Effects of Soil Property Variation on Tillage Layer Soil Quality in Purple Soil Sloping Farmland: Postprint

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Abstract

Sloping farmland represents the land use type most susceptible to soil and water loss within a region, and its severe soil erosion, non-point source pollution, and tillage layer degradation directly threaten the sustainable utilization of sloping farmland as well as local food security and ecological security; tillage layer soil quality is relatively sensitive to both natural factors and anthropogenic cultivation activities. This study examined the tillage layer soil quality of purple soil sloping farmland at three sites in southern China, and from the perspective of soil properties, comparatively analyzed the soil nutrient characteristics, soil physical properties, soil water reservoir features, tillage performance differences, and their formation causes at different vertical depths of the tillage layer in Hechuan of Chongqing, Xingguo of Jiangxi, and Chuxiong of Yunnan. The results indicated that: (1) Soil organic matter in the tillage layer of sloping farmland exhibited the following trend: Chuxiong of Yunnan (28.80 g/kg) > Xingguo of Jiangxi (9.03 g/kg) > Hechuan of Chongqing (8.80 g/kg); except for total potassium content, the contents of total nutrients and readily available nutrients showed the trend of Chuxiong of Yunnan > Xingguo of Jiangxi > Hechuan of Chongqing; the vertical distribution pattern of readily available nutrients in the tillage layer of sloping farmland was basically consistent, mainly manifested as the enrichment of soil readily available nutrients primarily in the 0-20 cm soil layer, while no significant differences were observed between the 20-40 cm and 40-60 cm soil layers. (2) The soil physical properties of the tillage layer in purple soil sloping farmland varied significantly among different locations, with the soil physical quality being poorest in Hechuan of Chongqing, characterized by sand content > 60%, maximum soil bulk density (1.43 g/cm3), and minimum total porosity (45.97%) and capillary porosity (34.36%); from the perspective of vertical variation characteristics of soil physical properties in the tillage layer of sloping farmland, the tillage layer (0-20 cm) was superior to the subsoil layer (20-40 cm) and bottom soil layer (40-60 cm). (3) The initial infiltration rate of the tillage layer in purple soil sloping farmland was highest in Xingguo of Jiangxi (0.32 mm/min) and lowest in Hechuan of Chongqing (0.19 mm/min); both the stable infiltration rate and average infiltration rate showed the trend of Chuxiong of Yunnan > Hechuan of Chongqing > Xingguo of Jiangxi; the maximum effective storage capacity of the tillage layer in sloping farmland was the best in Chuxiong of Yunnan (873.311 t/hm2), indicating that the tillage layer soil of purple soil sloping farmland in Chuxiong of Yunnan has better capacity to resist seasonal drought; the vertical variation of total storage capacity, dead storage capacity, beneficial storage capacity, flood detention storage capacity, and maximum effective storage capacity in the tillage layer of sloping farmland at different locations showed that the tillage layer (0-20 cm) was greater than the subsoil layer (20-40 cm) and bottom soil layer (40-60 cm). (4) Both soil shear strength and penetration resistance of the tillage layer in purple soil sloping farmland at different locations exhibited the same variation pattern, with soil shear strength showing Hechuan of Chongqing (15.39 kg/cm2) > Chuxiong of Yunnan (14.74 kg/cm2) > Xingguo of Jiangxi (10.66 kg/cm2), while soil penetration resistance values were Hechuan of Chongqing (424.83 kPa) > Chuxiong of Yunnan (252.50 kPa) > Xingguo of Jiangxi (188.87 kPa), and these changes in soil mechanical properties indicated that the tillage layer soil of purple soil sloping farmland in Hechuan of Chongqing has better capacity to resist shear failure and greater tillage resistance. The above research results can provide theoretical basis and data support for soil quality diagnosis of purple soil sloping farmland tillage layer and evaluation of rational tillage layer at different locations.

Full Text

Effects of Different Soil Properties on Plow-Layer Quality of Sloping Farmland in Purple Hilly Areas

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Abstract

Sloping farmland represents the land use type most susceptible to soil erosion in a region, with severe soil erosion, non-point source pollution, and plow layer degradation directly threatening regional food security and ecological security. Plow-layer quality is highly sensitive to both natural factors and anthropogenic farming activities. This study examined plow-layer soil quality at three sloping farmland sites in southern purple hilly regions (Hechuan-Chongqing, Xingguo-Jiangxi, and Chuxiong-Yunnan), analyzing differences in soil physical properties, reservoir characteristics, and nutrient profiles, along with their vertical distribution patterns and formation mechanisms from a soil attribute perspective. The results indicated that soil organic matter in the plow layer across the three locations decreased in the order: Chuxiong-Yunnan (28.80 g/kg) > Xingguo-Jiangxi (9.03 g/kg) > Hechuan-Chongqing (8.80 g/kg). Except for total potassium content, both total and available nutrient contents followed the order: Chuxiong-Yunnan > Hechuan-Chongqing > Xingguo-Jiangxi. The vertical distribution patterns of available nutrients in sloping farmland plow layers were consistent, with nutrients concentrated primarily in the 0–20 cm soil layer, while no significant differences were observed between the 20–40 cm and 40–60 cm layers. Significant differences also existed in plow-layer physical properties among the three purple hilly locations. Hechuan-Chongqing exhibited the poorest soil physical quality, characterized by sand content >60%, maximum bulk density of 1.43 g/cm^3, minimum total porosity of 45.97%, and capillary porosity of 34.36%. From a vertical perspective, the physical properties of the tillage layer (0–20 cm) were superior to those of the subsoil (20–40 cm) and bottom layer (40–60 cm). The initial infiltration rate was highest in Xingguo-Jiangxi plow layers (0.32 mm/min) and lowest in Hechuan-Chongqing (0.19 mm/min). Both infiltration and average infiltration rates followed the order: Chuxiong-Yunnan > Xingguo-Jiangxi > Hechuan-Chongqing. The maximum effective reservoir capacity was best in Chuxiong-Yunnan (873.311 t/hm^2), indicating superior resistance to seasonal drought. Vertical variations in total and maximum effective reservoir capacities consistently showed: tillage layer (0–20 cm) > subsoil (20–40 cm) > bottom layer (40–60 cm). Soil shear strength and penetration resistance exhibited consistent patterns across locations. Shear strength decreased as Hechuan-Chongqing (15.39 kg/cm^2) > Chuxiong-Yunnan (14.74 kg/cm^2) > Xingguo-Jiangxi (10.66 kg/cm^2), while penetration resistance followed Hechuan-Chongqing (424.83 kPa) > Chuxiong-Yunnan (252.50 kPa) > Xingguo-Jiangxi (188.87 kPa). These mechanical properties indicate that Hechuan-Chongqing plow-layer soil possesses better resistance to shear failure and greater tillage resistance. These findings provide theoretical foundations and data support for diagnosing plow-layer soil quality and evaluating rational plow-layer development across different purple hilly regions.

Keywords: plow layer; sloping farmland; soil quality; tillage performance; vertical distribution; purple soil

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1. Study Materials and Research Area Overview

Three typical purple soil sloping farmland sites were selected in Hechuan District (Chongqing), Xingguo County (Jiangxi), and Chuxiong City (Yunnan) as research subjects. The parent rock in all three regions consists of purple sandstone and mudstone from different geological periods. Purple sandstone has coarse grains, loose structure, and high quartz content, making it resistant to erosion except through mechanical collapse. In contrast, purple mudstone, with fine particles, weathers easily into fragments under natural light, heat, and water conditions.

The Hechuan sampling site is located in Tangwan Village, Shuangfeng Town, characterized by a subtropical humid monsoon climate with mean annual precipitation of 1107.9 mm, mean annual temperature of 18.1°C, >10°C accumulated temperature of 5903.1°C, frost-free period of 331 days, and annual sunshine hours of 1316.2 h. The Xingguo sampling site is located in Dongshao Village, Shefu Township, with a subtropical southeast monsoon climate, mean annual precipitation of 1600 mm, mean annual temperature of 18°C, >10°C accumulated temperature of 6135-6699°C, frost-free period of 284 days, and annual sunshine hours of 1861.4 h. The Chuxiong sampling site is located in Lengshui Village, Zixi Town, with a subtropical monsoon climate, mean annual precipitation of 800-1000 mm, mean annual temperature of 14.8-21.9°C, >10°C accumulated temperature of 2500°C, frost-free period of 221-275 days, and annual sunshine hours of 2450 h. Basic information for each sampling site is presented in .

2. Sampling Methods

Typical purple soil sloping farmland plots were selected in each region. Soil samples were collected in an "S" pattern within each plot for bulk sampling, while vertical distribution samples were collected from soil profile pits excavated at central locations. Soil profile configurations and property distributions are illustrated in [Figure 1: see original paper]. Soil bulk density samples were collected using the ring knife method at 0-20, 20-40, and 40-60 cm depths. Samples for porosity and field capacity analysis were collected at 0-10, 10-20, 20-30, 30-40, 40-50, and 50-60 cm intervals. Mechanical property samples were sealed with plastic film, while moisture content samples were collected using aluminum boxes at each horizon with three replicates.

3. Soil Physicochemical Property Testing Methods

Soil physicochemical properties were determined using standard methods [13-14]. Moisture content was measured by oven-drying, porosity by the ring knife method, and mechanical composition by the pipette method. Soil infiltration was measured using the single-ring method, with the initial infiltration rate defined as the permeation rate during the first 3 minutes and the stable infiltration rate representing the constant rate achieved when percolation stabilized. After infiltration testing, the ring was sealed, gravitational water was drained, and field capacity was determined. Total nitrogen was measured by semi-micro Kjeldahl method, total phosphorus by MgO extraction-colorimetry, available phosphorus by double-acid extraction, total potassium by NaOH fusion-flame photometry, available potassium by NH_4OAc extraction, and organic matter by dichromate oxidation with external heating. Ammonium nitrogen was determined by diffusion method.

4. Soil Reservoir Characteristic Value Calculation Methods

Soil reservoir storage capacity was calculated according to literature methods [15]. For a given depth H below the surface with soil water content , the water storage W for that depth is calculated as follows:

$$\text{Total capacity} = \sum_{i=1}^{n}(S_i \times r_i \times H_i)$$

$$\text{Dead capacity} = \sum_{i=1}^{n}(W_{li} \times r_i \times H_i)$$

$$\text{Active capacity} = \sum_{i=1}^{n}[(C_i - W_{li}) \times r_i \times H_i]$$

$$\text{Flood detention capacity} = \sum_{i=1}^{n}[(S_i - C_i) \times r_i \times H_i]$$

$$\text{Maximum effective capacity} = \text{Total capacity} - \text{Dead capacity}$$

where S is saturated water content (%), C is field capacity (%), W is wilting point (%), r is soil bulk density (g/cm^3), H is soil layer thickness (cm), and n is the number of soil horizons.

5. Soil Mechanical Index Testing Methods

Soil shear strength was measured using a Dutch-made 14.10 Pocket Vane Tester at depths of 5, 15, 25, 35, 45, and 55 cm. At each test point, a small area was leveled while preserving soil structure. The vane tester was zeroed, the head was pressed to the predetermined depth at a constant rate over 2–3 minutes until soil failure occurred, and the reading X was recorded. The shear strength Y (kg/cm^2) was calculated as:

$$Y = 2.734X$$

Soil penetration resistance was measured using a PT-type pocket penetrometer (Tianmu Instrument Factory, Jiangsu). For this instrument, the calibration parameter K is constant, and the penetration value P is directly related to penetration resistance P (kPa) by:

$$P_t = K_t \times P$$

Therefore, P values represent soil penetration resistance. The penetrometer specifications are listed in .

6. Results and Analysis

6.1 Differences in Plow-Layer Soil Organic Matter Soil organic matter plays a crucial role in improving crop growth conditions and is vital for agricultural environmental protection and sustainable sloping farmland utilization. Analysis of organic matter distribution across locations revealed significant differences both among different purple soil sloping farmland sites and within vertical depths at the same site. Organic matter content decreased in the order: Chuxiong-Yunnan (28.80 g/kg) > Xingguo-Jiangxi (9.03 g/kg) > Hechuan-Chongqing (8.80 g/kg). The higher organic matter in Chuxiong-Yunnan results from long-term intensive cultivation and frequent fertilization, leading to greater organic matter inputs. Vertically, organic matter decreased with depth, with the 0-20 cm layer showing the highest content (24.45 g/kg) and the 40-60 cm layer the lowest (9.89 g/kg). This pattern arises from deep plowing practices that incorporate surface soil into deeper layers while bringing subsoil to the surface. The YN-2 sampling site showed the most pronounced vertical gradient.

6.2 Differences in Plow-Layer Soil Nutrients Soil nutrients, essential elements for plant growth, are influenced by parent material, time, and human activities, exhibiting complex formation processes and high spatial variability [16]. Significant differences existed in total and available nutrients among locations. Except for total potassium, both total and available nutrient contents were highest in Chuxiong-Yunnan, followed by Hechuan-Chongqing, then Xingguo-Jiangxi. Total nitrogen ranged from 0.50-1.36 g/kg in Chuxiong-Yunnan, 0.39-0.75 g/kg in Hechuan-Chongqing, and 0.45-0.91 g/kg in Xingguo-Jiangxi. Total phosphorus showed similar patterns. Total potassium differences were not significant among locations, though Hechuan-Chongqing had the lowest values (17.17 g/kg). Available potassium differences were also insignificant. However, significant variations occurred in alkali-hydrolyzable nitrogen (91.40-237.00 mg/kg) and available phosphorus (3.40-44.00 mg/kg) across sites.

Vertical distribution of nutrients showed distinct patterns. Maximum total nitrogen occurred at different depths depending on location: 20-40 cm in CQ-2, 0-20 cm in JX-1, and 40-60 cm in YN-1. Total phosphorus maxima appeared at various depths, while total potassium showed no clear vertical differences. Available nutrients were concentrated primarily in the 0-20 cm layer, with no significant differences between the 20-40 cm and 40-60 cm layers. Soil pH ranged from 7.3-7.9 (alkaline) in Chuxiong-Yunnan, 5.2-5.9 (acidic) in Xingguo-Jiangxi, and 5.3-6.2 (acidic) in Hechuan-Chongqing. The alkaline conditions in Chuxiong-Yunnan likely result from long-term no-till or minimum tillage practices .

6.3 Differences in Plow-Layer Soil Physical Properties Soil physical properties are key indicators for rational plow-layer construction in sloping farmland, directly affecting crop growth periods. Mechanical composition, bulk density, and porosity are critical physical properties influencing soil fertility. Significant differences existed in mechanical composition among locations. Hechuan-Chongqing soils were dominated by sand particles (>60% sand), with silt content reaching 61.04-63.11%. Xingguo-Jiangxi soils contained 37.80-54.00% sand and 36.20-47.80% silt. Chuxiong-Yunnan soils were primarily sand and silt, with 47.13% sand (1-0.05 mm) and 49.93% silt (0.05-0.001 mm) in the 0-20 cm layer. Vertical variations in particle composition were evident, with the 0-20 cm tillage layer showing significantly higher sand content than deeper layers due to regular tillage and weeding activities that break up compacted soil and improve permeability.

Bulk density, a crucial indicator of soil environmental quality, directly affects aeration, root penetration resistance, and water-nutrient supply. Hechuan-Chongqing had the highest bulk density (1.43 g/cm^3), followed by Xingguo-Jiangxi (1.40 g/cm^3), while Chuxiong-Yunnan had the lowest (1.30 g/cm^3). These differences stem from both parent material and local cultivation practices. Vertically, bulk density increased with depth (0-20 cm < 20-40 cm < 40-60 cm). Porosity also varied significantly among locations, with Chuxiong-Yunnan showing the best structural properties: total porosity (54.12%) > Xingguo-Jiangxi (47.22%) > Hechuan-Chongqing (45.97%), and similar trends for capillary porosity. The 0-20 cm tillage layer consistently showed better porosity than deeper layers across all sites .

6.4 Differences in Plow-Layer Soil Infiltration Characteristics Soil infiltration performance is closely related to surface runoff and erosion intensity, directly affecting plow-layer quality and productivity [17]. Infiltration rates varied among locations, decreasing over time to reach different stable values. Initial infiltration rates were highest in all sites at the beginning of testing, with Xingguo-Jiangxi showing the maximum initial rate (0.32 mm/min) and Hechuan-Chongqing the minimum (0.19 mm/min). As infiltration proceeded, increasing soil moisture content caused rates to decline and stabilize. Both stable and average infiltration rates followed the order: Chuxiong-Yunnan > Xingguo-Jiangxi > Hechuan-Chongqing.

Vertically, infiltration rates decreased with depth across all locations. The 0-20 cm layer had the best permeability, while the 40-60 cm layer showed the poorest. This pattern results from root activity and tillage disturbance in surface layers creating larger pores and enhanced water-holding capacity. Deeper layers have fewer pores and greater compaction. When rainfall intensity exceeds initial infiltration capacity, runoff occurs. The 20-40 cm layer can generate subsurface flow when saturated, while the 40-60 cm layer may produce throughflow that carries fine particles out of the soil profile, contributing to water erosion in purple hilly regions .

6.5 Differences in Plow-Layer Soil Reservoir Characteristics Soil reservoirs play a unique role in agricultural water supply, drought mitigation, and irrigation water savings [17-18]. Significant differences existed in reservoir characteristics among locations. Total reservoir capacity followed: Chuxiong-Yunnan (1052.52 t/hm^2) > Xingguo-Jiangxi (974.15 t/hm^2) > Hechuan-Chongqing (867.30 t/hm^2). Dead reservoir capacity showed similar patterns, with Chuxiong-Yunnan having the highest (179.20 t/hm^2), indicating lower available water for crops in Hechuan-Chongqing (150.82 t/hm^2). Active reservoir capacity was highest in Hechuan-Chongqing (182.28 t/hm^2), while flood detention capacity was greatest in Xingguo-Jiangxi (293.02 t/hm^2). Maximum effective reservoir capacity, indicating water storage capability, was highest in Chuxiong-Yunnan (873.311 t/hm^2), suggesting better drought resistance.

Vertically, all reservoir characteristics (total, dead, active, flood detention, and maximum effective capacities) consistently decreased with depth: 0-20 cm > 20-40 cm > 40-60 cm. This pattern was most pronounced in Chuxiong-Yunnan. Reservoir capacity is influenced by soil texture, porosity, organic matter, and layer thickness. Lower bulk density, higher sand content, and greater organic matter contribute to larger maximum effective capacities and better water storage .

6.6 Differences in Plow-Layer Soil Mechanical Properties Soil mechanical properties, including shear strength and penetration resistance, are widely used in agricultural production for improving tillage performance, optimizing structural stability, and enhancing bearing capacity. Shear strength reflects the difficulty of shear deformation under external forces and varied significantly among locations and depths. The order of shear strength was: Hechuan-Chongqing (15.39 kg/cm^2) > Chuxiong-Yunnan (14.74 kg/cm^2) > Xingguo-Jiangxi (10.66 kg/cm^2). Xingguo-Jiangxi showed the lowest values (3.94 kg/cm^2 at 50-60 cm), indicating susceptibility to shear deformation, while Hechuan-Chongqing demonstrated better resistance.

Vertical patterns of shear strength varied by location. Hechuan-Chongqing showed an initial increase then decrease, with maxima at 30-40 cm (CQ-1) and 40-50 cm (CQ-2). Xingguo-Jiangxi exhibited a gradual increase with depth, while Chuxiong-Yunnan showed maxima at 30-40 cm and 40-50 cm (19.083 kg/cm^2) [Figure 3: see original paper].

Penetration resistance is a critical parameter for predicting mechanical implement performance and vehicle trafficability. At 0-10 cm depth, penetration resistance values were: Hechuan-Chongqing (424.83 kPa) > Chuxiong-Yunnan (252.50 kPa) > Xingguo-Jiangxi (188.87 kPa). This pattern persisted across all depths, indicating that Chuxiong-Yunnan soils are more susceptible to compaction from mechanical traffic. Within each location, penetration resistance generally increased with depth due to long-term traffic compaction of deeper layers without tillage remediation .

7. Discussion

7.1 Effects of Soil Erosion on Plow-Layer Soil Quality in Purple Soil Sloping Farmland Purple soil is characterized by rapid soil formation, good tillage properties, and high productivity, but also high erodibility and severe degradation. Zhu Bo [20] identified soil thickness as a fundamental constraint on purple soil productivity, with 60 cm thick purple soil storing only one-fifth the water of 100 cm thick soil. Shi Dongmei [3] noted that deep, well-structured soils with high organic matter experience less erosion, while poor structure and low organic matter exacerbate water loss, drought, and flooding.

Soil erosion reduces plant-available water, depletes nutrients, destroys fertility structure, and severely degrades soil quality [21]. Research on sloping farmland quality degradation has focused on rainfall and tillage erosion effects. Nyssen et al. [22] found that tillage erosion concentrates soil at slope bottoms while thinning topsoil at slope crests. Kosmas et al. [23] reported that tillage displacement affects soil properties and crop biomass. Nie et al. [24] used ^{137}Cs tracing to evaluate erosion in Sichuan' s purple soil region, finding tillage erosion contributes up to 52.6 t/hm^2 on steep slopes. Chen et al. [25] demonstrated that erosion reduces capillary and total porosity by 3.7% in dry-hot valleys. Shi et al. [26] established that erosion-induced degradation reduces fertility and quality across southern China. Wang et al. [27] showed that black soil erosion in northeast China causes exponential yield declines. Guo et al. [28] simulated erosion effects, finding 20 cm of surface erosion reduced organic matter by 33.48-85.71%, available phosphorus by 14.37-46.87%, and available potassium by 8.09-36.27%, while causing substantial yield losses.

Our analysis indicates that Hechuan-Chongqing' s high bulk density (1.43 g/cm^3), low total porosity (45.97%), and poor permeability result in inferior overall physical quality, making it vulnerable to erosion-induced degradation.

7.2 Suitable Thresholds for Plow-Layer Tillage Parameters Tillage performance reflects integrated soil physical and mechanical properties, including cohesion, plasticity, and porosity. Ding et al. [29] identified soil texture, structure, and moisture as the physical basis for mechanical behavior. Research shows that eroded purple soils have coarse skeletal characteristics, with physical sand particles comprising 52.00-69.97% and physical clay 31.40-41.99%. In dry-hot valleys, eroded surface soils contain 2.4-9.6 g/kg organic matter, with severe compaction (bulk density 1.36-1.54 g/cm^3) and alkalinity (pH 8.0-8.9) [30-33].

Based on previous research, we established suitable tillage parameter thresholds and evaluated the three locations . Average values for all sites fell within suitable ranges, though some individual measurements exceeded thresholds, particularly in 20-40 cm and 40-60 cm layers. Maximum bulk density reached 1.70 g/cm^3, minimum organic matter was 4.90%, and maximum total porosity was 70.06%, all outside optimal ranges. These deviations reduce water retention and fertility, limiting crop growth. Appropriate measures such as deep loosening, organic fertilization, and straw incorporation are needed to improve deep soil quality and achieve sustainable high yields.

8. Conclusion

Significant differences in chemical and physical properties existed among purple soil sloping farmland sites. Chuxiong-Yunnan exhibited superior fertility with organic matter reaching 28.80 g/kg and highest total and available nutrient contents. Hechuan-Chongqing showed poor physical quality with highest bulk density (1.43 g/cm^3), lowest total porosity (45.97%), and lowest capillary porosity (34.36%). Within sites, physical quality decreased with depth: 0–20 cm > 20–40 cm > 40–60 cm.

Infiltration rates and reservoir characteristics varied significantly among locations. Chuxiong-Yunnan had the highest stable and average infiltration rates, largest total reservoir capacity (1052.52 t/hm^2), and maximum effective reservoir capacity (873.311 t/hm^2), indicating excellent water storage and drought resistance. Shear strength and penetration resistance were highest in Hechuan-Chongqing (15.39 kg/cm^2 and 424.83 kPa, respectively), demonstrating superior resistance to shear failure and mechanical compaction.

While all sites generally fell within suitable tillage parameter ranges, some subsoil measurements exceeded optimal thresholds. Implementing appropriate deep loosening, straw return, and organic fertilization practices will be crucial for improving deep soil quality and establishing rational plow-layer structures in purple soil sloping farmland.

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