

A modified pipe model improved the accuracy of crown biomass estimation in a larch (*Larix olgensis*) plantation forest in northeast China

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Abstract

Pipe model theory has the potential to be widely applied in the estimation of tree allometry parameters, although it remains uncertain whether it can provide accurate estimation of the crown biomass of plantation forest. In this study, an improved pipe model was used for the first time to estimate the crown biomass of *Larix olgensis* plantations in northeast China. The results of linear regression analysis showed that crown biomass could be accurately estimated from the stem area at the crown base, which could be calculated using the tree height, crown base height, and stem area at breast height. Furthermore, covariance analysis was applied to analyze the differences in site-related factors that affect crown biomass. There was no significant difference between sites in the crown biomass of *L. olgensis* plantations in the research area, while the effect of tree age on crown biomass estimation should be considered. Our study showed that a modified pipe model could accurately estimate the crown biomass of larch plantations in northeast China, which has great significance for the determination of crown biomass in Chinese plantations using pipe model theory.

1. Introduction

Crown biomass is generally considered to be the sum of branch biomass and leaf biomass (Zou et al. 2015). As an important component of the aboveground biomass (Clark et al. 2001), the crown biomass typically accounts for almost 30% of the aboveground biomass of tree species (Meng et al. 2021). Crown biomass is one of the most important parameters for studying forest productivity and production processes due to the key role of the crown in the primary production of forests (Ogawa et al. 2010). In addition, crown biomass impacts on the amount of carbon allocated to the stem, which further affects the growth and development of the stand (Schneider et al. 2011). Therefore, accurate estimation of crown biomass is important for the efficient management of forest resources.

The techniques currently used to measure forest crown biomass can be divided into direct measurement and indirect estimation. The direct approach entails cutting trees down, dividing them into different parts (i.e., stems, branches, leaves, and roots), and measuring the weight of each part. This process is considered to be the most accurate approach to estimate biomass (Dong et al. 2018), but it is time and labor consuming, and it is only available in specific regions with logging permits. In comparison, indirect methods, especially those based on models, are being used more frequently. This approach uses statistical models that relate the common independent variables of trees using allometry methods, such as tree diameter at breast height (DBH) and tree height, with other structural and functional characteristics to estimate crown biomass (Bond-Lamberty et al. 2002; Zeng et al. 2017). Although it is necessary to collect and process enough sample data in preliminary work, the model can be applied to other similar regions to estimate without damaging trees once it is established successfully. However, some models have different accuracy for biomass of different parts of trees (Henry et al. 2011), and the fitting of crown biomass is usually lower than that of stem biomass (Hosoda and Iehara 2010). For example, Pérez-Cruzado and Rodríguez-Soalleiro (2011) found that the coefficient of determination for leaf biomass model was 18% lower than total wood biomass model in *Eucalyptus nitens* plantations. In addition, there were significant variations in crown biomass estimation among different habitats (Inagaki et al. 2020; Zou et al. 2015). Therefore, it is necessary to develop a model that can accurately estimate crown biomass in various habitats.

Shinozaki et al. (1964a, 1964b) first proposed the pipe model theory, in which the stem and branches were considered to be an assemblage of unit pipes supporting a unit number of photosynthetic organs. This means that the sapwood cross-sectional area at the base of a crown is positively related to the total leaf mass, as well as to the total sapwood cross-sectional area of the crown branches (Hu et al. 2020). Based on the pipe model theory, equations have been developed for estimating foliage or crown biomass of tree species in different habitats (Sumida et al. 2009; Berninger et al. 2005; Shelburne et al. 1993). For example, Ogawa et al. (2010) estimated the foliage biomass of *Chamaecyparis obtusa* based on pipe model theory and found that leaf dry mass was proportional to the stem cross-sectional area at the crown base (A_B) of individual trees. The stem A_B , which is usually measured by climbing trees, is an essential variable when using the pipe model theory to estimate crown biomass (Inagaki et al. 2020). The inconvenience of obtaining this measurement has limited the application of pipe model theory for some tree species. To overcome this problem, Sumida et al. (2009) proposed a modified method to estimate the stem A_B of *Betula ermanii* using height, crown base height (H_B), and DBH, and successfully estimated the crown biomass using this modified pipe model.

Larix olgensis is one of the main reforestation species in northeast China (Pan et al. 2020), which is widely distributed in Heilongjiang, Jilin, and Liaoning provinces (Dong et al. 2020; Zeng et al. 2017). However, it has not been evaluated the applicability of the modified pipe model theory to Chinese northeast tree species. In this study, we used a method based on the modified pipe model theory to estimate the crown biomass (including the branches and foliage), leaf biomass, and branch biomass of *L. olgensis* for the first time. Our aim was to answer the following three questions. (1) Is it accurate to estimate the A_B of *L. olgensis* using the height, H_B , and DBH? (2) Is there a proportional relationship between leaf biomass, branch biomass, crown biomass, and A_B ? (3) Are there differences between leaf biomass, branch biomass, crown biomass, and A_B in the different densities and ages of *L. olgensis* forest?

2. Materials And Methods

2.1 Research data

The fieldwork was conducted in Heilongjiang Province by the Heilongjiang Academy of Forestry at four sites: The Hengdaohezi Forest Farm of the Hailin Forestry Bureau, the Dahailin Forestry Bureau, the Linkou Forestry Bureau, and the Mengjiagang Forest Farm of the Huanan Forestry Bureau (Fig. 1). The altitude of each site was approximately 170-800 m, and a temperate continental monsoon climate was dominant. The annual average temperature was 2.3-3.5°C. The main terrain was low mountains. Inventory plots were uniformly set in forest stands of different sites, densities, and ages, and each selected stand was observed to have grown well. A total of 183 inventory plots were analyzed. Their statistical characteristics are shown in Table 1. One dominant and one average tree were analyzed on each standard plot. The height, DBH, H_B , crown width, crown length, and other related attributes of each tree were measured (Table 2). Stem analysis data with incomplete records were removed. A total of 318 trees from 183 plots were used in the analysis. Biomass was measured

by drying all the live branches and foliage in the crown and weighing them. The sum of the branch biomass and leaf biomass was considered as crown biomass (Table 3).

2.2 Estimation of A_B

Sumida et al. (2009) proposed a method to estimate A_B (m^2) from height (H) (m), crown base height (H_B) (m), and the stem area at DBH ($A_{1.3}$) (m^2) in *B. ermanii* forests. Linear regression analysis was performed after the logarithmic transformation of A_B and $[A_{1.3}(H-H_B)/(H-1.3)]$ (Fig. S1):

$$\ln(A_B) = \ln[A_{1.3}(H - H_B)/(H - 1.3)] + b \quad (1)$$

If the slope (a) and intercept (b) were not significantly different from one and zero, respectively, then Eq. 2 holds:

$$A_B = A_{1.3}[(H - H_B)/(H - 1.3)] \quad (2)$$

We investigated the above relationships for 318 individual trees in the four forestry bureaus of Hailin, Dahailin, Linkou, and Huanan (Table 4). We determined the 95% confidence intervals for the slope and intercept in Eq. 1.

2.3 Estimation of crown biomass

Heteroscedasticity is common in biomass and volume data (Dong et al. 2019). Measures should therefore be taken to eliminate the influence of heteroscedasticity before constructing biomass models. Weighted regression and logarithmic transformation are widely used methods to eliminate heteroscedasticity (Dong et al. 2015; Zhao et al. 2015). In this study, a logarithmic transformation was performed to remove the heteroscedasticity.

According to pipe model theory, leaf biomass, branch biomass, and crown biomass were estimated using the A_B crown base model (Eq. 3):

$$\ln(Y) = \ln(A_B) + b \quad (3)$$

where Y is a component of the biomass of a single tree crown, such as leaf biomass, branch biomass, or crown biomass.

An analysis of covariance (ANCOVA) was used to evaluate X (A_B), Y , and their interactions for all stem analysis data. Y could refer to plot, density, or age, respectively. The regression slope and intercept, together with 95% confidence intervals, were also calculated. If the slope of the regression line in the A_B model was not significantly different from one, it was considered a proportional relationship between leaf biomass, branch biomass, or crown biomass and A_B . The bias of logarithmic transformation was adjusted by calculating the correction factor according to Baskerville (1972). All statistical analyses were performed using JMP software (ver. 13.0, SAS Institute).

3. Results

3.1 Estimation of A_B

In this study, data for 318 *L. olgensis* trees were fitted using Eq. 1. The results of the fitting were determined using Eq. 4 (Fig. 2). Table 5 shows the relevant parameters of the fitting equation.

$$\ln(A_B) = 0.999\ln[A_{1.3}(H - H_B) / (H - 1.3)] - 0.065(CF = 1.012) \quad (4)$$

Eq. 2 was valid and could be used to estimate A_B because the slope and intercept of the regression in Eq. 4 were not significantly different from one and zero, respectively.

3.2 Estimation of crown biomass

For all of the stem analyses, the slope of the regression line for crown biomass in the A_B model did not differ from one. The slope for leaf biomass was 0.891 (i.e., <1), while the slope for branch biomass was 1.307 (i.e., >1) (Fig. 3, Table 6).

The results of the ANCOVA analysis are shown in Table 7 and Fig. 4. In the northeast forest, the effects of plot were not significant on leaf biomass, branch biomass, and crown biomass, and the interactions between A_B and plot on leaf biomass, branch biomass, or crown biomass were also not significant. The effects of A_B on leaf biomass, branch biomass, and crown biomass in the larch forest in this area were significant ($P < 0.05$). In contrast, the interactions between density and A_B had significant effects on leaf biomass, branch biomass, and crown biomass ($P = 0.012$), although the effects of stand density were not significant on leaf biomass, branch biomass, and crown biomass. The effects of tree age on leaf biomass, branch biomass, and crown biomass were significant ($P < 0.0001$), as were the interactions between age and A_B . The accuracy of the A_B model fitting for crown biomass was significantly improved ($R^2_{adj} = 0.964$) when age was considered.

4. Discussion

Estimations of forest structural properties, such as crown height and aboveground biomass, are essential for monitoring forest dynamics and assessing the global carbon cycle (Schlund and Boehm 2021). As an important part of the aboveground biomass, crown biomass should be estimated accurately using an appropriate model. Allometric models are often used to estimate crown biomass (Dong et al. 2019). However, the results from allometric models vary

(António et al. 2007), and an allometric relationship must be determined for each forest. The pipe model theory can be used to estimate the crown biomass of various habitats (with different slopes, aspects, and positions), without the variations in model accuracy caused by various factors (Forrester et al. 2017). Inagaki et al. (2020) compared the results of common allometric models with the pipe model, and their results showed that the pipe model was better able to simulate crown biomass. Therefore, a single equation, based on pipe model theory, could be used to model crown biomass accurately at different topographic locations within the same area. In this study, an improved pipe model, in which the stem A_B was calculated by several simple measurement variables (i.e., height, DBH, and height under live branches), was used to estimate crown biomass in larch plantations in northeast China.

4.1 Estimating A_B

For the 318 larch trees investigated in the study, there was a 1:1 relationship between the measured and predicted A_B (Fig. 2). The result proved that the ratio of the crown basal stem area to the stem area at breast height and the ratio of the crown length to the height above breast height were the same. Therefore, A_B could be easily predicted using Eq. 2 for larch plantations in northeast China. This method avoided the need to climb a tree or use instruments to measure A_B . Comparable results were found in earlier studies of Japanese cedar, *B. ermanii*, Scots pine, and Norway spruce (Hu et al. 2020; Inagaki et al. 2020; Sumida et al. 2009), suggesting that the 1:1 relationship might be a general feature that could be applied to a variety of tree species.

4.2 Proportionality between biomass and A_B

According to Table 6, the slope of the regression between crown biomass and the stem cross-sectional A_B did not significantly differ from one in the A_B model. Previous studies have found that the regression slope for the relationship between leaf biomass and A_B ranged from 0.991 to 1.275, and the slope for branch biomass ranged from 1.015 to 1.208 in a middle-aged Japanese cedar forest (Inagaki et al. 2020). Ogawa et al. (2010) found that this ratio was 1.008 in an analysis of hinoki cypress (*Chamaecyparis obtusa*). Studies of *B. ermanii* (Sumida et al. 2009), and Scots pine and Norway spruce (Hu et al. 2020) produced similar results. These results indicated that the total crown biomass was proportional to A_B . This relationship also supported pipe model theory (Shinozaki et al. 1964a, 1964b).

The slope of the regression for branch biomass was greater than one, indicating that these trees had a higher branch biomass per unit of stem A_B (Table 6). The crown is an important site for the photosynthesis and respiration of trees (Chen and Li 2010), in which the net photosynthetic production of living branches is the main driver of cambial growth (diameter expansion) (Fernández et al. 2011). However, not all living branches play a part in the growth of trunk. Some living branches in the lower parts of tree crown only synthesize photosynthetic materials for their growth and respiration, because they are sheltered by the upper branches and leaves, or neighboring trees (Møller 1960). Some studies have shown that older branches in the lower parts of the crown where light is weaker have less photosynthetic output (Roberts 1994), and they may not have any extra photosynthate to provide to the stem (O'hara et al. 1998). As such, the growth rate of branch biomass might be slightly higher than that of A_B , leading to a slope slightly higher than one, possibly because some living branches do not contribute to the growth of the trunks.

The regression slope for leaf biomass was less than one, indicating that the trees had a low leaf biomass per unit of stem A_B (Table 6) for larch plantations in northeast China. There are two possible explanations for this phenomenon. The first is that the lower living branches consume some of the photosynthetic output from the other branches in the process of sustaining their growth and respiration, rather than contributing to the growth of the stem (Roberts 1994). Some previous studies have also shown that lower branches gradually shift from net producers to net consumers, as their ability to provide carbohydrates to the trunk is diminished (Fernández et al. 2011; Kozłowski and Pallardy 1997). Therefore, the growth rate of leaf biomass was slightly lower than that of A_B . The other possible reason is that the crown biomass (including leaves and branches) is easily affected by human activities and extreme weather (Zhao et al. 2020; Pile et al. 2016), and therefore the actual crown biomass is lower than the ideal state. This may also have led to a low value of the regression slope.

4.3 Effect of site factors

There was no significant difference between the plots in terms of the leaf biomass, branch biomass, and crown biomass in the northeast larch plantations (Table 7). These results indicated that different topographic positions had no effect on the crown biomass per unit A_B (topographic information is presented in Table S2). Previous studies have suggested that plot type could affect tree crown biomass and the pipe model outcomes because plot nutrients might be related to leaf physiological activity (Berninger et al. 2005; Lehtonen 2005). However, Lehtonen et al. (2020) found insignificant differences in the pipe model outcomes between plot types in Norway spruce forests. Another study of *Eucalyptus nitens* (Medhurst et al. 1999) confirmed that the relationship between leaf traits and sapwood area was independent of the topography. Because the leaf biomass of a species is relatively constant in a closed canopy, topography usually only has a minimal effect on leaf biomass (Inagaki et al. 2020). Based on these results, it could be concluded that topographic locations had no general effect on crown biomass per unit A_B . Our study showed that the plot effect on leaf biomass, branch biomass, and crown biomass in the A_B model was negligible for *L. olgensis* plantations, although stem productivity often varied with topography. This result was important because it indicated that crown biomass at different topographic locations could be estimated using a single equation in northeast China.

In the A_B model, the density effect was not significant, while the interaction between A_B and density was significant (Table 7). Shelburne et al. (1993) found that inhibited trees in dense forests had a lower hydraulic conductivity in their stems because they had a high proportion of tracheids with narrow diameters. This led to increasing resistance and decreasing leaf area. The leaf area per unit sapwood area was highest in low-density old forests and lowest in high-density stands (Pearson et al. 1984). The increase in carbohydrate production may lead directly to more leaves due to the increase in leaf area. In addition, the mean DBH of a stand usually decreases with increasing density, and trees in a high-density forest usually have thinner stems than those in a low-density forest at the same age, which may be due to the greater competition in high-density forests. A positive correlation between tree crown biomass and DBH has previously been reported (Zhao et al. 2015), and our study also showed that there was a significantly positive correlation between A_B and DBH in northeast

plantations. These results suggested that crown biomass was indirectly affected by density, and therefore the effect of stand density should be considered when estimating the crown biomass of different stem diameters.

Age dependence has been found in many parametric studies of the pipe model theory. Tian et al. (2021) found that age significantly affected the canopy leaf area index in their study of larch plantations in the Liupan Mountains of the Loess Plateau. Sumida et al. (2009) found a significant allometric relationship between leaf area and leaf biomass. Therefore, a positive correlation between crown biomass and tree age was expected. The original pipe model was based on the assumption of sapwood rather than the total cross-sectional area at the base of the crown. Shinozaki et al. (1964a) suggested that the used pipes, which once supported the branches and foliage, remained in the trunk after falling off and became the heartwood of the tree as it aged. However, Hari et al. (1985) found that heartwood was almost impossible to find at the crown base of young Scots pine trees in staining experiments. It could therefore be concluded that the cross-sectional area at the crown base could replace the sapwood area for younger trees, while the gap between the two would increase in older trees. This led to a decrease in the accuracy of crown biomass estimation using the stem A_B as trees aged (Fig. S2). In summary, age and its interaction with A_B had a significant impact on crown biomass in northeast *L. olgensis* plantations, and this should be considered in simulation of crown biomass.

5. Conclusion

In conclusion, an improved pipe model was used for the first time to simulate the crown biomass of *L. olgensis* plantations in northeast China. The simulation showed that crown biomass was proportional to stem A_B , and that there was no plot effect on crown biomass, although age had a significant effect. It was inferred that a single equation for estimating crown biomass (including branches and leaves) could be applicable to larch plantations in different topographic positions within the same region, but age should be considered in the simulation. These results suggested that the modified pipe model could accurately estimate the crown biomass of *L. olgensis* plantations in northeast China, which will have great significance for the effective management of Chinese plantations and the general application of pipe model theory.

Declarations

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Conflict of interest

The authors declare no competing financial interests.

Availability of data and material

The data that support the findings of this study are available from Heilongjiang Academy of Forestry but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with permission of the Heilongjiang Academy of Forestry.

Code availability

Not applicable.

Authors' contributions

Chenyu Huang: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. Lu Chen: Investigation, Data curation, Writing - original draft. Liwen Zhuang: Investigation, Formal analysis, Validation. Weiguo Sang: Supervision, Project administration, Funding acquisition, Resources, Writing - review & editing.

Appendix A. Supplementary material

Supplementary data associated with this article can be found online at XXX.

References

1. António N, Tomé M, Tomé J, Soares P, Fontes L (2007) Effect of tree, stand, and site variables on the allometry of Eucalyptus globulus tree biomass. *Can J For Res* 37(5): 895-906
2. Baskerville, GL (1972) Use of logarithmic regression in the estimation of plant biomass. *Can J For Res* 2(1): 49-53
3. Berninger F, Coll L, Vanninen P, Mäkelä A, Palmroth S, Nikinmaa E (2005) Effects of tree size and position on pipe model ratios in Scots pine. *Can J For Res* 35(6): 1294-1304
4. Bond-Lamberty B, Wang C, Gower ST (2002) Aboveground and belowground biomass and sapwood area allometric equations for six boreal tree species of northern Manitoba. *Can J For Res* 32(8): 1441-1450
5. Chen D, Li F (2010) The characteristics and biomass distribution in crown of *Larix olgensis* in Northeastern China. *Jour Korean For Soc* 99(2): 204-212

6. Clark DA, Brown S, Kicklighter DW, Chambers JQ, Thomlinson JR, Ni J (2001) Measuring net primary production in forests: concepts and field methods. *Ecol Appl* 11(2): 356-370
7. Dong L, Zhang L, Li F (2015) Developing additive systems of biomass equations for nine hardwood species in Northeast China. *Trees* 29(4): 1149-1163
8. Dong L, Zhang L, Li F (2018) Additive biomass equations based on different dendrometric variables for two dominant species (*Larix gmelini* Rupr. and *Betula platyphylla* Suk.) in natural forests in the Eastern Daxing'an Mountains, Northeast China. *Forests* 9(5): 261
9. Dong L, Zhang L, Li F (2019) Evaluation of stand biomass estimation methods for major forest types in the eastern Da Xing'an Mountains, Northeast China. *Forests* 10(9): 715
10. Dong L, Zhang Y, Zhang Z, Xie L, Li F (2020) Comparison of tree biomass modeling approaches for larch (*Larix olgensis* Henry) trees in Northeast China. *Forests* 11(2): 202
11. Fernández MP, Norero A, Vera JR, Pérez E (2011) A functional-structural model for radiata pine (*Pinus radiata*) focusing on tree architecture and wood quality. *Ann Bot* 108(6): 1155-1178
12. Forrester DI, Tachauer IHH, Annighoefer P, Barbeito I, Pretzsch H, Ruiz-Peinado R, Stark H, Vacchiano G, Zlatanov T, Chakraborty T, Saha S, Sileshi GW (2017) Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. *For Ecol Manag* 396: 160-175
13. Hari P, Kaipiainen L, Korpilahti E, Mäkelä A, Nilson T, Oker-Blom P, Ross J, Salminen R (1985) Structure, radiation and photosynthetic production in coniferous stands. University of Helsinki, Department of Silviculture, Research Notes 54: 233
14. Henry M, Picard N, Trotta C, Manlay R, Valentini R, Bernoux M, Saint-André L (2011) Estimating tree biomass of sub-Saharan African forests: a review of available allometric equations. *Silva Fenn* 45(3): 477-569
15. Hosoda K, Iehara T (2010) Aboveground biomass equations for individual trees of *Cryptomeria japonica*, *Chamaecyparis obtusa* and *Larix kaempferi* in Japan. *J Forest Res* 15(5): 299-306
16. Hu M, Lehtonen A, Minunno F, Mäkelä A (2020) Age effect on tree structure and biomass allocation in Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* [L.] Karst.). *Ann Forest Sci* 77(3): 1-15
17. Inagaki Y, Nakanishi A, Tange T (2020) A simple method for leaf and branch biomass estimation in Japanese cedar plantations. *Trees* 34(2): 349-356
18. Kozłowski TT, Pallardy SG (1997) Growth control in woody plants. Elsevier
19. Lehtonen A (2005) Estimating foliage biomass in Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) plots. *Tree Physiol* 25(7): 803-811
20. Lehtonen A, Heikkinen J, Petersson H, Ľupek B, Liski E, Mäkelä A (2020) Scots pine and Norway spruce foliage biomass in Finland and Sweden - testing traditional models vs. the pipe model theory. *Can J For Res* 50(2): 146-154
21. Medhurst JL, Battaglia M, Cherry ML, Hunt MA, White DA, Beadle CL (1999) Allometric relationships for *Eucalyptus nitens* (Deane and Maiden) Maiden plantations. *Trees* 14(2): 91-101
22. Meng S, Yang F, Hu S, Wang H, Wang H (2021) Generic additive allometric models and biomass allocation for two natural oak species in northeastern China. *Forests* 12(6): 715
23. Møller CM (1960) The influence of pruning on the growth of conifers. *Forestry* 33(1): 37-53
24. O'hara KL, Knowles RL, Dean M, West GG, McInnes I (1998) Growth efficiency of *Pinus radiata* stand elements: implications for stand growth modelling strategies. *NZ J Forestry Sci* 28: 373-388
25. Ogawa K, Adu-Bredu S, Yokota T, Hagihara A (2010) Leaf biomass changes with stand development in hinoki cypress (*Chamaecyparis obtusa* [Sieb. et Zucc.] Endl.). *Plant Ecol* 211(1): 79-88
26. Pan L, Mei G, Wang Y, Saeed S, Chen L, Cao Y, Sun Y (2020) Generalized Nonlinear Mixed-Effect Model of Individual TREE Height to Crown Base for *Larix olgensis* Henry in Northeast China. *J Sustain Forest* 39(8): 827-840
27. Pearson JA, Fahey TJ, Knight DH (1984) Biomass and leaf area in contrasting lodgepole pine forests. *Can J For Res* 14(2): 259-265
28. Pérez-Cruzado C, Rodríguez-Soalleiro R (2011) Improvement in accuracy of aboveground biomass estimation in *Eucalyptus nitens* plantations: effect of bole sampling intensity and explanatory variables. *For Ecol Manag* 261(11): 2016-2028
29. Pile LS, Maier CA, Wang GG, Yu D, Shearman TM (2016) Responses of two genetically superior loblolly pine clonal ideotypes to a severe ice storm. *For Ecol Manag* 360: 213-220
30. Roberts SD (1994) The occurrence of non-ring producing branches in *Abies lasiocarpa*. *Trees* 8(6): 263-267
31. Schlund M, Boehm HD (2021) Assessment of linear relationships between TanDEM-X coherence and canopy height as well as aboveground biomass in tropical forests. *Int J Remote Sens* 42(9): 3405-3425
32. Schneider R, Fortin M, Berninger F, Ung CH, Swift DE, Zhang SY (2011) Modeling jack pine (*Pinus banksiana*) foliage density distribution. *For Sci* 57(3): 180-188
33. Shelburne VB, Hedden RL, Allen RM (1993) The effect of site, stand density, and sapwood permeability on the relationship between leaf area and sapwood area in loblolly pine (*Pinus taeda* L.). *For Ecol Manag* 58(3-4): 193-209
34. Shinozaki K, Yoda K, Hozumi K, Kira T (1964) A quantitative analysis of plant form-the pipe model theory: I. Basic analyses. *Jpn J Ecol* 14(3): 97-105
35. Shinozaki K, Yoda K, Hozumi K, Kira T (1964) A quantitative analysis of plant form-the pipe model theory: II. Further evidence of the theory and its application in forest ecology. *Jpn J Ecol* 14(4): 133-139
36. Sumida A, Nakai T, Yamada M, Ono K, Uemura S, Hara T (2009) Ground-based estimation of leaf area index and vertical distribution of leaf area density in a *Betula ermanii* forest. *Silva Fenn* 43(5): 799-816

37. Tian A, Wang Y, Webb AA, Liu Z, Ma J, Yu P, Wang X (2021) Water yield variation with elevation, tree age and density of larch plantation in the Liupan Mountains of the Loess Plateau and its forest management implications. *Sci Total Environ* 752: 141752
38. Zeng W, Duo H, Lei X, Chen X, Wang X, Pu Y, Zou W (2017) Individual tree biomass equations and growth models sensitive to climate variables for *Larix spp.* in China. *Eur J Forest Res* 136(2): 233-249
39. Zhao D, Bullock BP, Montes CR, Wang M, Westfall J, Coulston JW (2020) Long-term dynamics of loblolly pine crown structure and aboveground net primary production as affected by site quality, planting density and cultural intensity. *For Ecol Manag* 472: 118259
40. Zhao D, Kane M, Markewitz D, Teskey R, Clutter M (2015) Additive tree biomass equations for midrotation loblolly pine plantations. *For Sci* 61(4): 613-623
41. Zou WT, Zeng WS, Zhang LJ, Zeng M (2015) Modeling crown biomass for four pine species in China. *Forests* 6(2): 433-449

Tables

Table 1 Sample plot and stand characteristics

Site	Plot	Area (ha)			Density (n/ha)			Age (year)		
		Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Hailin	50	0.1225	0.0100	0.0707	7800	500	1410.88	40	9	31.90
Dahailin	37	0.1000	0.0500	0.0543	3415	700	1700.57	28	12	20.50
Linkou	51	0.1000	0.0660	0.0885	2210	730	1384.70	22	6	16.90
Huanan	45	0.1200	0.0400	0.0778	4525	408	2071.51	40	12	26.00
Total	183	0.1225	0.0100	0.0735	7800	408	1654.37	40	6	24.13

Table 2 Summary of the features of the trees analyzed in the study area

Site	Plot	Tree number	DBH (cm)			Height (m)			H_B (m)			CW (m)			CL (m)		
			Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Hailin	50	82	27.8	5.0	18.9	25.95	5.28	19.63	17.80	1.10	11.26	7.55	1.25	3.28	14.70	2.95	8.37
Dahailin	37	69	26.1	7.4	13.9	21.32	7.20	13.59	10.40	0.62	5.00	6.00	2.15	3.88	14.57	3.95	8.59
Linkou	51	77	18.0	5.0	11.3	14.60	2.70	10.86	7.40	0.50	3.37	6.05	2.33	3.59	10.40	1.65	7.49
Huanan	45	90	29.6	6.1	15.7	23.60	6.30	15.34	13.40	0.21	7.45	5.85	0.83	2.74	14.55	2.92	7.88
Total	183	318	29.6	5.0	15.0	25.95	2.70	14.98	17.80	0.21	6.91	7.55	0.83	3.32	14.70	1.65	8.07

H_B : height at crown base, CW: crown width, CL: crown length

Table 3 Biomass of the trees analyzed in the study area

Site	Tree number	Leaf biomass (kg)			Branch biomass (kg)			Crown biomass (kg)		
		Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Hailin	82	9.71	0.33	5.44	44.75	0.31	20.44	54.7	0.51	25.93
Dahailin	69	8.48	0.74	2.79	36.70	1.02	8.05	45.40	1.58	10.71
Linkou	77	3.79	0.21	1.74	11.26	0.16	3.80	14.98	0.27	5.36
Huanan	90	10.32	0.49	3.73	48.92	0.57	12.54	59.46	0.91	16.21
Total	318	10.32	0.21	3.48	48.92	0.16	11.49	59.46	0.27	14.90

Table 4 Estimation of the stem area at the crown base (A_B)

Site	Tree number	A _{1,3} (m ²)			Measured A _B (m ²)			Estimated A _B (m ²)		
		Max	Min	Mean	Max	Min	Mean	Max	Min	Mean
Hailin	82	0.0607	0.0020	0.0299	0.0308	0.0013	0.0128	0.0329	0.0017	0.0136
Dahailin	69	0.0535	0.0043	0.0168	0.0423	0.0020	0.0112	0.0454	0.0023	0.0121
Linkou	77	0.0254	0.0020	0.0106	0.0196	0.0016	0.0083	0.0195	0.0021	0.0084
Huanan	90	0.0688	0.0029	0.0218	0.0343	0.0011	0.0111	0.0432	0.0015	0.0121
Total	318	0.0688	0.0020	0.0201	0.0423	0.0011	0.0109	0.0454	0.0015	0.0116

A_B: stem area at crown base, A_{1,3}: stem area at 1.3m

Table 5 Slope and intercept of the model for estimating A_B

$$\ln(A_B) = a \cdot \ln[A_{1,3}(H-H_B)/(H-1.3)] + b$$

Site	Slope(a)		Intercept(b)		R ²	R ² _{adj}
	a	95% CI	b	95% CI		
Hailin	1.067	(1.008,1.125)	0.211	(-0.052,0.474)	0.943	0.942
Dahailin	0.960	(0.901,1.020)	-0.254	(-0.533,0.024)	0.940	0.939
Linkou	1.000	(1.010,1.115)	0.288	(0.043,0.533)	0.960	0.960
Huanan	0.977	(0.934,1.020)	-0.176	(-0.378,0.026)	0.958	0.958
Total	0.999	(0.974,1.026)	-0.065	(-0.186,0.055)	0.949	0.949

A_B: stem area at crown base, A_{1,3}: stem area at 1.3m, H: tree height, H_B: height at crown base, R²: coefficient of determination, R²_{adj}: adjusted R-squared, CI: confidence interval

Table 6 Slope and intercept values for the biomass estimation by the A_B model

$$\ln(y) = a \cdot \ln(A_B) + b, y = LB/BB/CB$$

Site	Slope(a)		Intercept(b)		R ²	R ² _{adj}
	a	95% CI	b	95% CI		
Leaf biomass						
Hailin	0.702	(0.555,0.848)	4.731	(4.058,5.404)	0.531	0.526
Dahailin	0.692	(0.572,0.812)	4.128	(3.552,4.703)	0.663	0.658
Linkou	0.841	(0.706,0.976)	4.586	(3.918,5.255)	0.673	0.668
Huanan	0.958	(0.829,1.088)	5.582	(4.966,6.198)	0.711	0.708
Total	0.891	(0.810,0.973)	5.204	(4.817,5.591)	0.596	0.595
Branch biomass						
Hailin	1.028	(0.814,1.243)	7.404	(6.417,8.391)	0.531	0.526
Dahailin	1.014	(0.838,1.191)	6.52	(5.676,7.363)	0.663	0.658
Linkou	1.233	(1.035,1.431)	7.192	(6.212,8.172)	0.673	0.668
Huanan	1.405	(1.215,1.594)	8.652	(7.749,9.555)	0.711	0.708
Total	1.307	(1.188,1.426)	8.097	(7.529,8.665)	0.596	0.595
Crown biomass						
Hailin	0.965	(0.764,1.167)	7.383	(6.457,8.310)	0.531	0.526
Dahailin	0.952	(0.786,1.118)	6.554	(5.762,7.345)	0.663	0.658
Linkou	1.157	(0.972,1.343)	7.185	(6.265,8.105)	0.673	0.668
Huanan	1.318	(1.140,1.497)	8.555	(7.707,9.403)	0.711	0.708
Total	1.227	(1.115,1.338)	8.034	(7.501,8.567)	0.596	0.595

R^2 : coefficient of determination, R^2_{adj} : adjusted R -Squared, CI: confidence interval

Table 7 Analysis of covariance results

Y	X	Covariates	Effects(P)			R^2	R^2_{adj}
			X	Covariates	Interaction		
LB	A_B	Plot	0.008	0.705	0.075	0.903	0.724
BB	A_B	Plot	0.008	0.705	0.075	0.903	0.724
CB	A_B	Plot	0.008	0.705	0.075	0.903	0.724
LB	A_B	Density	<0.0001	0.126	0.012	0.918	0.767
BB	A_B	Density	<0.0001	0.126	0.012	0.918	0.767
CB	A_B	Density	<0.0001	0.126	0.012	0.918	0.767
LB	A_B	Age	<0.0001	<0.0001	<0.0001	0.987	0.964
BB	A_B	Age	<0.0001	<0.0001	<0.0001	0.987	0.964
CB	A_B	Age	<0.0001	<0.0001	<0.0001	0.987	0.964

LB: leaf biomass, BB: branch biomass, CB: crown biomass. A_B : stem area at crown base, R^2 : coefficient of determination, R^2_{adj} : adjusted R -squared. $P < 0.05$ indicates that the effect of variables is significant.

Figures

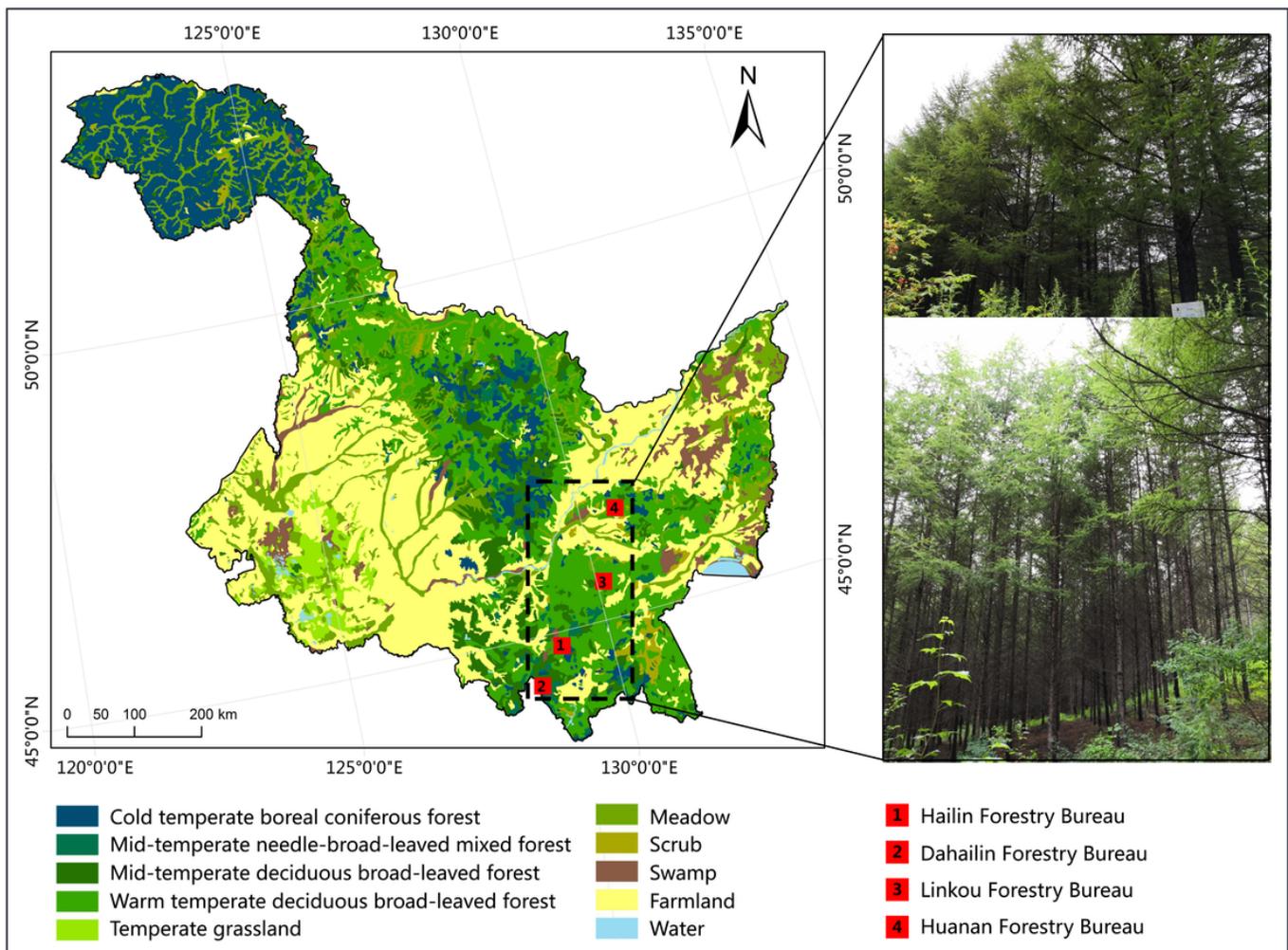


Figure 1

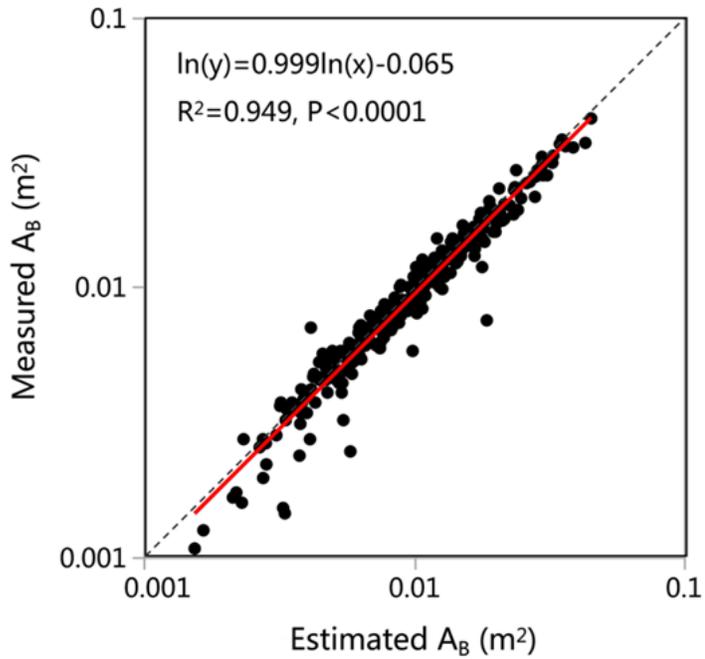


Figure 2
Relationship between the measured and predicted A_B for *Larix olgensis*. The broken diagonal line indicates the 1:1 relationship. Abbreviation: A_B , stem area at crown base

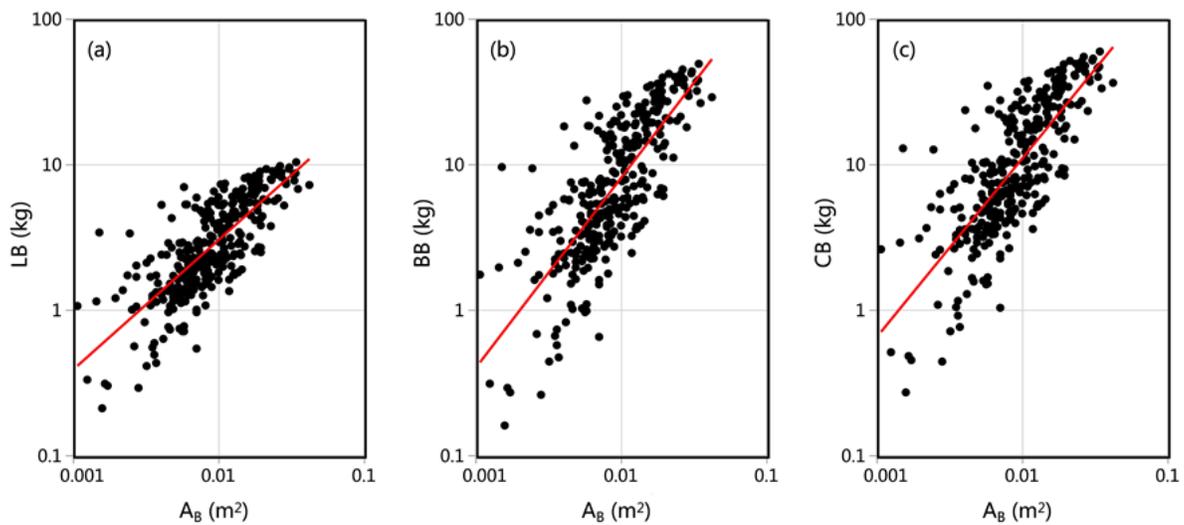


Figure 3
Relationships between A_B and LB, A_B and BB, and A_B and CB in *Larix olgensis* plantations. The details of the regression lines are presented in Table 6. Abbreviation: A_B , stem area at crown base; LB, leaf biomass; BB, branch biomass; CB, crown biomass

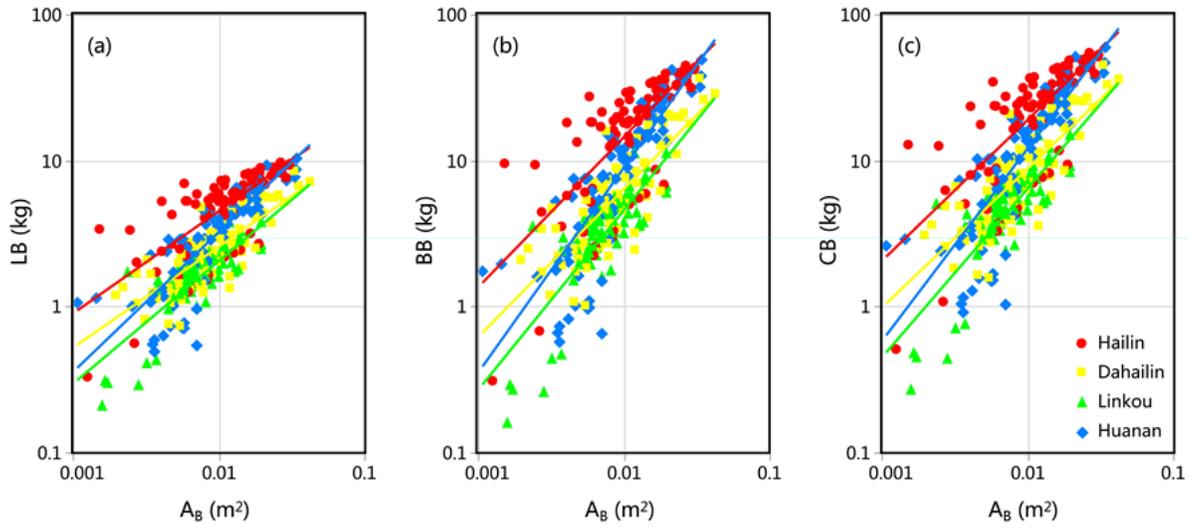


Figure 4

Relationships between A_B and LB, A_B and BB, and A_B and CB in four *Larix olgensis* plantations. The details of the regression lines are presented in Table 7. Abbreviation: A_B , stem area at crown base; LB, leaf biomass; BB, branch biomass; CB, crown biomass

Supplementary Files

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- [HuangSangSupplementaryDataforEurJForestRes.doc](#)