Postprint: Effects of Different Intensity Thinning on Spatiotemporal Patterns of Water Conservation Function in Pinus massoniana Stands

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Abstract

To understand the dynamic changes in water conservation function during the transformation process of *Pinus massoniana* stands and enhance their ecological service functions, 22-year-old *Pinus massoniana* stands were selected in 1994 in the urban landscape forest of Youxi State-owned Forest Farm in Fujian Province. Variance analysis was used to analyze changes in stand water holding capacity among four treatments: 20% intensity thinning transformation, 35% intensity thinning transformation, 50% intensity thinning transformation, and a control. The results showed that with increasing transformation time, water conservation capacity in all treatments increased significantly ($P < 0.05$), with more pronounced increases observed under higher thinning intensities. Soil layer water holding capacity accounted for 95.89%-97.18% of total stand water holding capacity. During the first 5 years post-transformation, no significant differences were observed among treatments in water holding capacity of either the 0-20 cm or 20-40 cm soil layers ($P > 0.05$). After 10 years of transformation, water holding capacity in both the 0-20 cm and 20-40 cm soil layers of transformed stands was significantly higher than in control stands ($P < 0.05$). Aboveground water holding capacity accounted for only 2.82% (45.64 t/hm^2)-4.11% (76.81 t/hm^2) of stand water conservation capacity, yet exhibited significant changes post-transformation ($P < 0.05$). Canopy layer water holding capacity was significantly higher than control stands after 10 years of stand transformation ($P < 0.05$), but decreased with increasing thinning intensity. Understory vegetation layer water holding capacity was significantly lower than control stands after 5 years of stand transformation ($P < 0.05$), also decreasing with increasing thinning intensity. Litter layer water holding capacity was significantly higher than control stands after 5 years of stand transformation ($P < 0.05$), increasing with thinning intensity. The proportion of water holding capacity in the canopy and litter layers showed a significant increasing trend over time ($P < 0.05$), while the understory vegetation layer showed a significant decreasing trend ($P < 0.05$).

These results indicate that stand water holding capacity changed dramatically during the initial transformation stage, with higher thinning intensities resulting in lower stand water holding capacity; however, transformed stands were more conducive to enhancing water conservation function in the long term.

Full Text

Preamble

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Effects of Different Thinning Intensities on Spatiotemporal Patterns of Water Conservation in *Pinus massoniana* Stands

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Abstract

This study aimed to understand the dynamic changes in water conservation functions during the stand improvement process of *Pinus massoniana* forests to enhance their ecological service functions. We analyzed changes in stand water holding capacity between control and improved stands using thinning intensities of approximately 20%, 35%, and 50% in a 22-year-old *P. massoniana* forest at the Youxi State-owned Forest Farm in Fujian Province. The results showed that forest water conservation capacity increased significantly over time after stand improvement ($P < 0.05$), and after 10 years, water conservation increased significantly with increasing thinning intensity. The soil layer' s water holding capacity accounted for 95.89%–97.18% of the total stand water holding capacity. During the first five years of stand improvement (1994–1999), water holding capacity of the 0–20 cm and 20–40 cm soil layers was not significantly different between control and improved stands ($P > 0.05$). However, after 10 years of improvement (2004), both soil layers in improved stands showed significantly higher water holding capacity than the control stand ($P < 0.05$). The water holding capacity of the canopy, vegetation, and litter layers accounted for 2.82% (45.64 t/hm^2) to 4.11% (76.81 t/hm^2) of total stand capacity. In the canopy layer, improved stands had significantly higher water holding capacity than the control stand when improvement exceeded 10 years ($P < 0.05$), though capacity decreased with increasing thinning intensity. In contrast, the vegetation layer of improved stands showed significantly lower water holding capacity than the control stand after >5 years ($P < 0.05$), also decreasing with thinning intensity. The litter layer of improved stands was significantly higher than the control after >5 years ($P < 0.05$), increasing with thinning intensity. The water holding ratio of canopy and litter layers increased significantly over time ($P < 0.05$), while the vegetation layer ratio decreased significantly in improved stands ($P < 0.05$). These results indicate that stand water holding capacity changed dramatically in the early stage of improvement, with higher thinning intensities reducing capacity. However, over the long term, improved stands were more beneficial for water conservation.

Keywords: *Pinus massoniana*; stand improvement; thinning intensity; water conservation; spatiotemporal dynamics

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Introduction

Water conservation is one of the most important ecological functions of forests. In arid regions, this function is prominently manifested as water resource supplementation, while in rainy areas it is primarily expressed through water retention and soil fixation. Previous studies have shown that in the red soil region of Fujian Province, the area of soil erosion has decreased through long-term afforestation efforts, with *Pinus massoniana* being the main species planted. However, the water holding capacity of pure *P. massoniana* stands is significantly lower than that of evergreen broad-leaved forests or mixed coniferous-broadleaved forests. Due to soil erosion issues and pine wood nematode disease in *P. massoniana* stands, many regions have implemented stand improvement programs. Thinning intensity is a critical factor in this process—if too low, broadleaved trees planted under the canopy struggle to grow or form stands; if too high, water holding and soil retention capacity change abruptly, increasing the risk of landslides or soil erosion. Currently, few studies have examined the dynamic changes in stand water holding capacity during the improvement process, leading to considerable uncertainty in practical *P. massoniana* pure stand improvement efforts. This experiment was conducted at the *P. massoniana* urban landscape forest base of Youxi State-owned Forest Farm in Fujian Province, where different thinning intensities were applied with interplanting of *Altingia gracilipes* (a native species) to explore the spatiotemporal dynamics of water conservation function during stand improvement, providing empirical reference and theoretical basis for future improvements from a soil and water conservation perspective.

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1. Study Site Overview

The study site is located at the Youxi State-owned Forest Farm in Youxi County, Fujian Province. Youxi County lies in central Fujian, north of the Daiyun Mountains, with a mid-subtropical maritime monsoon climate. The geographic coordinates are 25°80 -26°40 N, 117°80 -118°60 E, with elevations of 300–600 m. The site has an average annual temperature of 19.2°C and average annual precipitation of 1620 mm. The experimental forest was planted in 1985 with an initial density of 2500 stems/hm² and post-establishment density of 1800–1950 stems/hm². The soil is red soil. Thinning was conducted every 5–7 years. Before improvement, the stand was a single-layer, even-aged forest with canopy density of 0.8–0.9. The canopy layer consisted of *Pinus massoniana* with DBH of 16.2 cm and height of 13.4 m. Understory shrubs included *Ilex chinensis*, *Ilex pubescens*, *Symplocos sumuntia*, and *Eurya hebeclados*. Herbs included *Dicranopteris dichotoma*. Additional species were *Pleioblastus amarus*, *Syzygium buxifolium*, *Melastoma dodecandrum*, *Schima superba*, *Diplopterygium chinense*, *Phyllostachys viridis*, and *Pseudosasa amabilis*. Understory vegetation height was 80–100 cm.

In 1994, thinning improvement was conducted. Pre-improvement stand density was 1650 stems/hm². The thinning principle was to maintain overall stand uniformity, locally removing small trees while retaining large ones, and keeping the upper canopy space uniform after felling. Thinning intensities were 20%, 35%, and 50%, with unthinned stands as controls. After thinning, *Altingia gracilipes* (a local native species with high acceptance by forest farmers) was interplanted at a density of 900 stems/hm². Additional tending included weeding in August 1995 and block hoeing in September. Stand conditions after improvement are shown in .

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2. Methods

2.1 Plot Setup

A completely randomized block design was used for plot setup. Standard plots of 20 m × 20 m were established in the improvement year (1994) and in post-improvement years 5 (1999), 10 (2004), and 20 (2014) for tree inventory surveys.

2.2 Water Holding Capacity Measurement and Calculation

2.2.1 Canopy Layer Water Holding Capacity Following the method of Chen Shaoshuan [15], we measured canopy water holding capacity by species. Leaves and branches were sampled and brought to the laboratory to determine moisture content and maximum water holding rate. In each standard plot, sample trees were selected based on height and DBH surveys. Water holding capacity was calculated as:
$W = w \times (1 - p) \times P \times N$

where W is water holding capacity (t/hm²), w is fresh weight of branches or leaves of sample trees (t), p is moisture content (%), P is maximum water holding rate (%), and N is number of trees per hectare.

2.2.2 Understory Vegetation and Litter Layer Water Holding Capacity Following methods from Li Yanqiong et al. [12] and Wei Qiang et al. [16], five 1 m × 1 m quadrats were established along the diagonal in each standard plot. Fresh weights of understory vegetation and litter layers were measured, and samples were taken to the laboratory for moisture content and maximum water holding rate determination. Biomass and water holding capacity were calculated as:
$W = w \times (1 - p) \times P \times 10{,}000$
where W is water holding capacity (t/hm²), w is fresh weight of understory vegetation or litter in the quadrat (t), p is moisture content (%), and P is maximum water holding rate (%).

2.2.3 Soil Layer Water Holding Capacity In each standard plot, soil profiles were excavated to collect samples from two layers: Layer 1 (0–20 cm) and Layer 2 (20–40 cm). Samples were taken to the laboratory to determine soil porosity and maximum water holding capacity. Soil layer water holding capacity was calculated as:
$W = H \times Qv \times d$
where W is soil layer water holding capacity (t/hm²), H is soil layer thickness (cm), Qv is maximum water holding rate of soil (%), and d is water density (g/cm³ = 1.0).

2.3 Data Processing

Single-factor ANOVA was used for significance testing. Data are presented as mean ± standard error. All figures were created using SigmaPlot 10.0.

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3. Results

3.1 Temporal Dynamics of Water Conservation After Different Thinning Intensities

After thinning improvement, stand water conservation capacity showed an increasing trend over time. Control stand water conservation increased from (1657.16 ± 29.17) t/hm² (1994) to (1690.89 ± 18.75) t/hm² (2014), though the difference was not significant ($P > 0.05$). Regardless of thinning intensity, stand water conservation capacity increased significantly with time since improvement ($P < 0.05$). In 2004 (10 years post-improvement), water conservation in the 50% thinning intensity stand increased significantly from (1624.52 ± 24.42) t/hm² (1994) to (1892.19 ± 21.05) t/hm² ($P < 0.05$), representing a 16.48% increase.

In the improvement year (1994), stand water conservation capacity generally decreased with increasing thinning intensity, though differences were not significant ($P > 0.05$), with maximum differences of 8.96% between thinning intensity plots. By 1999 (5 years post-improvement), water conservation capacity showed an upward trend with increasing thinning intensity, though still not reaching significant differences ($P > 0.05$). By 2004 (10 years post-improvement), control stand water conservation was significantly lower than that of 20% and 35% thinning intensity stands ($P < 0.05$), while the 50% intensity stand was higher but not significantly different ($P > 0.05$). By 2014 (20 years post-improvement), trends were similar to those at 10 years.

3.2 Spatial Patterns of Water Conservation After Different Thinning Intensities

Stand water conservation capacity comprises water holding capacity of the canopy layer, understory vegetation layer, litter layer, and soil layer. [Figure 1: see original paper] shows the temporal dynamics of water conservation in *P. massoniana* stands under different thinning intensities.

In 1994 (improvement year), water holding capacity distribution for all treatments was: soil layer > understory vegetation layer = litter layer > canopy layer, with the soil layer significantly higher than other layers ($P < 0.05$). In 1999 (5 years post-improvement), the pattern remained soil layer > understory vegetation layer = litter layer > canopy layer, with the soil layer still significantly higher ($P < 0.05$). In 2004 (10 years post-improvement), the pattern changed to soil layer > canopy layer > understory vegetation layer = litter layer, with the soil layer significantly higher than other layers ($P < 0.05$). In 2014 (20 years post-improvement), the pattern became canopy layer > soil layer > understory vegetation layer = litter layer, with significant differences between canopy and understory vegetation layers in 35% and 50% thinning intensity stands ($P < 0.05$).

Within the same layer, water holding capacity differed among treatments. In 1994, canopy layer capacity decreased significantly with increasing thinning intensity, while control stand canopy capacity remained higher than improved stands. In 1999, 35% and 50% thinning intensity stands showed significant differences from the control ($P < 0.05$). In 2004, 20% and 35% intensity stands differed significantly from the control ($P < 0.05$). In 2014, all three thinning intensity stands showed significant differences from the control ($P < 0.05$).

Understory vegetation layer capacity in control stands was higher than in improved stands in 1994, but differences were not significant ($P > 0.05$). In 1999, 20% intensity stands showed no significant difference from the control ($P > 0.05$), while 35% and 50% intensity stands were significantly lower ($P < 0.05$). In 2004 and 2014, all improved stands were significantly lower than the control ($P < 0.05$).

The litter layer showed the opposite pattern to the understory vegetation layer.

In 1994, no significant differences existed among treatments ($P > 0.05$). In 1999, 35% and 50% intensity stands were significantly higher than the control ($P < 0.05$). In 2004 and 2014, all improved stands were significantly higher than the control ($P < 0.05$).

For the soil layer, no significant differences existed among treatments in 1994 and 1999 ($P > 0.05$). However, in 2004 and 2014, control stand soil layer capacity was significantly lower than that of improved stands ($P < 0.05$). [Figure 2: see original paper] illustrates the spatial variations in water conservation capacity.

3.3 Spatiotemporal Dynamic Patterns of Water Conservation

As improvement time progressed, the proportion of water holding capacity in each layer of *P. massoniana* stands showed dynamic changes. Water holding capacity was primarily distributed in the soil layer, which consistently accounted for 95.89%-97.18% of total capacity. The most pronounced changes occurred in the canopy and understory vegetation layers.

Canopy layer proportion increased significantly over time in all treatments ($P < 0.05$): control stands increased by 51.22%, 20% intensity stands by 204.12%, 35% intensity by 225.56%, and 50% intensity by 275.00%. Understory vegetation layer proportion decreased significantly over time: control stands decreased by 4.17% ($P > 0.05$), 20% intensity by 77.62% ($P < 0.05$), 35% intensity by 75.00% ($P < 0.05$), and 50% intensity by 79.45% ($P < 0.05$).

Litter layer proportion changes resembled those of the canopy layer, increasing significantly over time in improved stands: 20% intensity increased by 35.59%, 35% intensity by 42.37%, and 50% intensity by 43.33%. Control stand changes were not significant. Soil layer proportion remained relatively stable over time, with minimal variation ($P > 0.05$), except for a significant decrease in 50% intensity stands after improvement ($P < 0.05$). presents the detailed spatiotemporal dynamic patterns of water holding ratios across stand layers.

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4. Discussion and Conclusion

Forests regulate, transform, and redistribute precipitation through canopy interception, litter retention and absorption, and soil infiltration, thereby performing soil and water conservation functions. Changes in forest vegetation alter leaf area index in the canopy layer, as well as the composition of understory vegetation, litter quantity, and soil porosity, consequently changing forest water holding capacity. This study found that total stand water holding capacity increased over time for all treatments. After 10 years, improved stands showed higher total water holding capacity than control stands, with significant differences after 20 years, indicating that all three thinning intensities enhanced water conservation functions over the long term.

However, during the early improvement stage, higher thinning intensities caused greater reductions in total stand water holding capacity compared to controls. At 50% thinning intensity, stand water holding capacity decreased by 32.64 t/hm² (1.97% of control stand aboveground capacity, or 60.96% of control stand aboveground water holding capacity). Therefore, from a soil and water conservation perspective, excessive thinning intensity should be avoided during *P. massoniana* stand improvement, particularly in the improvement year, and strip or block clear-cutting should be avoided.

Forest soil serves as the primary carrier of water conservation, with soil water holding capacity accounting for over 85% of total stand capacity in most studies. In this study, soil layer capacity accounted for 95.89%-97.18% of total, with the 0–20 cm layer contributing (53.22 ± 0.30)%-(55.21 ± 0.21)% and the 20–40 cm layer contributing (41.88 ± 0.20)%-(43.15 ± 0.05)%. Soil layer proportions remained temporally stable with minimal variation, likely because mixed forest root systems more efficiently utilize space, facilitating soil water infiltration and retention. Both soil layers in control stands were significantly lower than in improved stands after 10 years ($P < 0.05$), indicating enhanced soil water storage and retention capacity after improvement.

Aboveground stand water holding capacity plays a positive role in forest ecosystem water conservation. Efficient spatial configuration and stable stand structure are key to full hydrological function. In this study, aboveground capacity accounted for only 2.82% (45.64 t/hm²) to 4.11% (76.81 t/hm²) of total water conservation. The canopy and understory vegetation layers intercept and store precipitation while returning some water to the atmosphere through evaporation, and the well-developed root systems of shrubs and herbs improve soil structure and properties, enhancing water storage and erosion resistance. After thinning, canopy layer capacity decreased significantly with increasing intensity ($P < 0.05$), while understory vegetation and litter layer capacities remained relatively balanced in 1994. The minimum aboveground water holding capacity (55.76 t/hm²) occurred in 50% intensity stands at 20% thinning.

As improved stands continued growing, aboveground water holding capacity gradually recovered or exceeded pre-improvement levels. After 10 years, canopy and litter layer capacities in improved stands were significantly higher than in control stands ($P < 0.05$), likely due to the manifestation of water conservation functions from interplanted broadleaved trees. Litter water holding capacity increased with thinning intensity due to increased litter quantity. Although understory vegetation layer capacity and proportion decreased after improvement, this did not affect the overall increase in aboveground water holding capacity. After 20 years, aboveground capacity in all improved stands exceeded that of control stands.

The early stage of stand improvement is a critical period when water holding capacity changes dramatically, with higher thinning intensities reducing total capacity and increasing soil erosion risk. The soil layer, accounting for 95.89%-97.18% of total capacity, is the primary carrier and fundamental stabilizer of water conservation during improvement. After 10 years, total stand water holding capacity exceeded pre-improvement levels; after 15 years, aboveground capacity reached pre-improvement levels; and after 20 years, aboveground capacity exceeded control stands. Therefore, at least 5-20 years are required for improved stands to stabilize and fully express the water conservation functions of mixed forests.

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