Postprint: Comparison of Nutrient Uptake, Accumulation, and Use Efficiency in Chinese Fir Forests of Different Rotation Generations

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Date: 2018-06-09T00:00:00+00:00

Abstract

Based on over 40 years of continuously measured biomass and nutrient data from permanent plots of first-generation and second-generation successively planted Chinese fir (Cunninghamia lanceolata) forests, we analyzed differences in nutrient uptake, accumulation, and utilization efficiency between the two generations. The results demonstrated that: at the same growth stage, concentrations of N, P, K, Ca, and Mg in second-generation Chinese fir trees were 2.85-3.48, 0.16-0.25, 1.86-2.72, 2.10-2.50, and 0.77-1.31 g/kg higher than those in the first generation, respectively; nutrient accumulation in the first generation at ages 7, 20, and 25 years exceeded that of the second generation by 9.14%, 2.01%, and 0.22%, respectively, whereas at ages 11 and 16 years it was 6.72% and 3.44% lower, respectively, indicating that successive planting does not necessarily reduce nutrient accumulation in the tree layer of second-generation forests; the mean annual nutrient uptake during ages 1-7 years in the first generation was 7.94% higher than that in the second generation, while during ages 8-11, 12-16, 17-18, and 21-25 years it was 13.04%, 2.52%, 7.93%, and 14.58% lower, respectively; at stand ages of 1-7, 8-11, 12-16, 17-20, and 21-25 years, the nutrients required to produce 1 t of dry matter were 1.28, 3.19, 4.28, 4.09, and 4.09 kg greater in the second generation than in the first, respectively; successive planting of Chinese fir can lead to increased nutrient uptake but decreased nutrient use efficiency in second-generation stands.

Full Text

Preamble

Acta Ecologica Sinica (ChinaXiv Partner Journal)
Vol. 38, No. 11, June 2018

DOI: 10.5846/stxb201705230956

Nutrient Uptake, Accumulation, and Utilization Efficiency Comparisons in Plantations Containing Different Generations of Chinese Fir

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Abstract

Using 40 years of continuous biomass and nutrient data from first-generation and successive second-generation Chinese fir (*Cunninghamia lanceolata*) plantations at the Huitong National Research Station of Chinese Fir Plantation Ecosystem in Hunan Province, we analyzed differences in nutrient absorption, accumulation, and utilization efficiency between the first and second rotations. The results showed that at the same growth stage, N, P, K, Ca, and Mg concentrations in second-rotation trees were 2.85–3.48, 0.16–0.25, 1.86–2.72, 2.10–2.50, and 0.77-1.31 g/kg higher than in first-rotation trees, respectively. Nutrient accumulation in the first generation was 9.14%, 2.01%, and 0.22% higher than in the second generation at ages 7, 20, and 25 years, respectively, while it was 6.72% and 3.44% lower at ages 11 and 16 years. Continuous planting of Chinese fir does not necessarily lead to reduced nutrient accumulation in the tree layer of second-generation stands. Annual nutrient absorption in the first rotation (ages 1-7) was 9.14% higher than in the second rotation at the same age. However, at ages 8-11, 12-16, 17-18, and 21-25, it was 13.04%, 2.52%, 7.93%, and 14.58% lower than in the second rotation, respectively. At the same age classes, the second rotations required 1.28, 3.19, 4.28, 4.09, and 4.09 kg more nutrients to produce one ton of dry matter compared to the first rotations. These results indicate that successive rotations increase nutrient uptake and decrease nutrient use efficiency in second-rotation plantations across central-south subtropical regions.

Keywords: planting generation; Chinese fir; nutrient accumulation; nutrient utilization; productivity

Introduction

Since Ebermayer measured nutrient contents in broadleaf and coniferous forests, and scholars such as Cole, Duvigneaud, Bormann, Tsutsumi, and Bazilevich made important contributions to research methods and classification of nutrient cycling in forests, the study of forest nutrient dynamics has progressed rapidly. In the 1950s, Hou Xueyu analyzed the chemical composition of Chinese plant species, while Pan Weichou and Feng Zongwei initiated research on nutrient cycling in Chinese fir (*Cunninghamia lanceolata*) plantations. Over the past 40 years, many scholars have conducted extensive studies on nutrient cycling in different forest types, especially plantations, producing results of great practical and theoretical significance. However, most domestic research has focused on static characteristics of nutrient accumulation and distribution at specific growth stages, although some scholars have explored dynamic changes across growth stages. Evans (1990) reported that productivity decline and soil fertility deterioration occur after successive plantation rotations. To explore the causes of soil fertility decline under Chinese fir successive planting, some scholars have compared nutrient cycling between generations using the space-for-time method, while others analyzed nutrient use efficiency in first- and second-generation stands established immediately after harvesting the first generation. However, methods for calculating net productivity and annual nutrient absorption at different growth stages have not been entirely accurate, potentially leading to flawed results. This study uses 40 years of biomass and nutrient data from first- and second-generation successive plantations at Huitong, employing new research methods to analyze differences in nutrient absorption, accumulation, and utilization across growth stages, and to explore the causes of productivity decline and soil fertility deterioration after successive planting, providing a scientific basis for sustainable plantation management.

1. Study Area Overview

This study was conducted at the Huitong Chinese Fir Ecosystem Research Station in Hunan Province (26°50 N, 109°45 E). The region has a mid-subtropical monsoon climate with an annual average temperature of 16.9°C and annual precipitation of 1100-1400 mm. The soil is a thick-layer yellow soil derived from Sinian slate with deep weathering. The first-generation Chinese fir plantation was clear-cut in winter, and the second-generation plantation was established on the clear-cut site the following spring with the same planting density and site preparation method. Both generations received tending in the first spring and autumn after planting, then grew naturally.

2. Sample Collection

Sampling was conducted in fixed sample plots established in small watersheds. For the first-generation plantation, fixed sample plots were established at ages 7, 11, 16, 20, and 25 years. For the second-generation plantation, fixed sample plots were established at ages 7, 11, 16, and 20 years after establishment. To ensure representativeness, sample trees were felled and divided into stem base, middle, and upper sections. Equal weights of wood from each section were combined into a composite stem sample. Bark sampling followed the same method as for stems. Branches and leaves were separated into current-year and older categories. Roots were divided into root collar ($ $1 cm), medium roots (0.2–1 cm), and fine roots (<0.2 cm).

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3. Nutrient Determination

Chinese fir organ tissue samples were dried to constant weight in a 105°C oven. Total nitrogen in plants was determined by the semi-micro Kjeldahl method, phosphorus by spectrophotometry, and potassium, calcium, and magnesium by atomic absorption spectrophotometry following soil agrochemical analysis methods.

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4. Calculation of Nutrient Accumulation Stock at Different Growth Stages

Nutrient accumulation stock at a given stand age was calculated using the formula:

$$M = \sum_{i=1}^{5} C_i \times W_i$$

where M represents nutrient accumulation stock (kg/ha), C_i represents nutrient concentration in organ i (g/kg), and W_i represents biomass of organ i at a given stand age (t/ha).

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5. Calculation of Nutrient Uptake at Different Growth Stages

5.1 Estimation of Biomass Production at Different Growth Stages

Previous studies calculated nutrient uptake at growth stages using the method of "biomass at current stage minus biomass at previous stage plus litterfall." This is only valid when litterfall nutrients are entirely from biomass produced during that stage. In reality, litterfall may include material produced in previous stages, especially in evergreen stands. Accurate estimation requires determining the actual biomass production during a growth stage.

Stem wood and bark experience little shedding during growth, so biomass production can be estimated from differences in standing biomass between two growth stages. However, leaves and branches continuously shed. Therefore, accurate estimation must account for: (1) the lifespan of leaves and branches, (2) how much of the current standing leaf/branch biomass was produced in previous stages, and (3) the amount of leaf/branch material produced in the current stage that died during that stage.

Root systems also undergo turnover, but this study treated roots similarly to stem wood and bark. Based on long-term observations at Huitong, leaf lifespan was set at 3.5 years and branch lifespan at 5 years following Liu Aiqin et al.

5.2 Calculation of Nutrient Uptake at Different Growth Stages

The traditional calculation method is only correct when nutrient concentrations in all organs remain constant between growth stages. If concentrations change, nutrients may transfer between existing biomass and newly produced biomass. The improved formula for nutrient uptake from soil is:

$$U = \sum_{i=1}^{5}(P_i \times C_i) + \sum_{i=1}^{5}[(S_i \times C_i) - (S_i \times C_{i-1})]$$

where *U* is nutrient uptake (kg/ha), *P_i* is biomass production at the growth stage (t/ha), *C_i* is nutrient concentration at the current stage (g/kg), *C_{i-1}* is nutrient concentration at the previous stage (g/kg), and *S_i* is standing biomass at the previous stage (t/ha).

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6. Nutrient Use Efficiency

Nutrient use efficiency is characterized by the amount of nutrients required to produce one ton of dry matter. The formula is:

$$NUE = \frac{M}{W}$$

where *NUE* represents nutrient use efficiency (kg/t), *M* represents nutrient uptake at a growth stage (kg), and *W* represents biomass production at that stage (t). Lower nutrient requirement indicates higher efficiency.

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7. Data Analysis

All data were processed using Excel and analyzed with SPSS 20.0 software. One-way ANOVA was used for significance testing of nutrient concentrations, accumulation, and distribution across different generations and growth stages.

Results

1. Comparison of Nutrient Concentrations

At the same stand age, second-generation Chinese fir had significantly higher nutrient concentrations in all organs than first-generation trees (Figure 1). N, P, K, Ca, and Mg concentrations were 2.85-3.48, 0.16-0.25, 1.86-2.72, 2.10-2.50, and 0.77-1.31 g/kg higher, respectively. Significance tests showed these differences were highly significant ($p < 0.01$) or significant ($p < 0.05$).

Organ-specific analysis revealed that second-generation roots had 6.86-8.79% higher N, 11.71-20.60% higher P, 13.17-21.06% higher K, 10.82-15.25% higher Ca, and 9.76-17.78% higher Mg concentrations than first-generation roots. Except for stem nutrient concentrations, which showed significant differences ($p < 0.05$), all other organ comparisons showed highly significant differences ($p < 0.01$).

Analysis of nutrient concentration changes with age showed that the rate of increase in second-generation trees was 81.41% and 40.56% of first-generation rates at ages 7 and 11 years, respectively, while the rate of decrease at ages 12-16, 17-20, and 21-25 was only 61.35% of first-generation rates (Figure 2).

2. Comparison of Annual Nutrient Absorption Between Generations

Annual nutrient absorption in first-generation stands was 13.04% higher than in second-generation stands at ages 1-7 (22.40 kg/ha), but 7.94%, 2.52%, 7.93%, and 14.58% lower at ages 8-11 (7.01 kg/ha), 12-16 (4.27 kg/ha), 17-20 (15.27 kg/ha), and 21-25 (27.53 kg/ha), respectively (Table 1).

For individual elements at ages 1-7, first-generation N, P, K, Ca, and Mg absorption was 6.74%, 11.88%, 9.68%, 7.30%, and 8.88% higher than second-generation. At later stages (8-11, 12-16, 17-20, 21-25), first-generation absorption was 2.27-13.75%, 2.41-12.25%, 7.02-21.29%, 10.64-17.91%, and 22.15-36.39% lower, respectively.

The pattern of annual nutrient absorption with age followed a parabolic curve, peaking at 17-20 years. First-generation stands showed a decreasing trend after age 17, while second-generation stands exhibited a double-peak pattern at 8-11 and 17-20 years. The decline rate after age 20 was 9.98% for first-generation and 8.35% for second-generation stands.

3. Comparison of Nutrient Accumulation

At ages 7, 20, and 25 years, first-generation nutrient accumulation was 9.14% (45.48 kg/ha), 2.01% (32.06 kg/ha), and 0.22% (3.96 kg/ha) higher than second-generation, respectively. At ages 11 and 16, it was 6.72% (54.42 kg/ha) and 3.44% (32.06 kg/ha) lower (Table 2).

Overall, first-generation N, P, and K accumulation was higher at ages 7 and 20 but lower at age 11. Ca and Mg accumulation patterns varied by age. These results demonstrate that successive planting does not necessarily reduce nutrient accumulation in second-generation tree layers.

4. Comparison of Nutrient Distribution in Organs

Except at ages 7 and 11, the ranking of nutrient accumulation among organs differed between generations (Figure 3). From young to mature stages, first-generation stem and bark accumulated 15.21% more nutrients than second-generation at age 7, but 9.81-16.36% less at later ages. Branch and leaf nutrient accumulation in first-generation was 30.32-35.56% higher at age 7, but 7.12-16.59% lower thereafter. Root nutrient accumulation was 29.79-79.12% lower in first-generation stands.

First-generation stands allocated proportionally more nutrients to stem and bark (2.99-13.31% and 0.09-1.79% higher, respectively) and less to branches and leaves (0.70-2.35% and 1.31-8.48% lower, respectively) compared to second-generation stands.

5. Nutrient Requirements for Producing One Ton of Dry Matter

Second-generation stands required 1.28, 3.19, 4.28, 4.09, and 4.09 kg more nutrients per ton of dry matter than first-generation stands at growth stages 1-7, 8-11, 12-16, 17-20, and 21-25 years, respectively (Table 3). For individual elements, the additional requirements were 0.85-1.35 kg N, 0.05-0.14 kg P, 0.51-1.08 kg K, 0.70-1.50 kg Ca, and 0.17-0.51 kg Mg per ton of dry matter.

Consequently, first-generation stands could produce 9.28-11.60 t dry matter with the same nutrient amount that second-generation stands required, while second-generation stands produced only 7.66-8.58 t, representing a 17.46-33.19% reduction in productivity (Table 4).

Discussion

The higher nutrient concentrations in second-generation organs at the same growth stage are consistent with findings by Ma Xiangqing et al. However, our results differ from Ma Xiangqing and Liu Aiqin, who reported that first-generation stands always had higher nutrient accumulation at any age. This discrepancy likely stems from methodological differences. Our study used continuous plots on the same site, ensuring spatial consistency and temporal continuity, whereas previous studies used the space-for-time method or selected different stands, which may introduce bias.

Site conditions also differ: Ma Xiangqing's study site in Youxi, Fujian has a mid-subtropical maritime monsoon climate, while Huitong has a mid-subtropical humid climate. Different environmental conditions can cause variations in biomass distribution and organ nutrient content, leading to differences in nutrient accumulation patterns.

Our finding that annual nutrient absorption decreased after age 17 differs from Liu Aiqin et al., who reported increasing absorption with developmental stage. This may be because: (1) Liu' s study selected different stands rather than successive rotations on the same site; (2) their age intervals were larger (only 7 and 16 years); and (3) they used the traditional calculation method that doesn' t account for leaf/branch lifespan or nutrient transfer between stages. Our improved method, considering actual organ lifespans and nutrient concentration changes, provides more realistic estimates.

The lower nutrient use efficiency in second-generation stands means they extract more nutrients from soil for the same biomass production, potentially causing soil fertility decline. This may explain productivity reduction in successive rotations. However, plant growth depends not just on nutrient quantity but also on nutrient balance. Analysis of nutrient element ratios (Table 3) shows different proportional relationships between generations. If first-generation nutrient ratios are optimal for growth, the imbalance in second-generation stands could be a primary cause of reduced productivity and nutrient use efficiency.

Management interventions are crucial. Mixed-species plantations can alter the nutrient cycling dysfunction of pure stands, while tending and different harvesting intensities can improve soil fertility and mitigate yield decline. Sustainable plantation management requires addressing these nutrient dynamics.

Conclusion

This study, conducted on successive first- and second-generation plantations at Huitong with improved calculation methods, reveals:

1. At the same growth stage, second-generation Chinese fir organs had significantly higher nutrient concentrations than first-generation: N by 2.85-3.48 g/kg, P by 0.16-0.25 g/kg, K by 1.86-2.72 g/kg, Ca by 2.10-2.50 g/kg, and Mg by 0.77-1.31 g/kg.
2. First-generation nutrient accumulation was higher at some ages (7, 20, 25 years) but lower at others (11, 16 years), indicating successive planting does not necessarily reduce tree-layer nutrient accumulation.
3. Nutrient distribution among organs differed between generations: first-generation stands allocated more to stem and bark, less to branches and leaves.
4. Annual nutrient absorption was higher in first-generation stands at ages 1-7 but lower at later stages (8-25 years), while second-generation stands showed higher absorption during the rapid growth period.

5. Nutrient use efficiency was lower in second-generation stands, requiring 1.28–4.09 kg more nutrients per ton of dry matter. This higher nutrient demand and lower efficiency likely contribute to soil fertility decline and productivity reduction in successive rotations.

These findings underscore the need for improved silvicultural practices, such as mixed planting and site management, to maintain sustainable plantation productivity.

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