Article

Effects of sand-fixing poplar stands on wind erosion in sandy areas in northern China

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Abstract: To assess the ecological effects of poplar stands with different densities and ages, fixed observation sites were established in selected standard forest plots. Daily dynamics of wind speed and sand transport rate were monitored over an erosive period (March to June) in 2017. Soil characteristics were also measured at these plots. Average daily wind speed and average daily wind erosion modulus decreased significantly after the establishment of sand-fixing poplar trees on sandy land, while soil density decreased significantly, soil hardness increased greatly, and soil organic carbon, total N, and available P levels increased significantly. With increasing stand density, average daily wind speed and daily sediment transport first decreased and then increased, while the investigated soil nutrients showed the opposite trend. A tree density of 1,320–1,368 trees·hm−2, and wind speed power surface wind erosion was lowest. With the increase in forest age, the average daily wind speed and daily sediment transport gradually declined, while soil physical and chemical properties were gradually improved. At a stand age of 40 years, wind-caused soil erosion was close to zero. Taking these effects into consideration, the design and management of protective forest systems in arid and semi-arid areas can be greatly improved.

Keywords: sandy land; wind erosion; soil improvement; density; age

1. Introduction

Land degradation as a result of wind erosion is one of the most important ecological problems in arid and semiarid regions, which cover 41% of the global land area, posing an increasing threat to global biochemical cycles and agricultural productivity and facilitating human health hazards and climate change [1–3]. China is one of the countries particularly susceptible to land degradation by wind erosion, where almost 40% of the national territory and over 170 million residents were threatened by wind erosion [4]. Land degradation by wind erosion occurs widely in Northwest China, where low annual precipitation and frequent strong winds prevail [1].

To mitigate this problem, the Chinese government has implemented a variety of measures that led to significant achievements in curbing the effects of land degradation on the environment and human life in some affected regions [5,6]. Sand-fixing and windbreak forests are widely used to improve the local ecological conditions in arid and semi-arid regions [7,8] and are the main components of the Three-North Shelterbelt Project, known as the “Green Great Wall” of China [9–11]. As part of the project, some sandy land in the Zhangbei area has been mainly afforested by poplar...
shelterbelts in the past 40 years. In the early stage of afforestation, due to the lack of field experimental data in terms of vegetation structure and function, local governments carried out afforestation with the fundamental starting point of increasing the number of trees and shortening afforestation periods on sandy land. In addition, because of the large size of the project, it was subdivided into different stages. As a result, large amounts of sand-fixing poplars, at different densities and ages, were established in the Zhangbei area.

A full understanding of the wind erosion characteristics is essential to arrange and manage sand-fixing and windbreak forests [12–16]. However, studies of land degradation by wind erosion have generally been conducted on farmland, deserts, or highly disturbed locations, with considerable challenges [17]. In this sense, until recently, wind erosion across forest ecosystem has hardly been investigated.

The spacing and shape of woody plants determine the spatial density of roughness elements, which may in turn affect wind erosion [17–19]. Numerous studies have indicated that wind erosion could be alleviated through shelterbelts, but nevertheless, studies on wind erosion under different shelterbelt structures, especially at different density structures and age levels, are rare [1,10,20,21].

In this context, to address this knowledge gap, some basic questions still remain to be answered: 1. How do forests on sandy land affect wind speed, surface erosion, and soil improvement compared to non-forested sandy land? 2. To which extent do such forests of different densities and ages affect wind speed, surface erosion, and soil improvement? 3. When establishing sand-fixing shelterbelts, which tree density is appropriate? By answering these questions, we can provide important information for regional and national policy makers to make reasonable decisions to further combat land degradation by wind erosion in the fragile arid regions of China.

2. Materials and Methods

2.1. Experimental site

The experimental site was located in Zhangbei County, Hebei Province, on the southern edge of the Inner Mongolia plateau in northern China, between 40°57'N and 41°34'N and between 114°10'E and 115°27'E (Fig. 1). Average elevation is 1,300 m above sea level. The climate is mid-latitude temperate monsoon climate, with obvious continental characteristics. Average annual temperature is 3.2 °C, with an annual precipitation of about 300 mm, of which 70.8% occur from June to August. Both precipitation and temperature show a high inter-annual variation. Evaporation is four times greater than precipitation, with a drying degree of 1.50–2.20, and sunshine hours of 2,898 h each year. For most of the year, this area is under the control of the Mongolian high pressure and the terrain was open and flat with an annual average wind speed of 3.9 m s⁻¹, besides the prevailing winds are northwest in winter and spring and southwest averaged 4.1 m s⁻¹ to south in summer and autumn during the growing season averaged 3.1 m s⁻¹. Dust events occur most frequently in spring, with an accumulated time of more than 1,440 hours per year. The original vegetation in the area was Carex lanceolata Boott, Potentilla chinensis Ser, Rumex patientia Linn, with sparsely scattered trees (mainly Ulmus pumila).
2.2. Experimental design

Six poplar forests with different densities and six poplar forests with different ages were selected for this study, a piece of sandy land without protective forest cover was used as control. These forests were planted since the 1978, with the main purpose of breaking the wind and fixing the sandy underground. Prior to the establishment of these forests, the area was a sandy area with severe wind erosion. The size of the experimental sites was 100 × 100 m, with a rectangular shape. Importantly, each site was unobstructed in the upper wind direction of the prevailing northwestern wind within 200 m. The basic conditions of the fields are shown in Table 1.

To quantify the role of different poplar forests in soil improvement, daily wind speed dynamics, wind and sand transport efficiency, and soil characteristics were studied quantitatively by using fixed observation sites located inside the forest stands, located in the center of each site. Additionally, one observation site was set up on sandy land with a wind direction of about 1,000 m above the forest edge towards the northwest and used as control site (CK), representing the initial conditions before the establishment of poplar forests.

Table 1. Summary of the basic conditions of the forest sites and the un-forested control site in Zhangbei County, Hebei Province, China.

<table>
<thead>
<tr>
<th>Number</th>
<th>Field site</th>
<th>Age (a)</th>
<th>Density (trees-hm⁻²)</th>
<th>Mean height (m)</th>
<th>Mean diameter at breast height (cm)</th>
<th>Average crown extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A1</td>
<td>15</td>
<td>750</td>
<td>5.2</td>
<td>10.3</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>A2</td>
<td>21</td>
<td>750</td>
<td>7.6</td>
<td>12.9</td>
<td>2.8</td>
</tr>
<tr>
<td>3</td>
<td>A3</td>
<td>28</td>
<td>750</td>
<td>11.0</td>
<td>18.9</td>
<td>3.9</td>
</tr>
<tr>
<td>4</td>
<td>A4</td>
<td>32</td>
<td>750</td>
<td>11.7</td>
<td>20.8</td>
<td>3.6</td>
</tr>
<tr>
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<td>A5</td>
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<td>750</td>
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<td>24.0</td>
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</tr>
<tr>
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<td>A6</td>
<td>41</td>
<td>750</td>
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<td>27.9</td>
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</tr>
<tr>
<td>7</td>
<td>D1</td>
<td>15</td>
<td>500</td>
<td>5.7</td>
<td>10.6</td>
<td>2.9</td>
</tr>
<tr>
<td>8</td>
<td>D2</td>
<td>15</td>
<td>750</td>
<td>5.2</td>
<td>10.3</td>
<td>2.4</td>
</tr>
</tbody>
</table>
2.3. Measurements of wind speed and sand transport

For each experimental site, the transport rate of sand by wind was measured over an erosive period from March through May in 2017 with five traps. The traps consisted of cylindrical enamel containers with a diameter of 30 cm and a height of 15 cm. To facilitate sediment collection, we used thick galvanized iron sheets to make an additional container (slightly larger than the size of the trap) as the basket for the catcher. First, we buried the bracket in the soil (the upper edge of the bracket was about 1 cm above the ground) and subsequently placed the trap into the bay. Each day, at a fixed time, we removed the trap from the scaffold, extracted the sediment with a brush, and then returned the trap to the scaffold for the following measurement. To avoid the loss of dry sand due to turbulence effects, we added small gravel blocks with a diameter of 2 cm to the trap, covering the entire bottom of the trap. The results of repeated comparison tests showed that the sand mining volume obtained by the gravel cover method (dry method) was only 3% lower than that obtained with the water method (hydrometallurgy). For this reason, the efficiency of this method can exceed 90%. The collected sediment was weighed with an electronic balance, and the sediment transport rate was expressed as the amount of silt collected daily per unit area.

Wind velocity and direction were measured using PC-2F multi-channel auto-count telemetry (Jinzhou Sunshine Technology Development Co. Ltd., China). The anemometer sensor was mounted at a height of 2.0 m to measure wind speed, while a wind direction sensor was mounted at a height of 5 m for the determination of the wind direction (only at the CK site). Data were collected at intervals of 1 min, and the mean daily wind speeds at different heights at the 13 observation points were calculated.

2.4. Measurements of soil properties

Soil sampling was carried out in August 2017. For each site, three replicated soil samples were collected from the upper 5 cm. All samples were sieved to pass a 2-mm mesh, and roots and other debris were removed and discarded. Soil particle size distribution was determined by the dry sieve method, using 0.02, 0.2, and 2.0 mm mesh sieves. Three samples were also taken from each site with stainless steel soil ring kits (100 cm³) to measure bulk density. Soil surface hardness was measured with a hardness meter (Yamanaka-07202301, Fujiwara Scientific Co. Ltd., Tokyo, Japan), while organic carbon was determined using the dichromate-wet combustion method. Total N was determined using the Kjeldahl method (DK Heating Digester, UDK140 Automatic Steam Distilling Unit, Titroline 96, Italy), and available P was determined by the Bray method.

2.5. Data analysis

The data were processed using SigmaPlot 12.0 and SPSS 19.0. To rule out the impact of wind direction, only 25 days of NW wind (spring main wind) were selected for 60 days from April to May. The differences in daily mean wind speed, daily wind sediment transport rate, daily dust transfer rate, and soil and vegetation parameters were tested by analysis of variance (ANOVA) and Fisher's LSD, using the statistical software package SPSS; significance was set at 5%.
To quantitatively evaluate the wind resistance effects of different poplar forests, the wind speed Attenuation Index (AI) was calculated by using the following formula, that is, the attenuation percentage of wind speed to CK at different observation points:

\[ AI = \frac{V_{ck} - V_{s}}{V_{ck}} \times 100\% \] (1)

Where AI is the Attenuation Index of wind speed, which reflects the relative reduction of wind speed, \( V_{ck} \) is the daily average wind speed at a height of 2 m in the CK site, and \( V_{s} \) is the daily average wind speed at a height of 2 m in the forest stands. Higher AI values generally correspond to a higher wind resistance.

Similarly, to assess the impacts of the forest stands against wind erosion, the reduction of the ground wind erosion index was calculated on the basis of the following formula, that is, the percentage of sediment transport rate at different observation points relative to the control:

\[ DI = \frac{Q_{ck} - Q_{s}}{Q_{ck}} \times 100\% \] (2)

Where DI is the reduction index of the surface wind erosion, which reflects the relative degree of soil erosion reduction, \( Q_{ck} \) is the daily sediment transport rate in the CK site, and \( Q_{s} \) is the daily sediment transport rate in the different poplar forest sites. The higher the DI value, the better the anti-wind erosion effect of the forest stand.

3. Results

3.1. Effects of stand density and age on surface erosion

3.1.1. Density and surface erosion

Figure 2. Variations in (a) mean daily wind speed at 2-m height and the attenuation index (AI) of wind speed; and (b) mean daily sand transport rate and the declining index (DI) of wind erosion. Means with different letters indicate significant differences at \( P < 0.05 \). Vertical bars represent ± Standard deviation.
Figure 3. Relationships between poplar density and mean daily wind speed and daily sand transport rate, (a) relationship between mean daily wind speed at 2-m height in the six experiment sites with different densities and mean daily wind speed at 2-m height in the control site; and (b) relationship between mean daily sand transport rate in the experiment sites with different densities and mean daily wind speed at 2-m height in the control site.

To compare the impacts of poplar forest density on wind speed, six different densities within the same stand age were compared. Overall, the daily mean wind speed at a height of 2 m was consistently lower in the six sites than in the CK site, while the average daily wind speed in the CK site was 1.31 times that of the poplar forests with different densities, with a steady decrease in the beginning, followed by a gradual increase with increasing stand density (Fig. 2a). A similar trend was observed when analyzing the data for individual days (Fig. 3a), without any significant differences in mean wind speed at values below 3 m s\(^{-1}\), with the exception of the site D4 site; however, when wind speed was higher than 3 m s\(^{-1}\), the differences between stand with different densities were significant. In addition, the average daily wind speed of the stands which tended to be the largest and smallest tree density increased more significantly with increasing wind speed in the CK site, while the average daily wind speed of the medium-density stands increased only slightly. However, site D4 generally showed the lowest wind speed levels. Averaged over the 25 days selected, the attenuation index of wind speed (AI) was greatest in D4 site (61.35%), followed by D5 (43.00%), D3 (37.60%), D2 (26.32%), D6 (20.88), and D1 (10.51%).

In general, the forest stands had a significant impact on wind erosion. \((F_{6,175} = 105.212, P < 0.001)\). Daily mean sand transport rate was evidently lower in the six forested sites than in the unforested CK site (Fig. 2b). It should also be noted that with increasing tree density, the sediment transport rate showed a trend of first decreasing and then increasing, and the sediment flux of D6 was significantly larger than that of D4 (Fig. 2b). A similar situation was observed in the analysis of data under various wind erosion events (Fig. 3b). Relative to the control, the greatest reduction in surface wind erosion occurred in D4 (88.73%), followed by D5 (86.36%), D6 (81.32%), D3 (79.63%), D2 (73.88%), and D1 (68.55%). The changes in the declining index of wind erosion values (DI) of the seven sites showed a marked quadratic curve, i.e., DI increased from CK to D4 and then declined from D4 to D6. To establish the regression model, the seven sites on the x-axis were designated as 0 CK), 500 (D1), 750 (D2), 1,025 (D3), 1,200 (D4), 1,475 (D5), and 1,700 (D6). Based on the measured data of the seven sites, a quadratic regression model was established to estimate the density conditions of poplar forests for optimal sand-fixing function. Regression analysis indicated a quadratic relationship between DI and the x-axis value \((x): DI = -5E-05x^2 + 0.1363x + 3.5711, R^2 = 0.97, P < 0.001\). We estimated that when \(x = 1,368\), DI was close to 96.46%, indicating that the optimal poplar density is 1,368 tress-hm\(^{-2}\), at a stand age of 15 years.

3.1.2. Age and surface erosion

Figure 4. Variations in (a) mean daily wind speed at 2-m height and the attenuation index (AI) of wind speed; (b) mean daily sand transport rate and the decline index (DI) of wind erosion: Means...
with different letters indicate significant differences at \( P < 0.05 \). Vertical bars represent ± Standard deviation.

**Figure 5.** Relationships between poplar age and mean daily wind speed and daily sand transport rate, (a) relationship between mean daily wind speed at 2-m height in the six experiment sites with different ages and mean daily wind speed at 2-m height in the control site; and (b) relationship between mean daily sand transport rate in the six experiment sites with different ages and mean daily wind speed at 2-m height in the control site.

In general, the average daily wind speed of the six differently aged forest stands was significantly lower when compared to the un-forested control stand (Fig. 4a). There were clear trends of changes in daily mean wind speed along the time gradient of the 15-41-year-old plantations. Average daily wind speed could roughly be partitioned into two stages along the age gradient (A1–A5 and A5–A6). A similar pattern was observed when analyzing data from individual days (Fig. 5a). In the first period, daily average wind speed showed a slow decreasing trend with increasing stand age, which became more distinct in the following period. At the same time, the attenuation index of wind speed (A1) increased with stand age, as shown in Figure 4a, with an approximately showed three-fold increase in A1 from A1 to A6.

Figure 4b shows that the average daily sand transport rates of the forested stands were significantly lower than that of the control site, irrespective of the stand age. However, with increasing stand age, the average daily sediment transport rate showed a gradual decreasing trend. Similar patterns were observed for individual days (Fig. 5b). On average, the daily sediment transport rate of these six forest stands was 0.43 g·m\(^{-2}\), while the average daily sediment transport in the control site was 3.10 g·m\(^{-2}\). Within the experimental period of 25 days, the declining index (DI) of wind erosion was highest in A6, followed by A5, A4, A3, A2, and A1. Based on the increasing DI (from 70.56 to 98.04%) with increasing stand age, it can be inferred that the average growth rate of DI is about 1.06% at a poplar stand age between 15 and 41 years. According to this trend, the DI will be close to 100% at a stand age of 40 years.

**3.2. Effects of stand density and age on soil amelioration**
Figure 6. Relationship between poplar density, age, and soil particulate size composition, (a) particulate size composition of soil in the six experiment sites with different densities and the control site; and (b) particulate size composition of soil in the six experiment sites with different ages and the control site.

Figure 7. Relationship between poplar density, age, and soil bulk density and soil surface hardness, (a) bulk density and soil surface hardness of soil in the six experiment sites with different densities and the control site; and (b) bulk density and soil surface hardness of soil in the six experiment sites with different ages and the control site. Means with different letters indicate significant differences at P<0.05. Vertical bars represent ± Standard deviation.

Figure 8. Relationship between poplar density, age, and chemical indexes, (a) organic C, total N and available P of soil in the six experiment sites with different densities and the control site; and (b) organic C, total N and available P of soil in the six experiment sites with different ages and the control site. Means with different letters indicate significant differences at P<0.05. Vertical bars represent ± Standard deviation.

3.2.1. Density and soil amelioration
Figure 6-8 shows the soil physical and chemical properties of poplar stands with different densities and ages. The coarse sand content (0.2–2 mm) of the control site was higher than that in the forest stands, while the contents of fine sand (0.02–0.2 mm) as well as silt and clay (< 0.02 mm) were significantly lower (Fig. 6a), suggesting that the forested sites had a smaller particle size compared to the un-forested control site. This significant structural difference indicates that poplar trees may have effects on soil development in sandy areas. With the increase in tree density, the content of soil coarse sand decreased first and then increased; however, the contents of soil silt and clay showed the opposite trend. Soil surface hardness is a parameter related to soil surface texture and compactness, as well as an indicator reflecting the stability of sandy land [7]. As is shown in Figure 7a, soil hardness of the poplar stands was significantly larger than in the control site. Nevertheless, the results of the significance analysis showed that the six different poplar stands, with different ages, did not differ significantly in soil particle size. Soil bulk density was lower in the forested sites compared to the un-forested control site, with a steady decline from D1 to D4 and an increase thereafter. However, the amounts of total C, total N, and available P showed a tendency to increase first and then decrease (Fig. 8a).

3.2.2. Age and soil amelioration

We observed clear trends in soil texture, bulk density, and soil surface hardness along the time gradient of the 0–41-year-old plantations (Fig. 6b, 7b). Soil bulk density is an important physical parameter indicating soil nutrient storage, water transportation, and gas penetration [22]. At a depth of 0–5 cm, bulk density decreased from 1.74 g cm⁻³ in the CK site (age 0) to 1.40 g cm⁻³ under the 41-year-old plantation site. With increasing stand age, the content of coarse sand decreased, while those of silt and clay increased. Soil surface hardness increased from an average of 0.64 kg cm⁻² at the CK site (age 0) to 5.92 kg cm⁻² under the 41-year-old poplar forest site. At select sites, total C, total N, and available P under tree canopies were significantly higher than in the control site (Fig. 8b); the levels of these elements significantly changed along the age gradient. At 15, 21, 28, 32, 37, and 41 years after stand establishment, total soil C levels in the 0–5 cm layer increased, respectively, by 2.49, 3.41, 3.57, 3.86, 3.86, and 3.95 times compared to those in the control site. Soil total N levels followed the same pattern, with an 18-fold increase at a stand age of 41 years. In terms of nutrient availability, available P increased progressively with stand age, reaching a maximum of 5.84 times that of the control site.

3.3. Comprehensive effects of stand age and density on surface erosion

![Figure 9. Relationship between poplar density, age, and daily sand transport rate in Zhangbei County, Hebei Province, China.](image-url)
Wind erosion is a complex process governed by numerous mechanisms and factors, which makes it difficult to establish an accurate mathematical model to evaluate this process. Modeling is usually performed using a test analysis, applying large amounts of data. In this study, two factors (poplar density and poplar age) were used to build a multivariate wind erosion model. Specifically, we used the SAS 9.0 statistical analysis software to analyze the data from the field experiment and established a multi-factor wind erosion model (Fig. 9):

\[ z = 2.6324 + (-0.0024)x + (-0.0349)y + 8.8054E-007x^2 + 0.0001y^2 \]  

(3)

where \( z \) is the daily sand transport (g·m\(^{-2}\)), \( x \) is the forest age (a), and \( y \) is the forest density (trees·hm\(^{-2}\)).

Table 2. Daily sand transport rates under different poplar stand densities and age combinations in Zhangbei County, Hebei Province, China.

<table>
<thead>
<tr>
<th>Density (trees·hm(^{-2}))</th>
<th>Age (y)</th>
<th>Density (trees·hm(^{-2}))</th>
<th>Age (y)</th>
<th>Density (trees·hm(^{-2}))</th>
<th>Age (y)</th>
<th>Density (trees·hm(^{-2}))</th>
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<tbody>
<tr>
<td>400</td>
<td>10</td>
<td>1.47</td>
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<td>1.16</td>
<td>10</td>
<td>0.86</td>
<td>10</td>
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<tr>
<td>600</td>
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<td>0.85</td>
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<td>0.06</td>
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<td>0.67</td>
<td>2,000</td>
<td>0.37</td>
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</tr>
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</table>

Based on this model, we obtained the daily average sediment transport values for different stand density and age combinations (Tab. 2). Against this background, with increasing stand age, the daily sand transport shows a decreasing trend, influenced by tree density. When the poplar stand reaches an age of 40 years, the daily sand transport rate tended to be negative, indicating that wind-caused soil erosion is negligible.

4. Discussion

4.1. Impacts of poplar stand density and age on wind velocity and erosion

Overall, the effects of sand-fixing poplar trees on wind speed and sand fixation were highly significant. In this aspect, we observed significant differences among the different stands as influenced by density and age. Comparing the differences in wind speed and sediment transport rate between the forested stands and the un-forested control stand, we solve the problem of variation of sand fixation with different density and age in wind breaking and sand fixation. To eliminate the influence of wind direction, we controlled the wind direction for the NW orientation, only considering 25 days of daily average wind speed and daily sediment transport rate data.

Our research shows that the establishment of poplar shelterbelts has a significant influence on wind conditions and erosion in sandy areas. Numerous studies have shown that artificially and naturally established vegetation has an important protective effect on wind and surface soil erosion [23–25]. One of the main findings of this study is that in the poplar shelterbelts, the average daily wind speed and the daily sediment transport showed a tendency to decrease first and then increased with increasing stand density, which is consistent with previous findings [26]. When the stand density continues to increase to a certain definite value, the cover degree of sand-fixing poplar also reaches a certain critical value, and the effect of cover on wind speed and sand fixation is basically stable. At this time, the influence of stand density on wind speed and sand fixation mainly depends on the branch structure of the lower part of the canopy. Due to the continuous increase in the density of sand-fixing poplar trees, the distance of sand-fixing poplar branches decreases, resulting in the formation of several high-speed "streets" (narrow tube effect) between the trees; these areas will increase wind speed and, most likely, erosion rate. Similar results have been found in field observations [27], wind tunnel experiments [28], and simulation studies [29, 30]. Liu et al. [23], in a wind tunnel study, have also evaluated the effects of plant density on internal airflow and found that under
the condition of smaller plant spacing, the lateral transverse flow of adjacent plants was greatly inhibited, resulting in increased pressure in front of the plants, which led to an increase inflow. The authors concluded that dense areas were poorly protected compared with sparse distribution. In our study, there were two functional relationships between the wind speed Change index (AI), the surface wind Erosion Drop Index (DI), and the density of the sand-fixing poplar, and the maximum corresponding density of AI was 1,320 trees·hm⁻². DI the maximum corresponding density of DI was 1368 trees·hm⁻². Similar results have been found in another study [26], where wind erosion control was highest at a plant cover of 60–65%. The coverage value corresponding to the optimal density value was slightly higher in our study, possibly because of the different characteristics of the tree species. Compared with poplar trees, shrubs have no distinct trunk, consisting of branches and lobes, and larger shrubs may otherwise have a better anti-wind erosion effect at the bottom. Similar results were found in previous studies [23,30], where the lower part of the dense shrubs provided better wind erosion control that the lower part of the trees. In this sense, adding some larger shrubs and herbs to the tree stands can be a valid approach to further improve the efficiency of wind erosion protection.

With increasing forest age, the average daily wind speed and the daily sediment transport in shelterbelts decrease, probably because of the high branch density, coverage, and tree height, which increase surface roughness and therefore lead to a decreased average wind speed. In addition, the diversity and cover level of herbaceous herbs also increased, which eventually led to a downward trend in sediment transport, as also observed previously [26,31]. In these studies, with increasing vegetation cover, at certain wind speeds, wind-caused soil erosion decreased rapidly, mainly because of the higher vegetation cover.

Our results lead us to infer that at a poplar stand age of 40 years, the near surface wind speed reduction rate is greater than 80%, and the surface coverage is greater than 70%, with a wind erosion volume close to zero. Because studies in this field are scarce, we cannot further compare our data with previous results. However, in a study by Dong et al. [32], soil erosion was less severe when the shrub cover was greater than 60% in arid and semi-arid areas, while at cover rates of 20–60% and 20%, erosion was moderate and severe, respectively.

4.2. Impacts of poplar stand density and age on soil properties

Our results clearly show that soil properties can be improved by establishing and developing sand-fixing poplar stands. Soil particle size, surface soil hardness, and bulk density were significantly smaller in the forested sites when compared to the un-forested control site; these results are in agreement with the findings of previous studies [25,33].

With increasing stand density, soil bulk density decreased first and then increased. However, organic carbon, total N, and effective phosphorus levels showed the opposite tendency, most likely because, within a certain density range, poplar promotes herbal restoration and litter decomposition through shade provision, and the contents of total C, total N, and effective phosphorus increases gradually, thus improving soil porosity and other soil traits and further decreasing soil bulk density. Poplar is a species with a high water consumption [34], and the increase in poplar density is accompanied with high competition for water, resulting in a poor growth of other tree species and herbal species and decreased decomposition rates. The rapid use of soil moisture and nutrients leads to poor soil properties, which eventually results in increased soil bulk density [6]. It is also possible that, when the stand density exceeds a certain critical value, the wind-reducing and sand-fixing effects are weakened, resulting in a relative coarsening of the topsoil [27,29].

An important finding of this study is that with increasing poplar stand age, the contents of coarse soil particles decreased, the contents of fine particles increased, organic carbon, total N, and effective phosphorus levels gradually increased, and soil bulk weight and hardness decreased. Partly, this might be because, as stand age increased, soil erosion decreased, resulting in an increased accumulation of fine particulate matter in the surface soil. In addition, the canopy provides shade, reduces soil evaporation, improves soil moisture levels, and accelerates the growth of herbs and the decomposition of litter. Finally, with increasing forest age, the development of undergrowth herbs...
constitutes an important part of net primary productivity, and the decomposition of these plants results in substantial inputs of C, N, and other nutrients. Our results are similar to those of previous studies [35,36], while other studies have shown that with the increase of forest age, there may be several reasons for the improvement of soil properties. First, photosynthetic carbon sequestration, leaf litter transfer, and root turnover play a certain role in promoting soil carbon accumulation. Secondly, the level of microbial activity in sandy ecosystems is generally low, but after the establishment of artificial vegetation, microbial nitrogen fixation and litter decomposition release n lead to an increase in soil n content. Third, vegetation restoration results in an improved microclimate and better soil conditions.

5. Conclusions

In the semi-arid region of northern China, the establishment of sand-fixing poplar stands plays an important role in the restoration of sandy ecosystems. Our main conclusions are as follows: (1) The establishment of sand-fixing poplar stands in sandy areas can significantly reduce wind speed and wind erosion, improve soil physical properties, and enhance soil fertility. (2) In terms of soil property improvement, the optimal stand density is 1,320-1,368 trees hm⁻². (3) The effects of such stands gradually increase with increasing stand age. At an age of 40 years, wind erosion within the stand is close to zero.

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References


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