Soil Infiltration Capacity and Its Influencing Factors under Different Fruit Tree-Crop Intercropping Patterns: Postprint

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Abstract

To investigate soil infiltration capacity and its influencing factors under different fruit-crop intercropping patterns in apple orchards in the loess tableland-gully region, soil water infiltration parameters were measured using the field double-ring infiltrometer method in apple orchards under four intercropping patterns in Yongshou County: fruit-fallow (CK), fruit-grass (M1), fruit-vegetable (M2), and fruit-grain (M3). Correlation analysis and linear redundancy analysis (RDA) were employed to study the factors influencing soil infiltration characteristic parameters. Three commonly used soil infiltration models were utilized to fit the infiltration processes of the four orchard types. The results showed that under the four fruit-crop intercropping patterns, initial infiltration rates of orchard soils ranged from 7.18 to 13.57 $mm \cdot min^{-1}$; stable infiltration rates ranged from 1.87 to 2.94 $mm \cdot min^{-1}$; average infiltration rates ranged from 3.36 to 5.65 $mm \cdot min^{-1}$; and cumulative infiltration amounts ranged from 260.51 to 423.65 mm. For apple orchards under various intercropping patterns, initial and average infiltration rates exhibited the trend M1 > M3 > M2 > CK, while stable infiltration rates and cumulative infiltration amounts showed the trend M1 > M2 > M3 > CK. All infiltration indices in the M1 plot were significantly greater than those in other management plots, whereas the CK plot displayed the minimum infiltration characteristic indices. Correlation analysis revealed that soil infiltration characteristic indices were negatively correlated with soil bulk density, clay content, and silt content, and positively correlated with maximum water holding capacity, minimum water holding capacity, capillary water holding capacity, capillary porosity, non-capillary porosity, total porosity, and sand content. Linear redundancy analysis results indicated that soil silt content, soil porosity, soil water holding capacity, and soil bulk density are the primary factors affecting soil infiltration capacity. The soil infiltration capacity ranking evaluated by principal component analysis (PCA) was M1 (2.75) > M2 (0.04) > M3 (-0.63)

> CK (-2.17). Intercropping crops in apple orchards can effectively enhance soil infiltration capacity. Comparison of the three models demonstrated that the Jiang Dingsheng model exhibited high fitting accuracy ($R^2 = 0.97$) for soil infiltration processes in apple orchards under the four intercropping patterns in the loess tableland-gully region, making it suitable for describing actual soil infiltration conditions in this area.

Full Text

Soil Infiltration Capacity and Its Influencing Factors Under Different Fruit-Agriculture Intercropping Patterns

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Abstract

To investigate soil infiltration capacity and its influencing factors under different fruit-agriculture intercropping patterns in apple orchards in the gully region of Loess Plateau, we measured soil water infiltration parameters using the double-ring method in Yongshou County orchards under four intercropping patterns: apple-wild (CK), apple-herbage (M1), apple-Brassica (M2), and apple-Zea mays (M3). Correlation and redundancy analyses (RDA) were employed to identify influencing factors of soil infiltration parameters, while three common soil infiltration models were used to fit the infiltration processes. Results showed that across the four intercropping patterns, initial infiltration rates ranged from 7.18 to 13.57 $mm \cdot min^{-1}$, stable infiltration rates from 1.87 to 2.94 $mm \cdot min^{-1}$, average infiltration rates from 3.36 to 5.65 $mm \cdot min^{-1}$, and cumulative infiltration from 260.51 to 423.65 mm. The initial and average infiltration rates followed the order M1 > M3 > M2 > CK, while stable infiltration rates and cumulative infiltration followed M1 > M2 > M3 > CK. The M1 treatment exhibited significantly higher infiltration indices than other patterns, whereas CK showed the lowest values. Correlation analysis revealed that soil infiltration characteristics were negatively correlated with soil bulk density, clay content, and silt content, but positively correlated with maximum water holding capacity, minimum water holding capacity, capillary water holding capacity, capillary porosity, non-capillary porosity, total porosity, and sand content. RDA indicated that soil silt content, porosity, water holding capacity, and bulk density were the primary factors influencing soil infiltration. Principal component analysis ranked soil infiltration capacity as M1 (2.75) > M2 (0.04) > M3 (-0.63) > CK (-2.17), demonstrating that intercropping crops in apple orchards effectively enhances soil infiltration capacity. Among the three models, Jiang Dingsheng' s model demonstrated high fitting accuracy ($R^2 = 0.97$) for soil infiltration processes under different intercropping patterns in the gully region of Loess Plateau, making it suitable for describing actual soil infiltration conditions in this area.

Keywords: gully region of Loess Plateau; fruit-agriculture intercropping patterns; soil infiltration; infiltration model; influencing factors; Shaanxi

Introduction

Soil infiltration refers to the process by which precipitation or irrigation water enters the soil surface [?], representing a critical link in the transformation among rainfall, surface water, soil water, and groundwater [?]. Soil infiltration directly affects plant water absorption and utilization, soil water and fertilizer migration, surface runoff and sediment production, and rainfall redistribution [?]. Numerous studies on soil infiltration have been conducted domestically and internationally, yielding important results. Appropriate fruit-agriculture intercropping patterns can physically improve soil quality, which is significant for enhancing water and fertilizer conditions and the growth environment for fruit trees [?]. However, few reports have addressed the impacts of apple orchard intercropping patterns on soil infiltration capacity.

The gully region of Loess Plateau in Shaanxi features fragmented terrain, dry climate, and uneven rainfall distribution, representing one of China' s most ecologically fragile areas [?]. In recent years, apple industry development driven by national poverty alleviation policies has become a dominant regional industry playing an important role in agricultural economy. However, as a high water-consumption crop, large-scale apple orchard planting has intensified local water resource conflicts, making water availability a key factor limiting apple growth and yield [?]. Studies have shown that dry layers commonly exist in soil profiles of old apple orchards on the Loess Plateau, with dry layer depths reaching [?]. These dry layers hinder rainwater recharge to deep soil water [?], posing potential hazards to apple production. Investigating soil infiltration characteristics and main influencing factors under different fruit-agriculture intercropping patterns in the gully region can improve understanding of current orchard management rationality, provide data support for intercropping pattern selection, and contribute to sustainable apple orchard development.

Study Area and Methods

Study Area The experimental site was located at Mafang Plateau, Yongshou County, Xianyang City, Shaanxi Province (geographic coordinates:

34°29 ~34°59 N, 107°56 ~108°20 E). Situated on the southern edge of the Weibei Loess Plateau, the area has a warm temperate continental climate with average annual temperature of 10.2°C and average annual precipitation of 610.66 mm. Soil parent material is Quaternary aeolian loess, classified as cinnamon soil (loess subcategory). Groundwater depth ranges from 20 to 120 m. The area is a typical dry farming region with no pollution sources around the experimental site. Apple (*Malus pumila* Mill.) economic forests cover large areas, with fruit income accounting for over 80% of farmers' income. Topsoil organic matter content is 11.66 $g \cdot kg^{-1}$, alkali-hydrolyzable nitrogen is 26.69 $mg \cdot kg^{-1}$, available phosphorus is 16.94 $mg \cdot kg^{-1}$, and available potassium is 100.59 $mg \cdot kg^{-1}$.

Soil Infiltration Measurement Soil infiltration experiments were conducted in July 2019 in orchard plots at Mafang Town, Yongshou County. All orchards were located on the same plateau surface (108.162°~108.299°E, 34.776°~34.781°N) at 1022-1031 m elevation, minimizing environmental differences. Four representative fruit-agriculture intercropping patterns were selected: apple-wild (CK), apple-herbage (M1), apple-Brassica (M2), and apple-Zea mays (M3). All orchards contained contiguous plots of *Malus pumila* 'Red Fuji' grafted onto *Malus prunifolia* rootstock, with 4 m × 4 m planting density and consistent fertilizer and organic manure application across patterns.

Four 20 m × 20 m sample plots were established for each intercropping pattern (16 total plots). In each plot, three relatively flat sites were selected for double-ring infiltration tests. The inner ring diameter was 20 cm, outer ring diameter was 40 cm, and both rings were 20 cm high. Before testing, surface vegetation was removed and rings were gently driven into the soil with a rubber hammer to minimize soil structure disturbance. Water was simultaneously added to both rings, and measurements began when water depth reached 10 cm in both rings. A stopwatch was used to record water supply bucket scale readings at intervals until stable infiltration was achieved at 30 minutes. Water height in both rings was maintained at 10 cm throughout, and water temperature was recorded during readings. To minimize soil moisture effects on results, experiments were conducted within a concentrated timeframe and ensured no rainfall occurred within 72 hours prior. Concurrently, soil samples were collected using cutting rings at 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, and 40-50 cm depths for determination of soil bulk density, maximum water holding capacity, minimum water holding capacity, capillary water holding capacity, non-capillary porosity, capillary porosity, and total porosity, following methods in *Analytical Methods for Forest Soils* [**?**].

Soil Infiltration Models Soil infiltration models are important tools for studying infiltration processes. Many empirical models have been established to simulate temporal changes in soil infiltration. This study selected three classic empirical models to fit measured data: Horton, Kostiakov, and Jiang Dingsheng models [**?**]. Model formulas and parameters are shown in .

Data Analysis Experimental data were analyzed using Origin 2018 and SPSS 20.0, with figures created using Canoco. All data were tested for normal distribution, with non-normal data square-root transformed. One-way ANOVA was used to analyze differences in infiltration parameters among intercropping patterns. Pearson correlation analysis and redundancy analysis (RDA) were employed to examine relationships between soil infiltration characteristics and physical properties. Principal component analysis (PCA) was used to evaluate soil infiltration capacity under different patterns.

Results

Soil Infiltration Characteristics Under Different Intercropping Patterns Soil infiltration is a complex process influenced by multiple factors. Ten soil environmental factors were selected as influencing factors: soil bulk density, maximum water holding capacity, minimum water holding capacity, capillary water holding capacity, capillary porosity, non-capillary porosity, total porosity, clay content, silt content, and sand content. As shown in [Figure 1: see original paper], soil infiltration rates in all intercropping patterns declined rapidly during the first 10 minutes (transient stage), during which water movement was primarily driven by molecular forces. Average infiltration rates at 1 minute were significantly higher than at 10 minutes. Between 10-60 minutes (leakage stage), the decline rate slowed noticeably, with infiltration rates showing obvious fluctuations. After 60 minutes, infiltration rates reached relatively stable conditions. Cumulative infiltration increased rapidly during early stages due to high initial rates, but the slope stabilized after 60 minutes when infiltration rates became constant, with clear differences in slope among intercropping patterns.

shows that M1 plots exhibited the highest values for all infiltration characteristic indices, indicating superior infiltration capacity compared to other plots. Initial and average infiltration rates followed the order M1 > M3 > M2 > CK, while stable infiltration rates and cumulative infiltration followed M1 > M2 > M3 > CK. The M1 infiltration indices differed significantly from other management patterns, while CK showed the lowest values.

Relationships Between Infiltration Characteristics and Soil Factors Correlation analysis () revealed that initial infiltration rate and average infiltration rate were extremely significantly negatively correlated with soil bulk density and silt content. Cumulative infiltration was significantly negatively correlated with bulk density and extremely significantly negatively correlated with silt content. Higher bulk density and silt content resulted in poorer infiltration performance. Infiltration characteristic indices were positively correlated with maximum water holding capacity, minimum water holding capacity, capillary water holding capacity, capillary porosity, non-capillary porosity, total porosity, and sand content. Clay content showed no significant effect on soil infiltration characteristics, likely because study area soils were dominated by silt (with clay content only 0.08%-0.34%).

Linear redundancy analysis further examined relationships between soil factors and infiltration characteristics. The selected soil factors explained 99.4% of variation in soil infiltration characteristics. Soil silt content showed the strongest negative correlation with infiltration indices, while non-capillary porosity showed the strongest positive correlation ([Figure 2: see original paper]). Contribution rates of soil factors to infiltration characteristics () ranked silt content highest (54.8%), followed by total porosity, non-capillary porosity, minimum water holding capacity, and maximum water holding capacity, indicating that soil particle composition, porosity, and water holding capacity were the main factors influencing infiltration.

Evaluation of Soil Infiltration Capacity To evaluate soil infiltration capacity under different intercropping patterns, PCA was performed on four infiltration characteristic indices: initial infiltration rate (X_1), stable infiltration rate (X_2), average infiltration rate (X_3), and cumulative infiltration (X_4). The first two principal components explained 98.28% of total variance, accurately representing soil infiltration capacity. The principal component equations were:

$$P_1 = 0.491X_1 + 0.458X_2 + 0.521X_3 + 0.545X_4$$
$$P_2 = -0.545X_1 + 0.740X_2 + 0.200X_3 - 0.348X_4$$

Standardized infiltration parameters were substituted into these equations to calculate scores for each intercropping pattern (). Soil infiltration capacity ranking () was M1 > M2 > M3 > CK, consistent with PCA results. The presence of herbaceous vegetation in M1 plots increased root density and loosened surface soil, enhancing infiltration capacity. In contrast, CK plots with weed removal had sparse roots and poor soil structure, resulting in the weakest infiltration capacity.

Model Fitting and Evaluation Since soil infiltration gradually slows over time, with high initial rates and low stable rates, three common empirical models were used to fit measured data (). Fitting accuracy varied among models and intercropping patterns (), with goodness-of-fit ranking as Jiang Dingsheng > Kostiakov > Horton. The Jiang Dingsheng model achieved R^2 values of 0.96-0.99 (average 0.97), Kostiakov model 0.93-0.96 (average 0.94), and Horton model 0.91-0.96 (average 0.93). The Jiang Dingsheng model best reflected actual soil water infiltration under different intercropping patterns.

Average relative error (MRE) and root mean square error (RMSE) were used to compare model performance (). For the Horton and Jiang Dingsheng models, MRE ranged 5.49%-39.95% and RMSE ranged 0.38-1.42 $mm \cdot min^{-1}$. For the Kostiakov model, MRE ranged 7.31%-15.33% and RMSE ranged 0.26-0.87 $mm \cdot min^{-1}$. The Jiang Dingsheng model showed smaller relative errors and better agreement with measured infiltration processes. Considering both goodness-of-fit and error magnitude, the Jiang Dingsheng model was most suitable for simulating soil infiltration processes in the gully region of Loess Plateau.

Discussion

This study used correlation and RDA analyses to examine factors influencing infiltration characteristics. Most orchard infiltration research has focused on different orchard types [?], with few reports on infiltration capacity changes under different intercropping patterns. Diverse management practices in agroforestry production improve ecosystem service functions [?] while altering soil physicochemical properties that directly or indirectly affect infiltration capacity. Understory crops and their root distributions significantly modify soil physical properties including particle size composition and porosity [?]. Understory vegetation can reduce raindrop impact, provide nutrients, improve soil structure [?], and incorporate organic matter through root systems [?]. Well-developed plant roots create preferential pathways after decomposition, promoting water infiltration [?]. Intercropping patterns also affect soil fauna communities, with understory grass significantly increasing micro-fauna populations [?], which further improves soil properties. Conversely, weed removal through manual cultivation compacts soil surfaces, reducing infiltration rates. This study found that plots with herbaceous layers exhibited significantly better infiltration than weeded plots, attributable to differences in root biomass, root activity, soil fauna communities, and anthropogenic disturbance among intercropping patterns. Additionally, M2 and M3 plots showed lower infiltration rates than M1 because crop and vegetable residues were removed at harvest, leaving only roots, resulting in lower vegetation density than permanent grass cover.

Soil physicochemical properties varied among intercropping patterns, directly and indirectly influencing infiltration capacity. Analysis of soil physical properties revealed that particle composition, porosity, and bulk density were the most important factors affecting infiltration in this region. Silt content, bulk density, and clay content negatively affected infiltration, while other indices showed positive effects, consistent with findings by Lyu et al. [?] and Li [?]. Clay content' s non-significant negative effect likely reflects its low proportion (0.08%-0.34%) compared to dominant silt and sand contents.

Soil infiltration models are important research tools that qualitatively or quantitatively evaluate infiltration processes. The Kostiakov model assumes infinite initial infiltration rate and approaches zero over time [?], which is unrealistic under vertical infiltration where gravity maintains stable infiltration rates. The Horton and Jiang Dingsheng models include constant terms reflecting stable infiltration under gravity [?], better aligning with soil water dynamics. Among the three models, Jiang Dingsheng' s showed highest fitting accuracy, making it most suitable for describing soil infiltration in the gully region of Loess Plateau, consistent with Wu et al.' s [?] findings in loess areas. Research on intercropping effects on infiltration capacity can inform orchard management decisions.

Conclusions

Through field double-ring infiltration experiments, this study observed soil infiltration processes under four fruit-agriculture intercropping patterns in apple orchards of the gully region of Loess Plateau, evaluated the applicability of three common infiltration models, analyzed effects of ten soil environmental factors on infiltration characteristics, and assessed soil infiltration capacity using principal component analysis. Key findings include:

1) Across four intercropping patterns, initial infiltration rates ranged 7.18-13.57 $mm \cdot min^{-1}$, stable infiltration rates 1.87-2.94 $mm \cdot min^{-1}$, average infiltration rates 3.36-5.65 $mm \cdot min^{-1}$, and cumulative infiltration 260.51-423.65 mm. Infiltration characteristic parameters differed significantly among patterns.

2) Correlation analysis showed that among selected environmental factors, infiltration characteristics were negatively correlated with soil bulk density, clay content, and silt content, but positively correlated with maximum, minimum, and capillary water holding capacities, capillary and non-capillary porosity, total porosity, and sand content.

3) RDA revealed that the ten soil environmental factors explained 99.4% of variation in infiltration characteristics. Soil silt content, porosity, water holding capacity, and bulk density were the primary factors influencing apple orchard soil infiltration in this region.

4) PCA indicated that the four selected infiltration indices contributed 98.28% to soil infiltration capacity evaluation. Soil infiltration capacity ranking was M1 > M2 > M3 > CK, demonstrating that intercropping crops in apple orchards effectively enhances infiltration capacity.

5) Model fitting accuracy for different intercropping patterns ranked as Jiang Dingsheng ($R^2 = 0.97$) > Kostiakov > Horton, with the Jiang Dingsheng model most accurately representing actual soil infiltration conditions in the gully region of Loess Plateau.

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