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:

\[ M = kN^{3/2} \]

Where, \( M \) is the mean plant mass, \( N \) is density, and \( k \) is a constant specific to species, and the exponent \( \beta \) 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 43 power of density N:

\[ M = gN^{4/3} \]

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).

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:

\[ SDI = N(D_4/25.4)^{1.6} \]

Where, \( N \) is the number of trees per hectare and \( D_4 \) 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 studies on the stem volume-density relationship have been reported in *P. massoniana* stands (Xue and Hagihara, 2001,
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. The summary characteristics of the experimental stands are shown in 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. $SDI \propto N$) from Eq. 3, the mean tree mass $M$-SDI relationship can be derived by inserting Eq. 3 into Eq. 1:

$$M = \bar{\text{SDI}}^\gamma$$

(4)

Where, $\bar{\text{SDI}}$ is a constant specific to each species, and $\gamma$ is the exponent.

The exponents and the intercept of the mean tree mass–density relationship and the mean tree mass–SDI 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 faster than at the other sites with decreasing density.

### Table 1: Quantile regression (QR) exponents and y-intercepts ($\text{QR}$ and log $\text{QR}$, respectively) for log10-transformed 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

<table>
<thead>
<tr>
<th>Site</th>
<th>$\log_{10}(\text{SE})$</th>
<th>Log $\log_{10}(\text{SE})$</th>
<th>$n$</th>
<th>$Pr (&lt;t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bishan, Chongqing</td>
<td>-2.07 (0.07)</td>
<td>8.41 (0.24)</td>
<td>13</td>
<td>0.000</td>
</tr>
<tr>
<td>Zizhong, Sichuan</td>
<td>-1.44 (0.09)</td>
<td>6.52 (0.27)</td>
<td>11</td>
<td>0.000</td>
</tr>
<tr>
<td>Shimen, Hunan</td>
<td>-0.90 (0.12)</td>
<td>4.69 (0.40)</td>
<td>19</td>
<td>0.000</td>
</tr>
<tr>
<td>Yongshun, Hunan</td>
<td>-0.83 (0.09)</td>
<td>4.71 (0.30)</td>
<td>16</td>
<td>0.000</td>
</tr>
<tr>
<td>Anhua, Hunan</td>
<td>-1.96 (0.07)</td>
<td>8.47 (0.21)</td>
<td>14</td>
<td>0.000</td>
</tr>
<tr>
<td>Shupu, Hunan</td>
<td>-0.59 (0.11)</td>
<td>3.48 (0.40)</td>
<td>15</td>
<td>0.000</td>
</tr>
<tr>
<td>Xiangtan, Hunan</td>
<td>-1.10 (0.16)</td>
<td>5.39 (0.54)</td>
<td>32</td>
<td>0.000</td>
</tr>
<tr>
<td>Hengnan, Hunan</td>
<td>-1.12 (0.16)</td>
<td>5.62 (0.51)</td>
<td>25</td>
<td>0.000</td>
</tr>
<tr>
<td>Longli, Guizhou</td>
<td>-1.10 (0.05)</td>
<td>5.66 (0.18)</td>
<td>21</td>
<td>0.000</td>
</tr>
<tr>
<td>All sites</td>
<td>-1.34 (0.16)</td>
<td>6.55 (0.53)</td>
<td>58</td>
<td>0.000</td>
</tr>
</tbody>
</table>

**Fig. 1**: Geographical distribution range (shaded area) of *P. massoniana* adapted (adapted from He *et al.*, 1996)
Table 2: Quantile regression (QR) exponents and y-intercepts (log 10 and log 10 QR, respectively) for log10-transformed 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               | Log 10(SE)   | Log 10QR(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    |
| Yongshan, Hunan    | 0.92 (0.03)  | -0.51 (0.08) | 16 | 0.000    |
| Anhua, Hunan       | 0.58 (0.10)  | 0.76 (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. 2: Relationship between mean tree mass and density across the nine sites.

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-rupprechti* 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 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.

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