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Effects of Different Configurations of Farmland Shelterbelts on Soil Moisture and Nutrient Storage in the Hetao Irrigation District: Postprint

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Among them, machine learning is the discipline that studies how to enable computer systems to improve their performance through experience~[?], while deep learning is a branch of machine learning that achieves high-level abstract representations of data by constructing deep neural network models~[?]. In particular, neural networks in deep learning models are considered to possess universal approximation capability, that is, for any continuous function defined on a compact subset of $\mathbb{R}^n$, there exists a feedforward neural network that can approximate this function with arbitrary precision~[?, ?]. This theorem provides a theoretical foundation for the application of deep learning in complex function fitting tasks., Wang Dong1

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Abstract

Farmland shelterbelts, as an effective agricultural management practice for enhancing ecological and environmental benefits, are of great significance for improving soil physicochemical properties, ameliorating the ecological environment, and increasing crop yields. In the Hetao Irrigation District, three typical farmland shelterbelts (4-row, 5-row, and 8-row belts) were selected to measure soil properties at 0~100 cm depth and vegetation attributes of both shelterbelts and cropland at distances of 0.3 H, 0.7 H, 1 H, 2 H, 3 H, and 4 H from the shelterbelts during the 2019-2021 growing seasons. Soil moisture storage (SMS) and soil nutrient storages [carbon storage (SCS), nitrogen storage (SNS), and phosphorus storage (SPS)] were calculated. The results showed that: (1) Soil bulk density and soil clay content differed significantly among different shelterbelt systems in the horizontal direction, and all soil properties showed significant differences in the vertical direction. (2) Shelterbelts exhibited favorable water retention capacity and nutrient supply function, with the 4-row belt having higher soil moisture storage and nutrient storages than other belts, specifically SMS of 237.44 mm, SCS of 544.93 g · m-2, SNS of 953.72 g · m-2, and SPS of 859.04 g ·

m-2. (3) The 4-row belt demonstrated better overall growth performance, with an average tree height of 30.06 m and a diameter at breast height of 0.41 m, and the 4-row shelterbelt achieved the highest crop yield of 15.75 t • hm-2. (4) Redundancy analysis results revealed that in different shelterbelt systems, close relationships exist between environmental factors and ecosystem functions, soil characteristics are closely related to soil moisture and nutrient storages, and additionally, vegetation attributes are basically negatively correlated with SNS and SPS. In summary, the 4-row belt possesses the strongest water and nutrient supply capacity, and the findings of this study can provide an effective theoretical basis for shelterbelt construction and ecological restoration in ecologically fragile regions.

Full Text

Abstract

As an effective agricultural management practice for improving ecological and environmental benefits, farmland shelterbelts play a crucial role in enhancing soil physical and chemical properties, improving the ecological environment, and increasing crop yields. In the Hetao Irrigation District, three typical farmland shelterbelt configurations (four-row, five-row, and eight-row belts) were selected to measure soil properties (0–100 cm depth) and vegetation attributes at varying distances from the shelterbelts (0.3 H, 0.7 H, 1 H, 2 H, 3 H, and 4 H) during the 2019–2021 growing seasons. Soil moisture storage (SMS) and soil nutrient storage, including soil carbon storage (SCS), soil nitrogen storage (SNS), and soil phosphorus storage (SPS), were quantified. The results demonstrated that: (1) soil bulk density and clay content differed significantly among shelterbelt types in the horizontal direction, while all soil properties showed significant vertical variation; (2) shelterbelts exhibited strong water retention and nutrient supply functions, with the four-row configuration showing higher soil water and nutrient reserves than the five- and eight-row patterns (SMS = 237.44 mm; SCS = 544.93 $\mathrm{g \cdot m^{-2}}$; SNS = 953.72 $\mathrm{g \cdot m^{-2}}$; SPS = 859.04 $\mathrm{g \cdot m^{-2}}$); (3) the four-row shelterbelt achieved the best overall growth performance with an average tree height of 30.06 m and DBH of 0.41 m, and produced the highest crop yield of 15.75 $\mathrm{t \cdot hm^{-2}}$; and (4) redundancy analysis revealed close relationships between environmental factors and ecosystem functions across shelterbelt systems, with soil characteristics strongly linked to soil water and nutrient reserves, while vegetation attributes were negatively correlated with SNS and SPS. In conclusion, the four-row shelterbelt configuration demonstrated the strongest capacity for water and nutrient supply, providing a robust theoretical basis for shelterbelt construction and ecological restoration in ecologically fragile regions.

Keywords: farmland shelterbelt; soil properties; vegetation attributes; ecosystem function; farmland management

1.1 Study Area Overview

The experimental site is located at the Dengkou Desert Ecosystem National Observation Research Station in Dengkou County, Inner Mongolia, within the Hetao Irrigation District. The region experiences a temperate continental monsoon climate characterized by cold, long winters; brief spring and autumn periods; and hot summers. Annual precipitation averages 142 mm, concentrated primarily from July to September and accounting for approximately 70% of total annual rainfall. The evaporation rate reaches 2387.6 mm, with an average annual temperature of 7.6 °C and significant diurnal temperature variation. Sunshine is abundant, with annual sunshine hours of about 3000 h. The average annual groundwater level stands at 420 m. Irrigation within shelterbelts relies on flood irrigation using Yellow River water, while farmland employs mulched drip irrigation at 7-10 day intervals, with a total annual irrigation volume of 6300 $\mathrm{m}^3 \cdot \mathrm{hm}^{-2}$. The shelterbelt system comprises traditional small-grid, narrow-belt configurations, with main species including *Populus alba* var. *pyramidalis*, *Populus tomentosa*, *Populus popularis*, and *Sabina chinensis*. The primary crops associated with the shelterbelts are maize (*Zea mays*) and sunflower (*Helianthus annuus*).

1.2 Experimental Design

To investigate soil moisture and nutrient storage dynamics during crop growth, three shelterbelt plots were selected centered around a meteorological station. The shelterbelt configurations included four-row, five-row, and eight-row patterns of *Populus popularis*. Surveys began in May 2019, documenting tree species composition, height, belt length, spacing, and stand age. Adjacent farmland plots with maize crops were selected as experimental sites, receiving basal fertilizer applications of diammonium phosphate at 600 $\mathrm{kg} \cdot \mathrm{hm}^{-2}$ and topdressing urea at 600 $\mathrm{kg} \cdot \mathrm{hm}^{-2}$. Sampling points were established at distances of 0.3 H, 0.7 H, 1 H, 2 H, 3 H, and 4 H from the shelterbelt (where H represents average tree height), with three replicates per plot per sampling event.

1.3 Data Collection

1.3.2 Soil Moisture and Nutrient Storage Calculations

Soil moisture storage (SMS, mm), soil carbon storage (SCS, $\mathrm{g} \cdot \mathrm{m}^{-2}$), soil nitrogen storage (SNS, $\mathrm{g} \cdot \mathrm{m}^{-2}$), and soil phosphorus storage (SPS, $\mathrm{g} \cdot \mathrm{m}^{-2}$) were calculated using the following formulas:

$$SMS = \sum_{i=1}^{n} \theta_i \times BD_i \times T_i \times 10$$

where i represents the soil layer number, n is the total number of layers, θ_i and T_i are the soil mass water content and thickness of layer i, respectively, BD_i is the bulk density of layer i, and S is the plot area transfer coefficient.

$$SCS = \sum_{i=1}^{n} C_{fi} \times BD_i \times (1 - C_i) \times T_i \times 10$$

where C_{fi} represents the mass fraction of soil carbon in layer i, and C_i is the percentage of coarse particles (gravel, etc.) with diameter >2 mm in layer i.

Similar methods were used to calculate soil nitrogen storage (SNS) and soil phosphorus storage (SPS):

$$SNS = \sum_{i=1}^{n} N_{fi} \times BD_i \times (1 - C_i) \times T_i \times 10$$

$$SPS = \sum_{i=1}^{n} P_{fi} \times BD_i \times (1 - C_i) \times T_i \times 10$$

where N_{fi} and P_{fi} represent the mass fractions of soil nitrogen and phosphorus in layer i, respectively.

1.3.3 Vegetation Attribute Survey

Vegetation attributes were surveyed in July 2020. A RIEGL VZ-6000 series ground-based LiDAR scanner was used to obtain point cloud data. Data preprocessing involved 拼接, denoising, and normalization using GeoCue software to reduce redundancy. An improved progressive triangulation densification algorithm classified ground points, followed by irregular triangular network interpolation to generate high-resolution digital elevation models for point-cloud-ground separation. Individual plant data were extracted, including tree height, canopy size, DBH, crown volume, and under-branch height. Farmland vegetation attributes were assessed through high-angle photography and Adobe Photoshop 2018 image analysis to estimate vegetation coverage. Crop height and yield were measured through standard sampling and farmer surveys.

Fine root biomass density (FRBD) was calculated for both farmland and shelterbelts using a root auger (50 mm diameter) at 20 cm intervals to a depth of 100 cm. Soil samples were sealed in plastic bags, transported to the laboratory, sprayed with water, and manually extracted. Roots were oven-dried at 70 °C to obtain dry biomass, with FRBD calculated as:

$$FRBD = \frac{W_{root}}{V_{soil}}$$

where W_{root} is the dry root weight and V_{soil} is the soil volume.

1.4 Data Analysis and Processing

Statistical analysis was performed using Excel and SPSS software. One-way ANOVA was used for significance testing, with Duncan’ s method for multiple mean comparisons. Figures were generated using Origin software. CANOCO 5 software was employed for redundancy analysis (RDA) to determine the relative contribution of environmental factors to shelterbelt ecosystem functions. Soil characteristics (bulk density, pH, clay, silt, and sand content), vegetation attributes (height, DBH, canopy size, crown volume, under-branch height, fine root biomass density, and coverage) were used as environmental variables, with soil water and nutrient reserves as response variables.

2.1.1 Horizontal Variation in Soil Basic Properties

Figure 2 shows the horizontal variation in soil basic properties across different shelterbelt systems. Soil bulk density, pH, and particle composition varied significantly among the three configurations. Bulk densities were 1.63 $g \cdot cm^{-3}$, 1.62 $g \cdot cm^{-3}$, and 1.65 $g \cdot cm^{-3}$ for four-, five-, and eight-row belts, respectively, with no significant differences. Soils were weakly alkaline across all configurations (pH 8.70, 8.47, and 8.61, respectively). Particle composition showed significant differences, with generally low clay content and high sand content across systems. Average clay, silt, and sand contents were 4.47%, 43.99%, and 51.54% for four-row; 6.91%, 77.41%, and 15.68% for five-row; and 8.70%, 68.97%, and 22.33% for eight-row belts. The four-row configuration showed lower clay and silt but higher sand content compared to the other patterns.

2.1.2 Vertical Variation in Soil Basic Properties

Figure 3 illustrates vertical variation in soil properties across shelterbelt systems. Soil bulk density showed no significant vertical trend in the four-row belt, peaking at 1.68 $g \cdot cm^{-3}$ in the 20-40 cm layer. Soil pH varied little with depth, remaining weakly alkaline, with the 20-40 cm layer in the eight-row belt showing significantly lower pH. Particle composition varied significantly vertically: clay content was lowest in the four-row belt and increased with depth; silt content increased with depth while sand content decreased. Differences were significant within 0-60 cm, with sand content in the four-row belt showing significant variation across 0-20 cm.

2.2 Water, Nutrient, and Carbon Storage Among Different Shelterbelts

Soil water storage across horizontal distances is shown in Figure 4. Both horizontal and vertical variations were significant, following a trend of initial increase then decrease with distance from the belt. Minimum water storage occurred at 0.3 H for all configurations, with the four-row belt showing the lowest value (149.63 mm). Peaks occurred at 0.7 H for four-row (227.55 mm) and five-row

(290.80 mm) belts, and at 1 H for the eight-row belt (279.59 mm). Overall, the four-row belt exhibited the highest total water storage (237.44 mm), followed by five-row (236.75 mm) and eight-row (199.51 mm) configurations. Deep soil layers contributed more to total storage than surface layers, with 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm layers contributing 15.11%, 25.37%, 22.99%, 25.32%, and 11.28%, respectively. The 40-100 cm layer contributed significantly more than the 0-40 cm layer.

Soil carbon storage at 0-20 cm depth averaged 103.92, 166.89, and 149.41 $g \cdot m^{-2}$ for four-, five-, and eight-row belts, respectively, accounting for 22.76%, 20.41%, and 20.28% of total storage. The 20-40 cm, 40-60 cm, 60-80 cm, and 80-100 cm layers contributed 20.28%, 18.34%, 18.30%, and 20.32%, respectively. Total carbon storage in the four-row belt (544.93 $g \cdot m^{-2}$) exceeded that of five-row (406.27 $g \cdot m^{-2}$) and eight-row (418.76 $g \cdot m^{-2}$) configurations. Horizontally, carbon storage decreased gradually with distance in the four-row belt, while the five-row pattern showed an initial increase then decrease.

Soil nitrogen and phosphorus storage varied significantly with distance (Figure 4). Nitrogen storage in the four-row belt decreased initially then increased, reaching a minimum of 815.70 $g \cdot m^{-2}$ at 0.7 H and maximum of 1042.67 $g \cdot m^{-2}$ at 4 H. The five-row belt showed fluctuating increases, peaking at 3 H (924.08 $g \cdot m^{-2}$), while the eight-row belt decreased gradually. The four-row belt achieved the highest total nitrogen storage (953.72 $g \cdot m^{-2}$), significantly exceeding other configurations. Phosphorus storage in the four-row belt followed a similar pattern, with the highest total storage (859.04 $g \cdot m^{-2}$). The five-row belt showed an initial increase then decrease, while the eight-row belt exhibited the opposite trend.

2.3 Vegetation Attributes of Different Shelterbelts

Vegetation attributes are compared in Table 2. The four-row shelterbelt showed significantly greater average tree height (30.06 m) and DBH (0.41 m) than other configurations. Crown size and volume were significantly lower in the four-row belt, while under-branch height (1.09 m) was significantly higher. Individual plant biomass was significantly greater in the four-row belt. Crop yield was highest in the four-row configuration (15.75 $t \cdot hm^{-2}$), significantly exceeding the five-row belt (9.29 $t \cdot hm^{-2}$) but not significantly different from the eight-row belt (15.64 $t \cdot hm^{-2}$). Overall plant height and vegetation coverage showed no significant differences among systems.

2.4 Relationships Between Environmental Factors and Ecosystem Services

Redundancy analysis results (Figure 5) show the relative contribution of influencing factors to soil water and nutrient reserves. In the four-row belt, soil bulk density and clay content contributed most to variation, with height showing negative correlation with water and nutrient storage and coverage negatively correlated with all storage variables. In the five-row belt, height was positively correlated with storage, while silt content showed strong positive correlations. In the eight-row belt, height and sand content were positively correlated with storage. Across all systems, soil factors contributed most to variation (75.63% in four-row, 85.65% in five-row, 72.93% in eight-row), with vegetation attributes contributing less. The four-row belt was most strongly influenced by soil factors (48.58% contribution), while the five-row belt showed the highest vegetation attribute contribution (43.04%). Overall, soil characteristics were the dominant drivers of water and nutrient storage, with vegetation attributes playing secondary roles.

3 Discussion

Farmland shelterbelts improve environmental conditions and soil quality at varying rates through the interdependent and ecologically complementary relationship between trees and crops. In this study, soil properties varied significantly among shelterbelt systems. Similar cultivation practices and fertilization management resulted in non-significant differences in soil bulk density and pH, highlighting the important influence of human activities on soil properties. However, significant differences in soil particle composition suggest that different shelterbelt configurations create distinct microclimatic effects that may influence long-term soil development. Spatial variability in soil texture may also contribute to these differences. Soil mechanical composition affects water-holding capacity, hydraulic conductivity, and nutrient storage conditions, thereby improving soil ecological functions. This study demonstrates that different shelterbelt systems have varying nutrient storage capacities, consistent with previous research. Shelterbelt root systems enhance soil aeration, and the spatial distribution of fine roots directly influences water absorption and soil organic carbon accumulation, promoting carbon sequestration and improving soil chemical cycling. Litter decomposition and microbial activity improve soil structure, increase organic matter content, and enhance soil fertility and sustainable productivity.

Significant differences in soil water content and storage occurred horizontally, showing an initial increase then decrease with distance, indicating severe water competition near shelterbelt edges that reduces crop yields. Studies have shown that root pruning significantly increases soil water content and crop yields. In this study, soil nitrogen and phosphorus storage showed non-significant differences with distance but generally increased then decreased from 0.7 H, demonstrating competition between shelterbelts and farmland for nutrients. Crop yield reductions are more pronounced closer to shelterbelts due to shading effects. Vertically, soil properties also varied significantly, with 0–40 cm layers contributing more to water storage than 40–100 cm layers, indicating greater water uptake by crops and shelterbelts in shallow layers. Fine root biomass density decreased with depth (0–100 cm), with most roots concentrated in 0–60 cm, influencing water and nutrient utilization. Resource distribution differences within shelterbelt networks create competition and synergism among species, affecting resource utilization by both shelterbelts and crops.

Rational arrangement of shelterbelt width, structure, orientation, and spacing modifies environmental factors (climate, water, soil) to improve ecosystem functions and mitigate agricultural natural disasters. This study found the four-row configuration provided the best protection benefits. Differences in water and nutrient utilization due to competition resulted in varying vegetation growth states, making structural selection crucial for shelterbelt construction. This study examined several mature shelterbelt patterns with good nutrient supply functions. In practice, shelterbelt construction should incorporate fertilization and agricultural management practices that vary by restoration year and shelterbelt configuration to reduce competition and maximize ecological benefits. The four-row pattern' s superior water and nutrient supply capacity makes it more suitable for local conditions. Shelterbelts improve the ecological environment and stabilize ecosystems, playing important protective and regulatory roles in vulnerable ecological regions. Nature-based solutions for sustainable integrated agricultural management align with these findings. As environmental concerns grow, understanding how different shelterbelt patterns affect soil properties and environmental factors becomes increasingly important for realizing local ecosystem benefits.

4 Conclusion

This study examined three mature farmland shelterbelt systems in the Hetao Irrigation District, measuring soil properties, vegetation attributes, and ecosystem functions (soil water and nutrient storage) to evaluate ecological benefits. The conclusions are: (1) Soil bulk density showed little variation among systems (1.63, 1.62, and 1.65 $g \cdot cm^{-3}$ for four-, five-, and eight-row belts), and all soils were weakly alkaline (pH 8.70, 8.47, and 8.61), but soil properties varied significantly in both horizontal and vertical directions. (2) Vegetation attributes differed among systems, with the four-row belt showing superior growth (average height 30.06 m, DBH 0.41 m) and highest crop yield (15.75 $t \cdot hm^{-2}$). (3) Shelterbelts demonstrated good water retention and nutrient supply functions, but with significant horizontal and vertical variations; the four-row belt showed the highest soil water and nutrient reserves (SMS = 237.44 mm; SCS = 544.93 $g \cdot m^{-2}$; SNS = 953.72 $g \cdot m^{-2}$; SPS = 859.04 $g \cdot m^{-2}$), indicating stronger water and nutrient supply capacity than other configurations. (4) Redundancy analysis revealed close relationships between environmental factors and ecosystem functions, with soil factors most closely related to water and nutrient storage, suggesting that both shelterbelt configuration and actual growth conditions should be considered in practice.

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