranged from 0.58–1.10 g/cm^3, 57.00%–72.47%, 53.33%–67.59%, and 3.20%–4.87%, respectively. The ranking for bulk density was: 3200 m, 3600 m, 4400 m, 4000 m, 4200 m, 4600 m, 3400 m, 3800 m. Total porosity and capillary porosity ranked as: 3800 m, 3400 m, 4200 m, 4600

m, 4000 m, 4400 m, 3600 m, 3200 m. Non-capillary porosity ranked as: 3800 m, 4400 m, 4600 m, 3400 m, 3200 m, 4200 m, 4000 m, 3600 m.

(3) Saturated water content and capillary water content at all altitudes decreased with soil depth, with significant decreases at all elevations except 3600 m and 3200 m ($P < 0.05$). Surface soil (0-10 cm) outperformed deep soil (>10-30 cm) in water retention capacity. Field capacity also decreased significantly with depth ($P < 0.05$), with more pronounced reduction in the >20-30 cm layer than in the >10-20 cm layer. Field capacity showed an M-shaped fluctuating trend with altitude.

(4) Initial infiltration rate, stable infiltration rate, and average infiltration rate all showed clear vertical zonation patterns with altitude: 3400-3800 m > 4000-4600 m > 3200 m. The three index values at 3400 m and 3800 m were maximum, while those at 3200 m and 3600 m were minimum.

(5) Soil physical properties showed strong spatial heterogeneity in both altitude and soil depth, with greater heterogeneity in surface soil than in deep soil. On altitude gradients, mid-slope heterogeneity exceeded upper-slope heterogeneity. Human disturbance clearly contributed to spatial heterogeneity of soil physical properties.

(6) Comprehensive analysis of soil physical properties across altitudes revealed strong regularity in soil physical structure. The 3200 m and 3600 m sites showed the poorest structure, while 3400 m and 3800 m showed the best. Dense vegetation cover is crucial for maintaining good soil structure. Even at cold summits, natural recovery can maintain good soil structure with minimal human disturbance, while high-intensity human disturbance is a major cause of soil structure degradation and can disrupt fragile ecosystem balance.

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Note: Figure translations are in progress. See original paper for figures.