Effect of intraspecific competition on biomass partitioning of *Larix principis-rupprechtii*

Wensong Zhou, Xiaqin Cheng, Ran Wu, Hairong Han, Fengfeng Kang, Jiang Zhu and Ping Tian

Key Laboratory for Silviculture and Conservation, Ministry of Education, The College of Forestry, Beijing Forestry University, Beijing, People’s Republic of China

**ABSTRACT**

It is acknowledged that trees biomass allocation in response to environmental conditions. However, it remains poorly understood what strategies of plant biomass allocation with inter- and intraspecific interactions of tree species in forest stands. Such information is important for revealing strategies of plant biomass allocation with plant competition. To address this problem, a study was conducted in *Larix principis-rupprechtii* plantations to evaluate the impact of plant competition on plant biomass allocation in Shanxi Province, China. We measured a competition index (CI), stem, branch, foliage, and root biomass as well as element content (Carbon (C), Nitrogen (N), Phosphorus (P), Potassium (K)). Stem-foliage ratio (S/F), aboveground–belowground biomass ratio (T/R), average annual increment of biomass (AAB), height (AAH), and DBH (AAD) were calculated. The study found that the competition intensity of neighboring trees was closely related to the partitioning of biomass. Our results demonstrated that competition pressure of neighboring trees was a crucial factor to drive and regulate the distribution of biomass. Predicting biomass allocation–competition relationships could represent a supportive method for improving management of *Larix principis-rupprechtii* plantations in Mountain Taiyue areas.

**ARTICLE HISTORY**

Received 6 June 2017
Accepted 14 November 2017

**KEYWORDS**

Competition; biomass partitioning; element content; fine root; redundancy analysis

**Introduction**

Competition between individuals influences growth, shape and structure, survival, as well as distribution, change, and species diversity of vegetation communities (Wu and Wang 2000; Liu et al. 2010; Cao et al. 2013). Competition is driven by the acquisition of environmental resources by species in close spatial proximity. Changes in biomass partitioning of plant organs is an important mechanism to maintain productivity (Davidson 1969; Sebastia 2007). Some studies have found that competition can greatly increase the productive potential of forest stands (Fox et al. 2007). Productivity and decomposition processes in forests are affected by changes in biomass partitioning. The characteristics of plant biomass allocation have great importance in the study of the forest carbon cycle.

Many studies have investigated the relationship between biomass partitioning and plant competition. An individual-based model was proposed by Lin et al. 2014, which allowed exploring the plant mass–density relationship in realistic settings by representing plasticity of biomass allocation and different modes of competition in the above- and belowground compartment. They found that changes in biomass allocation induced by belowground resource limitation explained the deviations from the mass–density relationship predicted by metabolic scaling theory (Lin et al. 2014). By using modified root exclusion tubes, Cahill and Casper (2000) carried out an experiment to seedling of *Amaranthus retroflexus* at ‘Laurels Preserve,’ located in SE Pennsylvania, USA, they found a strong relationship between neighbor root biomass and belowground competitive intensity suggested relatively small variations in root biomass could lead to large variations in belowground competition. A field experiment proved that root pruning could increase the aboveground biomass of white cabbage (Bath et al. 2008). A study by Villacorta (2015) analyzed loblolly pine (*Pinus taeda*) of different genotypes in the southeast US, and found that loblolly pine took up more resources by changing the canopy structure. Meanwhile, a study in northern China found that aboveground–belowground biomass ratio (T/R) had no correlation with competition of khingan fir (*Abies nephrolepis*) (Wang et al. 2012b). Another study in the Coast Range of Washington State showed that after removing the effect of competition, aboveground biomass of Douglas-fir (*Pseudotsuga menziesii*) significantly increased (Petersen et al. 2008). These examples show that competition is closely related to biomass partitioning.

*Larix principis-rupprechtii* is one of the main afforestation species in the mountainous areas and is also a dominant species of plantations in the Shanxi province, northern China. This species has many advantages as an afforestation species such as fast-growing, good building timber, and high corrosion resistance (Chai et al. 2014). Biomass distribution directly affects plantation productivity, and productivity is closely related to competition in forests. In the present study, we hypothesize that biomass partitioning and nutrient content change with changing competition intensity, and discuss these changes. The objectives of this study are to examine the relationship between biomass allocation and competition intensity, and to explore the response mechanism of plants to competition intensity.
Materials and methods

Study area and experimental design

The study area is located in a L. principis-rupprechtii plantation established on Mt. Taiyue in Shanxi Province, China (36°35′–36°53′N, 111°91′–112°04′E, 2100–2400 m above sea level). The area is characterized by a continental monsoon climate with an annual average temperature of 8.6°C. The soil is both brown soil and cinnamon soil. June–August is the rainy season and average annual precipitation is about 600 mm. Dominant tree species are L. principis-rupprechtii, and Betula platyphylla. Shrub species are mainly Salix caprea, Spiraea pubescens, and Lonicera sereana. Herb species are mainly Phlomis umbrosa, Senecio nemorensis, and Epilobium angustifolium.

Investigation measurements

Twelve trees of L. principis-rupprechtii were chosen as sample trees based on the DBH (Table 1). All the trees within 7 m of the sample tree were chosen as the competition trees. Measurements of diameter at breast height (DBH, cm), tree height (H, m), crown length (CL, m), and crown width (CW, m) were made for each sample and competition tree in August in 2014.

Stem analysis

For the 12 sample trees complete above- and belowground harvests were carried out. Each sample tree was cut at the base and separated into stems, branches, foliage, and roots (coarse roots: >1 mm diameter, fine roots: <1 mm diameter). The total green weight of each component was weighed independently and measured in the field. Subsample disks of stems were cut from each base diameter, breast diameter, and crown diameter areas, and annual growth rings were counted, weighed, and bagged for laboratory drying. All subsamples were dried to a constant mass at 85°C in an oven and the dry weight of each component was calculated by moisture content. Subsamples of each tissue were ground and homogenized to pass through a 0.25-mm stainless steel sieve. Carbon (C) and nitrogen (N) content were determined using an elemental analyzer (AEAL Analyzer 3 HR, Germany), and potassium (K) content was determined using an atomic absorption spectrometer (TAS-990AFG).

Data analysis

Data were used to calculate Hegyi competition index (Hegyi 1974) of sample trees:

\[ CI_i = \sum_{j=1}^{n} \frac{D_j}{(D_i \times L_j)}, \]

where CI is the Hegyi competition index of the sample tree i, j is the competition tree, D is the DBH of the sample tree, D is the DBH of competition tree, L is the distance of sample and competition tree, n is number of competition trees. In current study, we refer to local previous studies, defined all the trees within 7 m of the sample tree as the competition trees (Zhou et al. 2017).

Linear regression equations were used to analyze the relationship between competition index and biomass of each component, as well as C, N, P, and K content.

\[ y_0 = a_0x_0 + b_0, \]

where \( y_0 \) is the biomass of each component or element, \( x_0 \) is the competition index, \( a_0 \) and \( b_0 \) are fit parameters.

Relationships between competition index and biomass traits were analyzed by an exponential regression equation. Biomass, stem-foliage ratio (S/F), aboveground–belowground biomass ratio (T/R), average annual increment of biomass (AAB), height (AAH), and DBH (AAD) were calculated as biomass partitioning traits.

\[ y_1 = a_1 \times e^{b_1x_1}, \]

where \( y_1 \) is the trait of sample tree 1, \( x_1 \) is the competition index, \( a_1 \) and \( b_1 \) are fit parameters.

The variability of biomass partitioning, basic traits, and element content in relation to explanatory variables (competition index and age) were analyzed by redundancy analysis (RDA) using Canoco for Windows 4.5 (Ter Braak and Smilauer 1998). All regression figures were made using SigmaPlot 10.0.

Results

Biomass partitioning

In all components, stem biomass was the greatest biomass component, branch, and root biomass were similar, and foliage biomass was the smallest (Figure 1, Table 2). The range of total biomass for sample trees was from 9.007 to 327.302 kg. Linear regression analysis of the competition index showed that the proportion of stem and root biomass decreased as competition index increased (Figure 2). The proportion of branch and foliage biomass had positive linear correlations with competition

| Table 1. Basic characteristics of sample trees. |
|-----------------|--------|--------|--------|--------|-------------------|-------------------|-------------------|
| Number | Age (years) | DBH (cm) | Height (m) | CL (m) | CW (m) | Height-diameter ratio | Crown-height ratio | Competition index |
| 1 | 15 | 5.7 | 5.9 | 3 | 3 | 1.030 | 0.511 | 3.522 |
| 2 | 26 | 7.8 | 10.4 | 3.7 | 3.1 | 1.333 | 0.327 | 2.934 |
| 3 | 16 | 8.8 | 8.5 | 2.5 | 2.2 | 0.966 | 0.276 | 1.814 |
| 4 | 16 | 9.8 | 9.4 | 4.4 | 3.3 | 0.959 | 0.410 | 1.629 |
| 5 | 26 | 11.2 | 13.3 | 3.9 | 3.6 | 1.188 | 0.282 | 1.879 |
| 6 | 15 | 11.6 | 9.0 | 4.2 | 3.7 | 0.773 | 0.440 | 1.299 |
| 7 | 16 | 13.9 | 13.1 | 5.5 | 4.3 | 0.942 | 0.370 | 1.244 |
| 8 | 30 | 15.9 | 14.3 | 5.7 | 7.2 | 0.899 | 0.451 | 1.498 |
| 9 | 33 | 16.4 | 16.1 | 3.2 | 4.2 | 0.982 | 0.230 | 1.186 |
| 10 | 40 | 23.2 | 20.3 | 4 | 8.1 | 0.873 | 0.299 | 1.357 |
| 11 | 33 | 25.6 | 17.1 | 4.8 | 6.8 | 0.725 | 0.339 | 1.022 |
| 12 | 37 | 31.3 | 20.5 | 5.9 | 7.5 | 0.655 | 0.327 | 0.528 |
index (Figure 2). There was a significant linear correlation between stem and branch biomass with the competition index ($P < .05$), while foliage and root biomass had no significant correlation (Figure 2). The height-diameter ratio had a significant positive linear correlation between with competition index, while crown-height ratio had no significant correlation between with competition index.

**Biomass partitioning traits with competition index**

The current study analyzed the relationships between competition index and the following biomass allocation traits: total biomass, average annual increment of biomass (AAB), height (AAH) and DBH (AAD), T/R, and S/F (Table 3). The correlation between T/R and competition index was not significant. However, the total biomass, AAB, AAH, AAD, and S/F were all significantly positively correlated with the competition index (Figure 3).

**Element content with competition index**

Results indicated that changes in C, N, P, and K content in every biomass component had weak correlations with competition index, except fine roots (Figure 4, Table 4). There was a significant positive correlation between the competition index and N and P content. C and K had no significant correlation with the competition index. The results also showed that changes of N and P element were sensitive to the competition in the environment.

**Redundancy analysis**

To explore the effect of competition on the growth of trees, competition index and age were selected as environment factors, biomass partitioning, basic traits, and element content were analyzed by RDA (Figure 5). Both CI and Age had strong significant correlation with the first 1 axis (Table 5). The CI was found to have significant and positive effect on FRN, FRP, H/D. In contrast, the CI was found to have significant and negative effect on biomass variables, such as AAB, AAD, AAH, Canopy, Height, DBH, and S/F. There was a significant positive correlation between Age and biomass variables, S/F, Canopy, Height, and DBH. As well, Age was also found to have negative effect on T/R, C/H, FRC, and FRK.

Variance partitioning analysis showed that CI and Age explained 26.1% and 23.4% of the variation in the distribution of biomass, respectively. Interaction between the CI and Age factors explained 37.3% of the variation in the distribution of biomass. Both CI and Age explained 86.8% of the variation in the distribution of biomass (Figure 6).

**Discussion**

**Competition affect biomass allocation**

Competition is a ubiquitous phenomenon in plant communities. In the process of growth and development, plants compete with adjacent individuals for water, light, and nutrient resources (Wang et al. 2012a). In the present study, stem and branch biomass of *L. principis-rupprechtii* had a low, but significant ($P < .05$) relationship with the competition index. This indicates that there was a significant effect of competition on stem, and branch biomass. According to the theory of biomass allocation, intense light competition index.
can increase biomass allocation to foliage and reduce biomass allocation to plant stems (Waring et al. 1980; Rodri et al. 2003). The results of this study are consistent with this theory of biomass allocation, and it also suggests that competition intensity is not the main factor affecting root and foliage biomass. Despite the low $R^2$ values, Figure 2 also shows the proportion of branch and foliage biomass increased with increased competition intensity suggesting there is a slight competition effect. The main type of aboveground competition is for light resources. DBH and the height of trees are closely related to light capture. With increasing competition intensity, DBH and height decreases. The height-diameter

### Table 3. Biomass traits of sample trees.

| Number | AAB (kg) | AAH (m) | AAD (cm) | T/R | S/F |
|--------|----------|---------|----------|-----|-----|
| 1      | 0.600    | 0.391   | 0.380    | 3.446 | 8.493 |
| 2      | 0.652    | 0.400   | 0.300    | 4.030 | 4.885 |
| 3      | 1.286    | 0.531   | 0.550    | 3.632 | 4.072 |
| 4      | 2.097    | 0.588   | 0.613    | 3.986 | 3.830 |
| 5      | 1.727    | 0.512   | 0.431    | 5.374 | 4.661 |
| 6      | 4.125    | 0.598   | 0.773    | 5.437 | 5.855 |
| 7      | 2.726    | 0.485   | 0.515    | 5.696 | 7.247 |
| 8      | 3.534    | 0.477   | 0.530    | 4.460 | 9.552 |
| 9      | 2.918    | 0.488   | 0.497    | 2.469 | 12.477 |
| 10     | 7.880    | 0.506   | 0.580    | 5.185 | 12.893 |
| 11     | 8.177    | 0.518   | 0.715    | 2.916 | 17.966 |
| 12     | 12.711   | 0.554   | 0.846    | 2.289 | 24.135 |

Figure 2. Linear regression of stem biomass (A), branch biomass (B), foliage biomass (C), root biomass (D), height-diameter ratio (E), and crown-height ratio (F) with competition index for the 12 sample trees of *L. principis-rupprechtii.*
The ratio reflects the relationship between radial growth strategy and height growth strategy (Rottmann 1985; Wonn and O’Hara 2001; Vospernik et al. 2010). In this study, the height-diameter ratio was significantly positively correlated with competition intensity. For individuals subject to high competitive pressure, radial growth was significantly restricted. Plant height is the main factor influencing light capture for photosynthesis. The crown-height ratio reflects the size of the whole crown and quantifies competition among trees (Hailemariam et al. 2005; Tanka 2006; Toma 2013). In this paper, the crown-height ratio was not affected by aboveground competition. The growth of leaves is greatly influenced by light but the effects of water, nutrients, and soil conditions also significantly affect growth. The distribution of leaf position is also connected with tree height, branch location, and crown density, and then effect the size and structure of the whole crown.

As plants grow the competitive environment changes constantly and the competitive pressure on plants also changes. The AAB, AAH, and AAD increased exponentially with plant growth (Figure 3), which is similar with some previous studies (Wang et al. 2012a). In that study, they found a linear relationship between these variables and competition intensity.

Changes in T/R often reflect the optimal allocation strategy to maximize biomass and the absorption of limited resources.
resources. Accordingly, T/R is often used to quantify the competition effect between plants (Newton and Cole 1991; Wilson and Tilman 1995). The current study found that the correlation between T/R and competition index was relatively low, suggesting that T/R of L. principis-rupprechtii is not affected by competition intensity. This is consistent with the results of many other studies (Casper et al. 1998; Watt et al. 2003). The study by Watt showed weed competition for light and water did not influence T/R of young Pinus radiata. With the decrease of the competition intensity, we found that the ratio of root biomass in belowground biomass increased slightly, while in aboveground biomass, the ratio of branch and foliage biomass decreased, and stem biomass increased. The phenomenon indicates that the adjustment of biomass allocation aboveground is mainly a tradeoff between stem and branch.

Foliage had little relation to belowground biomass, thus it led to the low effect of competition intensity on T/R. S/F reflects the relative ratio of leaf weight. In this study we found that there was a strong negative correlation between S/F and competition index. In order to contend for more light resources for photosynthesis, S/F decreases when competition intensity increases, which manifests as increased foliage biomass ratio (Wang et al. 2012a).

**Figure 4. Linear regression of C (A), N (B), P (C), and K element (D) with competition index for the 12 sample trees of L. principis-rupprechtii.**

**Table 4. Content of C, N, P, and K element for fine root.**

| Number | C (g/kg) | N (g/kg) | P (g/kg) | K (g/kg) |
|--------|----------|----------|----------|----------|
| 1      | 377.956  | 8.468    | 1.373    | 4.134    |
| 2      | 323.683  | 6.730    | 1.001    | 4.447    |
| 3      | 341.599  | 6.353    | 1.047    | 3.937    |
| 4      | 315.341  | 6.208    | 1.009    | 4.250    |
| 5      | 323.561  | 5.709    | 1.080    | 4.621    |
| 6      | 405.960  | 5.607    | 0.919    | 3.161    |
| 7      | 269.813  | 4.757    | 0.967    | 4.694    |
| 8      | 405.433  | 5.989    | 1.038    | 2.686    |
| 9      | 314.173  | 5.741    | 1.038    | 3.735    |
| 10     | 331.325  | 5.351    | 0.962    | 3.199    |
| 11     | 296.207  | 6.370    | 0.959    | 4.360    |
| 12     | 267.801  | 5.119    | 0.876    | 3.186    |

**Competition affect element content**

The function of various elements and nutrients is also necessary for the growth and development of plants. However, our study found that competition index had weak relationships with element and nutrient contents in all biomass components except fine roots. N and P had high correlations with competition intensity in fine roots. Fine roots are an important source and sink for nutrients in terrestrial ecosystems. Plants depend on fine roots for water and mineral uptake (Meier et al. 1985; Caldwell 1987; Wendy and Robert 2000). Our results showed that increasing competition intensity could lead to increasing absorption of N and P by plants. The two nutrients are both mobile and essential, especially in fine roots development. The results showed that plant responds to competition mainly by adjusting biomass allocation aboveground. At the same time, the content of N and P in fine roots increased. The plants not only increase the biomass of branch and foliage to compete for light resources, but also promote the growth and turnover of fine
roots to absorb more nutrients from soil resources when competition exists.

**RDA verification**

The correlation results by RDA matched the previous ones, and confirmed the effect of competition on trees either (Gao et al. 2016). The variance partitioning results show that competition explained more variance than the age indicating competition is one of main factors that affecting trees. There was an unexplained variance of 13.2% in the analysis suggesting other factors also can affect plant growth and biomass partitioning, such as climate, light, and soil factors (You et al. 2016).

**Conclusion**

Our results demonstrate that inter- and intraspecific competition could be used to control biomass allocation patterns in *L. principis-rupprechtii* plantations. Increases in the biomass ratio of organs of trees depend on competition intensity from neighboring trees. In this study, the biomass ratio of roots and stems decreased with increasing competition intensity from neighboring trees, while the opposite was true for the biomass ratio of branches and leaves. This variation can also be attributed to differences in light, soil nutrients, water, etc. The ratios of each component to the total biomass varied with Age. Our results provide evidence that competition pressure of neighboring trees factor is the important factors affecting trees growth and biomass partitioning. We suggest that modeling plant biomass allocation should consider the effect of competition. Our findings would be useful for improving our current understanding of the dynamics of the strategies of plant biomass allocation.

![Figure 5](image-url)  
**Figure 5.** RDA for variability of biomass partitioning, basic traits and element content in relation to explanatory variables (competition index (CI) and age (Age)). Twenty-one factors were analyzed, including total biomass (TB), aboveground biomass (AB), underground biomass (UB), root biomass (RB), stem biomass (SB), branch biomass (BB), foliage biomass (FB), diameter at breast height (DBH), height (Height), crown width (Canopy), aboveground–belowground biomass ratio (T/R), stem-foliation ratio (S/F), crown-height ratio (C/H), height-DBH ratio (H/D), average annual increment of biomass (AAB), height (AAH) and DBH (AAD), element C content in fine root (FRC), element N content in fine root (FRN), element P content in fine root (FRP), element K content in fine root (FRK). Continuous explanatory variables are represented by arrows (indicating their direction of steepest increase). The approximated correlation between two variables is equal to the cosine of the angle between the corresponding arrows. Arrows pointing in the same direction correspond to variables that are predicted to have a large positive correlation, whereas variables with a large negative correlation are predicted to have arrows pointing in opposite directions.

![Table 5](image-url)  
**Table 5.** Correlation coefficients of CI and Age with the first two axes.

| Variable | AX1     | AX2     |
|----------|---------|---------|
| CI       | 0.8443**| −0.2977 |
| Age      | −0.8293**| −0.3158 |

**P < .01.

![Figure 6](image-url)  
**Figure 6.** Variance partitioning of CI and Age factors. 'a' and 'b' represent independent effects, and 'c' and 'd' represent the interaction and residuals, respectively.
Acknowledgements
Thanks to the Mt. Lingkong National Nature Reserve for their support of our field work. We also thank colleagues for assistance with field measurements and those who provided helpful suggestions. We would also like to thank Alison Beamish at the University of British Columbia for her assistance with English language and grammatical editing of the manuscript.

Disclosure statement
No potential conflict of interest was reported by the authors.

Funding
This project was supported by the National Key Research and Development Program of China under grant no. 2016YFD0600205; the National Forestry Public Welfare Professional Scientific Research project under grant no. 201404213.

References
Bäth B, Kristensen HL, Thorup-Kristensen K. 2008. Root pruning reduces root competition and increases crop growth in a living mulch cropping system. J Plant Interact. 3(3):211–221.
Cahill JF Jr, Casper BB. 2000. Investigating the relationship between neighbor root biomass and belowground competition: field evidence for symmetric competition belowground. Oikos. 90:311–320.
Calderwood MM. 1987. Competition between roots in natural communities. Semin Ser Exp Biol. 30:167–185.
Cao Y, Wang T, Xiao Y, Zhou B. 2013. The interspecific competition between and Hamulas scandens and Alternanthera philoxeroides. J Plant Interact. 9(1):194–199.
Casper BB, Cahill JF Jr, Hyatt LA. 1998. Above-ground competition does not alter biomass allocated to roots in Abutilon theophrasti. New Phytol. 140(2):231–238.
Chai ZZ, Wang DX, Hao YZ, Zhang LN, Zhu HY, Zhang CS. 2014. Succession dynamics of Larix principis-ruprechti plantation in intermediate section of qinling mountains. Sci Silvae Sin. 50(2):14–21.
Davidson RL. 1969. Effect of root/leaf temperature differentials on root/shoot ratios in some pasture grasses and clover. Ann Bot. 33(3):561–569.
Fox TR, Jokela EJ, Allen HL. 2007. The development of pine plantation silviculture in the southern United States. J For. 105:337–347.
Gao J, Guo ZJ, Liu YH. 2016. Biomass allocation pattern and its influencing factors across natural Chinese pine forests of different ages in Songshan, Beijing. Chin J Ecol. 35(6):1475–1480. Chinese.
Hailemariam T, Valerie L, Stephen JM. 2005. Tree crown ratio models for multi-species and multi-layered stands of southeastern British Columbia. Forest. 81:1.
Hegyi F. 1974. A simulation model for managing jack-pine stands. Growth models for tree and stand simulation. R Coll For. 30:74–90.
Lin Y, Huth F, Berger U, Grimm V. 2014. The role of belowground competition and plastic biomass allocation in altering plant mass–density relationships. Oikos. 123(2):248–256.
Liu FY, Li K, Liao SX, Cui YZ. 2010. Interspecific competition, population structure and growth dynamics of endangered Calocedrus macrolepis. Sci Silvae Sin. 46(10):23–26. Chinese.
Meier CE, Grier CC, Cole DW. 1985. Below- and aboveground N and P use by Abies amabilis stands. Ecology. 66:1928–1942.
Newton M, Cole EC. 1991. Root development in planted Douglas-fir under varying competitive stress. Can J For Res. 21(1):25–31.
Petersen KS, Ares A, Terry TA, Harrison RB. 2008. Vegetation competition effects on aboveground biomass and macronutrients, leaf area, and crown structure in 5-year old Douglas-fir. New for. 35:299–311.
Rodri GR, Espinosa M, Hofmann G, Marchant M. 2003. Needle mass, fine root and stem wood production in response to silvicultural treatment, tree size and competitive status in radiata pine stands. For Ecol Manag. 186(1/3):287–296.
Rottmann M. 1985. Waldbauliche Konsequenzen aus Schneebreichskatastrophen. Schweizerische Zeitschrift für das Forstwesen. 136(3):167–184. German.
Sebastia MT. 2007. Plant guilds drive biomass response to global warming and water availability in subalpine grassland. J Appl Ecol. 44(1):158–167.
Tanka PA. 2006. Prediction of distribution for total height and crown ratio using normal versus other distributions [master’s thesis]. Alabama: Auburn University.
Ter Braak CJF, Šmilauer P. 1998. Canoco reference manual and user’s guide to canoco for windows. Ithaca, NY: Microcomputer Power.
Toma B. 2013. Prediction equations for estimating tree height, crown diameter, crown height and crown ratio of Pinus biglobosa in the Nigerian Guinea savanna. Afr J Agric Res. 7(49):6541–6543.
Villacorta AMG, Martin TA, Jokela EJ, Cropper WP Jr, Gezan SA. 2015. Variation in biomass distribution and nutrient content in loblolly pine (Pinus taeda) clones having contrasting crown architecture and growth efficiency. For Ecol Manag. 342:84–92.
Vospernik S, Monserud RA, Sterba H. 2010. Do individual–tree growth models correctly represent height: diameter ratios of Norway spruce and Scots pine. For Ecol Manag. 260(10):1735–1753.
Wang JS, Fan XH, Fan J, Zhang CY, Xia FC. 2012a. Effect of above-ground competition on biomass partitioning of understory Korean pine (Pinus koraiensis). Acta Ecol Sin. 32(8):2447–2457. Chinese.
Wang JS, Fan XH, Fan J, Zhang CY, Xia FC. 2012b. Effect of tree competition on the biomass partitioning of Abies nephrolepis. Sci Silvae Sin. 48(4):14–20. Chinese.
Waring RH, Thies WG, Muscato D. 1980. Stem growth per unit of leaf area: a measure of tree vigour. For Sci. 26(1):112–117.
Watt MS, Whitehead D, Mason EG, Richardson B, Kimberley MO. 2003. The influence of weed competition for light and water on growth and dry matter partitioning of young Pinus radiata, at a dryland site. For Ecol Manag. 183(1/3):363–376.
Wendy SG, Robert BJ. 2000. Nutrient concentrations in fine roots. Ecology. 81(1):275–280.
Wilson SD, Tilman D. 1995. Competitive responses of eight old-field plant species in four environments. Ecology. 76(4):1169–1180.
Wonn HT, O’Hara KL. 2001. Height: diameter ratios and stability relationships for four Northern Rocky Mountain tree species. West J Appl For. 28(5):1119–1130.
Wu GS, Wang ZQ. 2000. Individual tree growth competition model in mixed plantation of Manchurian ash and Dahurian larch. Chin J Appl Ecol. 11(3):646–650. Chinese.
You YM, Xu JY, Cai DX, Liu SR, Zhu HG, Wen YG. 2016. Environmental factors affecting plant species diversity of understory plant communities in a Castanopsis hystrix plantation chroonoque in Pingxiang, Guangxi, China. Acta Ecol Sin. 36(1):164–172. Chinese.
Zhou WS, Han HR, Kang FF, Cheng XQ, Wu R, Yang J, Tian P, Huang LS. 2017. Intra- and inter-specific interactions of Larix principis-ruprechtti plantation in Mt. Taiyue, Shanxi, China. Chin J Ecol. 36(2):335–342.