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RESEARCH ARTICLE

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Root biomass and productivity in dominant plantation populations in the mountainous area in western Sichuan

Abstract This study investigated root biomass and productivity in dominant populations in western Sichuan, China. A total of 4 plots (*Picea balfouriana* plantation for 22 age in Maerkang, 9 trees, mean DBH of population for 10.4 cm and height for 10.5 m; *Larix maxteriana* plantation for 22 age in Wolong, 9 trees, mean DBH of population for 17.0 cm and height for 13.8 m; *Abies fabri* plantation for 35 age in Ebian, 18 trees, mean DBH of population for 14.1 cm and height for 11.9 m; *Larix kaempferi* plantation for 23 age in Miyaluo, 8 trees, mean DBH of population for 17.4 cm and height for 14.5 m; a 20 m×25 m plot located on each of the 4 types in western Sichuan, China) were randomly selected and excavated to a depth of 60 cm for each of the 4 plantation types. To estimate the root biomass of an individual tree using D^2H, an exponential model was selected with the highest coefficient ranging from 0.94 to 0.99. The total root biomass per hm^2 varied among plantation population types following the order: *L. kaempferi* (37.832 t/hm^2) > *A. fabri* (24.907 t/hm^2) > *L. maxteriana* (18.320 t/hm^2) > *P. balfouriana* (15.982 t/hm^2). The biomass fractions of a given root size class compared to the total root biomass differed among plantation population types. For all 4 studied plantation types, the majority of the roots were distributed in the top 40 cm of soil, e.g., 97.88% for *P. balfouriana* population, 96.78% for *L. maxteriana*, 95.65% for *A. fabri*, and 99.72 for *L. kaempferi* population. The root biomass fractions distributed in the top 20 cm of soil were 77.13% for *P. balfouriana*, 77.13% for *L. maxteriana*, 65.02% for *A. fabri* and 80.66% for *L. kaempferi*, respectively. The root allocation in the 0–20, 20–40, and 40–60 cm soil layers gave ratios of 34:12:1 for *P. balfouriana*, 24:6:1 for *L. maxteriana*, 15:7:1 for *A. fabri*, and 64:4:1 for *L. kaempferi* populations. The root biomass density of dominant plantation population was 10.782 t/(hm^2·m) for *P. balfouriana*, 8.230 t/(hm^2·m) for *L. maxteriana*, 24.546 t/(hm^2·m) for *A. fabri*, and 13.211 t/(hm^2·m) for *L. kaempferi* population, respectively. The root biomass productivity was found to be 0.57 t/(hm^2·year) for *P. balfouriana*, 0.83 t/(hm^2·year) for *L. maxteriana*, 0.71 t/(hm^2·year) for *A. fabri* and 1.64 t/(hm^2·year) for *L. kaempferi* population, respectively.

Keywords biomass, mountainous area in western Sichuan, plantation population, biomass density, productivity, root system, *Picea balfouriana*, *Larix maxteriana*, *Abies fabri*, *Larix kaempferi*

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1 Introduction

The plant root system absorbs water and minerals from soil, synthesizes and deposits organic matters. The root microorganisms, root remnants and pores after the death of the root system can still play a great role in transforming inorganic nitrogen and soil organic matter. Fine root biomass accounts for only 5% of the total root biomass, but its production covers 50%–75% of the primary productivity of forests (Hendrick and Pregitzer, 1992; Nadelhoffer and Raich, 1992). The return of element N to the soil via the death of the root system is 18%–58% more than that via the above-ground litter (McClaugherty et al., 1982; Vogt et al., 1986), and root system activities directly influence the growth and metabolism of plants and improve soil structure to a certain degree. Hence, the studies of root system tended to be specialized in the 1970s (Hoffmann, 1974; Bohm and Kopke, 1977), and has drawn global attention in the recent 30 years (McClaugherty et al., 1982; Persson, 1983; Vogt et al., 1986; Santantonio and Grace, 1987; Goldfarb, 1990; Roy and Singh, 1995; Ruess et al., 1996; Thorup-Kristiina and Riki, 1998; Robinson et al., 1999). Since the 1990s, many studies on root systems in China have been reported (Shan et al., 1993; Chang et al., 1996; Shi et al., 1996; Han and Liang, 1997; Chen et al., 1999; Liao et al., 1999; Wen et al., 1999; Liao et al., 2000; Li et al., 2002; Zhai et al., 2002; Cui et al., 2003). Many of these studies focus on the fine roots (Yang et al., 2002). Recently, fine root production and circulation in major forest ecosystems and their roles in energy and mass flow, as well as the comparison of different measurement methods for fine roots and studies concerning their global change, have become the important research trends (Janssens et al., 1998; Zhang and Wu, 2001).

Fundamental researches on root systems still need to be accumulated because the studies are time-consuming and results are inaccurate (Bohm et al., 1977; Bohm and Kopke, 1977; Bohm, 1979). The plantation coverage in western Sichuan is getting higher and the competition among species is intense. Accordingly, the singleness of tree species in the plantation brings about many problems such as the plantation degradation and outbreak of pests (Yang and Li, 1992; Liu et al., 2004). Hence, as a series of studies of plantation ecology in the mountainous area of western Sichuan, a systematic research on the distribution of plantation root system and root biomass is significant for us to understand the accumulation and distribution of nutrients, hydrology, benefit of mixed tree species and root system competition (Liu et al., 1998, 2003a, 2003b, 2004). It can also provide us some fundamental documents for evaluating ecosystem functions and especially measuring the carbon storage in plantations.

2 Study area and research methods

2.1 Study area

The topography (physiognomy) of mountainous forests is dominated by mountains and valleys with the elevation ranging from 2,500 to 4,500 m and the relative difference of 1,000 m. The sub-tropical characteristics of this area are not distinct and a vertical zonality in this area is evident due to topographic influence and the redistribution and recombination of water and heat. An intense afforestation was carried out from the 1960s and a plantation area of 7.3 million hm^2 was finished up to the year 2000, of which 5.8 million hm^2 was covered with a volume of 305 million m^3, becoming the major subsequent resource in the mountainous area in western Sichuan (Yang and Li, 1992; Liu et al., 2004). Plantations dominated by *Picea balfouriana* and *P. saperata* form after the logging of primary forests of *Abies faxoniana* and *P. purpurea*; *P. likiangensis* plantations form after the felling of primary forests of *A. georgei* and *P. likiangensis*; the plantations with the same dominant species form after the cutting of primary forests of *A. fabri* and *P. brachytyla* var. *complanat* due to the little change of the humid environment. Plantations of *Larix maxteriana* and *L. kaempferi* also exist. Their stand characteristics and environmental conditions are presented in Table 1.

2.2 Research methods

2.2.1 Plot setting and investigation

Plots of 20 m×25 m were set in major plantations in western Sichuan, and individual trees were investigated for their stand factors and parameters.

2.2.2 Measurement of root biomass

Standard trees were selected with 2.0 as a diameter class in the plots (one tree in each diameter class), and their diameter at breast height (DBH), height, canopy size, height of the first living branch, and the location of neighbouring trees were measured. The standard trees were felled, and a method of "layered cutting" was adopted to measure the fresh weights of trunk, bark, branches and leaves (Monsi, 1968; Fujimori et al., 1976; Feng et al., 1982). At the same time, each organ was sampled for further test.

The whole root system was collected according to different layers (every 20 cm as a layer) for the underground parts of standard trees. The fresh weights of root stumps, thick roots (diameter > 2.0 cm), medium roots (1.0 cm < diameter ⩽ 2.0 cm) and fine roots (diameter ⩽ 1.0 cm) in each layer were measured (Jiang, 1986). The biomass of shrub layer, herb layer and litter layer was also measured.

2.2.3 Analysis and modelling

The samples were oven-dried at 90°C for 2 hours, and then at 85°C to a constant weight. Then they were weighed using an electronic balance. The ratio of dry weight to fresh weight was calculated and the fresh weight of each organ was converted into dry weight. Then the dry biomass in a given area was obtained according to the plot information.

The correlation between variable parameters and the biomass of each organ was analyzed for the measured root biomass. A statistical model was established according to "relative growth law" (Huxley, 1931), and the root biomass in the whole plantation was calculated.

Table 1 Characteristics of the investigation forest-stand in Mountainous region in western Sichuan

Plantation type and site	Landform and physiognomy	Elevation /m	Climatic index				Stand characteristics				
			Mean annual temperature /°C	Mean temperature in January /°C	Mean temperature in July /°C	Mean annual rainfall /mm	Age /year	Density /(trees·hm^{-2})	Canopy density /%	Mean DBH /cm	Mean height /m
P. balfouriana plantation in Maerkang, Sichuan	Mountain and valley	2,700	8.6	–1.0	16.5	753.0	28	3,460	0.9	10.4	10.5
L. maxteriana plantation in Wolong, Sichuan	Mountain and valley	2,200	10.9	2.5	22.5	1,100.0	22	1,359	0.7	17.0	13.8
A. fabri plantation in Ebian, Sichuan	Mountain and valley	2,300	16.4	6.3	23.6	825.0	35	2,834	0.7	14.1	11.9
L. kaempferi plantation in Miyaluo, Sichuan	Mountain and valley	2,950	4.7	–6.0	13.0	1,193.5	23	1,940	0.9	17.4	14.5

2.2.4 Calculation of root productivity

Root productivity is the net production of organic matters in a given area and a given period. The net production (ΔP_N) is the sum of three factors, e.g., plant yield (ΔY_N), litter amount (ΔL_N) and loss due to the gnawing of animals (ΔG_N) during the period of T_1–T_2. Because of the difficulty of measuring ΔL_N and ΔG_N, this study ignores these two factors. The net root productivity is calculated according to Eq. (1) (Monsi, 1965; Feng et al., 1982).

$$\Delta P_N = W/a \quad (1)$$

where ΔP_N is the average net production (referred as productivity), W is the root biomass and a is the population age.

2.2.5 Coefficient between aboveground parts and roots

The ratio of aboveground parts to roots is the common parameter to evaluate the growth relationship and to differentiate the dry weights between the two parts. This study uses the coefficient between aboveground parts and roots (RC) proposed by Boonstra (1931) as Eq. (2):

$$RC = W_{AB}/W_{RB} \quad (2)$$

where W_{AB} is the aboveground biomass (kg/hm^2) and W_{RB} is the root biomass (kg/hm^2).

2.2.6 Calculation of biomass density

Aboveground biomass density (ABD) refers to the biomass within a given height, and root biomass density (RBD) refers to the biomass within a given root system depth. These are two important indexes for population structure and functions. ABD and RBD can be calculated by Eqs. (3) and (4) respectively.

$$ABD = W_{AB}/H \quad (3)$$

$$RBD = W_{RB}/D_R \quad (4)$$

where W_{AB} is the aboveground biomass (kg/hm^2), H is the tree height (m), W_{RB} is the root biomass (kg/hm^2) and D_R is the depth of root system (m).

3 Results and analysis

3.1 Establishment and selection of prediction model of root biomass

The establishment and selection of prediction model of root biomass should be based on that the variable parameters have significant correlation with the biomass of each organ. Then, according to the relative growth law, the significance analysis between individual tree's DBH, height and the biomass of each organ should show a significant relationship, and each factor of individual tree's DBH, height and height should has an extremely significant relationship with any factor among trunk, bark, branches, leaves and total biomass. Thereafter, using biomass (W) as the dependent variable, using basal diameter (D), height (H) and D^2H as independent variables, some models like $Y = aX^b$, $Y = ae^b$, $Y = aX + b$, $Y = 1/(u + ab^X)$ and $Y = a + b\ln X$ would be used for regression fitness to calculate the values of a and b.

After selection, a model for estimating individual tree's organ biomass was established (Table 2). In the selection, the exponential model is optimum in suitable models using D^2H to estimate individual tree's organ biomass, and the correlation coefficient is high (0.94–0.99), reaching an ex

Table 2 Optimal models of biomass for root of dominant plantation population in mountain land in western Sichuan

Tree species	Model	Dependent variable (Y)	Independent variable (X)	a	b	Correlation coefficient	Standard error	Sample size (n)	Range of practicality
P. balfouriana	$Y=aX^b$	W_R	D^2H	0.931,6	–2.114,3	0.992,3	0.096,9	9	D: 2.0–19.0 cm; H: 5.0–11.0 m
L. maxteriana	$Y=aX^b$	W_R	D^2H	0.001,0	1.075,5	0.942,5	0.040,4	9	D: 8.0–24.0 cm; H: 12.1–18.0 m
A. fabri	$Y=aX^b$	W_R	D^2H	0.153,0	0.520,8	0.989,1	0.141,4	18	D: 6.2–29.1 cm; H: 7.7–25.8 m
L. kaempferi	$Y=aX^b$	W_R	D^2H	0.001,9	1.095,1	0.994,8	0.082,9	8	D: 10.5–23.7 cm; H: 12.5–16.2 m

tremely significant level. The remaining regressive standard deviation is low, indicating a high fitness between estimated and measured values as well as a low estimating error.

3.2 Root biomass and its distribution

Results of root biomass are presented in Table 3. It shows that the total biomass follow the order of *L. kaempferi* (37.832 t/hm^2) > *A. fabri* (24.907 t/hm^2) > *L. maxteriana* (18.320 t/hm^2) > *P. balfouriana* (15.982 t/hm^2); the production of each root diameter class ranks in the order of root stumps > thick roots > medium roots > fine roots, and the biomass of each root diameter class has a different percentage of the total root production. The biomass of each root class of *P. balfouriana* is 8.742, 5.770, 0.831 and 0.639 t/hm^2, accounting for 54.70%, 36.10%, 5.20% and 4.00% of the total root biomass, respectively; the biomass of each root class of *L. maxteriana* is 8.000, 8.120, 1.540 and 0.660 t/hm^2, sharing 43.67%, 44.32%, 8.41% and 3.60% of the total root biomass; the biomass of each root class of *A. fabri* is 9.132, 10.710, 2.159 and 2.906 t/hm^2, occupying 36.76%, 43.00%, 8.70% and 11.60% of the total root biomass; the biomass of each root class of *L. kaempferi* is 10.077, 22.984, 2.302 and 2.469 t/hm^2, accounting for 26.64%, 60.75%, 6.08% and 6.53% of the total root biomass.

The percentage of biomass of propping roots (root stumps and thick root that support aboveground part of trees) to the total root biomass is similar, with *P. balfouriana* 90.80%, *L. maxteriana* 87.99%, *A. fabri* 79.70% and *L. kaempferi* 87.39%; but that of nutritional roots (medium roots and fine roots that absorb water and nutrients) differs: *A. fabri* is highest (20.30%), and the others roughly the same (*P. balfouriana* 9.20%, *L. maxteriana* 12.01% and *L. kaempferi* 12.61%). In the vertical distribution, the biomass of propping roots, nutritional roots and the total roots concentrated mostly in the depth of 0–40.0 cm, with a percentage of 88.00%–90.00%, 96.00%–100.00% and 95.00%–98.00%, respectively (Fig. 1).

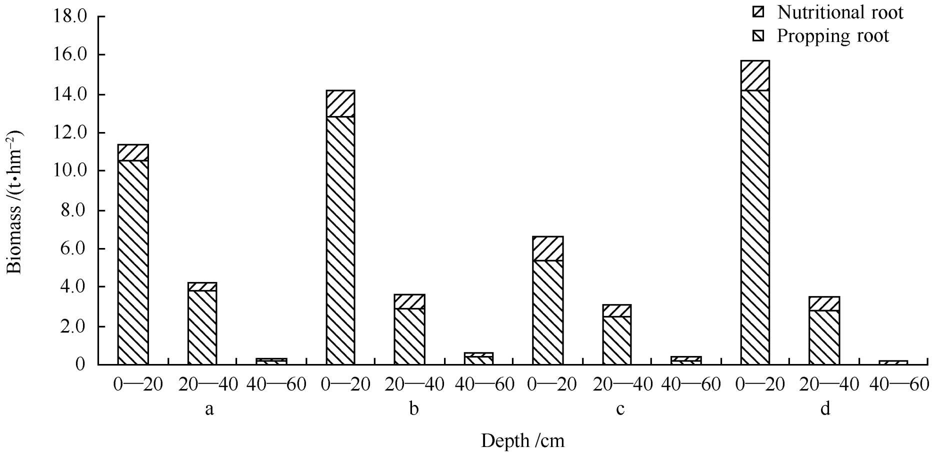
3.3 Vertical distribution of root biomass

It is shown in Fig. 2 that the root system is mainly distributed in the depth of 0–40.0 cm, and mostly in 0–20.0 cm; in the three layers of 0–20.0 cm, 20.0–40.0 cm and 40.0–60.0 cm, the ratios of root biomass of each population are as follows: *P. balfouriana* 34:12:1, *L. maxteriana* 24:6:1, *A. fabri* 15:7:1 and *L. kaempferi* 63:14:1. The root biomass of *P. balfouriana* distributed in the layers of 0–40.0 and 0–20.0 cm accounts for 97.88% and 77.13%, that of *L. maxteriana* for 96.78% and 77.13%, that of *A. fabri* for 95.65% and 65.02%, and that of *L. kaempferi* for 99.72% and 80.66%. The biomass of propping roots of *P. balfouriana* (14.51 t/hm^2) accounts for 90.80% of the total root biomass, that of *L. maxteriana* (16.12 t/hm^2) for 87.99%, that of *A. fabri* (8.06 t/hm^2) for 79.64%, and that of *L. kaempferi* (17.03 t/hm^2) for 87.38%. The biomass of nutritional root of *P. balfouriana* (1.47 t/hm^2) accounts for 9.20% of the total biomass, that of *L. maxteriana* (2.20 t/hm^2) for 12.01%, that of *A. fabri* (2.06 t/hm^2) for 20.36%, and that of *L. kaempferi* (1.29 t/hm^2) for 12.62%. The biomass of nutritional roots, total root biomass and the ratio of the former to the latter all decrease with the soil depth, presenting a trend of an inverse pyramid.

Table 3 Root biomass of dominant plantation population in mountainous area in western Sichuan

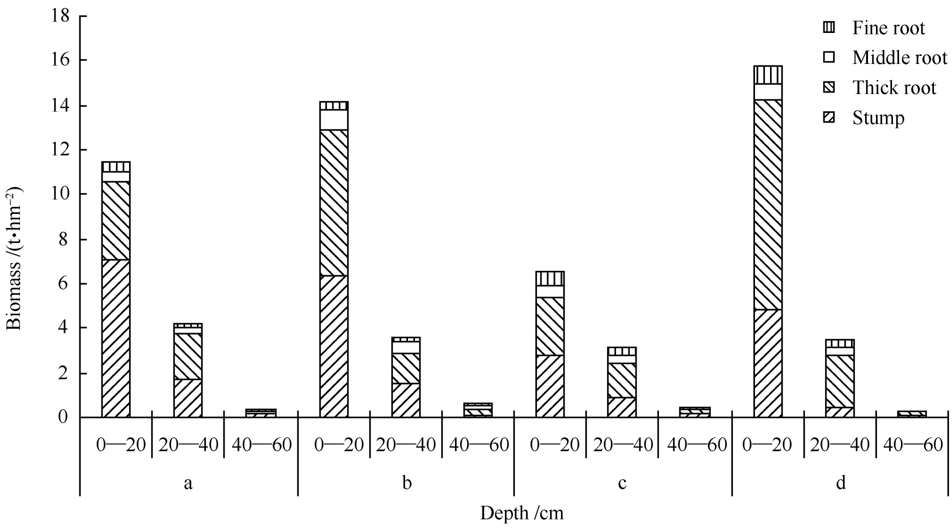
Forest type, site and age	Biomass and distribution /(t·hm^{-2})				
	Stump	Thick root	Middle root	Fine root	Total
P. balfouriana plantation in Maerkang, Sichuan, 28 years	8.742 (54.70)	5.770 (36.10)	0.831 (5.20)	0.639 (4.00)	15.982 (100.00)
L. maxteriana plantation in Wolong, Sichuan, 22 years	8.000 (43.67)	8.120 (44.32)	1.540 (8.41)	0.660 (3.60)	18.32 (100.00)
A. fabri plantation in Ebian, Sichuan, 35 years	9.132 (36.70)	10.710 (43.00)	2.159 (8.70)	2.906 (11.60)	24.907 (100.00)
L. kaempferi plantation in Miyaluo, Sichuan, 23 years	10.077 (26.64)	22.984 (60.75)	2.302 (6.08)	2.469 (6.53)	37.832 (100.00)

Values in the brackets are the percentage to the total root biomass of the same population type



a: *Picea balfouriana*; b: *Larix maxteriana*; c: *Abies fabri*; d: *Larix kaimpferi*

Fig. 1 Vertical distribution pattern of biomass of propping roots and nutritional roots



a: *Picea balfouriana*; b: *Larix maxteriana*; c: *Abies fabri*; d: *Larix kaimpferi*

Fig. 2 Vertical biomass distribution of dominant plantation population in mountainous land in western Sichuan

3.4 Relationship between root biomass and assimilative organs

Results show that, in the populations in western Sichuan, no obvious correlation exists between root biomass and aboveground biomass as well as the biomass of assimilative organs. However, the correlation coefficient between aboveground parts and roots, and the biomass of assimilative organs have evident regularity: the correlation coefficient is more than 6.7 for evergreen coniferous species, and that for deciduous coniferous species ranges from 5.0 to 6.2; the biomass of assimilative organs of *Picea* and *Abies* (14.0–15.0 hm^2) is twice or three times larger than that of *Larix* species (4.0 hm^2). The ratios of root biomass to assimilative organ biomass for the four populations are 1:1.1 (*P. balfouriana*), 1:4.6 (*L. maxteriana*), 1:1.7 (*A. fabri*) and 1:9.2 (*L. kaempferi*), indicating that *Picea* and *Abies* species need more photosynthetic organ to maintain their growth.

Table 4 Relationship between root biomass and aboveground biomass and biomass for assimilation organ of dominant plantation population in mountain land in western Sichuan

Tree species	*P. balfouriana*	*L. maxteriana*	*A. fabri*	*L. kaempferi*
Aboveground biomass /($t \cdot hm^{-2}$)	107.818	113.57	173.10	191.559
Root biomass /($t \cdot hm^{-2}$)	15.982	18.32	24.907	37.832
Assimilation organ biomass /($t \cdot hm^{-2}$)	14.234	3.97	15.059	4.103
Relationship coefficient	6.746	6.199	6.950	5.063

3.5 Root productivity

The analysis of root productivity (Table 5) shows that annual average net production of root system, its percentage to net production, and mean annual assimilative efficiency all have a trend of *Larix* species > *Picea* and *Abies* species. The mean annual net production of *L. kaempferi*, a species introduced from Japan, is 2.88 times that of *P. balfouriana*, 1.96 times that of *L. maxteriana* and 2.34 times that of *A. fabri*. And the mean annual assimilative efficiency of *L. kaempferi* roots is also higher than domestic species, 2.26 times that of *P. balfouriana*, 1.96 times that of *L. maxteriana*, and 2.93 times that of *A. fabri*. Collectively, the root productivity of these four populations follow the order of *L. kaempferi* > *L. maxteriana* > *A. fabri* > *P. balfouriana*, with a value of 1.64, 0.83, 0.71 and 0.57 t/(hm^2·year).

The comparison of root biomass and productivity is shown in Table 6. It indicates that the plantations in the mountainous area are still under-age and have great potential for development.

3.6 Root biomass density

Table 7 shows that the root biomass density of the four plantations follows the order of *A. fabri* > *L. kaempferi* > *P. balfouriana* > *L. maxteriana*, with a value of 14.456, 13.211, 10.782 and 8.230 t/(hm^2·m), respectively. The aboveground biomass density ranks in the order of *L. kaempferi* > *A. febri* > *L. maxteriana* > *P. balfouriana*, with a value of 63.053, 41.512, 30.533 and 26.637 t/(hm^2·m). No evident correlation exists between the population biomass density and height of aboveground parts, which is in agreement with the results of previous studies (Kira and Shidei, 1967; Fang et al., 1993). But the aboveground biomass density differs greatly, ranging from 26.0 to 63.0 t/(hm^2·m), and root biomass density differs gently, fluctuating from 8.0 to 14.0 t/(hm^2·m). Compared with the aboveground biomass density of common closed populations, which was found to be 10.0–15.0 t/(hm^2·m) (Kira and Shidei, 1967) and 7.0–11.0 t/(hm^2·m) (Fang et al., 1993), the aboveground biomass density of plantations in western Sichuan is 2–4 times higher, and the root biomass density is similar to that of *Pinus tabulaeformis* (Fang et al., 1993).

4 Conclusions

Using D^2H to estimate individual tree's root biomass in western Sichuan, it is found that the exponential model is optimum in the suitable models, and the correlation coefficient of the selected model is high (between 0.94–0.99), indicating a good fitness between estimated and measured value.

The total root biomass ranks in the order of *L. kaempferi* > *A. fabri* > *L. maxteriana* > *P. balfouriana*, with a respective value of 37.832, 24.907, 18.320 and 15.982 t/hm^2, and the proportion of root biomass of each root class is different.

The root biomass is mainly distributed in the depth of 0–40 cm, accounting for over 96%. The distribution ratios of root biomass in the depth of 0–20, 20–40 and 40–60 cm for the populations are as follows: *P. balfouriana* 34:12:1, *L. maxteriana* 24:6:1, *A. fabri* 15:7:1 and *L. kaempferi* 63:14:1.

Table 5 Mean annual net production and mean annual net assimilation efficiency of root of dominant plantation population in the mountainous area in western Sichuan

Forest type, site and age	Mean annual net production /(kg·hm^{-2}·year^{-1})	Percentage /%	Mean annual net assimilation efficiency /(g·m^{-2}·year^{-1})	Productivity /(t·hm^{-2}·year^{-1})
P. balfouriana plantation in Maerkang, Sichuan, 28 age	570.8	7.5	3.9	0.57
L. maxteriana plantation in Wolong, Sichuan, 22 age	832.73	9.30	6.7	0.83
A. fabri plantation in Ebian, Sichuan, 35 age	703.6	8.3	3.0	0.71
L. kaempferi plantation in Miyaluo, Sichuan, 23 age	1,644.85	13.42	8.8	1.64

Table 6 Comparison of root biomass of different forests in other regions

Forest type, site and age	Root biomass （t/hm^2）	Productivity /(t·hm^{-2}·year^{-1})	Reference
P. purpurea natural forest in Songpan, Sichuan, 41–50 years	26.076	0.56	Jiang (1986)
A. georgei natural forest in Zhongdian, Yunnan, 200 years	49.570	1.55	Dang et al. (1994)
P. brachytla var. *complanata* natural forest in Zhongdian, Yunnan, 50 years	8.343	0.94	Wu et al. (1994a, 1994b)
P. brachytla var. *complanata* natural forest in Zhongdian, Yunnan, 150 years	15.164	1.46	Wu et al. (1994a, 1994b)
P. schrenkiana var. *tianshanica* natural forest in Changji, Xinjiang, 200 years	40.206	3.40	Wang and Zhao (1999)
P. koraiensis plantation in Suileng, Heilongjiang, 30 years	16.620	1.53	Mu et al. (1999)
P. koraiensis plantation in Suileng, Heilongjiang, 25 years	6.812	0.99	Mu et al. (1999)
P. crassifolia natural forest in Qilian Mountains, Qinghai, 120–210 years	54.270	3.41	Mu et al. (1999)
P. balfouriana plantation in Maerkang, Sichuan, 28 years	15.982	0.57	This study
L. maxteriana plantation in Wolong, Sichuan, 22 years	18.320	0.83	This study
A. fabri plantation in Ebian, Sichuan, 35 years	24.907	0.71	This study
L. kaempferi plantation in Miyaluo, Sichuan, 23 years	37.832	1.64	This study

The mean annual net production of the introduced species *L. kaempferi* is 2.88 times of *P. balfouriana*, 1.96 times of *L. maxteriana* and 2.34 times of *A. fabri*. Its mean annual net assimilative efficiency is also higher than local species, 2.26 times of *P. balfouriana*, 1.96 times of *L. maxteriana* and 2.93 times of *A. fabri*. The root productivity of the populations in western Sichuan follows the order of *L. kaempferi* (1.64 t/(hm^2·year)) > *L. maxteriana* (0.83 t/(hm^2·year)) > *A. fabri* (0.71 t/(hm^2·year)) > *P. balfouriana* (0.57 t/(hm^2·year)).

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