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Biomass and nutrients of *Pinus massoniana* plantations in southern China: Simulations for different managing practices

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Abstract

We measured the dynamics of both biomass and nutrient pools on 7-, 17-, 31- and 51-year-old *Pinus massoniana* plantations in southern China. Using a chronosequence approach, we found that biomass of each component increased with aging while its proportion decreased except stem-wood. Nutrient pools varied with biomass pools except for foliage. For all harvest intensities (stem only, stem and branches, and aboveground), increasing the rotation length from 31 yrs to 51 yrs increased the biomass collection by ≥7.1% and reduced the nutrient export for K, Ca and Mg by ≤6.3% during 155 years, while N and P pools varied with harvesting intensities. A decreasing rotation length from 51 yrs to 17 yrs would increase the biomass collection by ≥12.4%, but remove significantly more nutrients. Although more biomass would be collected if harvesting intensity increased, the nutrient removal would have disproportionally increased. Therefore, increasing the rotation length and decreasing harvest intensity are recommended to sustain the site productivity for future Masson pine plantation.

Key words: Biomass, nutrient accumulation, rotation length, harvest intensity.

Introduction

Forests cover about four billion hectares on the earth's surface [1]. Less than five percent of them are plantations of about 160 million hectares, which provide one-third of the world's wood supply. With increasing populations and living standard across the world, demands for wood and wood products have been significantly increased. Yet, today's requirement for ecosystem services from world forests has never been higher [2]. Therefore, plantations are a clear choice for not only meeting wood demands and subsequently reducing harvesting natural forests [3], but also restoring degraded soils and enhancing biodiversity on the legacy lands left from the previous land-use [4]. However, many intensively-managed short-rotation plantations require high nutrient input and might lead to high rates of nutrient removal in harvesting, raising concerns about long-term site quality and sustainability [5].

Research on nutrient accumulation and distribution has been conducted for several decades throughout the world. It has been reported that biomass and nutrient accumulation of tree crowns peaked at ages of 20-30 years and sustained a fairly constant level after that, while stand volume productivity and stem biomass increased at a higher rate [6]. Nutritional requirements of stands are greatest in developing tree crowns and root systems between about 5 and 15 years [7]. Ranger *et al.* [8] found that young stands immobilized almost the same quantity of nutrients, although they produced only half the biomass, as did the older stands. When the crown canopy closes, two thirds of the nutrients required for growth could be obtained by retranslocation from older or dying tissues or cycling through the litter layer [9]. Ma *et al.* [10] found that nutrient cycling in Chinese fir plantation was gradually dominated by biological processes and less depended on external nutrient sources from soil and rainfall deposition after 14 years. By extending rotation length in Chinese fir plantations by five years soil nutrient status would be improved for successive plantings [10]. Soil nutrients are also improved by reducing harvest intensity [8]. Mechanical whole-tree harvesting removed more biomass and nutrients than hand-fell bole-only harvesting [11]. It is suggested that an input-output nutrient budget should be a key indicator of soil fertility and of sustainability of forest management [12].

Masson pine (*Pinus massoniana* Lamb.) is a native species in Southern China (Lat. 21º41'-33º51' N). It is also a pioneer species in community succession for its high adaptability and tolerance to drought and lean soil [13]. Masson pine is a prominent reforestation species in southern China, comprising 20% of the plantations [14]. In some regions, the rotation of these plantations has been shortened to about 17 years (personal observations). Forest managers face a great challenge in sustaining long-term site productivity. Although a few studies examined stand biomass or nutrient content in plantations in China [13-17], research that integrated these variables during various developmental stages was rare, and no study compared biomass and nutrients budget under different managing practice.

In this study, we measured biomass and nutrient content in four adjacent Masson pine plantations with different ages. The objectives were i) to quantify the dynamics of biomass and nutrients of individual trees and stands at different stand ages, and ii) to evaluate the effect of different rotation lengths and harvest intensities on biomass collection and nutrient removal.

Materials and Methods

Study site: We chose four plantations representing four different developmental stages of Masson pine in the Sanmenjiang state-owned forest farm in 2007. The farm is located in northeast Guangxi Zhuang Autonomous Region, China. It is in the mid-subtropical climate zone with mean annual temperature of 20.7ºC. Annual precipitation is about 1367.7 mm in the region. The site is hilly, with an average altitude of 200 m, and slopes of about 22%. Soil properties varied slightly among four stands being primarily red, slightly calcareous (Table 1).

Stand selection: Four stands at ages of 7, 17, 31 and 51 were selected with stand densities of 1518, 1091, 500 and 325 stems per hectare, respectively. The stand height averaged 7.8, 17.2, 21.2 and 31.9 m and DBH averaged 9.4, 21.3, 25.9 and 39.4 cm from younger to older stands, respectively.

Growth and biomass determination: We selected three representative trees in each stand and cut them down at stump to weight biomass and for stem analysis. The aboveground part of trees was separated into 5 components and the roots were dug up and classified into 4 components. Each component in every tree was weighed fresh and sub-sampled in the woods. Then, all sub-samples were oven-dried at 65ºC to constant weight to calculate water content for biomass estimation. We calculated DBH-based allometric equations for each component of individual trees based on 12 harvested trees in this study and individual-tree biomass data of 89 more trees available from previously published literature [15-16, 18] and unpublished data collected in the region. Individual tree biomass was estimated based on allometric equations for various components. Stand-level biomass was calculated by adding all trees in the plot together in each stand.

Nutrient analysis: Samples for different components were digested by H_2SO_4-$HClO_4$ to prepare N, P, K, Ca and Mg test solutions. Total N was determined using the Kjeldahl technique, P was determined using the Mo-Lan colorimetric method, and K, Ca and Mg were determined by atomic absorption spectrometry (Varian AA240).

Scenario simulations: Three harvesting intensities were considered to estimate nutrient removal at three rotation lengths. Stands were compared for 153-155 years which represent 9, 5 and 3 rotations for the 17-, 31- and 51-year-old stands. Three intensities of harvesting simulated were: 1) stem-wood harvest only, 2) stem harvest including stem-wood and stem-bark and 3) aboveground harvest including foliage, branches and stems.

Results

Biomass accumulation and partition: Total biomass was 40.8, 221.7, 179.9 and 419.3 Mg per hectare at age 7, 17, 31 and 51, respectively. The 31-yr-old stand carried less total biomass than both 17-yr-old and 51-yr-old stands (Table 2) because it had a lower stand density than the 17-year-old stand and the tree size was smaller than the 51-year-old stand. Individual tree biomass increased from 26.8 kg·tree^{-1} at age of 7 yrs to 203.2, 359.9 and 1290.1 kg·tree^{-1} at age of 17, 31 and 51 yrs, respectively. In spite of increasing biomass of each component with increasing tree age, percentage of stand-level biomass increase differed among components (Table 2). The proportion of stem-wood, stump and roots increased, while the proportion of stem-bark, branches and foliage decreased. For example, stem-wood accounted for about 51.5%, 59.0%, 60.2%, and 57.4% of total tree biomass, while foliage was 6.9%, 2.4%, 1.7% and 0.8% of total tree biomass at ages 7, 17, 31 and 51 yrs, respectively.

Table 2. Individual-tree biomass and stand-level biomass for various components in four Masson pine plantations at Sanmenjiang state-owned forest farm in Guangxi, China.

Component	7-yr-old	17-yr-old	31-yr-old	51-yr-old
Individual-tree biomass (kg tree^{-1})				
	26.8	203.2	359.9	1290.1
Stand-level biomass (Mg ha^{-1})				
Foliage	2.8	5.2	3.0	3.2
Small branches	8.1	21.5	13.7	17.9
Coarse branches	1.8	16.9	11.6	14.0
Stem wood	21.0	130.9	108.3	240.6
Stem bark	3.4	14.0	10.2	17.5
Stump	2.8	23.8	21.8	59.1
Coarse roots	0.2	6.9	9.8	64.5
Middle roots	0.5	1.8	1.3	2.0
Fine roots	0.2	0.5	0.3	0.5
Aboveground	37.0	188.6	146.7	293.1
Total biomass	40.8	221.7	179.9	419.3

Nutrient accumulation: At the stand level, all nutrient accumulations peaked at age of 51 yrs, consistent with stand-level biomass accumulation. Biomass increased 89.1%, at 3.3, 5.4, 3.3, 3.7 and 9.8 times the rate of N, P, K, Ca and Mg accumulation; N, P, K, Ca and Mg accumulation increased 26.9%, 16.6%, 27.1%, 23.8% and 9.1%, respectively, from age of 17 to 51 yrs (Fig. 1).

Among different components, nutrient pools developed with different trends. For simplicity, we grouped nutrient pools into four components (Fig. 2). Foliage and branches contained the largest proportion of the total amount of nutrients; all elements peaked at age of 17 yrs and declined with age. Roots carried the least, but the pool increased with age. In contrast, the stem nutrient pool grew very quickly; N and P pools peaked at age of 31 yrs and K, Ca, and Mg pools maximized at age of 51 yrs.

Table 1. Major soil properties on four Masson pine plantations at Sanmenjiang state-owned forest farm in Guangxi, China.

Stand age	7-yr-old		17-yr-old		31-yr-old		51-yr-old	
Soil depth (cm)	0-20	20-40	0-20	20-40	0-20	20-40	0-20	20-40
Total C (g kg^{-1})	23.92	20.23	14.48	13.49	12.66	10.28	25.77	26.26
Total N (g kg^{-1})	1.50	1.16	1.19	0.95	1.05	0.74	1.35	1.18
C/N	15.95	17.44	12.17	14.20	12.06	13.89	19.09	22.25
Total P (g kg^{-1})	0.54	0.50	0.32	0.29	0.26	0.25	0.32	0.31
Exchangeable K (mmol kg^{-1})	2.19	2.31	1.71	2.03	1.77	1.71	1.62	1.25
Exchangeable Ca (mmol kg^{-1})	21.21	14.19	0.36	0.89	5.25	6.91	2.18	1.84
Exchangeable Mg (mmol kg^{-1})	29.21	22.46	6.21	5.71	11.92	11.62	6.11	6.88

Nutrients removal under different management regimes: To evaluate the effect of rotation length and harvest intensity on biomass and nutrient pools, we simulated the effect of three rotation lengths and three management options over a 153- or 155-yr-period, which yielded nine, five and three rotations assuming ages of 17, 31 and 51 years, respectively (Table 3). Under the management option one (stem-wood harvesting only), an increasing rotation length from 31 to 51 years would increase the biomass collection by about 14.5%. However, this management practice would decrease the removal of K by 6.3%, Ca by 8.8% and Mg by 0.6%, and increase the N pool by 12.5% and P by 12.3%. By increasing rotation length from 17 to 51 years, biomass yield would decrease about 12.4% and nutrient export would be significantly reduced for P (34.2%), K (27.0%), Ca (46.6%) and Mg (28.9%) except for N (1.8%).

Management option two to harvest stem including branches showed that by increasing rotation length from 31 to 51 years biomass collection would increase by 13.2% and would decrease all nutrient export by 3.5-11.6% except for N, which would increase by 2.5%. The increase of rotation length from 17 to 51 years would reduce biomass collection by 15.0% with much higher proportion decrease in nutrient export by 19.5% for N and 42.3% for P (Table 3).

If the entire above-ground portion were harvested (Option 3), a similar pattern of nutrient removal would be observed. When rotation length increased from 31 to 51 years, biomass collection increased 7.1% and all nutrient export decreased (11.7-23.0%). Although there was a diminishing biomass collection (26.7%) with the increase in rotation length from 17 to 51 years, all nutrients removal decreased considerably, the removal of N, P, K, Ca and Mg decreased 61.2%, 68.3%, 73.0%, 57.8% and 84.7%, respectively.

Although the biomass collection could increase about 8.2-10.7% by harvesting the whole tree compared to harvesting stem-wood only, the proportion of nutrients removal increased about 3.2-7.3 times. With the harvest intensity increasing from stem-wood only to whole aboveground portion, the biomass collection increased by about 27.8-44.1%, while nutrient export increased significantly, for example at 17 years rotation length, the proportion of N, P, K, Ca and Mg removal increased by about 36.5, 21.9, 23.6, 12.5 and 22.9 times.

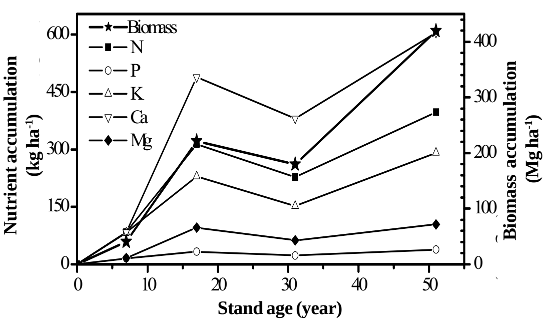

Figure 1. Stand-level nutrient and biomass accumulation at different development stage of Masson pine plantation.

Discussion

Biomass and nutrient accumulation: In general, biomass of each component was age dependent and crown biomass (foliage and branches) increased considerably in the developing young stage and reached a relatively stable stage [17, 19-20]. In this study, we found that crown biomass peaked in the 17-yr-old plantation, and yet, it varied between at ages of 31 and 51 yrs; the distribution proportion continuously declined from age of 17 to age of 31 and to age of 51 yrs. The phenomenon is most likely caused by the artificial thinning, which aimed to improve the condition of the live trees (or crop trees) in these stands [21]. In addition, growth efficiency would have shown a significant increase in the older stands than in the younger stands if it was calculated from Table 3. Of biomass components, stem was the biggest biomass sink (≥60%) as did findings in the previous studies [8, 22, 23]. The results should not be surprising because one of the purposes of thinning is to grow stem wood. Contrary to results of other species [20, 23, 24], below-ground biomass of Masson pine increased with ages in this study and in previous ones [17, 19]. This might be due to deep-rooted systems in *P. massoniana* [19]. It is possible that *P. massoniana* trees grown in infertile soils and arid zones must have more root biomass to improve water and nutrient uptake for growth as stand develops. In other words, high root/shoot ratio allowed plants to maximize nutrient uptake in infertile habitats with reduced nutrient availability [25].

Biomass accumulation at stand level was within the values reported in other parts of China [13, 15, 17, 19]. However, biomass did not keep increasing with age as was found in other studies. Biomass at age of 31 yrs was lower than at age of 17 and 51 yrs because biomass was not only affected by biomass of individual tree but also the stand density. The 31-yr-stand appeared to be over-thinned. Unfortunately, we had no density repetition to find the biomass potential.

Nutrient concentration and biomass pools determine distribution of nutrient contents among various components. Although the highest concentration of all nutrients appeared in the foliage [26],

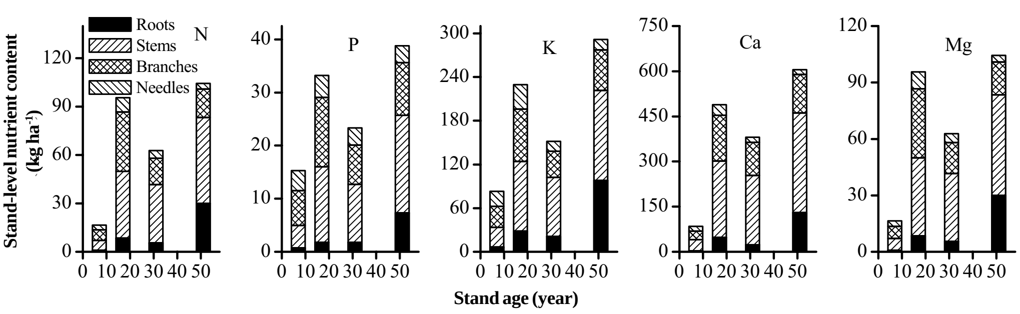

Figure 2. Stand-level nutrient accumulation on foliage, stem, branches and roots for N, P, K, Ca and Mg calculated from 7-, 17-, 31- and 51-yrs-old plantations at Sammenjiang state-owned forest farm in Guangxi, China.

Table 3. The effect of rotation length and harvest intensity on biomass collection and nutrient removal from plantations at Sanmenjiang state-owned forest farm in Guangxi, China.

Harvest intensity	Rotation length	Times of harvesting	Duration	Codes	Biomass	N	P	K	Ca	Mg
Stem-wood	17 years	9	153 years	A_1	1177.9	529.8	84.7	512.3	1701.7	227.5
	31 years	5	155 years	A_2	895.8	455.5	55.3	428.9	1262.7	177.6
	51 years	3	153 years	A_3	1048.2	520.4	63.1	403.4	1160.8	176.5
				$\Delta(A_3\text{-}A_2)/A_3\%$	14.5	12.5	12.3	-6.3	-8.8	-0.6
				$\Delta(A_3\text{-}A_1)/A_3\%$	-12.4	-1.8	-34.2	-27.0	-46.6	-28.9
Stem & branches	17 years	9	153 years	B_1	1304.2	946.8	127.8	860.2	2290.8	374.7
	31 years	5	155 years	B_2	984.8	772.3	93.0	666.5	1838.9	293.5
	51 years	3	153 years	B_3	1134.1	792.2	89.8	612.2	1648.4	265.9
				$\Delta(B_3\text{-}B_2)/B_3\%$	13.2	2.5	-3.5	-8.9	-11.6	-10.4
				$\Delta(B_3\text{-}B_1)/B_3\%$	-15.0	-19.5	-42.3	-40.5	-39.0	-40.9
Aboveground part	17 years	9	153 years	C_1	1697.2	2600.2	283.2	1807.9	3974.5	785.1
	31 years	5	155 years	C_2	1244.4	1801.3	192.7	1197.8	2981.8	522.6
	51 years	3	153 years	C_3	1339.9	1613.0	168.3	1045.3	2518.1	425.0
				$\Delta(C_3\text{-}C_2)/C_3\%$	7.1	-11.7	-14.5	-14.6	-18.4	-23.0
				$\Delta(C_3\text{-}C1)/C_3\%$	-26.7	-61.2	-68.3	-73.0	-57.8	-84.7
Comparison between harvest intensities	17 years	9	153 years	$\Delta(B_1\text{-}A_1)/A_1\%$	10.7	78.7	51.0	67.9	34.6	64.7
				$\Delta(C_1\text{-}A_1)/A_1\%$	44.1	390.8	234.4	252.9	133.6	245.1
	31 years	5	155 years	$\Delta(B_2\text{-}A_2)/A_2\%$	9.9	69.5	68.0	55.4	45.6	65.2
				$\Delta(C_2\text{-}A_2)/A_2\%$	38.9	295.4	248.3	179.3	136.2	194.2
	51 years	3	153 years	$\Delta(B_3\text{-}A_3)/A_3\%$	8.2	52.2	42.4	51.7	42.0	50.6
				$\Delta(C_3\text{-}A_3)/A_3\%$	27.8	209.9	166.6	159.1	116.9	140.8

(Biomass data is expressed in Mg ha^{-1} and nutrients in kg ha^{-1}; Data of biomass and nutrients included the thinning parts previously; The thinning intensity was 54.2% from ages of 17 to 31 yrs and 35.0% from age of 31 to 51 yrs in this study).

about half of total nutrient contents of individual *P. massoniana* tree allocated in the stem except for slightly lower at age of 7 yrs. The results are consistent with those in the same species determined by former reporters [16, 27]. Similar results were also reported in *P. patula*, the maximum nutrient pool was contained in the bole which accounted for about 58% to 85% of the total aerial contents of different elements [28].

Implications of plantation management: Due to significantly higher nutrient contents aboveground, we would have removed majority of nutrients, should these stands be harvested. Therefore, site productivity would not have been sustained. However, the amount of nutrient removal was closely related to harvesting intensity and rotation length. Under the same harvesting intensity, during the same period of time we found that the rotation length increasing from 31 to 51yrs not only improved the biomass collection by 7.1-14.5% but decreased the nutrients removal. The rotation length shortening from 51 to 17 yrs increased the biomass collected by 12.4-26.7% but much more nutrients would be exported. Comparing with the results of Ranger *et al.* [8] and Merino *et al.* [29] that increasing rotation length increased the biomass collected but saved more nutrients, we found that the result was not only connected with nutrient concentration and nutrient content of different stage but with thinning intensity. If we had considered nutrient leaching, runoff, erosion and removal from site in early years of stand establishment and following harvest without soil protection [30], nutrient losses at short rotation length would be doubled or even more.

Biomass collected would increase if harvesting intensity increased as we expected. However, nutrient removal from the site would disproportionally increase much more than the biomass collection. The result agreed with the argument that nutrient exports could be reduced by harvesting only stem-wood and large-diameter branch rather than total aboveground biomass [5, 31]. Hendrickson [32] drew a conclusion that whole-tree harvesting on nutrient-poor sites might lead to stands of low productivity. Increasing the rotation length and decreasing the harvest intensity would be preferable to sustain the fertility of plantation site, in particular for Southern China where *P. massoniana* distributed mainly on soil with lower site index.

Conclusions

Using chronosequence approach with four aged plantation, we found biomass accumulation increased with age although biomass distribution varied with different tree components. Yet, quantity of nutrient pools followed with biomass pools except for foliage, where the highest nutrient concentrations supported photosynthesis. Although species choice, rotation length and harvest intensity are three key factors influencing the sustainability of site productivity. Our results showed that decreasing plantation rotation length has negative effect on site nutrients especially if the harvest intensity increases at the same time.

Implications of our results to forest managers are to increase rotation length and decrease harvest intensity as much as a managing plan can tolerate, especially in the ecological fragile areas. In addition, it is a better practice to fertilize nutrients on the next forests to compensate the loss through the previous harvest. Returning branches, foliage, and even bark would be very effective to keep the site's long-term productivity. Because local people have historically harvested these materials including litters for their fuels or livestock feed, we suggest to masticate and incorporate these materials into soil as soon as possible. Final challenge for local government is to find energy sources for their citizens.

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