Postprint: Water-Holding Capacity of Typical Plantation Litter in Reclaimed Open-Pit Coal Mine Areas in Shanxi Province

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Abstract

To investigate the important role of water-holding capacity of plantation forest litter on coal mine dumps in soil and water conservation and ecosystem restoration in mining areas, this study employed a combination of field investigation and laboratory immersion methods to measure water-holding characteristics including litter storage capacity, water-holding rate, water-holding capacity, and water absorption rate at different decomposition stages for four typical plantation forests (Populus simonii, Ulmus pumila, Pinus tabuliformis, and Robinia pseudoacacia) on the dump of Antaibao Open-pit Coal Mine in Shanxi Province. The results showed that: the litter storage capacity of Populus simonii and Pinus tabuliformis was significantly higher than that of Robinia pseudoacacia and Ulmus pumila ($P<0.05$); the water-holding rate and water-holding capacity of litter at different decomposition stages for the four plantation forests exhibited extremely significant logarithmic relationships with immersion time ($P<0.01$); the water absorption rate of litter showed the order Robinia pseudoacacia > Ulmus pumila > Populus simonii > Pinus tabuliformis, and there existed extremely significant power function relationships between water absorption rate and immersion time ($P<0.01$). The maximum water-holding capacity and effective interception capacity of litter were 4.59~8.94 $t \cdot hm^{-2}$ and 3.42~7.31 $t \cdot hm^{-2}$, respectively, with the order for both being Populus simonii > Pinus tabuliformis > Robinia pseudoacacia > Ulmus pumila. Populus simonii litter had the strongest water-holding capacity, while Robinia pseudoacacia litter had the fastest water absorption rate. Therefore, prioritizing the planting of Populus simonii and appropriately mixing it with Robinia pseudoacacia has positive effects on water conservation in open-pit coal mine reclamation areas in Shanxi Province.

Full Text

Study on Water-Holding Capacity of Litter from Typical Artificial Forests in Reclaimed Regions of Opencast Coal Mines in Shanxi Province

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Abstract

To investigate the important role of water-holding capacity of plantation litter in coal mine dumps on soil and water conservation and ecosystem restoration in mining areas, this study employed a combination of field investigation and laboratory soaking methods to measure water-holding characteristics—including litter accumulation amount, water-holding rate, water-holding capacity, and water absorption rate at different decomposition stages—for four typical plantations (Populus simonii, Ulmus pumila, Pinus tabulaeformis, and Robinia pseudoacacia) in the Antaibao opencast coal mine dump in Shanxi Province. The results showed that litter accumulation in P. simonii and P. tabulaeformis forests was significantly higher than in R. pseudoacacia and U. pumila forests ($P < 0.05$). Both water-holding rate and capacity exhibited extremely significant logarithmic relationships with immersion time ($P < 0.01$), while water absorption rate showed an extremely significant power function relationship with immersion time ($P < 0.01$). The maximum water-holding capacity and effective retention capacity of litter across the four plantations ranged from 4.59–8.94 $t \cdot hm^{-2}$ and 3.42–7.31 $t \cdot hm^{-2}$, respectively, following the order: P. simonii > P. tabulaeformis > R. pseudoacacia > U. pumila. The P. simonii litter demonstrated the strongest water-holding capacity, whereas R. pseudoacacia litter showed the fastest water absorption rate. Therefore, prioritizing P. simonii planting with appropriate mixed cultivation of R. pseudoacacia can positively contribute to water conservation in opencast coal mine reclamation areas in Shanxi Province.

Keywords: reclamation area; artificial forest; litter; water-holding capacity; Shanxi Province

Introduction

Litter constitutes a crucial component of forest ecosystem structure, primarily comprising dead and decomposed plant branches and leaves scattered on the soil surface. Characterized by its loose structure, strong permeability, and excellent water-holding capacity, litter effectively intercepts precipitation, retains surface runoff, and reduces soil erosion. Consequently, forest litter provides important ecological services in water conservation, soil and water retention, and promotion of forest hydrological cycles. In recent years, as freshwater shortage and water environmental pollution have become increasingly prominent, the water conservation function of forests has garnered widespread attention. The water-holding capacity of forest litter serves as a key indicator reflecting the water conservation function of forests. Different forest types exhibit variations in litter accumulation and water conservation effects due to differences in tree biological characteristics, leading to inconsistent research findings. For instance, Liu et al. found that litter accumulation and water-holding capacity in Dinghu Mountain followed the order of coniferous forest, coniferous-broadleaf mixed forest, and evergreen broadleaf forest. In contrast, studies in Tiantai County of Zhejiang Province, Cangwu County of Guangxi, and mountainous areas of Beijing indicated that coniferous-broadleaf mixed forests or broadleaf forests had greater litter accumulation and water-holding capacity than coniferous forests. Therefore, investigating litter accumulation and water-holding capacity across different vegetation types is essential for understanding and evaluating the water conservation function of forest litter layers.

Most opencast coal mines in China are located in arid and semi-arid regions with fragile ecological environments. The mining process creates large-scale dumps characterized by steep slopes, long slope surfaces, complex material composition, and uneven subsidence, which bury original landforms and cause various problems including soil erosion, reduced biodiversity, and landscape fragmentation, seriously affecting ecological security in mining areas. Vegetation restoration and reconstruction have thus become important measures for ecological restoration of mine dumps, as plant roots, surface litter, and canopy coverage can mitigate soil erosion, improve soil quality, enhance water conservation function, and increase land productivity to some extent. Previous research on opencast coal mine dumps has primarily focused on soil erosion, slope stability, water loss, and heavy metal pollution, with limited reports on water-holding characteristics of different vegetation types in mining dump areas. Moreover, the water-holding characteristics of litter at different decomposition stages in different artificial forests and their impacts on ecological restoration of mining areas remain unclear. This study investigated the water-holding capacity of litter from four typical artificial forests in the Antaibao coal mine reclamation area to understand the water conservation and soil and water retention functions of different plantations, providing a theoretical basis for scientific forest management and vegetation restoration in this region.

1.3 Litter Collection

In each sample plot, five 0.5 m × 0.5 m quadrats were randomly established in the upper, middle, and lower sections to measure total litter thickness and collect litter samples from undecomposed and semi-decomposed layers. The undecomposed layer consisted of fresh litter with no visible decomposition traces, showing no obvious color change and maintaining a hard texture, while the remaining portion was classified as the semi-decomposed layer. Litter from each layer was bagged and transported to the laboratory, where fresh weight was measured before oven-drying at 85°C to constant weight. Litter accumulation in different decomposition layers was determined using the oven-drying method to measure natural water content. Dry weight of litter in each quadrat was calculated based on fresh weight and natural water content, then extrapolated to per-unit area accumulation for each decomposition layer, with total accumulation being the sum of both layers.

1.4 Litter Water-Holding Performance Measurement

The water-holding performance of litter was determined using the indoor soaking method. Oven-dried litter samples from different forest types and decomposition layers were placed in nylon mesh bags, sealed, and immersed in water. After soaking, bags were removed and drained until no more water dripped from the litter, then quickly weighed to determine wet weight before being oven-dried to constant weight to study water absorption speed and process. Litter water-holding capacity, water-holding rate, water absorption rate, and effective retention capacity at different immersion times were calculated using the following formulas:

Litter water-holding capacity ($t \cdot hm^{-2}$) = Litter wet weight ($t \cdot hm^{-2}$) - Litter dry weight ($t \cdot hm^{-2}$)
Litter water-holding rate (%) = (Litter water-holding capacity / Litter dry mass) $\times$ 100
Litter water absorption rate ($t \cdot hm^{-2} \cdot h^{-1}$) = Litter water-holding capacity ($t \cdot hm^{-2}$) / Absorption time (h)
Litter effective retention capacity ($t \cdot hm^{-2}$) = (Maximum water-holding rate - Average natural water content rate) $\times$ 0.85 $\times$ Litter standing crop

The water-holding capacity and rate when litter water content reaches saturation are considered the maximum water-holding capacity and rate for that litter.

1.5 Data Processing

Descriptive statistical analyses including means and standard deviations were performed using Excel 2010. One-way ANOVA in PASW Statistics 18.0 was used to test for significant differences in litter accumulation and water-holding indicators among different forest types and between decomposition layers within the same forest type. Nonlinear regression analysis was conducted to examine relationships between litter water-holding capacity and immersion time. Figures were created using SigmaPlot 12.5.

2.1 Litter Accumulation Amount

Total litter thickness in the typical plantations ranged from 2.33–3.60 cm, with Pinus tabulaeformis forest showing the greatest thickness, significantly higher than Populus simonii and Ulmus pumila forests ($P < 0.05$). Total litter accumulation ranged from 1.38–3.53 $t \cdot hm^{-2}$, with P. simonii forest having the highest accumulation, significantly greater than U. pumila forest ($P < 0.05$), while P. tabulaeformis and Robinia pseudoacacia were intermediate. Undecomposed litter accumulation in U. pumila forest was significantly higher than in the semi-decomposed layer, whereas P. tabulaeformis showed the opposite pattern with significantly higher accumulation in the semi-decomposed layer ($P < 0.05$). No significant differences were found between decomposition layers in P. simonii and R. pseudoacacia forests. Undecomposed litter accumulation was highest in P. simonii forest (1.78 $t \cdot hm^{-2}$), significantly greater than the other three forest types ($P < 0.05$). Semi-decomposed litter accumulation was highest in P. tabulaeformis forest (2.07 $t \cdot hm^{-2}$), significantly greater than in U. pumila forest, with P. simonii and R. pseudoacacia being intermediate.

2.2.1 Litter Water-Holding Capacity

The water-holding capacity of litter from the four plantations in the Antaibao reclamation area showed similar temporal patterns, increasing rapidly during the initial 0.5 h, then slowing gradually before stabilizing. Semi-decomposed litter from P. tabulaeformis and P. simonii forests had relatively high water-holding capacity, while U. pumila forest had the lowest. Undecomposed litter water-holding capacity was greatest in P. simonii forest, significantly higher than in P. tabulaeformis forest ($P < 0.05$), with R. pseudoacacia and U. pumila forests being intermediate and not significantly different from either P. simonii or P. tabulaeformis. After 0.5 h of soaking, water-holding capacity of undecomposed litter in U. pumila forest was significantly higher than in its semi-decomposed layer ($P < 0.05$), while other forests showed no significant differences between decomposition layers, indicating that water-holding capacity in U. pumila litter is related to its decomposition degree.

Water-holding capacity (W) of litter from the four plantations at different decomposition stages changed logarithmically with immersion time (t) according to the equation $W = a + b \cdot \ln(t)$, with all R^2 values greater than 0.96, indicating strong correlations (Table 3).

[Figure 1: see original paper]

2.2.3 Litter Water Absorption Rate

Litter water absorption rates for all plantations decreased rapidly after 0–1 h, then declined more gradually before stabilizing, indicating saturation. Semi-decomposed litter absorption rates were highest in U. pumila forest, followed by R. pseudoacacia forest, both significantly higher than P. simonii and P. tabulaeformis forests throughout the experiment. Undecomposed litter absorption rates were highest in R. pseudoacacia forest, followed by U. pumila forest, both significantly higher than P. tabulaeformis forest ($P < 0.05$). After 0.5 h, undecomposed litter absorption rate in P. simonii forest was also significantly higher than in P. tabulaeformis forest ($P < 0.05$). Semi-decomposed litter absorption rates in U. pumila and P. tabulaeformis forests were significantly higher than their undecomposed layers ($P < 0.05$), while P. simonii and R. pseudoacacia showed no significant differences, indicating that decomposition degree significantly affects absorption rates in U. pumila and P. tabulaeformis.

Water absorption rate (V) of litter from the four plantations at different decomposition stages changed as a power function of immersion time (t) according to $V = a \cdot t^{-}$, with all R^2 values greater than 0.95, indicating strong relationships (Table 5).

[Figure 2: see original paper]
[Figure 3: see original paper]

2.3 Litter Water-Holding Capability

Maximum water-holding capacity of semi-decomposed, undecomposed, and total litter layers was highest in P. simonii forest ($8.94\ t \cdot hm^{-2}$), significantly greater than in U. pumila forest ($P < 0.05$). Semi-decomposed litter effective retention capacity in P. simonii, P. tabulaeformis, and R. pseudoacacia forests was significantly higher than in U. pumila forest ($P < 0.05$). Undecomposed litter effective retention capacity was highest in P. simonii forest ($3.75\ t \cdot hm^{-2}$), significantly greater than the other three forests ($P < 0.05$). Undecomposed litter effective retention capacity in U. pumila forest was significantly lower than its semi-decomposed layer ($P < 0.05$), while other forests showed no significant differences between layers.

Total litter layer effective retention rates were highest in U. pumila and R. pseudoacacia forests, significantly higher than P. simonii and P. tabulaeformis forests ($P < 0.05$), with P. simonii significantly higher than P. tabulaeformis ($P < 0.05$). Semi-decomposed litter effective retention rates in U. pumila and R. pseudoacacia forests were significantly higher than in P. simonii and P. tabulaeformis forests ($P < 0.05$). Undecomposed litter effective retention rate in P. tabulaeformis forest (235.82%) was significantly lower than other forests. Semi-decomposed litter effective retention rates in U. pumila and P. tabulaeformis forests were significantly higher than their undecomposed layers ($P < 0.05$).

Maximum water-holding rates of total litter layers were highest in U. pumila and R. pseudoacacia forests, significantly higher than P. simonii and P. tabulaeformis forests ($P < 0.05$), with P. simonii significantly higher than P. tabulaeformis ($P < 0.05$). Semi-decomposed litter maximum water-holding rates in U. pumila and R. pseudoacacia forests were significantly higher than in P. simonii and P. tabulaeformis forests ($P < 0.05$). Undecomposed litter maximum water-holding rate in P. tabulaeformis forest (235.82%) was significantly lower than other forests. Undecomposed litter maximum water-holding capacity in U. pumila forest was significantly lower than its semi-decomposed layer ($P < 0.05$), while other forests showed no significant differences between layers.

[Figure 4: see original paper]
[Figure 5: see original paper]

3.1 Total Litter Accumulation

Forest litter accumulation depends primarily on litter input, decomposition rate, and accumulation period. In this study, the four plantations were of similar age with comparable accumulation periods. Tree species composition significantly affects litter input. Total litter thickness ranged from 2.33–3.60 cm, following the order P. tabulaeformis > R. pseudoacacia > P. simonii > U. pumila. Litter accumulation ranged from 1.38–3.53 $t \cdot hm^{-2}$, following the order P. simonii > P. tabulaeformis > R. pseudoacacia > U. pumila. These values were significantly lower than the average litter standing crop in North China (9.32 $t \cdot hm^{-2}$) and adjacent regions such as Beijing' s Baihua Mountain (15.1–18.5 $t \cdot hm^{-2}$) and Dongling Mountain (6.0–24 $t \cdot hm^{-2}$). This discrepancy relates not only to forest type, stand age, and growth characteristics, but also to differences in site conditions between dumps and natural mountains. Dump environments are harsh, with water and nutrient deficits and heavy metal pollution that inhibit normal vegetation growth and reduce surface litter. The inconsistent ranking between litter thickness and accumulation arises because different tree species produce litter with varying composition and spatial structure, making thickness independent of mass. Additionally, microorganisms in the ground layer are important factors affecting decomposition, with their activity closely related to environmental factors such as temperature, humidity, and soil water content. Therefore, different site conditions are important factors influencing litter decomposition and causing differences in litter thickness and mass among plantations.

Except for P. tabulaeformis forest, the proportion of undecomposed litter in the three broadleaf forests (P. simonii, U. pumila, R. pseudoacacia) was higher than semi-decomposed litter, contrasting with findings from Xiaolong Mountain in Gansu and Lanzhou' s north-south mountains. This reflects consistency in nutrient return among different stands under the same climatic conditions. The contrasting results may be attributed to differences in climate and stand types between study areas. In semi-arid regions, water is the main factor limiting litter decomposition, and the higher water-holding rate of semi-decomposed layers is due to their loose structure and strong water absorption capacity.

3.2 Litter Water-Holding Performance

Litter accumulation, maximum water-holding capacity, water absorption rate, and effective retention capacity are important indicators for evaluating the water conservation function of litter, determining its ability to intercept precipitation and reduce surface runoff. Maximum water-holding capacity and effective retention capacity are the most commonly used indicators. Litter water-holding rate and standing crop determine the magnitude of water-holding capacity. In the four plantations, P. tabulaeformis litter had the lowest water-holding rate and absorption rate, likely due to the water-repellent properties of pine resin. However, its high semi-decomposed layer accumulation resulted in the highest semi-decomposed litter water-holding capacity ($4.76\ t \cdot hm^{-2}$). Within the same forest type, different decomposition degrees led to variations in water-holding capacity, rate, and absorption rate. The total litter accumulation, maximum water-holding capacity, and effective retention capacity were highest in P. simonii forest, indicating that accumulation and decomposition degree significantly influence water conservation ability.

Litter water-holding capacity is greatly affected by water absorption rate, with higher rates enabling faster precipitation interception and reducing surface runoff. Robinia pseudoacacia had the highest maximum water-holding rate and absorption rate, but its lower accumulation resulted in smaller effective retention capacity compared to P. simonii. Therefore, R. pseudoacacia forest helps absorb rainfall more quickly in the short term, while P. simonii forest provides better long-term retention. The maximum water-holding rates of semi-decomposed litter in U. pumila and P. tabulaeformis forests were significantly higher than their undecomposed layers, consistent with previous research, possibly because higher carbon-to-nitrogen ratios in U. pumila litter (compared to P. tabulaeformis) accelerate microbial decomposition and affect water-holding rates.

Water-holding capacity and rate showed significant logarithmic relationships with time, while absorption rate showed significant power function relationships, consistent with findings from Zhao et al., Du et al., and He et al. In conclusion, litter accumulation is the primary determinant of water-holding performance. Populus simonii should be the priority species for local ecological restoration and afforestation, with R. pseudoacacia as a suitable mixed species to enhance retention capacity during short-duration heavy rainfall events.

4 Conclusion

Among the four typical plantations in the opencast coal mine reclamation area, P. simonii forest had the highest litter accumulation, maximum water-holding capacity, and effective retention capacity, followed by P. tabulaeformis forest, indicating strong accumulation and water-holding ability. Robinia pseudoacacia forest showed the best water absorption rate and maximum water-holding rate, demonstrating strong water absorption and retention capabilities. Therefore, using P. simonii or P. tabulaeformis as the main species with R. pseudoacacia as a mixed species to create P. simonii–R. pseudoacacia mixed forests represents an important approach for improving water conservation function and protecting ecologically fragile areas during restoration of mine dumps in Shanxi Province.

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