Full Length Article

Relationships between Mean Tree Mass-Density and Mass-Stand Density Indexes in *Pinus massoniana* Stands in China

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Abstract

Interrelationships between mean tree mass and density and mean tree mass and the stand density index (SDI) were investigated in *Pinus massoniana* stands across nine sites. Exponents of the relationship and of the biomass-SDI relationship varied across sites, which ranged from –2.07 to –0.59 for mean tree mass-density and from 0.58 to 2.54 for mean tree mass-SDI. The equation based on SDI provide an accurate fit to mean tree mass for *P. massoniana* stands at the nine sites, indicating SDI is a good predictor of mean tree mass across different sites. © 2018 Friends Science Publishers

Key words: Density; Exponent; Mean tree mass; *Pinus massoniana*; SDI, Stand

Introduction

Stand density affect resource utilization and growth of trees and stand biomass (Malhi *et al.*, 2006; Stegen *et al.*, 2009). The biomass-density relationship has long been regarded as important over recent decades (Xue and Hagihara, 1999). Yoda *et al.* (1963) first suggested "the 3/2 power law of self-thinning" for crowded even-aged monocultures as:

$$M = kN^b \qquad (1)$$

Where, M is the mean plant mass, N is density, and k is a constant specific to species, and the exponent b is close to –3/2, regardless of species, age, or site conditions. Enquist *et al.* (1998, 2000) proposed a model based on fractal geometry, which predicts mean mass within a crowded community on a scale of –4/3 power of density N:

$$M = gN^{-4/3}, \qquad (2)$$

Where, g is a constant specific to each species. The universality of the two laws has long been debated by many researchers who argued these parameters should not be universal for either Yoda's (Weller 1987a, b; Zeide 1987a, 2005, 2010; Xue *et al.*, 1999) or Enquist's approach (e.g. Deng *et al.*, 2006; Bai *et al.*, 2011; Zhang *et al.*, 2011, 2012).

The early works undertaken by Yoda *et al.* (1963) and Enquist *et al.* (1998, 2000) looked for two models applicable to crowded stands (Rivoire and Moguedec, 2012), and the models predict that mean plant mass decreases as density increases. However, in some cases, both models fail to describe the mean mass of the plant-

density relationship, because of the restriction on the limiting resource for each individual plant (Deng *et al.*, 2006; Zhang *et al*., 2012). As a result, we still do not understand how density affects mean tree mass in resource limiting forests. Therefore, a better understanding for biomass changes with density among such forests is critical.

Mean tree biomass accumulation is dependent upon individual tree diameter growth rate. So there is a priori expectation that mean tree mass will uniformly increase with mean diameter. Reineke (1933) first proposed a stand density index (SDI) as follows:

$$SDI = N(D_q/25.4)^{1.6}, \qquad (3)$$

Where, N is the number of trees per hectare and D_q is quadratic mean diameter (Long, 1985; Dean and Baldwin, 1996a) or mean diameter (Zeide, 2005). SDI is a density index based on combinations of mean tree size and density (Dean and Baldwin, 1996b), which is influenced directly by the change of the tree numbers (Woodall et al., 2005), and it is a suitable measure for biomass (Long and Smith, 1990). Xue (2014) found that SDI is a good predictor of mean tree mass for the stands with any stocking level. Although relative density based on SDI has been developed, a considerable knowledge gap exists concerning the relationship between tree biomass and SDI in forests (Xue *et al*., 2012).

Pinus massoniana is a fast-growing native conifer species and widely distributed in southern China with 17.392 million ha of plantations (Xue *et al*., 2014; Lie and Xue, 2016). This species is a major forest type and an important timber tree species in China. Although some

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studies on the stem volume-density relationship have been reported in *P. massoniana* stands (Xue and Hagihara, 2001, 2002), its biomass–SDI relationship is unclear. Thus, a study of the biomass–SDI relationship is still needed for this species.

We predict that mean tree mass varies with density or SDI among *P. massoniana* stands across nine sites that differ in annual precipitation and mean temperature. The objectives of this study are (1) to develop an equation describing mean tree mass and the SDI relationship and check the practicability of its use in *P. massoniana* stands and (2) to examine the exponents of the relationships between mean tree mass and density as well as between that and SDI.

Materials and Methods

Study Sites

The relationships of biomass–density and biomass–SDI were examined using a compilation of published data, mostly from Xiang *et al*. (2011). Additional data were collected from Ding (2003), Ding and Wang (2001), Ding *et al*. (1998). The study area was located in southern China between 23°23′N–32°23′N and 104°26′E–121°02′E (Fig. 1). All sites were located in humid subtropical monsoon climatic regions (Table 1).

Biomass Measurement

A total of 152 tree samples were taken using a destructive sampling method across nine site locations (Ding *et al*., 1998; Xiang *et al*., 2011). The biomass of each tree component was measured in *P. massoniana* stands. After sample trees were felled, their diameter at breast height (1.3 m) and at ground level were measured and total height was recorded; branches were stripped of stems and the stems were immediately cut at 1.3 m from their bases; stems were cut further into 1 m intervals thereafter up to the tips. The root biomass of individual trees was determined through excavation depth of 60 cm. The fresh mass of stems, branches, needles and roots were measured in situ. Dry biomass was obtained by multiplying fresh biomass by the dry mass ratio of sample trees; the summation of component mass was the total amount of tree biomass. Stand dry biomass was found by summing values of biomass for all *P. massoniana* trees in a stand (Xiang *et al*., 2011).

Since SDI is proportional to density *N* □i.e. SDI∝*N*) from Eq. 3, the mean tree mass *M*-SDI relationship can be derived by inserting Eq. 3 into Eq. 1:

$$M = \beta \mathrm{SDI}^{\alpha} \qquad (4)$$

Where, β is a constant specific to each species, and α is the exponent.

The exponents and the intercept of the mean tree mass–density relationship and the mean tree mass–SDI

Table 1: Quantile regression (QR) exponents and y-intercepts (α_{QR} and log β_{QR}, respectively) for log10-tranformed data of forest-level mean tree mass (kg) and density. Data, grouped according to stand sites, taken from Xiang *et al.* (2011) and other authors

| Site	α_{QR}(SE)	Log β_{QR}(SE)	*n*	Pr (>|t|)
Bishan, Chongqing	-2.07 (0.07)	8.41 (0.24)	13	0.000
Zizhong, Sichuan	-1.44 (0.09)	6.52 (0.27)	11	0.000
Shimen, Hunan	-0.90 (0.12)	4.69 (0.40)	19	0.000
Yongshun, Hunan	-0.83 (0.09)	4.71 (0.30)	16	0.000
Anhua, Hunan	-1.96 (0.07)	8.47 (0.21)	14	0.000
Shupu, Hunan	-0.59 (0.11)	3.48 (0.40)	15	0.000
Xiangtan, Hunan	-1.10 (0.16)	5.39 (0.54)	32	0.000
Hengnan, Hunan	-1.12 (0.16)	5.62 (0.54)	25	0.000
Longli, Guizhou	-1.10 (0.05)	5.66 (0.18)	21	0.000
All sites	-1.34 (0.16)	6.55 (0.53)	158	0.000
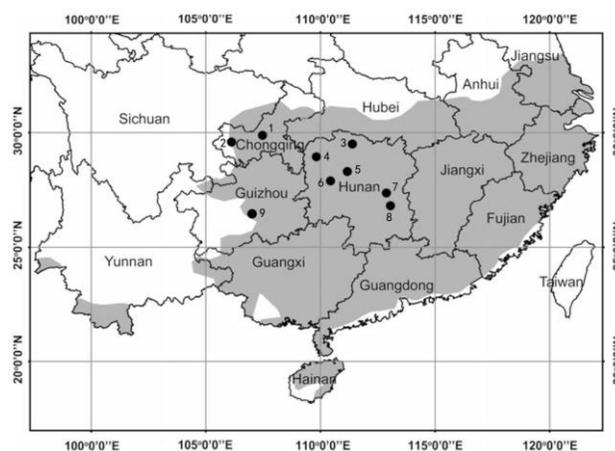
Fig. 1: Geographical distribution range (shaded area) of *P. massoniana* adapted (adapted from He *et al.*, 1996)

relationship were estimated by Quantile regression of log-transformed data and the *p*-value of 0.99 was used in parameter estimation, because this value is suitable for estimating relationship between mean tree mass–density (Xue *et al*., 2015).

Results

Quantile regression produced a self-thinning an upper limiting line above all plots for the maximum mean tree mass–density relationship (Table 1). The exponents for the mean tree mass-density measurements were quite variable, rather than clustering around any given theoretical value, and ranged from –2.07 to –0.59 across the nine sites (Fig. 2). Among the nine exponents derived, only one site (Zizhong) was close to –3/2, whereas the remaining exponents were significantly different from 3/2. All exponents were statistically different from –4/3. The exponent was -1.34 for all study sites, which was not statistically different from –4/3 (Fig. 3). The greater absolute value of the exponent for the Bishan and Anhua sites indicates that their biomass increment was increasing

Table 2: Quantile regression (QR) exponents and y-intercepts (α and log β $_{QR}$, respectively) for log10-tranformed data of forest-level mean tree mass (kg) and SDI. Data, grouped according to stand sites, taken from Xiang *et al.* (2011) and other authors

Site	α_{QR}(SE)	Log β_{QR}(SE)	n	Pr (>|t|)
Bishan, Chongqing	1.81 (0.08)	-2.75 (0.20)	13	0.000
Zizhong, Sichuan	2.54 (0.05)	-4.52 (0.14)	11	0.000
Shimen, Hunan	1.51 (0.18)	-2.07 (0.46)	19	0.000
Yongshun, Hunan	0.92 (0.03)	-0.51 (0.08)	16	0.000
Anhua, Hunan	0.58 (0.10)	0.78 (0.27)	14	0.000
Shupu, Hunan	2.21 (0.01)	-4.49 (0.03)	15	0.000
Xiangtan, Hunan	1.54 (0.04)	-2.04 (0.10)	32	0.000
Hengnan, Hunan	1.99 (0.18)	-3.33 (0.47)	25	0.000
Longli, Guizhou	1.43 (0.18)	-1.80 (0.50)	21	0.000
All sites	2.54 (0.05)	-4.52 (0.14)	158	0.000

Fig. 3: Relationship between mean tree mass and density for all sites
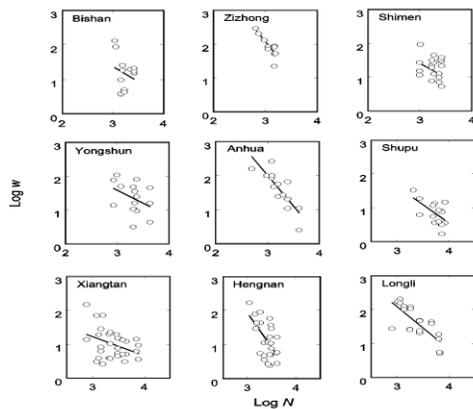

Fig. 2: Relationship between mean tree mass and density across the nine sites

faster than at the other sites with decreasing density.

The relationships between mean tree mass and SDI are shown in Table 2 and Fig. 4. The exponents ranged from 0.58 to 2.54 across the study sites. The exponent was 1.79 for all study sites (Fig. 5). The exponent was greatest for the Zizhong site, indicating that its biomass increment was greatest among all sites with increasing SDI.

Discussion

In this study, considerable variation in exponents of *P. massoniana* stands across nine sites was observed, and most of exponents are smaller than the values of –0.95
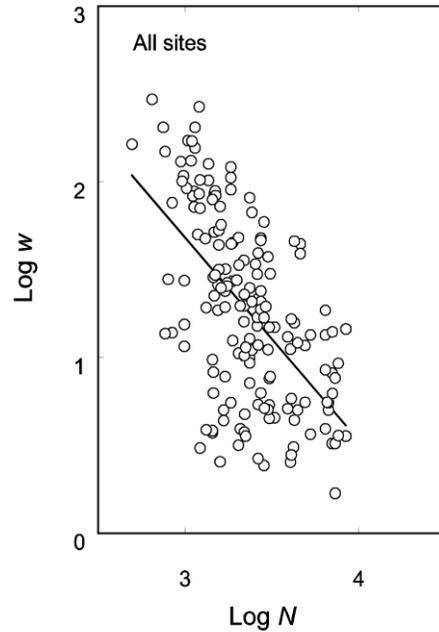
to –1.30 in balsam fir (*Abies balsamea*), –0.81 to –1.90 in pin cherry (*Prunus pensylvanica*) (Mohler *et al.*, 1978), –1.79 in *Larix principis-rupprechtii* and –1.72 in *Pinus tabulaeformis* (Xue *et al.*, 1999). These exponents were also smaller than –4/3 based on Enquist *et al.* (1998) and close to or smaller than –3/2 based on Yoda *et al.* (1963). Zeide (1987b) suggests that old stands have a larger portion of stem, which result in greater absolute values of the exponents than –3/2. Moreover, greater absolute values of exponents are associated with stands of optimal condition (Zeide, 1987a). The universal thinning exponent has been questioned by many researchers (White *et al.*, 2007; Chu *et al.*, 2008; Isaac and Carbone, 2010), because exponents are relatively dependent of growth habit and abiotic environmental conditions (Deng *et al.*, 2012). Empirical studies have shown the exponents for tree mass–density relationships can be site-specific (Deng *et al.*, 2006; Chu *et al.*, 2008; Bai *et al.*, 2010), as a result of differences in stand age, density, and site quality. A substantial variation that remains is undoubtedly biologically important when the focus shifts to particular habitats (Deng *et al.*, 2012).

Mean tree biomass is consistently related to density across sites in *P. massoniana* stands, because a significant correlation between mean tree biomass–density is observed from the nine sites. A negative intraspecific relationship between biomass and density for crowded stands results
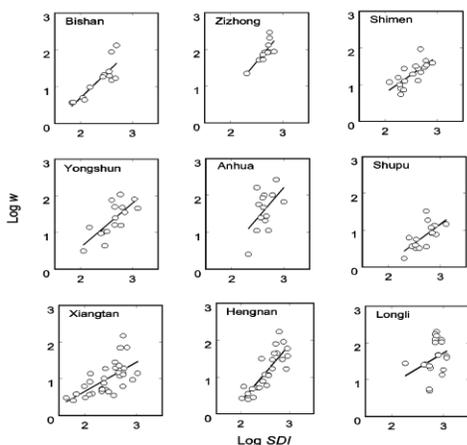
Fig. 4: Relationship between mean tree mass and SDI across the nine sites

Fig. 5: Relationship between mean tree mass and SDI for all sites

from structural constraint of plants. Yoda (1963) model showed that an exponent of about –3/2 for this relationship results from assumptions that plants grow isometrically, but many species do not grow isometrically, so that model exponents can deviate from 3/2 (Weller, 1987b). An exponent of –4/3 for Enquist *et al.* (1998) model results from considering that simple relationships between tree dimensions contain universal constants and it assumes the relationships between diameter, height, and other tree dimensions are fixed for all species; but this is unrealistic, because the height of trees with the same diameter can vary substantially depending on stand density (Zeide, 2010). Deng et al. (2006) and Bai *et al*. (2011) also showed that Enquist *et al.* (1998) model cannot describe the relationships between aboveground parts of plants and density in arid environments. By combining the equations for Reineke (1933) stand density index and Yoda (1963) model, tree mass can be expressed solely in terms of SDI. This new equation is supported with *P. massoniana* data from different sites. SDI is a more reasonable measure of biomass than density because it is a stable variable that integrates plant competition and environmental conditions (Zeide, 2005). Eq. 4 uses SDI as a measure of mean tree mass, as these measures take into account the allometric development stage of the stand.
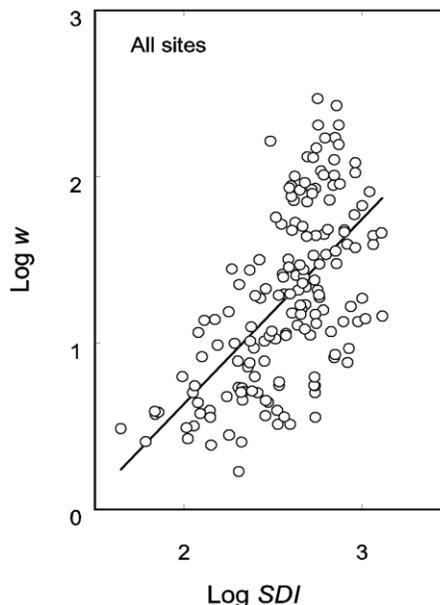
This makes intuitive sense: tree diameter is intimately

linked to stand biomass so that an increase in diameter with density leads to an increase in biomass with density. By using the site-specific SDI exponents, derived from corresponding plots, we may get an adequate and stable measure of tree mass in uneven aged with any stocking level. Therefore, it might be more informative to use a measure of SDI as measures of density-rather than just using numerical density.

Conclusion

Mean tree mass-SDI relationships can be modeled concisely using Eq. 4 for closed *P. massoniana* stands. This confirms the relationships which suggest mean tree mass-SDI significantly varies across sites, from a comparison of the allometric exponents. A biomass equation based on SDI is found to provide an accurate fit to tree biomass–for closed stands, indicating SDI is a good predictor of mean tree mass. Exponents of mean tree mass-density relationship may change with different sites, since competition exists across a range of values rather than a specific point.

Acknowledgments

References

Bai, Y.Y., W.P. Zhang, X. Jia, N. Wang, S.S. Xu and G.X. Wang, 2011. How lateral dimension of roots determines aboveground self-thinning. *Ecol. Compl.,* 8: 310–312

Bai Y.Y., W.P. Zhang, X. Jia, N. Wang, L. Zhou, S.S. Xu and G.X. Wang, 2010. Variation in root: shoot ratios induced the differences between above- and below-ground mass–density relationships along an aridity gradient. *Acta Oecol.,* 36: 393–395

Chu, C.J., F.T. Maestre, S. Xiao, J. Weiner, Y.S. Wang, Z.H. Duan and G. Wang, 2008. Balance between facilitation and resource competition determines biomass–density relationships in plant populations. *Ecol. Lett.,* 11: 1189–1197

Dean T.J. and V.C. Baldwin Jr., 1996a. Growth in loblolly pine plantations as a function of stand density and canopy properties. *For. Ecol. Manage.,* 82: 49–58

Dean, T.J. and V.C. Baldwin Jr., 1996b. The relationship between Reineke's stand-density index and physical stem mechanics. *For. Ecol. Manage.,* 81: 25–34

Deng, J.M., G.X. Wang, E.C. Morris, X.P. Wei, D.X. Li, B.M. Chen, C.M. Zhao, J. Liu and Y. Wang, 2006. Plant mass–density relationship along a moisture gradient in north-west *Chin. J. Ecol.,* 94: 953–958

Deng, J.M., W.Y. Zuo, Z.Q. Wang, Z.X. Fan, M.F. Ji, G.X. Wang, J.Z. Ran, C.M. Zhao, J.Q. Liu, K.J. Niklas, S.T. Hammond and J.H. Brown, 2012. Insights into plant size-density relationships from models and agricultural crops. *Proc. Natl. Acad. Sci. USA,* 109: 8600–8605

Ding, G.J. and P.C. Wang, 2001. Study on change laws of biomass and productivity of Masson pine forest plantation. II. Biomass and productivity of stand at different ages. *For. Res.,* 15: 54–60

Ding, G.J., 2003. Study on biomass and productivity of Masson pine planting stand. I. Biomass and density effect of different planting density. *J. Fujian Coll. For.,* 23: 34–38

Ding, G.J., P.C. Wang and R.F. Yang, 1998. Studies on the dynamic change of the commercial biomass of Masson pine pulpwood stands and its modeling. *Sci. Sil. Sin.*, 34: 33–41

Enquist, B.J., J.H. Brown and G.B. West, 1998. Allometric scaling of plant energetics and population density. *Nature,* 395: 163–165

Enquist, B.J., G.B. West and J.H. Brown, 2000. *Quarter-Power Allometric Scaling in Vascular Plants: Functional Basis and ecological Consequences.* Oxford University Press, New York, USA

He, Q.T., J.Z, Yuan and Z.P. Chen, 1996. Possible effects of the climate changes on the distribution of *Pinus massoniana* and Pinus yunnanensis in South China. *J. Beijing For. Univ., 1*8: 22–28

Isaac, N.J.B. and C. Carbone, 2010. Why are metabolic scaling exponents so controversial? Quantifying variance and testing hypotheses. *Ecol. Lett.,* 13: 728–735

Lie, G.W. and L. Xue, 2016. Biomass allocation patterns in forests growing different climatic zones of China. *Trees,* 30: 639–646

Long, J.N. and F.W. Smith, 1990. Canopy development and leaf 'area efficiency: links between production ecology and density management. *In*: *New Approaches to Spacing and Thinning in Plantation Forestry, Rotorua, New Zealand, 10. 4 April 1989,* pp: 260–216. James, R.N. and GL Tarlton (eds.). International Union of Forestry Research Organizations and Forest Research Institute Ministry of Forestry, New Zealand

Long, J.N., 1985. A practical approach to density management. *For. Chron.,* 61: 23–27

Malhi, Y., D. Wood, T.R. Baker, J. Wright, O.L. Phillips, T. Cochrane, P. Meir, J. Chave, S. Almeida, L. Arroyo, N. Higuchi, T.J. Killeen, S.G. Laurance, W.F. Laurance, S.L. Lewis, A. Monteagudo, D.A. Neill, P. Núñez Vargas, N.C.A. Pitman, C.A. Quesada, R. Salomão, J.N.M., A.T. Silva Lezama, J. Terborgh, R. Vásquez Martínez and B. Vinceti, 2006. The regional variation of aboveground live biomass in old-growth Amazonian forests. *Global Change Biol.,* 12: 1107–1138

Mohler, C.L., P.L. Marks and D.G. Sprugel, 1978. Stand structure and allometry of trees during self-thinning of pure stands. *J. Ecol.,* 66: 599–614

Reineke, L.H., 1933. Perfecting a stand-density index for even-aged forests. *J. Agric. Res.,* 46: 627–638

Rivoire, M. and G. Le. Moguedec, 2012. A generalized self-thinning relationship for multi-species and mixed-size forests. *Ann. For. Sci.,* 69: 207–219

Stegen, J.C., N.G. Swenson, R. Valencia, B.J. Enquist and J. Thompson, 2009. Above-ground forest biomass is not consistently related to wood density in tropical forests. *Global Ecol. Biogeogr.,* 18: 617–625

Weller, D.E., 1987a. A reevaluation of the 3/2 power rule of self thinning. *Ecol. Monogr.,* 57: 23–43

Weller, D.E., 1987b. Self-thinning exponent correlated with allometric measures of plant geometry. *Ecology,* 68: 813–821

White, C.R., P. Cassey and T.M. Blackburn, 2007. Allometric exponents do not support a universal metabolic allometry. *Ecology,* 88: 315–323

Woodall, C.W., P.D. Miles and J.S. Vissage, 2005. Determining maximum stand density index in mixed species stands for strategic-scale stocking assessments. *For. Ecol. Manage.,* 216: 367–377

Xiang, W.H., S.H. Liu, X.W. Deng, A.H. Shen, X.D. Lei, D.L. Tian, M.F. Zhao and C.H. Peng, 2011. General allometric equations and biomass allocation of *Pinus massoniana* trees on a regional scale in southern China. *Ecol. Res.,* 26: 697–711

Xue, L., 2014. The mean tree mass–stand density index relationship for forest stands in China. *Scand. J. For. Res.,* 29: 664–668

Xue, L. and A. Hagihara, 1999. Density effect, self-thinning and size distribution in *Pinus densiflora* Sieb. et Zucc. stands. *Ecol. Res.,* 14: 49–58

Xue, L. and A. Hagihara, 2001. Growth analysis on the competition-density effect in Chinese fir (*Cunninghamia lanceolata*) and Masson pine (*Pinus massoniana*) stands. *For. Ecol. Manage.,* 150: 331–337

Xue, L. and A. Hagihara, 2002. Growth analysis on the C-D effect in self-thinning Masson pine (*Pinus massoniana*) stands. *For. Ecol. Manage.,* 165: 249–256

Xue, L., D.F. Jacobs, S.C. Zeng, B. Liu, Z.Y. Yang and S.H. Gu, 2012. Relationship between aboveground biomass allocation and stand density index in *Populus × euramericana* stands. *Forestry,* 85: 611–619

Xue, L., Q.J. Li, X.L. Hou and Y.T. Hao, 2015. Self-thinning lines and allometric relation in Chinese fir (*Cunninghamia lanceolata*) stands. *J. For. Res.,* 26: 281–290

Xue, L., K. Ogawa, A. Hagihara, S. Liang and J. Bai, 1999. Self-thinning exponents based on the allometric model in Chinese pine (*Pinus tabulaeformis* Carr.) and Prince Rupprecht's larch (*Larix principis-rupprechtii Mayr*) stands. *For. Ecol. Manage.,* 117: 87–93

Xue, L., Q.J. Li and H.Y. Chen, 2014. Effects of a wildfire on selected physical, chemical and biochemical soil properties in a *Pinus massoniana* forest in south China. *Forests,* 5: 2947–2966

Yoda, K., T. Kira, H. Ogawa, and K. Hozumi, 1963. Self-thinning in overcrowded pure stands pure stands under cultivated and natural conditions. *J. Biol. Osaka City Univ.,* 14: 107–129

Zeide, B., 1987a. Analysis of the 3/2 power law of self-thinning. *For. Sci.,* 33: 517–537

Zeide, B., 1987b. Tolerance and self-tolerance of trees. *For. Ecol. Manage.,* 13: 149–166

Zeide, B., 2005. How to measure stand density. *Trees,* 19: 1–14

Zeide, B., 2010. Comparison of self-thinning models: an exercise in reasoning. *Trees,* 24: 1–10

Zhang, W.P., X. Jia, Y.Y. Bai and G.X. Wang, 2011. The difference between above- and below-ground self-thinning lines in forest communities. *Ecol. Res.,* 26: 819–825

Zhang, W.P., X. Jia, E.C. Morris, Y.Y. Bai and G.X. Wang, 2012. Stem, branch and leaf biomass-density relationships in forest communities. *Ecol. Res.,* 27: 819–825