frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 21 February 2025
DOI 10.3389/fenvs.2025.1477459

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RECEIVED 07 August 2024
ACCEPTED 27 January 2025
PUBLISHED 21 February 2025

CITATION
Guo X, Yang G, Ma Y, Qiao S, Chen H, Liu F and Ma S (2025) Effect of plant spacing on the soil properties and fertility of *Pinus sylvestris* var. *mongolica* plantations in sandy land of the agro-pastoral ecotone in northern China.
Front. Environ. Sci. 13:1477459.
doi: 10.3389/fenvs.2025.1477459

Effect of plant spacing on the soil properties and fertility of *Pinus sylvestris* var. *mongolica* plantations in sandy land of the agro-pastoral ecotone in northern China

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Duolun County in Inner Mongolia, a typical agro-pastoral ecotone, serves as an important ecological barrier in northern China. To combat windblown sand and land degradation, the government has established extensive *P. sylvestris* var. *mongolica* Litv. plantations. This study investigated the effects of three afforestation modes (2 m × 6 m, 2 m × 3 m, and 1 m × 1 m), which were used as treatments, and unafforested bare sandy land as a control, on soil physicochemical properties and soil fertility. The results showed that row spacing significantly affected soil characteristics and soil fertility. With an increase in plant row spacing, the content of coarse particles decreased, while fine particle content, soil water and nutrient levels, and soil porosity increased. Additionally, the bulk density of the soil decreased, particularly in the topsoil. However, planting *P. sylvestris* var. *mongolica* in sandy land increased the soil's electrical conductivity, which declined with wider spacing. Soil fertility of different types of plantation forests was evaluated using the soil quality index (SQI) and grey relation analysis (GRA) combined with the minimum dataset (MDS), and the results showed that: 2 m × 6 m > 2 m × 3 m > 1 m × 1 m > bare sandy land. The results of the two evaluation systems were consistent and their TDS (total dataset) and the MDS in the two evaluation systems were significantly positively correlated (SQI: $P < 0.05$, $R^2 = 0.9384$). GRA: $P < 0.05$, $R^2 = 0.8929$). Compared with bare sand, the soil bulk density and pH of 2 m × 6 m plantation was 13.72% and 4.02% lower; the soil water content and total porosity were 49.75% and 27.88% higher; the soil organic matter, total N, P, and K were 250.99%, 136%, 100%, and 19.53% higher; the available N, P, and K were 29.95%, 94.3%, and 12.71% higher; and the clay, silt and very fine sand contents were 242.55%, 343.1%, and 17.21% higher, respectively. These findings indicate that the development of soil characteristics and fertility accumulation are not ideal when the planting density is larger, among the above three afforestation modes, 2 m × 6 m plantation forests can better improve the soil characteristics and fertility quality of sandy soils.

KEYWORDS

Hunshandak sandy land, minimum data set, grey relation analysis, soil quality index, soil fertility quality

1 Introduction

Land desertification has emerged as a global phenomenon that threatens human livelihoods and activities. It is no longer merely an ecological or environmental problem; rather, it has evolved into an important economic and social problem (Qiu et al., 2024). With the deterioration of the ecological environment, the importance of vegetation communities has become increasingly recognized; to cope with ecological problems such as soil erosion and desertification, many countries have developed plantations to resist these natural disasters (Mongil-Manso et al., 2022; Sun et al., 2023). China faces one of the most severe land desertification problems in the world and is also a leader in desertification research and control. Since the 1970s, the government has initiated large-scale forestry projects such as the well-known "Three Norths" shelterbelt project (Guo et al., 2024).

The planting method of sand-fixing shelterbelts in China is usually a row belt with different spacing. Variation in planting spacing results in differences in plant density and, consequently, differences in stand structure (Yan et al., 2015). Factors affecting the growth of forest trees include site conditions, planting time, and planting density, with the latter being the most controllable (Smith and Brennan, 2006). Research has shown that different densities or spacing of plantations not only significantly impact soil characteristics and vegetation growth (Mallik et al., 2008; Prasad et al., 2010; Benomar et al., 2013; Sirohi and Bangarwa, 2017; Farooq et al., 2019) but also affect wood quality and yield (Kang et al., 2004; Cassidy et al., 2013). In recent years, the influence of plantations on soil quality has become a focal research topic, including the effects of forest age (Jin et al., 2008; Fuss et al., 2019; Guo et al., 2024), tree species (Augusto et al., 2002; Yang et al., 2021), and site conditions (Zhang et al., 2018). Soil quality is the quantitative analysis of the total properties of the soil, which is usually expressed through the biological and physicochemical properties of the soil (Guo et al., 2024).

The agro-pastoral ecotone is a semi-arid ecological transition zone connecting the agricultural areas of eastern China with the pastoral grassland of the west. This region is not only marginal for agricultural production but also ecologically fragile (Huang et al., 2007). Due to the combined effects of natural conditions and human activities, land degradation has emerged as the most pressing environmental problem in the agro-pastoral ecotone. In many areas, this degradation is characterized by the simultaneous occurrence of sandy desertification and soil erosion, resulting in soil barrenness, desertification, and aridification (Liu et al., 2018; Yang et al., 2020; Wuyun et al., 2022). The study area was located within a typical agricultural and pastoral zone that includes one of China's four major sandy regions, the Hunsandak Sandy Land, which is a key area for the Three-North Sheltering Forest Construction Project. *Pinus sylvestris* var. *Mongolica* Litv. is the most representative plantation species in this region. Numerous shelter forests of *P. sylvestris* var. *mongolica* with varying tree densities and row spacings have been established for sand fixation. Long-term community succession has altered stand growth, Some of these *P. sylvestris* var. *mongolica* plantations showed declines, yellowing, and tree mortality, and the performance of the plantations varied at different plant spacing.

As the foundation for plant growth and survival, soil plays a crucial role in the growth of forest trees. Although there are many relevant studies on plantations and soils mentioned above, there are few studies examining soil fertility across various stand structures, particularly within the agro-pastoral ecotone. Most researchers have relied on a single evaluation method to examine the soil quality of plantations, leading to a general lack of verification of results. Therefore, in order to elucidate the differences in soil properties of plantation forests with different spacing. We took three plantations of *P. sylvestris* var. *mongolica* with different spacing in the sandy agro-pastoral ecotones of China as the research object. We evaluated the quality of soil fertility by two methods (soil quality index and grey relational analysis) to determine the existing afforestation modes suitable for soil restoration in the study area. We hypothesized that planting *P. sylvestris* var. *mongolica* in the sandy land within the agro-pastoral ecotone would positively impact soil development and restoration and that this impact would be variable across soil depths. We further hypothesized that plant spacing would significantly influence soil properties, with appropriate spacing effectively improving soil fertility. The results of this study can serve as a reference for the construction and management of plantations in agro-pastoral ecotones and other fragile ecological zones.

2 Materials and methods

2.1 Description of the study area

The study area (Figure 1) is located in the Xilin Gol League of China, at the southern edge of the Inner Mongolia Plateau, near the northern foothills of the eastern end of the Yinshan Mountains and along the southern edge of the Hunshandak Sandy Land. Duolun County, situated 180 km from Beijing, exemplifies a typical agro-pastoral ecotone in northern China. This region has a continental climate that transitions from temperate semi-arid to semi-humid (Yan et al., 2012). The selected planting area of *P. sylvestris* var. *mongolica* was located within the Hunshandak Sandy Land in Duolun County, with geographical coordinates of 116°45′E, 42°15′N, at an altitude of 1,261 m. This area experiences windblown sand in the spring and autumn months, with an

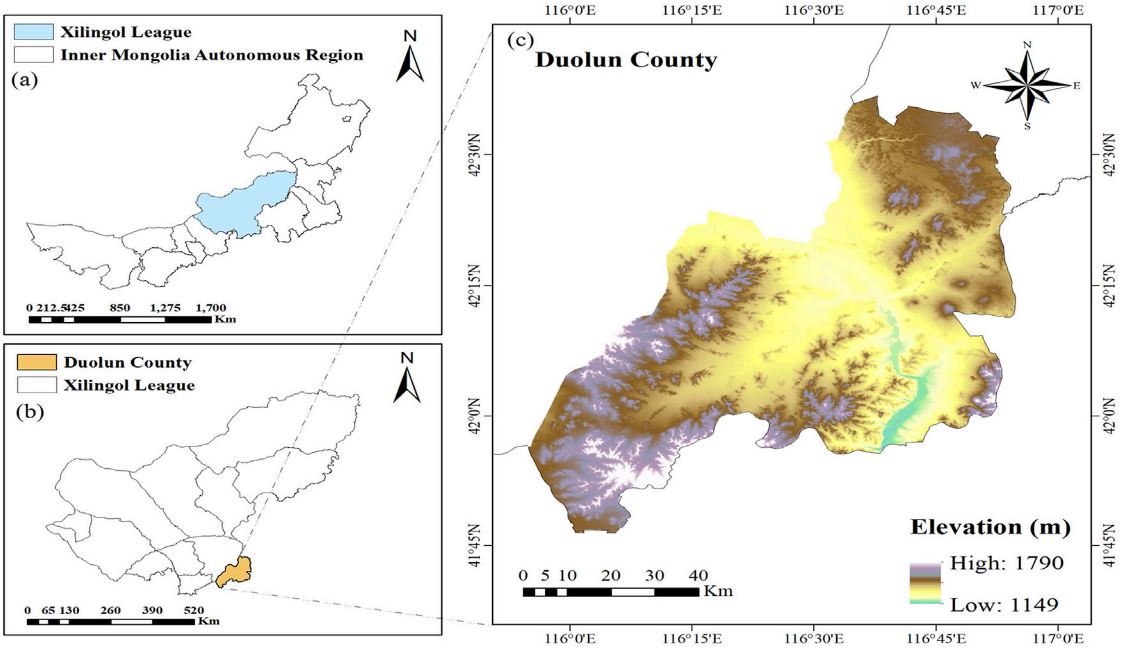

FIGURE 1
Maps of the study area showing the locations of **(A)** Xilingol League in the Inner Mongolia Autonomous Region, **(B)** Duolun County within the Xilingol League, and **(C)** A digital elevation map of Duolun County.

average annual wind speed of 3.6 m/s and an average annual precipitation of 385 mm. The frost-free period is about 100 days, with an average annual sunshine duration of 3,000 h and an average annual temperature of 1.6°C. *P. sylvestris* var. *mongolica* is a deep-rooted species, forest growth faster, light-loving, adaptable, can adapt to more arid sandy and gravelly sandy soil areas, therefore often used as the Three-North regions of the shelter forests and sand afforestation of the main tree species. In May 2000, the state launched the Beijing-Tianjin sand source control project, aimed at combating desertification in Duolun County through the establishment of plantations in the Hunshandak Sandy Land. Subsequently, Duolun County implemented a series of forestry ecological construction projects based on millions of acres of *P. sylvestris* var. *mongolica* plantations (Office of the People's Government of Duolun County, 2024). The study plot, was initially bare sand before afforestation, is now stabilized by vegetation. The main soil type in this region is aeolian sandy soil, with the zonal plant species including *Leymus chinensis* (Trin. ex Bunge) Tzvelev, *Cleistogenes squarrosa* (Trin.) Keng, and *Agropyron cristatum* (L.) Gaertn. (Yang et al., 2013; Dai et al., 2022; Liu et al., 2022; Zongfan et al., 2022).

2.2 Sample plot setting

A field survey of a *P. sylvestris* var. *mongolica* botanical garden in the study area was conducted in August 2023. The survey identified three of the most widely used afforestation models as the research objects, each of which was planted in 2001. Before the seedlings were planted, the hole preparation should be carried out in advance, and the size of the planting hole of the plantation in Duolun County is generally 60 cm × 60 cm × 50 cm. The planting areas were all located on sandy land, with consistent site conditions; the main differences among them was the plant and row spacing. We used Type I, Type II, and Type III to represent the three different models and selected unafforested bare sandy land as the control plot (CK) (Figure 2). Three replicate plots, each measuring 15 m × 15 m, were set up in each of the three afforestation types. The basic information for the sample plots is listed in Table 1.

2.3 Soil sample collection and analysis

Three soil sampling points were evenly distributed along the diagonals of each sample plot, and 40 cm soil profiles were obtained at these sampling points. Undisturbed soil was collected in two layers from the bottom to the top at depths of 0–20 cm and 20–40 cm, respectively. A total of 72 soil samples were collected in August 2023. The soil samples were used to determine soil water content, bulk density, and porosity, collected using a 100 cm^3 cutting ring. For soil particle size, pH, conductivity, nutrient analysis, and other indicators, plant residues removed were removed from the samples, which were then packed into sealed bags and brought back to the laboratory, where they were air-dried in a light-protected environment for the analysis.

The soil moisture content, bulk density, and porosity were determined by drying and weighing, according to the soil environmental protection standards issued by the PRC (National Forestry and Grassland Administration, 1999). The soil pH was determined by the potentiometric method, and the soil conductivity

Type Ⅰ 2m×6m

Type Ⅱ 2m×3m

Type Ⅲ 1m×1m

CK

FIGURE 2
Study site photos.

TABLE 1 Basic information on sample plots.

Plot type	Tree species	Plant spacing × row spacing (m × m)	Sandy land types	Herbaceous species
Type I	*Pinus sylvestris* var. *Mongolica* Litv	2 × 6	Fixed sandy land	*Cleistogenes squarrosa* (Trin.) Keng, *Setaria viridis* (L.) P. Beauv., *Leymus chinensis* (Trin. ex Bunge) Tzvelev, *Artemisia desertorum* Spreng., *Corispermum hyssopifoliu* L., *Agropyron cristatum* (L.) Gaertn., *Thalictrum aquilegiifolium* var. *sibiricum* Linnaeus, *Chenopodium acuminatum* Willd., *Artemisia sieversiana* Ehrhart ex Willd
Type II		2 × 3		
Type III		1 × 1		
CK	None	—	Bare sandy land	*S. viridis, C. squarrosa, A. desertorum, A. cristatum*

was determined by the electrode method. The combustion oxidation-titration method was used to measure the soil's organic matter content, and the Kjeldahl method was used to determine the soil total nitrogen content. The total potassium content of the soil was determined by acid-solubilization-flame photometry. The available nitrogen content was determined by the alkaline hydrolysis-diffusion method, the available phosphorus content was determined by sodium hydrogen carbonate solution-Mo-Sb anti-spectrophotometric method, and the available potassium content was measured using a CH_3COONH_4 extraction-flame photometer. We used an Analysette22 MicroTecPlus laser particle size analyzer (Fritsch GmbH, Idar-Oberstein, Germany) to determine the volume fraction of soil particle sizes acr the different types of plots.

2.4 Soil fractal dimension

The soil was divided into seven categories based on the United States Department of Agriculture (USDA) soil texture grading standards: clay ($r < 0.02$ mm), silt (0.02 mm $< r < 0.05$ mm), very fine sand (0.05 mm $< r < 0.1$ mm), fine sand (0.1 mm $< r < 0.25$ mm), medium sand (0.25 mm $< r < 0.5$ mm), coarse sand (0.5 mm $< r < 1$ mm), and very coarse sand (1 mm $< r < 2$ mm). Based on the particle size volume data obtained from the laser particle size analyzer, the volume fractal dimension was obtained using the following formula (Tyler and Wheatcraft, 1989):

$$\frac{V_{(r<R)}}{VT} = \left(\frac{R}{R_{\max}}\right)^{3-D} \tag{1}$$

Taking the logarithms of both sides of Equation 1 provides the formula for calculating the fractal dimension of the soil:

$$lg\left(\frac{V_{(r<R)}}{VT}\right) = (3-D)lg\left(\frac{R}{R_{max}}\right) \tag{2}$$

where V is the total volume of soil smaller than the particle size R (%); VT is the total volume of soil measured (%); R is the average value of the particle size between the two sieve particle size classes R_i and R_{i+1} (mm); R_{max} is the largest particle size in the soil particle size grading, where the largest particle size of the soil in this study was 2 mm; and D is the volumetric fractal dimension of the soil particles, where the left and right sides of Equation 2 are the longitudinal and transverse coordinates, respectively, of the fitted linear regression equation. The difference in the linear slope value is the soil fractal dimension D.

2.5 Comprehensive evaluation of soil fertility

Three spacing patterns of *P. sylvestris* var. *mongolica* planted in 2001 (2 m × 6 m, 2 m × 3 m, and 1 m × 1 m) in the sandy land of the agro-pastoral ecotone were used to analyze changes in forest soil characteristics. We used two methods, the soil quality index method and the grey correlation degree, to evaluate the soil fertility.

2.5.1 Determination of the membership degree of the evaluation indices

To solve the problem of differing dimensions among evaluation indicators, we normalized the indicators through the membership degree function. The membership function used in this study was expressed as Equation 3 (Cherubin et al., 2016; Hemati et al., 2020):

$$F(x) = A\Big/\left(1 + \left(X_i/X_0\right)^B\right) \tag{3}$$

where A is the maximum membership degree of the evaluation index with the value 1; X_i is the value of each evaluation index; X_0 is the average value of each evaluation index; B is the slope of the equation, where the value −2.5 indicates that the index has a positive effect on soil quality, and 2.5 means that the index has a negative effect on soil quality.

2.5.2 Construction of the minimum data set

In this study, 15 physical and chemical property indices related to soil fertility were selected to establish the dataset, and a principal component analysis (PCA) was used to determine the minimum dataset by combining the Norm values (comprehensive loading values) with Pearson correlation analysis. To avoid redundancy between indicators, only those with higher factor loadings and low correlations were retained in the minimum dataset (Larson and Pierce, 1994; Guo et al., 2024). The Norm values were calculated as Equation 4:

$$N_{ia} = \sqrt{\sum\nolimits_1^a \left(u_{ia}^2\lambda_a\right)} \tag{4}$$

where N_{ia} is the comprehensive factor load of index i in the principal component a; u_{ia} and λ_a are the factor load values and corresponding eigenvalues of index i in principal component a.

2.5.3 Soil quality index (SQI) method

PCA was performed on the standardized evaluation indices to calculate the variance contribution and determine the weight of each index. The weighted summation index method was then used to calculate the soil fertility quality. The specific mathematical model was as Equation 5 (Vasu et al., 2016; Paul et al., 2020):

$$SQI = \sum_{j=1}^{n} K_j \times S_j \tag{5}$$

where n is the total number of soil indicators, and K_j and S_j are the weights and membership values of the jth soil index, respectively.

2.5.4 Grey relation analysis

Grey system theory was introduced by Professor Deng Julong of Huazhong University of Science and Technology in China (Julong, 1989). Grey relation analysis is an important part of grey system theory. The principle behind it is that when the geometry shapes of curves formed by several statistical series are similar, i.e., there similar trends in the curves, the correlation is high. The proximity of the evaluation object to the ideal object is represented by the association order. This method is often used to compare and rank the evaluation objects, and the better the evaluation object, the closer it is to the ideal sequence (Liu and Forrest, 2010; Chen, 2023). The steps of grey relation analysis are as Equations 6–10:

(1) Establish the evaluation object sequence and the ideal sequence.

The ideal object order is:

$$X_t = \{X_t(1), X_t(2), ..., X_t(\mathrm{n})\} \tag{6}$$

The sequence of evaluation objects is as follows:

$$X_\mathrm{p} = \left\{X_p(1), X_p(2), ..., X_p(\mathrm{n})\right\} \tag{7}$$

where p = 1, 2, . . . , m.

(2) The grey relation factor is calculated as

$$\xi_p(h) = \frac{min_p\ min_\mathrm{h}\left|X_t(h) - X_p(h)\right| + \rho max_p\ max_h\left|X_t(h) - X_p(h)\right|}{\left|X_t(h) - X_p(h)\right| + \rho max_p\ max_h\left|X_t(h) - X_p(h)\right|\Big|} \tag{8}$$

where $|X_t(h)-X_p(h)|$ represents the absolute difference between data sequences X_t and X_p at a particular measurement point h. The term $min_p\ min_h|X_t(h)-X_p(h)|$ represents the minimum absolute difference corresponding to factor p = 1,2, . . . ,m at the same point h = 1,2, . . . , which is called the second-order minimum difference; $max_p\ max_h|X_0(h)-X_p(h)|$ represents the second-order maximum difference, and ρ is a resolution coefficient with a value between 0 and 1 that is usually set to 0.5.

(3) Grey relevance is determined as follows:

$$\gamma_p = \frac{1}{n}\sum_{h=1}^{n}\xi_p(h) \tag{9}$$

$$R_p = \sum_{h=1}^{n}\xi_p(h)\cdot K_p \tag{10}$$

Here, γ_p is the equal weight relevance; n is the number of evaluation indicators determined. R_p is the weighted relevance, and K_p is the weight of the soil index.

TABLE 2 Soil particle composition and fractal dimension characteristics.

Soil particle size	Soil depth	Sample plot type			
		I	II	III	CK
Clay	0–20 cm	0.90 ± 0.06Aa	0.78 ± 0.03Ba	0.69 ± 0.03Ca	0.38 ± 0.03Da
	20–40 cm	0.71 ± 0.04Ab	0.60 ± 0.03Bb	0.52 ± 0.05Cb	0.09 ± 0.02Db
Silt	0–20 cm	12.15 ± 0.39Aa	10.75 ± 0.59Ba	10.37 ± 0.53Ba	2.62 ± 0.37Ca
	20–40 cm	8.41 ± 0.41Ab	7.27 ± 0.54Bb	7.13 ± 0.46Bb	2.02 ± 0.11Cb
Very Fine Sand	0–20 cm	26.78 ± 0.91Aa	24.61 ± 0.61Ba	24.09 ± 0.86Ba	21.60 ± 0.47Ca
	20–40 cm	24.29 ± 0.62Ab	21.90 ± 0.94Bb	21.08 ± 0.85Bb	21.97 ± 0.65Ca
Fine Sand	0–20 cm	54.48 ± 0.72Ca	55.96 ± 0.94Ba	55.92 ± 1.23Ba	58.63 ± 0.74Aa
	20–40 cm	54.87 ± 0.88Ca	56.15 ± 1.19Ba	55.88 ± 1.25Ba	58.28 ± 0.56Aa
Medium Sand	0–20 cm	3.41 ± 0.27Da	5.19 ± 0.42Ca	6.15 ± 0.42Ba	11.09 ± 0.51Aa
	20–40 cm	9.69 ± 0.50Db	11.52 ± 0.67Cb	12.73 ± 0.47Bb	13.05 ± 0.32Ab
Coarse Sand	0–20 cm	1.83 ± 0.11Ca	1.95 ± 0.06Ba	1.98 ± 0.04Ba	3.31 ± 0.30Aa
	20–40 cm	1.62 ± 0.14Cb	1.84 ± 0.06Bb	1.88 ± 0.09Ba	2.51 ± 0.38Ab
Very Coarse Sand	0–20 cm	0.45 ± 0.02Ca	0.76 ± 0.03Ba	0.80 ± 0.05Ba	2.36 ± 0.55Aa
	20–40 cm	0.41 ± 0.02Ca	0.72 ± 0.03Ba	0.78 ± 0.03Ba	2.08 ± 0.49Ab
Fractal dimension	0–20 cm	2.27 ± 0.01Aa	2.24 ± 0.01Ba	2.22 ± 0.01Ca	2.09 ± 0.01Da
	20–40 cm	2.23 ± 0.01Ab	2.20 ± 0.01Bb	2.18 ± 0.01Cb	1.89 ± 0.01Db
R^2	0–20 cm	0.91	0.92	0.92	0.90
	20–40 cm	0.92	0.92	0.93	0.91

Note: Data are given as mean ± standard deviation. Different capitalized letters in the same soil depth indicate significant differences between sample plots, while different lowercase letters in the same sample plot indicate significant differences between different soil depths ($P < 0.05$). The figures and tables below also apply.

2.6 Data processing and analysis

We used one-way ANOVA and LSD multiple comparisons to determine whether there were statistically significant differences in soil physicochemical properties across plantations with different cropping patterns. The correlations between soil properties and vegetation characteristics were analyzed using Pearson correlation. PCA was used to determine the index weights of soil quality, which were then employed in the index method to evaluate soil fertility. The reliability of the minimum dataset was verified by linear regression analysis. All data analyses were performed using SPSS 26.0 software, with statistical significance defined as $P < 0.05$. Data visualization was performed using Origin Pro 2021.

3 Results

3.1 Physical properties of soils

3.1.1 Soil particle composition and fractal dimension

The contents of clay and silt at the same soil depth showed a pattern of Type I > Type II > Type III > CK (Table 2), while the contents of medium sand, coarse sand, and very coarse sand in the soil showed the opposite trend. There were significant differences in the soil clay and medium sand contents among different plots ($P < 0.05$). However, there were no significant differences in soil silt, very fine sand, fine sand, coarse sand, or very coarse sand contents between sample Type II and sample Type III ($P > 0.05$). In different soil depths within the same plantation land, the contents of clay, silt and very fine sand varied between the 0–20 cm and 20–40 cm layers, and there were significant differences among soil layers ($P < 0.05$). The variation trend for medium sand and very coarse sand was the opposite. The content of medium sand was significantly different among soil layers ($P < 0.05$), but the content of very coarse sand was not significantly different among soil layers ($P > 0.05$). The variation in soil fine sand content showed no clear pattern. The variation of the fractal dimension of soil particle size in different soil layers was in the order Type I > Type II > Type III > CK. All plots showed the pattern 0–20 cm > 20–40 cm, and there were significant differences between each plot and each soil depth ($P < 0.05$). The wider afforestation plant spacing increased the content of fine soil particles and the fractal dimension of the soil.

3.1.2 Soil porosity characteristics

Soil capillary porosity, non-capillary porosity, and total porosity were in the order 0–20 cm > 20–40 cm in all plots (Table 3). Except for the bare sandy land, there were significant differences in the sample plots of forest land in all soil layers ($P < 0.05$), while there was

TABLE 3 Soil porosity characteristics.

Sample plot type	Soil depth	Soil porosity characteristics		
		Capillary porosity	Non-capillary porosity	Total porosity
I	0–20 cm	29.38 ± 0.81Aa	3.78 ± 0.34Aa	33.15 ± 0.96Aa
	20–40 cm	27.54 ± 1.39Ab	3.56 ± 0.23Ab	31.11 ± 1.43Ab
II	0–20 cm	28.25 ± 1.06Ba	3.48 ± 0.10Ba	31.73 ± 1.09Ba
	20–40 cm	26.05 ± 0.83Bb	3.16 ± 0.16Bb	29.20 ± 0.78Bb
III	0–20 cm	27.95 ± 0.71Ba	3.35 ± 0.20Ba	31.30 ± 0.86Ba
	20–40 cm	25.74 ± 0.65Bb	3.04 ± 0.14Bb	28.78 ± 0.62Bb
CK	0–20 cm	22.67 ± 0.58Ca	2.62 ± 0.11Ca	25.29 ± 0.60Ca
	20–40 cm	22.39 ± 0.75Ca	2.57 ± 0.08Ca	24.96 ± 0.71Ca

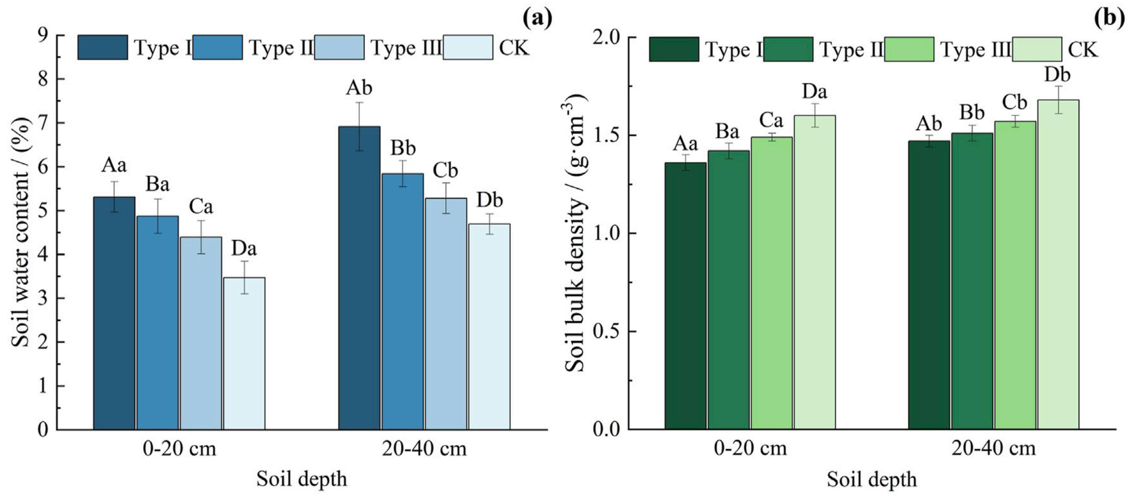

FIGURE 3
(A) Soil water content and **(B)** bulk density in different sample plots.

no significant difference among soil layers in bare sandy land ($P > 0.05$). The changes in soil capillary porosity, non-capillary porosity, and total porosity were in the order Type I > Type II > Type III > CK. There was no significant difference between Type II and Type III in the two soil layers ($P > 0.05$), but there was a significant difference between the two plots and Type I and CK ($P < 0.05$). Overall, the construction of plantations on bare sand significantly improved the soil porosity. Type II and Type III had similar effects on soil porosity; Type I had the best effect on soil porosity, and the total porosity of Type I was 1.25–1.31 times that of bare sand.

3.1.3 Soil water content and bulk density characterization

At the same soil depth, the soil water contents of the plantations with different plant spacing were in the order Type I > Type II > Type III > CK, and the pattern for the soil bulk density was the opposite (Figure 3). In different soil depths of the same sample plot, the soil water content and soil bulk density were in the order 0–20 cm < 20–40 cm. There were significant differences in soil water content and bulk density among different soil depths and plots ($P < 0.05$). The results showed that the difference in afforestation spacing had significant effects on the soil water content and bulk density.

3.2 Chemical properties of soils

3.2.1 Soil pH and electrical conductivity characteristics

At the same depth, the pH of the soil with different planting spacing was in the order Type I < Type II < Type III < CK. Soil electrical conductivity (EC) was in the order CK < Type I < Type II < Type III (Figure 4). In different soil depths of the same sample plot, soil pH and EC were in the order 0–20 cm > 20–40 cm. There were significant differences in soil EC among different soil depths and plots ($P < 0.05$). There were no significant differences in soil pH among different soil depths in the same sample plot ($P > 0.05$), and no significant differences between sample Type II and

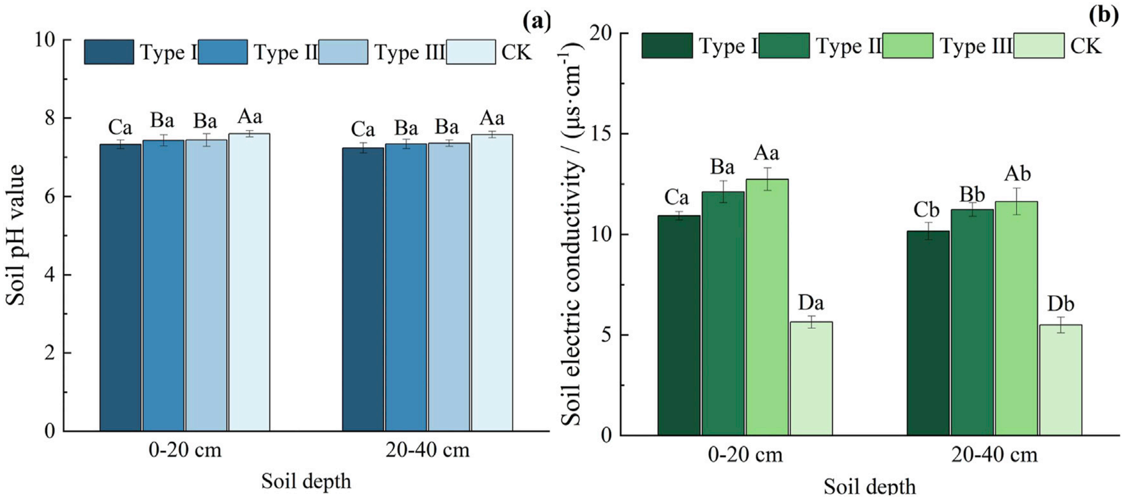

FIGURE 4
(A) Soil pH values and **(B)** electrical conductivity in different sample plots.

sample Type III at the same soil depth ($P > 0.05$). These results indicate that afforestation in sandy land can reduce soil pH and increase soil EC. The influence of plant spacing on soil pH value was reflected in the plantations with wide afforestation spacing, and the soil EC decreased with an increase in plant spacing.

3.2.2 Soil nutrients

The contents of soil organic matter, total nutrients, and available nutrients in the 0–20 cm layer were significantly higher than those in the 20–40 cm layer ($P < 0.05$). The contents of soil organic matter, total N, total P, available N, available P, and available K in all soil layers showed a pattern of Type I > Type II > Type III > CK, and the contents of soil organic matter, total N, total P, and available N were significantly different among sample plots and at each soil depth ($P < 0.05$). There were no significant differences in soil available P or K contents between sample Type II and sample Type III ($P > 0.05$). There was no significant difference in soil total K content in the plantations with different planting spacings ($P > 0.05$), but there was a significant difference in the soil total K content between the plantations and the moving sandy land ($P < 0.05$). In summary, afforestation in moving sandy land significantly improved the soil organic matter and nutrient contents, and the change in afforestation spacing had no significant effect on the soil total K content. The improvement of soil nutrients in sample plot Type I was the highest among all plots (Table 4).

3.3 Comprehensive evaluation of soil fertility

3.3.1 Establishment of the minimum data set

Fifteen indexes reflecting the soil fertility of *P. sylvestris* var. *mongolica* plantations were selected to establish a total data set (TDS) for soil fertility evaluation: fractal dimension of soil particle size, capillary porosity, non-capillary porosity, total porosity, bulk density, water content, pH, EC, organic matter, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium. The fractal dimension can describe the particle size composition and distribution of the soil, and thus the TDS did not include the soil particle composition. PCA was used to analyze the 15 soil indexes. The results showed that the cumulative contribution rate of the principal components of the two extracted eigenvalues ≥1 was 85.1% (Table 5), indicating that they could explain the variation of most of the soil indicators.

The factor loadings (>0.5) and the Norm values of the soil indices in the principal component analysis were considered for the minimum dataset (MDS). Figure 5 shows the results of Pearson correlation analysis of soil indicators in the study area. TN had the largest factor loading and Norm value in PC-1, and the other indexes in PC-1 were significantly correlated with TN ($P < 0.05$), and thus only TN was included in the MDS in PC-1. The indices with the highest Norm values in PC-2 were pH and SWC, with a correlation coefficient of −0.55, and these indices were included in the MDS. The weights of the indices were determined according to the contribution to the variance of each index, and the calculation results are shown in Table 5.

3.3.2 Evaluation of soil quality

The variation in TDS-SQI was in the order Type I (0.55) > Type II (0.50) > Type III (0.47) > CK (0.36). The variation in MDS-SQI was in the order Type I (0.60) > Type II (0.54) > Type III (0.48) > CK (0.34) (Figure 6A). The trends of TDS-SQI and MDS-SQI were the same among different soil depths (Figure 6B).

3.3.3 Evaluation results of grey relevance

The ranking of the evaluation results with equal weights in correlation degree between TDS and MDS was as follows: Type I > Type II > Type III > CK. In the evaluation of soil fertility, the importance of each soil index is different; therefore, the evaluation of soil fertility cannot be objectively reflected by the equal weighting of relation degree, and thus it is more appropriate to use the weighted relation degree for evaluation. In this study, the evaluation results of TDS and MDS weighted relation degrees were consistent with the ranking of equal weights for relation degrees (Table 6).

TABLE 4 Characteristics of soil nutrients.

Soil depth	Soil chemical properties	Sample plot type			
		I	II	III	CK
0–20 cm	SOM/(g·kg^{-1})	18.17 ± 0.55Aa	17.33 ± 0.38Ba	16.25 ± 0.15Ca	5.63 ± 0.62Da
	TN/(g·kg^{-1})	0.64 ± 0.04Aa	0.56 ± 0.05Ba	0.48 ± 0.03Ca	0.28 ± 0.02Da
	AN/(mg·kg^{-1})	52.89 ± 0.69Aa	48.07 ± 0.96Ba	44.67 ± 1.16Ca	40.20 ± 0.63Da
	TP/(g·kg^{-1})	0.51 ± 0.04Aa	0.46 ± 0.03Ba	0.41 ± 0.03Ca	0.27 ± 0.02Da
	AP/(mg·kg^{-1})	1.66 ± 0.06Aa	1.31 ± 0.06Ba	1.28 ± 0.05Ba	0.86 ± 0.08Ca
	TK/(g·kg^{-1})	35.80 ± 0.73Aa	35.52 ± 0.66Aa	35.31 ± 0.71Aa	29.73 ± 0.61Ba
	AK/(mg·kg^{-1})	43.57 ± 0.77Aa	41.07 ± 1.44Ba	40.78 ± 0.69Ba	38.61 ± 0.63Ca
20–40 cm	SOM/(g·kg^{-1})	17.21 ± 0.35Ab	15.92 ± 0.26Bb	15.09 ± 0.22Cb	4.45 ± 0.35Db
	TN/(g·kg^{-1})	0.54 ± 0.05Ab	0.44 ± 0.06Bb	0.39 ± 0.01Cb	0.22 ± 0.08Db
	AN/(mg·kg^{-1})	47.09 ± 0.68Ab	43.41 ± 0.80Bb	41.18 ± 0.64Cb	36.74 ± 0.72Db
	TP/(g·kg^{-1})	0.45 ± 0.04Ab	0.40 ± 0.02Bb	0.35 ± 0.03Cb	0.21 ± 0.02Db
	AP/(mg·kg^{-1})	1.41 ± 0.05Ab	1.09 ± 0.05Bb	1.02 ± 0.04Bb	0.72 ± 0.04Cb
	TK/(g·kg^{-1})	32.98 ± 0.96Ab	32.91 ± 0.75Ab	32.29 ± 0.65Ab	27.81 ± 0.40Bb
	AK/(mg·kg^{-1})	41.04 ± 0.94Ab	39.35 ± 1.20Bb	39.08 ± 0.62Bb	36.46 ± 1.43Cb

Note: SOM, soil organic matter; TN, soil total nitrogen; TP, soil total phosphorus; TK, soil total potassium; AN, soil available nitrogen; AP, soil available phosphorus; AK, soil available potassium. The figures and tables below also apply.

3.3.4 Reliability of the MDS

The rationality of the MDS construction was directly related to the accuracy of the evaluation of soil fertility. We compared the TDS with the MDS by regression analysis. The results showed that TDS-SQI was significantly positively correlated with MDS-SQI ($P < 0.05$, $R^2 = 0.9384$) (Figure 7A), and the grey correlation between the TDS and the MDS was significantly positive ($P < 0.05$, $R^2 = 0.8929$) (Figure 7B). Therefore, the MDS index could be used instead of the TDS to evaluate the soil fertility of *P. sylvestris* var. *mongolica* plantations with different planting spacings in the study area.

4 Discussion

As the basis for plant growth and survival, soil plays crucial roles in the growth of individual plants and the succession of vegetation communities, and the structure of these vegetation communities is closely tied to soil quality and nutrient cycling (Van der Putten et al., 2013; Normand et al., 2017; Gatica-Saavedra et al., 2023). Plants significantly influence the structure and properties of soil through mechanisms such as root growth, litter mulching, and the exudation of substances. In turn, soil provides the essential medium for plant growth and development, and any changes in soil properties can affect plant health and growth, highlighting the dynamic interaction between understory vegetation and soil. This reciprocal influence is known as "plant–soil feedback" (van der Putten et al., 2016), a phenomenon observed across various plants and soil types (Arunrat et al., 2023a; Arunrat et al., 2023b). Therefore, in any forestry project focused on ecological restoration, soil development and restoration are long and complex processes (Halme et al., 2013; Widyati et al., 2022). An increasing body of relevant research confirms that altering stand density has a significant effect on soil physico-chemical properties, a hypothesis that is corroborated by the results of the present study (Razafindrabe et al., 2010; Qiu et al., 2019; Menyailo et al., 2022). At present, many studies, focusing on the impact of stand density on soil characteristics and quality, conducted in arid and semi-arid areas have concluded that appropriately reducing stand density is beneficial to soil development, a conclusion that is consistent with the results of this study (Andrews et al., 2020; Liu et al., 2024). However, some researchers have found that both excessively high or low stand densities is not conducive to soil fertility. When the stand density is too low, it can hinder canopy closure, resulting in inadequate surface vegetation restoration and litter coverage; this condition can expose bare areas of forest land, leading to increased evapotranspiration of soil moisture and nutrients, while rainfall can lead to surface runoff and soil erosion. If the stand density is too high, it inevitably leads to intense competition for water and nutrients among vegetation and trees in arid areas characterized by poor soil nutrient and water conditions; this competition hinders the restoration of understory species diversity (Zhang, 2022). Therefore, varying climatic conditions and geographic locations across different study areas can influence the results of the study, making it essential to explore the thresholds for reasonable stand density of different tree species as a critical consideration in afforestation efforts.

The planting patterns in afforestation projects directly or indirectly lead to changes in soil properties (Enoki et al., 1996;

TABLE 5 Principal component analysis of soil property indexes.

Soil indicator	Symbol	Principal component		Norm value	Communality	Weight of TDS	Weight of MDS
		PC-1	PC-2				
Soil water content	SWC	0.483	−0.749	1.81	0.793	0.0589	0.3231
Soil bulk density	SBD	−0.879	−0.18	2.95	0.805	0.0598	-
Soil non-capillary porosity	SNP	0.913	−0.03	3.06	0.835	0.0620	-
Soil capillary porosity	SCP	0.946	0.008	3.17	0.894	0.0664	-
Soil total porosity	STP	0.959	0.003	3.21	0.92	0.0683	-
Soil fractal dimension	D	0.927	0.057	3.10	0.863	0.0641	-
Soil organic matter	SOM	0.955	−0.152	3.20	0.935	0.0694	-
Soil total nitrogen	TN	0.966	0.029	3.23	0.934	0.0694	0.3806
Soil total phosphorus	TP	0.945	0.075	3.16	0.899	0.0668	-
Soil total potassium	TK	0.926	0.192	3.11	0.894	0.0664	-
Soil available nitrogen	AN	0.928	0.178	3.11	0.892	0.0663	-
Soil available phosphorus	AP	0.948	0.084	3.17	0.907	0.0674	-
Soil available potassium	AK	0.854	0.26	2.87	0.796	0.0591	-
Soil pH	pH	−0.587	0.619	2.08	0.727	0.0540	0.2963
Soil electrical conductivity	EC	0.815	−0.082	2.73	0.671	0.0498	-
Characteristic root	11.606		1.159	-	-	-	-
Variance contribution rates/%	77.375		7.725	-	-	-	-
Accumulated variance contribution rates/%	77.375		85.1	-	-	-	-

Wang et al., 2019). The results of this study show that the wider spacing of *P. sylvestris* var. *mongolica* positively affects the soil characteristics and fertility of the understory. This can be attributed primarily to the lower canopy density associated with wider spacing that weakens the canopy's ability to intercept precipitation, allowing herbs to better absorb natural precipitation. As a result, the low-growing vegetation can access more sunlight, enhancing light compensation, promoting photosynthesis, and also improving the soil temperature, thereby providing a suitable environment for litter decomposition and microbial reproduction beneath the forest floor. Therefore, wider spacing can increase the richness and biomass of understory vegetation, thereby altering the soil microenvironment, and the return and decomposition of nutrients from community species further affect the characteristics of understory soil, improve soil quality, and promote soil nutrient cycling. Based on the above analysis, we investigated the vegetation in the sample plots and analyzed the correlations between vegetation characteristics and soil characteristics across different plots. There were significant correlations between vegetation characteristics, soil characteristics, and plant row spacing, with particularly strong correlations between vegetation characteristics and soil characteristics (Table 7).

Our study observed a notable phenomenon in which different plant spacings had a positive effect on most physical and chemical properties of the soil compared to the unafforested bare sandy land, while planting *P. sylvestris* var. *mongolica* in the study area resulted in increased soil conductivity, suggesting a potential risk soil salinization associated with the existing planting patterns of *P. sylvestris* var. *sylvestris* plantations. We speculate that this may be because *P. sylvestris* var. *mongolica* survives best in rain-fed conditions without artificial irrigation or fertilization. The average annual precipitation in Duolun County is about 350 mm, while the average annual evaporation is about 1,769 mm, which is five times the amount of precipitation. Under drought conditions characterized by minimal rainfall and a lack of irrigation, strong surface evaporation can cause water from deeper layers of the soil to rise due to capillary forces, resulting in the accumulation of salts on the soil surface. The results of this study show that the closer the plant spacing, the higher the soil EC, while increasing spacing leads to a decrease in soil EC. This phenomenon can be mitigated by adjusting the planting density during afforestation. In the field investigation, we found that the smaller the afforestation spacing, the greater the decline of the stand health (Figure 2). This decline potentially involves salt content in the soil, as excessive salinity can damage plants, hinder their normal growth and development, lead to physiological

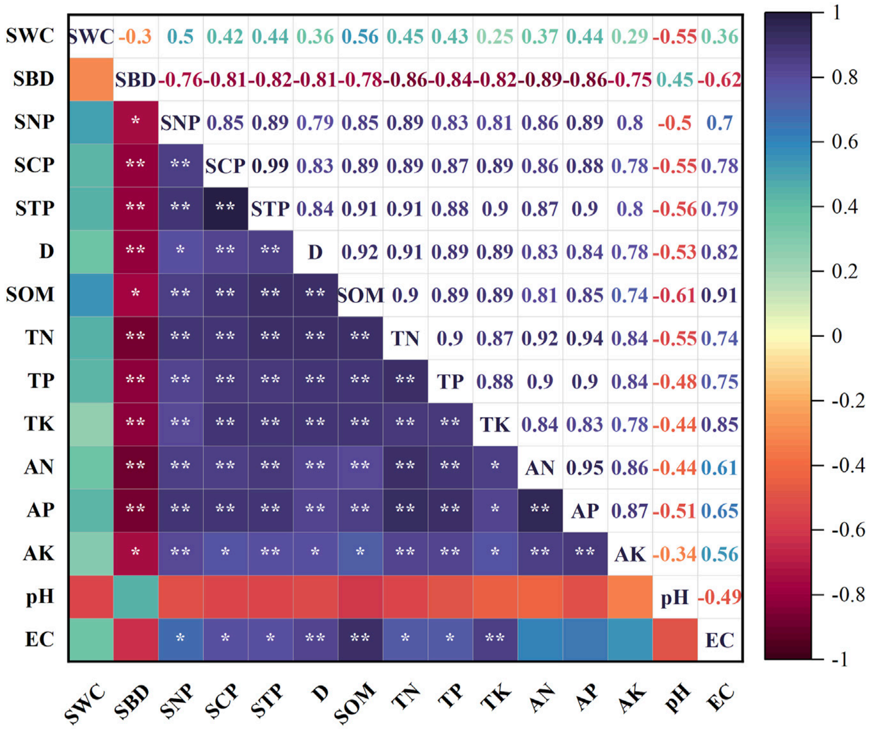

FIGURE 5
Pearson correlations between the soil properties. Note: SWC, soil water content; SBD, soil bulk density; SNP, soil non-capillary porosity; SCP, soil capillary porosity; STP, soil total porosity; D, soil fractal dimension; EC, soil electrical conductivity. The numbers displayed represent correlation coefficients. Purple, blue, and green indicate positive correlations between parameters, while red, orange, and yellow indicate negative correlations between parameters. The significance levels are *$P < 0.05$; **$P < 0.01$.

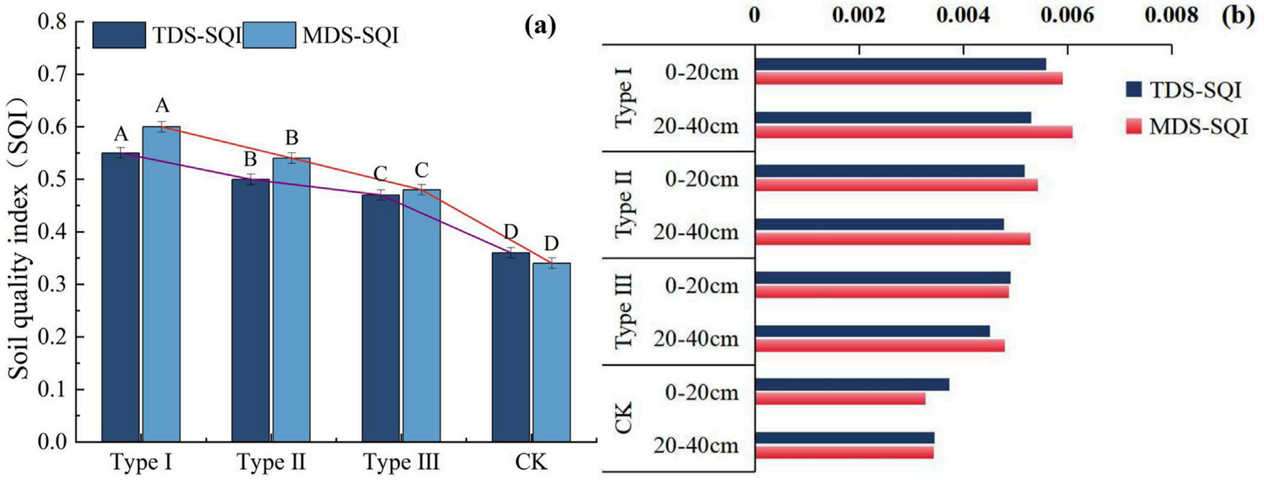

FIGURE 6
(A) SQI of the TDS and MDS. **(B)** SQI of the TDS and MDS in different soil depths.

drought, and finally result in plant desiccation and mortality (Munns, 2002; Mahajan and Tuteja, 2005). Existing studies have found that the root system of Pinus sylvestris sylvestris var. mongolica is largely distributed at depths of 1–1.5 m (MENG et al., 2018; Zhang et al., 2021), making it challenging for these trees to use groundwater effectively. Consequently, trees in these plantations often rely on soil moisture and rainfall. As mentioned above, increasing row spacing reduces canopy density of the stand, allowing for greater soil moisture replenishment from rainfall, and the results of this study demonstrate that wider

TABLE 6 Grey relevance evaluation results.

Sample plot type	Equal weight relevance				Weighted relevance			
	TDS		MDS		TDS		MDS	
	Relevance	Ranking	Relevance	Ranking	Relevance	Ranking	Relevance	Ranking
I	0.84	1	0.82	1	0.80	1	0.82	1
II	0.75	2	0.73	2	0.71	2	0.72	2
III	0.71	3	0.67	3	0.68	3	0.66	3
CK	0.59	4	0.57	4	0.55	4	0.55	4

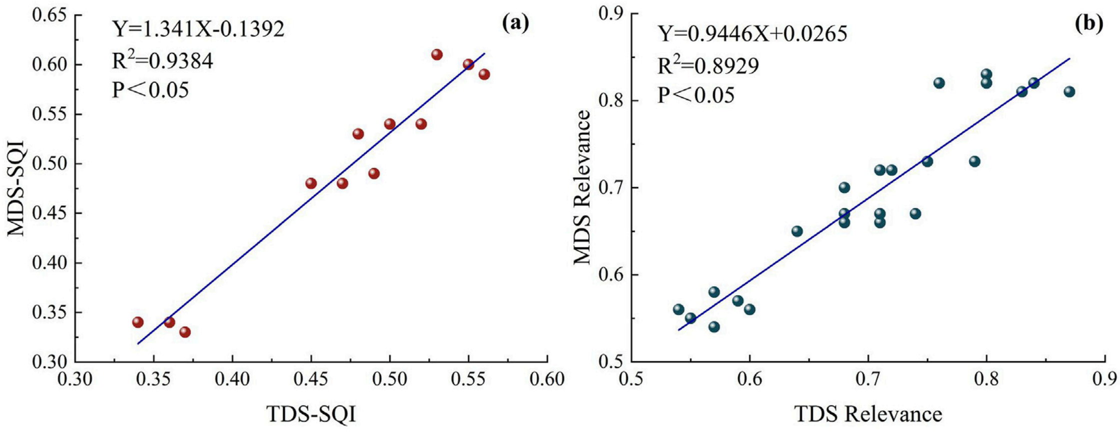

FIGURE 7
(A) The linear relationship between the SQI values of the TDS and the MDS. **(B)** The linear relationship between the grey relations of the TDS and MDS.

row spacing corresponds to higher soil moisture content, potentially alleviating the phenomenon of root salinity stress. This hypothesis required further experimental verification and thus shapes our future research directions.

5 Conclusion

Row spacing is critical for plantation ecosystems, as it directly affects the allocation of natural resources and further leads to differences in soil recovery. Here, we analyzed the changes in soil characteristics of *P. sylvestris* var. *mongolica* plantations in a typical agro-pastoral ecotone under different row spacing patterns and assessed their comprehensive soil fertility. Compared to the unafforested bare sandy land, planting *P. sylvestris* var. *mongolica* with different row spacing in the sandy land of the agro-pastoral ecotone can significantly improve the physical and chemical properties of soil (except EC). The soil improvement effect was notably greater in the 0–20 cm layer than that of the 20–40 cm layer. These findings suggest that our first hypothesis is valid. The row spacing of afforestation plants significantly affected soil characteristics and soil fertility. In the three afforestation modes studied in this experiment, as row spacing increased, soil coarse particle content decreased while fine particle content as well as water and nutrient content increased; soil porosity increased and soil bulk density decreased. Planting *P. sylvestris* var. *mongolica* in sandy land increased the soil electrical conductivity, which decreased with greater band spacing (Table 8). The results of the evaluation of fertility of different types of plantations were consistently in the order 2 m × 6 m > 2 m × 3 m > 1 m × 1 m > bare sandy land, and the results for the TDS and the MDS in the two evaluation systems were significantly positively correlated (Soil quality index method: $P < 0.05$, $R^2 = 0.9384$). Grey relation analysis: $P < 0.05$, $R^2 = 0.8929$). These findings suggest that our second hypothesis is also valid. In summary, *P. sylvestris* var. *mongolica* is a suitable tree species for afforestation in the degraded land of the agro-pastoral ecotone, but the development of soil characteristics and fertility accumulation are not ideal when the planting density is larger. It will also increase soil EC content, which may further lead to tree decline and soil salinization. Among the above three afforestation modes, 2 m × 6 m plantation forests can better improve the soil characteristics and fertility quality of sandy soils. The results of this study can serve as a reference for the construction and management of plantations in agro-pastoral ecotones and other fragile ecological zones.

TABLE 7 Correlation analysis of soil properties and vegetation characteristics among sample plots with different plant spacing.

Soil properties	Vegetation characteristics						
	Planting spacing	Crown density	Herbaceous vegetation cover	Simpson's diversity index	Shannon's diversity index	Margalef richness index	Pielou uniformity index
Planting spacing	1	−0.959**	0.969**	0.944**	0.976**	0.979**	0.948**
SWC	0.589**	−0.574**	0.561**	0.579**	0.586**	0.580**	0.559**
SBD	−0.649**	0.658**	−0.624**	−0.628**	−0.637**	−0.647**	−0.603**
SNP	0.615**	0.658**	−0.624**	−0.628**	−0.637**	−0.647**	−0.603**
SCP	0.434**	−0.361**	0.387**	0.381**	0.404**	0.403**	0.389**
STP	0.492**	−0.420**	0.454**	0.435**	0.459**	0.461**	0.430**
SOM	0.765**	−0.745**	0.746**	0.725**	0.737**	0.757**	0.736**
TN	0.698**	−0.664**	0.652**	0.664**	0.675**	0.684**	0.664**
TP	0.649**	−0.668**	0.673**	0.691**	0.703**	0.679**	0.699**
TK	0.143	−0.148	0.143	0.146	0.146	0.15	0.145
AN	0.756**	−0.739**	0.743**	0.701**	0.731**	0.734**	0.704**
AP	0.764**	−0.684**	0.742**	0.651**	0.708**	0.706**	0.687**
AK	0.574**	−0.506**	0.536**	0.524**	0.545**	0.543**	0.521**
pH	−0.349**	0.286*	−0.316*	−0.275*	−0.271*	−0.304*	−0.364**
EC	−0.715**	0.669**	−0.686**	−0.672**	−0.696**	−0.692**	−0.717**
D	0.717**	−0.687**	0.694**	0.677**	0.699**	0.701**	0.679**

Note: ** indicates significant correlation at the 0.01 level (two-tailed), * indicates significant correlation at the 0.05 level (two-tailed).

TABLE 8 Changes in soil properties of different plantations compared to bare sandy land.

Soil properties	Compared to bare sandy land (CK)/%			Increase or decrease
	Type I	Type II	Type III	
Soil bulk density	13.72	10.67	7.71	Decrease
Soil pH	4.02	2.7	2.5	Decrease
Soil EC	89.4	109.7	118.96	Increase
Soil water content	49.75	21.25	18.5	Increase
Soil total porosity	27.88	21.25	19.56	Increase
Soil organic matter	250.99	229.86	210.91	Increase
Soil total nitrogen	136	100	74	Increase
Soil total phosphorus	100	79.17	58.33	Increase
Soil total potassium	19.53	18.93	17.48	Increase
Soil available nitrogen	29.95	18.9	11.58	Increase
Soil available phosphorus	94.3	51.9	45.57	Increase
Soil available potassium	12.71	7.13	6.38	Increase
Clay	242.55	193.62	157.45	Increase
Silt	343.1	288.36	277.16	Increase
Very Fine Sand	17.21	6.75	3.67	Increase

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XG: Conceptualization, Formal Analysis, Investigation, Methodology, Visualization, Writing–original draft, Writing–review and editing. GY: Conceptualization, Funding acquisition, Methodology, Writing–review and editing. YM: Formal Analysis, Writing–review and editing. SQ: Investigation, Validation, Visualization, Writing–original draft. HC: Investigation, Writing–review and editing. FL: Investigation, Writing–review and editing. SM: Investigation, Validation, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This research was funded by the Inner Mongolia Autonomous Region "Unveiling the List of Commanders" Programme grant number 2024JBGS0023, the Inner Mongolia Autonomous Region Science and Technology Programme grant number 2021GG0070, the Inner Mongolia Autonomous Region Water Resources Department Financial Special grant number WH-1833-ZHJC-FW, and the Inner Mongolia Autonomous Region Water Conservancy Development Center Project Programme grant number BHZB-FW-202403036.

Acknowledgments

We thank LetPub (www.letpub.com.cn) for its linguistic assistance during the preparation of this manuscript.

Conflict of interest

Author FL was employed by National Energy Pingzhuang Coal Industry Mengdong Energy Holding Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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