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COMPARISON OF STAND DENSITY MEASURES AS PREDICTOR OF DIAMETER INCREMENT

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ABSTRACT

Seven expressions of stand density were compared in regard to overstory tree diameter increment in eastern cottonwood (*Populus deltoides* Bartram ex Marsh.)-silver maple (*Acer saccharinum* L.)-American sycamore (*Platanus occidentalis* L.) forests. Basal area (BA), trees per hectare (TPH), percent stocking, stand density index (SDI), relative minimum density of full site occupancy (R_{MDFO}), percent average maximum density (P_{AMD}) and relative density (RD) were evaluated as expressions of stand density. Relative stand density measures seemed to be better predictors of average diameter increment than absolute density measures. In addition, relative density measures were identical in regard to their influence on the tree diameter increment.

Keywords: absolute measures, basal area, diameter increment, relative measures, stocking

MEŞCERE SIKLIĞI ÖLÇÜ BİRİMLERİNİN ÇAP BÜYÜMESİNİ TAHMİN ETME YÖNÜNDEN KARŞILAŞTIRILMALARI

ÖZET

Yedi adet meşcere sıklığı ölçü birimi, Doğu kavağı (*Populus deltoides* Bartram ex Marsh.)-gümüşi akçaağaç (*Acer saccharinum* L.)-Amerikan çınarı (*Platanus occidentalis* L.) ormanlarındaki ağaç çap büyümesini tahmin etmeleri yönünden karşılaştırılmıştır. Göğüs yüzeyi alanı (BA), hektardaki ağaç sayısı (TPH), yüzde sıkışıklık, meşcere sıklık indeksi (SDI), tüm alan doluluğunun minimum nispi sıklığı (R_{MDFO}), ortalama maksimum sıklık yüzdesi (P_{AMD}) ve nispi sıklık (RD) meşcere sıklığını ifade etmeleri bakımından değerlendirilmiştir. Nispi meşcere sıklık ölçü birimlerinin ağaç çap büyümesini tahmin etme bakımından mutlak sıklık ölçü birimlerine nazaran daha başarılı oldukları saptanmıştır. Ayrıca, nispi meşcere sıklık ölçü birimlerinin ağaç çap büyümesine olan etkileri bakımından kendi aralarında benzer oldukları tespit edilmiştir.

Anahtar Kelimeler: çap büyümesi, göğüs yüzeyi alanı, mutlak ölçü birimleri, nispi ölçü birimleri, sıkışıklık

1. INTRODUCTION

Stand density is a quantitative measure of density that can be expressed in both absolute and relative units. It describes how much a site is being utilized. In addition, stand density indicates the intensity of competition among trees for light, water, and nutrients. A stand's available growing space and the self-thinning relationships are described by size-density relationships (Jack and Long, 1996; Zeide, 2010).

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Forest regeneration, diameter growth, tree mortality, stem quality and available growing space can be significantly influenced by stand density. Average tree size is usually determined by the growing space occupied by the tree; the tree will grow faster when the amount of growing space per hectare is greater (Clutter et al., 1983). Thus, reliable measures of stand density have been needed to increase forest productivity and control competition among trees (Krajicek et al., 1961; Zeide, 2005). Consequently, numerous methods of expressing stand density have been developed by silviculturists (Reineke, 1933; Gingrich, 1967; Drew and Flewelling, 1979). Silvicultural decisions are usually made based on such measures of stand density.

Stand basal area per hectare (BA), volume per hectare and trees per hectare (TPH) are quantitative measures of stand density. Percent stand stocking (Gingrich, 1967), stand density index (SDI) (Reineke, 1933), relative minimum density of full site occupancy (R_{MDFO}) (Lhotka and Loewenstein, 2007), percent average maximum density (P_{AMD}) (Lhotka and Loewenstein, 2007), and relative density (RD) (Turnblom, 2016) are some of the relative measures of stand density, and they refer to site occupancy as a percentage of a reference level (Ernst and Knapp, 1985).TPH is determined by counting trees in a unit area while BA (m^2 ha^{-1}) is the total cross-sectional area of the trees at breast height (dbh) in a stand. Percent stocking is the stocking level in relation to a reference level (i.e. 100% stocking) (Ernst and Knapp, 1985). SDI expresses stand density based on the relationships between number of trees per hectare and dbh of the tree of average BA (VanderSchaaf, 2013). R_{MDFO} is the proportion of observed stand density to the minimum density of full site occupancy while P_{AMD} is the proportion of observed stand density to the maximum density of normally stocked stands (Lhotka and Loewenstein, 2007). RD combines BA and average tree size, and increases with increasing BA for a given quadratic mean diameter (QMD) suggesting that higher RD means higher degree of competition (Turnblom, 2016).

Absolute measures of stand density are not comparable across stands because the available growing space of two stands with same BA or TPH varies depending on the average tree size. For example, stands with a larger QMD may represent more growing space than stands with smaller QMD at a given BA (Goelz, 1995; Martin, 1996). On the other hand, relative stand density measures may be comparable in terms of available growing space across stands because these measures refer to the crowding of trees in relation to what is considered the optimum (Ernst and Knapp 1985). Although there have been several measures of stand density, comparison of those measures as predictor of diameter increment has been limited. Whether density measures differ as predictor of diameter increment is still open to questions. In this study, the objective was to compare if BA, TPH, stocking, SDI, R_{MDFO}, P_{AMD} or RD was a better predictor of tree diameter increment in eastern cottonwood (*Populus deltoides* Bartram ex Marsh.)-silver maple (*Acer saccharinum* L.)-American sycamore (*Platanus occidentalis* L.) forests. It was hypothesized that relative stand density measures are better predictors of diameter increment in these forests.

2. MATERIALS AND METHODS

2.1. Dataset

In order to evaluate the stand density measures in regard to overstory tree diameter increment, the USDA Forest Service's Forest Inventory and Analysis (FIA) database for years 2003 through 2008 was used. Data plots from the state of Missouri (Figure 1) were downloaded from FIA website (FIA National Program, 2011). Only fixed-radius plots were chosen. Each plot consists of four 7.3 m radius subplots in which all trees with a dbh of 12.7 cm and greater were measured (O'Connell et al., 2014). Eighty plots that were dominated by eastern cottonwood, silver maple and American sycamore species was used (Table 1). Plots were within mixed stands with mostly uneven-aged structure. American elm (*Ulmus Americana)* and green ash (*Fraxinus pennsylvanica)* were other common species within the study plots. These forests are highly productive with site index ranging from 24 to 46 (at base age 50) (Larsen et al., 2010). Mean individual-tree diameter increment was calculated for 5-year measurement periods (i.e., 2003 through 2008) in each plot where no thinning occurred. The diameter increment of the trees was calculated as the difference between the measurement periods.

Figure 1. Location of Missouri State in the USA.

Table 1. Descriptive statistics of datasets used for comparison of stand density measures

Variable	Mean	Minimum	Maximum	Standard deviation
BA (m^2 ha^{-1})	26.1	2.42	55.22	12.82
TPH	666	244	1250	244
QMD (cm)	22.11	6.92	37.05	6.92

2.2. Stand density measures

Seven expressions of stand density were calculated for each plot. TPH and QMD (cm) were determined for each plot selected from the FIA dataset. BA (m^2 ha^{-1}) for each plot was then calculated using equation 1.

$$\mathrm{BA} = \mathrm{QMD}^2\ (0.00007854)\mathrm{TPH} \qquad \text{[eq. 1]}$$

Percent stocking was determined using the Gingrich stocking chart for eastern cottonwood-silver maple-American sycamore forests developed by Larsen et al. (2010). Using the chart, percent stocking was obtained based on any two of three measurements; BA, TPH and QMD as suggested by Gingrich (1967). SDI was calculated for each plot using equation 2 developed by Reineke (1933).

$$\mathrm{SDI} = \mathrm{TPH}\ (\mathrm{QMD}/25)^{\ 1.605} \qquad \text{[eq. 2]}$$

Next, using the equation 3, R_{MDFO} was defined as the proportion of observed stand density (N) to the minimum density of full site occupancy (MDFO) (trees ha^{-1}) as suggested by Lhotka and Loewenstein (2007).

$$\mathrm{R_{MDFO}} = \mathrm{N} / \mathrm{MDFO} \qquad \text{[eq. 3]}$$

In order to determine R_{MDFO}, first, MDFO was needed. MDFO refers to the minimum number of trees per hectare required for onset of full site occupancy. MDFO is given on the Gingrich stocking chart as B-line stocking (Gingrich, 1967). Thus, MDFO was obtained for each plot based on plots' BA and QMD using the stocking chart of Larsen et al. (2010). Then, R_{MDFO} was determined using equation 3.

P_{AMD} was calculated using equation 4 as suggested by Lhotka and Loewenstein (2007).

$$\mathrm{P_{AMD}} = \mathrm{N} / \mathrm{AMD} \qquad \text{[eq. 4]}$$

where N is observed stand density and AMD is average maximum density (trees ha^{-1}). AMD represents the minimum growing space required for a tree to survive under normally-stocked conditions which refers to undisturbed stands lacking of gaps and with relatively uniform spacing (Johnson et al., 2010). AMD is given on the Gingrich stocking chart as A-line stocking (Gingrich, 1967). Thus, for each plot, AMD was obtained based on plots' BA and QMD using the stocking chart of Larsen et al. (2010). Then, P_{AMD} was determined using equation 4.

Next, RD was calculated using the equation 5 for each plot as suggested by Turnblom (2016).

$$\mathrm{RD} = \mathrm{BA} \,/\, \sqrt{\mathrm{QMD}} \qquad \text{[eq. 5]}$$

2.3. Statistical analysis

Seven density measures were compared based on their relationships with diameter increment (i.e. diameter increment with BA, TPH, stocking, SDI, R_{MDFO}, P_{AMD} and RD) of the sampled eastern cottonwood-silver maple-American sycamore forests using regression analysis. Coefficient of determination (R^2) was utilized to evaluate relationship strength. R^2 represents the percent of variance explained by the regression model. Linear regression approach was completed using the "lm" function of R-Statistical software (R Development Core Team, 2010).

3. RESULTS AND DISCUSSION

Mean individual-tree diameter increment ranged from 0.2 to 6.40 cm for 5-year measurement periods across all study plots. Summary of the density measures across all plots was given in Table 2. It should be noted that summary of BA and TPH were given in Table 1. Both tables show that the study plots were well-distributed across BA, QMD, stocking, SDI, R_{MDFO}, P_{AMD} and RD.

Table 2. Data summary for density measures across all plots.

Stand density measures	Mean	Minimum	Maximum	Standard deviation
Percent stocking	68.4	10	125	29.05
SDI	217.8	30.9	393.4	92
R_{MDFO}	2.24	0.48	3.85	0.86
P_{AMD}	0.7	0.19	1.23	0.27
RD	5.38	0.85	9.45	2.18

Following the regression analyses between the diameter increment and the density measures, we found that there were statistically significant relationships between diameter increment and most of the density measures (BA, stocking, SDI, R_{MDFO}, P_{AMD} and RD) ($p<0.001$) (Figure 2). Calculated R^2 values ranged from 0.23 to 0.24 for relative density measures (stocking, SDI, R_{MDFO}, P_{AMD} and RD) while it was 0.09 and 0.20 for absolute density measures; TPH and BA, respectively (Figure 2). Of the seven density measures, relative density measures had more influence than absolute density measures on the tree diameter increment (Figure 2). TPH had no significant influence on the diameter increment (Figure 2). TPH is a useful measure of stand density in homogeneous and even-aged stands. For example, two stands with same TPH may not have same amount of available growing space if their average QMD differs. Stands with larger QMD will have less available growing space than stands with smaller QMD for a given TPH. Since trees in our plots varied in size, influence of TPH on tree diameter increment was smaller than other density measures. In addition, the insignificant relationships ($p=0.242$) between TPH and BA (Figure 3) suggest that TPH may not be a good indicator of stand density in stands that vary widely in tree diameters, and have non-normal diameter distributions such as uneven-aged stands.

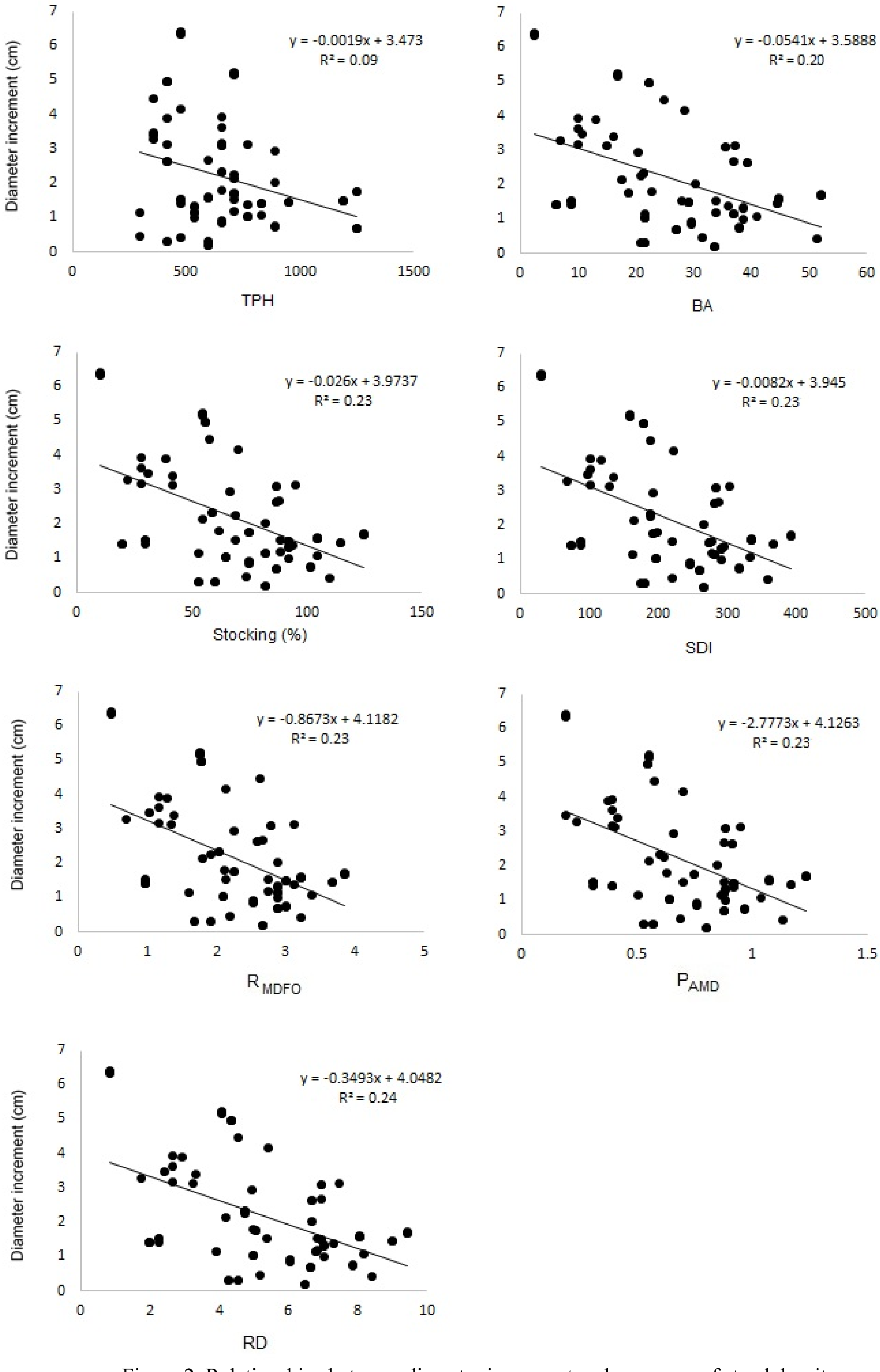

Figure 2. Relationships between diameter increment and measures of stand density.

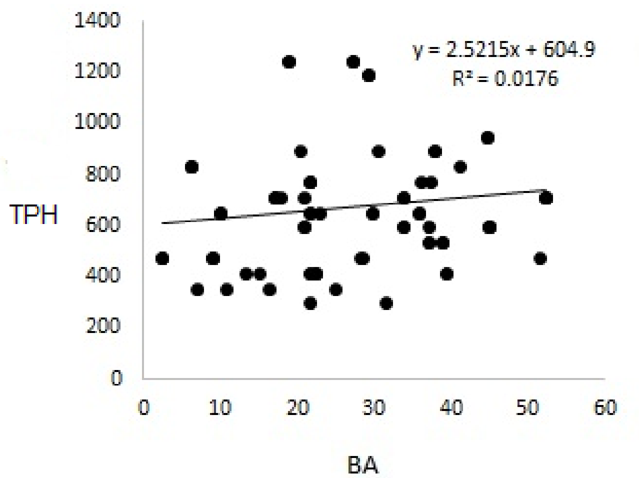

Figure 3. Relationships between the two absolute measures of stand density; TPH and BA.

Relative density measures (Percent stocking, SDI, R_{MDFO}, P_{AMD} and RD) had similar influence on the average tree diameter increment ranging from 0.23 to 0.24 in R^2 (Figure 2). These results suggest that relative density measures were identical in regard to average tree diameter increment in eastern cottonwood-silver maple-American sycamore forests. Most relative density measures have been developed by comparing the density of a stand with the maximum density that the stand could reach (West, 1982). This is probably the reason for the similar influence of relative density measures on tree diameter increment.

There was a high correlation between BA and the relative density measures (Percent stocking, SDI, R_{MDFO}, P_{AMD} and RD) with R^2 ranging from 0.90 to 0.97 of (Figure 4). However, influence of the relative measures of stand density on the tree diameter increment (ranging from 0.23 to 0.24 in R^2) was higher than influence of BA ($R^2 = 0.20$) (Figure 2). BA alone is a one of the most commonly used measure of density when allocating growing space. However, two stands with same BA may not occupy same amount of growing space depending on the average size of the trees (Gingrich, 1967). It has been stated that stands with a larger QMD represent lower stocking (i.e. fill less growing space) than stands with smaller QMD at a given BA (Gingrich, 1967; Goelz, 1995). Our analyses from eastern cottonwood-silver maple-American sycamore forests substantiate this statement. Average tree diameter increment can be explained better by relative measures of stand density rather than BA or TPH. However, additional comparisons could be conducted for different species or species groups.

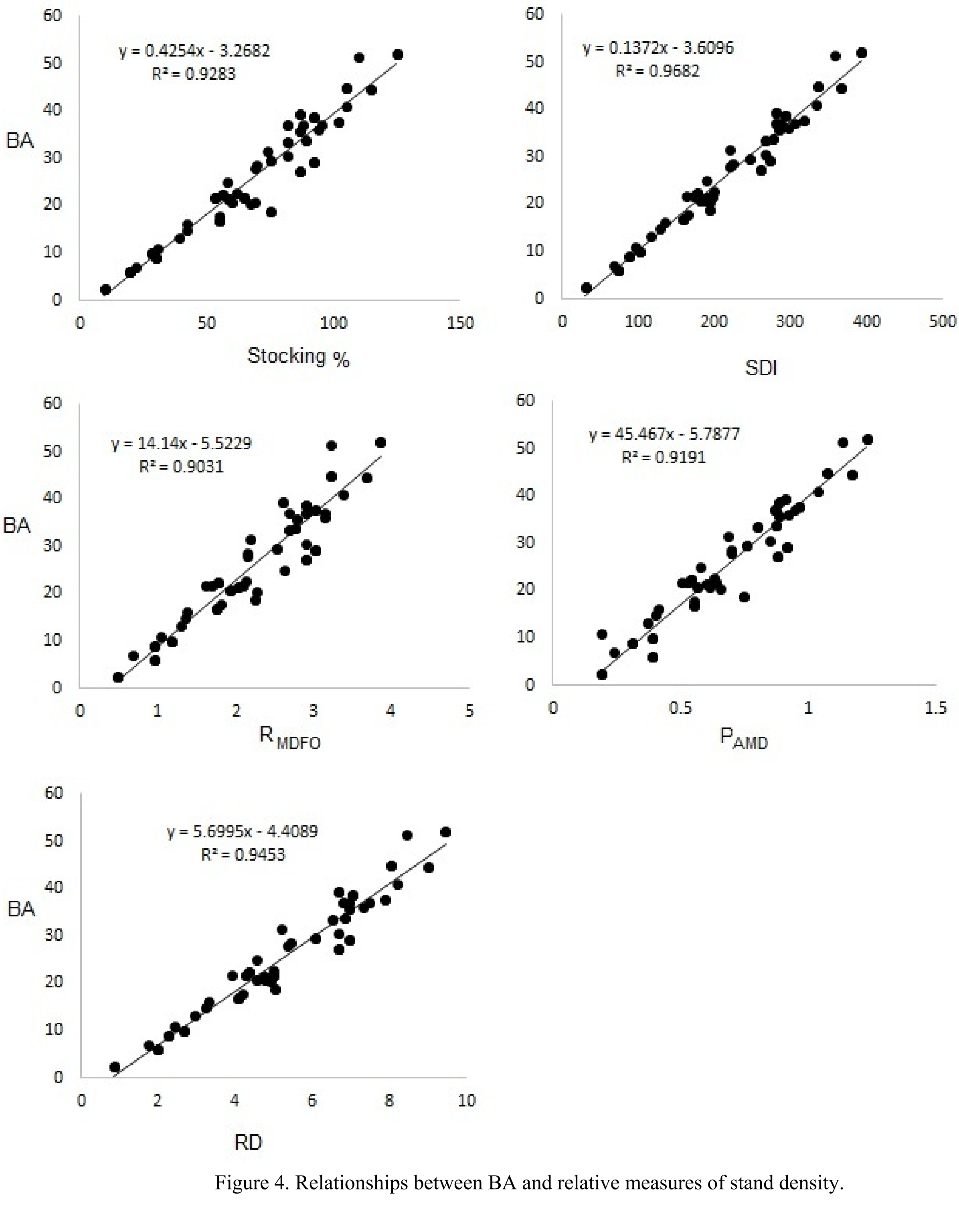

Figure 4. Relationships between BA and relative measures of stand density.

As stated before, relative density measures can provide additional information about stands by comparing a quantitative density measure to a reference level (Johnson, 2009). Growth and survival of trees can be significantly influenced by relative stand density (Johnson, 2009). Relative stand density may offer a greater precision than absolute density measures when allocating growing space through silvicultural manipulation of a forest stand (Martin, 1996). Consequently, several methods of expressing relative density such as density management diagrams and stocking charts have been developed for different species (Gingrich, 1967; Drew and Flewelling, 1979; Larsen et al., 2010). For example, Larsen et al. (2010) developed a Gingrich stocking chart for eastern cottonwood-silver maple-American sycamore forests. Due to its ease of use, they stated that this chart became a handy tool for managing the related forests, and it became an alternative to the use of BA or TPH. In addition, stocking charts that express stand density as percent stocking is adopted as the Forest Service standard for stocking guides (Ernst and Knapp, 1985; Zeide, 2010). Moreover, SDI is associated with stand volume and growth, and it has been used to develop other density management tools such as density management diagrams (Drew and Flewelling, 1979). Density management diagrams are also useful tools to compensate the disadvantages of absolute density measures such as BA and TPH. Moreover, Lhotka and Loewenstein (2007) compared R_{MDFO} and P_{AMD} with SDI in regard to diameter increment of loblolly pine (*Pinus taeda* L.), and concluded that R_{MDFO} and P_{AMD} were comparable with SDI in predicting diameter increment, and better than BA. It should be noted that there are other relative density measures in literature (West, 1982). Since relative density measures provide stand density in different ways and using different parameters (such as QMD, TPH, volume and BA), they may be complementary to each other.

4. CONCLUSIONS

Due to their ease of computation and measurements in the field, BA and TPH are usually preferred and commonly used over relative density measures when prescribing residual stand density and allocating growing space. However, relative measures of stand density may be better descriptions of residual stand density than BA or TPH because the amount of available growing space changes based on average tree diameter at a given BA or TPH. In this study, it was found that relative density measures are better predictor of tree diameter increment than absolute density measures. However, further research evaluating density measures in varying forest types is recommended.

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