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Determining maximum stand density index in mixed species stands for strategic-scale stocking assessments

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Abstract

Stand density index (SDI), although developed for use in even-aged monocultures, has been used for assessing stand density in large-scale forest inventories containing diverse tree species and size distributions. To improve application of SDI in uneven-aged, mixed species stands present in large-scale forest inventories, trends in maximum SDI across diameter classes and species combinations were observed for eight common tree species of the United States. Additionally, the relationship between a stand's mean specific gravity of component trees and maximum SDI was explored. Results indicate that the maximum SDI that any particular species may attain is affected to varying degrees by the species composition of subject stands. A strong relationship was found between the mean specific gravity of all trees in a stand and the 99th percentile of the observed distribution of stand SDI's by classes of mean stand specific gravity. A model is proposed whereby the mean specific gravity of individual trees in a stand may serve as a predictor of a stand's maximum stocking potential, regardless of the stand's diameter distribution and species composition.

Keywords: Stand density index; Mixed-species; Uneven-aged; Strategic-scale; Forest inventory and analysis

1. Introduction

1.1. Strategic-scale density assessment

Recent severe fire seasons have highlighted the need to identify current forest fire hazards across the United States by assessing the relative density of forests. Fire hazard assessments involve quantifying the potential for extreme forest fire conditions in specific forest areas resulting from the complex interaction of climatic conditions, topography, stand structure, location, species composition, and relative density of forest sites at scales ranging from one state to the entire country (Vissage and Miles, 2003; Fiedler et al., 2004; USDA Forest Service, 2005). Results from these studies, although still cursory, have the potential to influence implementation of public policy (e.g., Healthy Forests Restoration Act of 2003, U.S. Public Law 108–148.) in managing the forests across the U.S. The process of querying large-scale forest

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inventory databases for assessing the potential of stand treatments to reduce fire hazards is analogous to developing ''on-the-ground'' silvicultural treatments (Woodall and Fiedler, 2005). One critical component of any silvicultural treatment is quantification of observed stand density relative to desired density. If stand densities can be hypothetically reduced for inventory plots, then the subsequent reductions in fire hazards can be broadly quantified across the landscape using inventory population estimators (for example, see USDA Forest Service, 2005, inventory procedures see Bechtold and Patterson, 2005). Beyond large-scale fire hazard assessments, determining biologically justifiable maximum relative density levels has remained a hurdle for silviculturalists. Assessing the relative density of each individual forest stand across the U.S. is complicated by the diameter distributions, species compositions, and site conditions unique to each stand. Most techniques for assessing relative density were developed for application in individual stands consisting of monocultures or regionally common species mixtures (for examples, see Reineke, 1933; Krajicek et al., 1961; Gingrich, 1967; Drew and Flewelling, 1979). Although a substantial body of literature addresses the development of small-scale stand-specific relative density measures, scant research has been conducted to develop effective relative density assessment techniques for use at strategic scales inclusive of all tree species and size combinations.

1.2. Stand density index in even-aged stands

Stand density index (SDI) has been used in past strategic-scale fire hazard assessments for determining relative stand density (Vissage and Miles, 2003; USDA Forest Service, 2005). SDI was first proposed by Reineke (1933) as a stand density assessment tool based on size-density relationships observed in fully stocked pure or nearly pure stands. A metric version of SDI is defined as the equivalent trees per hectare at a quadratic mean diameter of 25 cm and is formulated as,

$$\mathrm{SDI} = \mathrm{tph}\left(\frac{\mathrm{DBH_q}}{25}\right)^{1.6} \tag{1}$$

where SDI is stand density index, tph is the number of trees per hectare, and $\mathrm{DBH_q}$ is quadratic mean diameter (cm) at breast height (1.4 m) (Long, 1985). SDI has been widely used in even-aged stands because it is independent of species composition (Curtis, 1970). The SDI of even-aged monocultures is typically compared to an empirically observed, species-specific maximum SDI for determining the stand's relative density. Maximum SDI ($\mathrm{SDI_{max}}$) may be defined as the maximum density (tph) that can exist for a given mean tree size (25 cm) in a self-thinning population (Long, 1996). The $\mathrm{SDI_{max}}$ has typically been determined strictly through empirical means: finding the most heavily stocked stand on the landscape (for examples, see Stout and Nyland, 1986; Cochran et al., 1994). To determine relative density, the SDI of any particular stand is compared to the $\mathrm{SDI_{max}}$ characteristic of the stand's species composition. Percentages of species $\mathrm{SDI_{max}}$ have been related to prominent stages of stand development (Long, 1985), making their determination valuable for strategic-scale assessments of stocking. A relative density of 25% of $\mathrm{SDI_{max}}$ is associated with the onset of competition, 35% of $\mathrm{SDI_{max}}$ is associated with the lower limit of full site occupancy, and 60% $\mathrm{SDI_{max}}$ is associated with the lower limit of self-thinning (Long and Daniel, 1990).

1.3. Stand density index in uneven-aged stands

Although SDI was developed for pure, even-aged stands, it has found use in single-species uneven-aged stands. The only way to appropriately determine SDI in stands with non-normal diameter distributions is to determine the SDI for individual DBH classes and then add them for the entire stand (Long and Daniel, 1990). This methodology, known both as the additive method and the summation method, has been extensively discussed, from Stage's (1968) initial work to contemporary discourses (Shaw, 2000; Ducey and Larson, 2003). The SDI summation method is formulated as:

$$\mathrm{SDI} = \sum \mathrm{tph}_i\left(\frac{\mathrm{DBH}_i}{25}\right)^{1.6} \tag{2}$$

where DBH_i is the midpoint of the ith diameter class (cm) and tph_i is the number of trees per hectare in the ith diameter class (Long and Daniel, 1990; Long, 1995; Shaw, 2000). Research on SDI in uneven-aged stands has predominantly involved the justification of the summation methodology (Long, 1995; Shaw, 2000; Ducey and Larson, 2003) and power functions of the SDI formulation (Sterba and Monserud, 1993; Woodall et al., 2003). Because determining desired stocking levels is a difficult part of uneven-aged management (Long and Daniel, 1990), SDI has been utilized in some studies to determine relative density in uneven-aged stands (Fiedler and Cully, 1995; Long, 1995). SDI may be used to balance stand growth among diameter classes in uneven-aged stand treatments by basing stocking levels on a percentage of maximum stocking levels (Fiedler and Cully, 1995).

1.4. SDI in mixed species stands

SDI has been infrequently applied in mixed species stands (for examples of application, see Binkley, 1984; Stout and Nyland, 1986; Puettman et al., 1993; Cochran et al., 1994; Torres-Rojo and Martinez, 2000; Williams, 2003) due to the lack of available $\mathrm{SDI}_{\max}$'s for the multitude of tree species mixtures. Binkley (1984) and Puettman et al. (1993) explored the use of SDI in the common western forest type of mixed red alder (*Alnus rubra*) and Douglas-fir (*Pseudotsuga mensiezii*) stands, Williams (2003) explored the use of SDI in even-aged hardwood stands of Ohio, and Stout and Nyland (1986) explored the dynamics of $\mathrm{SDI}_{\max}$ in the mixed hardwoods of the Allegeny plateau. Stout and Nyland (1986) found that SDI values fluctuated greatly as the proportion of black cherry (*Prunus serotina*) and sugar maple (*Acer saccharum*) changed in mixed hardwood stands, but did not state any broader conclusions. Cochran et al. (1994) found that slight variations of species proportions within common forest types altered the maximum SDI's in forests of eastern Oregon and Washington. In most studies, investigators were able to determine an empirically observed $\mathrm{SDI}_{\max}$ for their specific forest types in local areas, but were unable to state any broader conclusions.

Species-specific attributes, such as allometry or stem mechanics, may be driving the dynamics of self-thinning in forest stands (Mohler et al., 1978, White, 1981; Dean and Long, 1992). Dean and Baldwin (1996) found that a species' specific gravity explained much of the variation in maximum SDI among tree species. Dean and Baldwin (1996) suggested that inter-specific variation in the maximum mechanical leverage exerted by canopies on stems may help explain species' variation in $\mathrm{SDI}_{\max}$. As competition increases in any given stand, there is a reallocation of foliage further up tree crowns thus increasing bending stress on tree boles (wind effects) (Mar:Moller, 1947; Larson, 1963). The elasticity of tree boles is highly related to its specific gravity (Panshin and de Zeeuw, 1970). Therefore, species with a low specific gravity are more limited in terms of the amount of foliage their boles can support when compared to species with higher specific gravities. In terms of tree density, low specific gravity tree species must have a higher density of trees per acre to support an equivalent stand leaf area as opposed to trees with a high specific gravity that can support more foliage per tree. Dean and Baldwin (1996) found that a species' specific gravity was inversely related to its $\mathrm{SDI}_{\max}$. The $\mathrm{SDI}_{\max}$ versus specific gravity relationship has not been further explored or applied in stand inventory/management activities and may serve as a novel methodology to estimating $\mathrm{SDI}_{\max}$ in mixed species stands where extensive empirical SDI determination is not feasible.

Although thorough work has been completed with regards to self-thinning in mixed-species stands (Westoby, 1984; White, 1985; Stout and Nyland, 1986; Sterba and Monserud, 1993; Sturtevant et al., 1998; Wilson et al., 1999) and the impact of uneven-aged diameter distributions on SDI formulation (Stage, 1968, Shaw, 2000), considerable knowledge gaps exist concerning the application of SDI in mixed species stands (Stout and Nyland, 1986). The effect of increasing stand density of ‘‘other’’ species on SDI in otherwise pure species stands has never been assessed. Although most work in determining $\mathrm{SDI}_{\max}$ has been empirical, Dean and Baldwin's (1996) work suggests $\mathrm{SDI}_{\max}$ may be related to the specific gravity of subject trees. The goal of our study is to develop an approach for estimating $\mathrm{SDI}_{\max}$ in mixed species stands for application in strategic-scale density assessments. Our study has the following objectives:

(1) to assess the effect of species composition on $\mathrm{SDI}_{\max}$ for eight common tree species of the United States;
(2) to quantify the relationship between observed $\mathrm{SDI}_{\max}$ and specific gravity for eight common tree species of the United States;

(3) to develop and validate a technique for estimating the 99th percentile SDI for mixed species stands using the mean of specific gravities (SG_m) for individual trees in subject stands across the United States regardless of species compositions.

2. Methods

2.1. Data

Individual plot data from the National Resource Planning Act (RPA) database were used as observations in this study (Smith et al., 2004). The RPA database contains plot and tree data collected by the USDA Forest Service's Forest Inventory and Analysis (FIA) program. Briefly, the plot design for FIA inventory plots consists of four 7.2-m fixed-radius subplots spaced 36.6 m apart in a triangular arrangement. All trees located on forested subplots with a diameter at breast height of at least 12.7 cm are inventoried. For further information on the RPA database and FIA sample design, refer to Smith et al. (2004) and Bechtold and Patterson (2005). The analyses focused on eight common tree species representing a range of growth conditions and forest ecosystems across the U.S.: loblolly pine (*Pinus taeda*), ponderosa pine (*Pinus ponderosa*), Douglas-fir, paper birch (*Betula papyrifera*), trembling aspen (*Populus tremuloides*), white oak (*Quercus alba*), lodgepole pine (*Pinus contorta)*, and red maple (*Acer rubrum*). The study dataset consisted of data from all fully forested plots (no part of any inventory plot had a non-forest condition present) from the RPA database that had at least one tree of this study's list of eight species. Therefore, the study dataset had species compositions ranging from only minor fractions of study species in mixed species stands to 100% of study species in pure stands ($n = 119{,}235$ plots). A validation dataset was created using all fully forested inventory plots from the RPA database that did not contain any of the study tree species ($n = 29{,}307$ plots).

2.2. Analysis

For all study plots, the tph and SDI (Eq. (2)) for 10-cm diameter classes were determined for study species and other species in each plot. The specific gravity (SG) for all study trees was based on data available from the USDA Forest Service's Forest Products Laboratory (USDA, 1999). A mean SG (SG_m) was determined for each plot by averaging the SG for all trees for each inventory plot. SG_m serves as a very general stand-level index of species composition since it reflects the unique species composition on each plot. For very rare tree species missing published SG information a default conifer and hardwood SG was used (USDA, 1999). The relationship between the SG and SDI_{max} (observed in study dataset, RPA) in pure stands for this study's eight species was modeled as:

$$E(SDI_{max}) = b_0 + b_1(SG) + e \tag{3}$$

where $E(\cdot)$ is statistical expectation, SG the specific gravity for the study species, e is the random error term, and b_0 and b_1 are parameters to be estimated.

Linear regression was also used to estimate the relationship between the 99th percentile SDI (SDI_{99}) for classes of SG_m (0.015 SG_w class width, 26 classes) for the study dataset:

$$E(SDI_{99}) = b_0 + b_1(SG_m) + e \tag{4}$$

where $E(\cdot)$ is statistical expectation, SG_m the mean specific gravity for each study plot, e the random error term, and b_0 and b_1 are parameters to be estimated.

The 99th percentile SDI (SDI_{99}) was used instead of SDI_{max} as the response variable in order to accomplish objective three of this study. The process of modeling SDI_{max} relationships can be highly affected by outliers, acceptable with cursory examination of self-thinning dynamics (study objectives one and two), but problematic when trying to develop possible forest resource analysis tools. The regression model (Eq. (4)) was validated using the validation dataset by predicting SDI_{99} for SG_m classes (0.025 SG_m class width, 13 classes) and computing relative residuals [(observed − predicted)/observed)].

3. Results

The SDI_{max} that study species attained varied according to the unique species composition of study stands (Table 1). As the basal area occupied by study species increased relative to the total stand basal area, the observed SDI_{max} for individual study species

Table 1
Maximum observed stand SDI for common species of the United States based on the Resource Planning Act database (119,235 observations)

Study species	Species composition ratio[a]	Number of sample plots	Study species $\text{SDI}_{\max}$	Other species $\text{SDI}_{\max}$	Total stand SDI
Loblolly	0.00–0.20	3367	202	1434	1636
	0.21–0.40	2217	366	999	1365
	0.41–0.60	1996	646	663	1309
	0.61–0.80	1956	1016	308	1324
	0.81–1.00	3205	1704	0	1704
Ponderosa	0.00–0.20	2387	216	1188	1404
	0.21–0.40	1343	403	931	1334
	0.41–0.60	1109	697	787	1484
	0.61–0.80	986	975	285	1260
	0.81–1.00	2957	1269	0	1269
Douglas-fir	0.00–0.20	4224	318	1633	1951
	0.21–0.40	2804	629	1533	2162
	0.41–0.60	2216	814	1261	2075
	0.61–0.80	1889	1259	552	1811
	0.81–1.00	3014	1376	219	1595
Paper birch	0.00–0.20	8143	266	2019	2285
	0.21–0.40	1994	477	1102	1579
	0.41–0.60	641	567	607	1174
	0.61–0.80	194	851	240	1091
	0.81–1.00	91	972	89	1061
Aspen	0.00–0.20	7401	284	2356	2640
	0.21–0.40	3766	715	986	1701
	0.41–0.60	2496	825	848	1673
	0.61–0.80	1844	1050	624	1674
	0.81–1.00	2697	2214	71	2285
White oak	0.00–0.20	11242	229	1224	1453
	0.21–0.40	4145	354	770	1124
	0.41–0.60	1507	504	573	1077
	0.61–0.80	484	675	190	865
	0.81–1.00	105	559	98	657
Lodgepole	0.00–0.20	2375	261	2558	2819
	0.21–0.40	1304	587	1189	1776
	0.41–0.60	926	832	750	1582
	0.61–0.80	882	1258	437	1695
	0.81–1.00	2264	2376	264	2640
Red Maple	0.00–0.20	19041	315	1413	1728
	0.21–0.40	6564	563	1100	1663
	0.41–0.60	2311	659	501	1160
	0.61–0.80	812	793	290	1083
	0.81–1.00	336	1002	163	1165

[a] Species composition ratio = (basal area of study species)/(basal area of entire stand).

increased. For all species except white oak, the $\text{SDI}_{\max}$ occurred in pure or nearly pure stands. The rate of increase in $\text{SDI}_{\max}$ for study species, from very heterogenous species compositions to pure stands, appears to be greater for shade intolerant species (loblolly and lodgepole pine) as compared to more shade tolerant species (red maple and white oak) (Table 1). However, due to the lack of pure white oak stands across the landscape, $\text{SDI}_{\max}$ estimates in pure white oak stands carry a larger sampling error. The

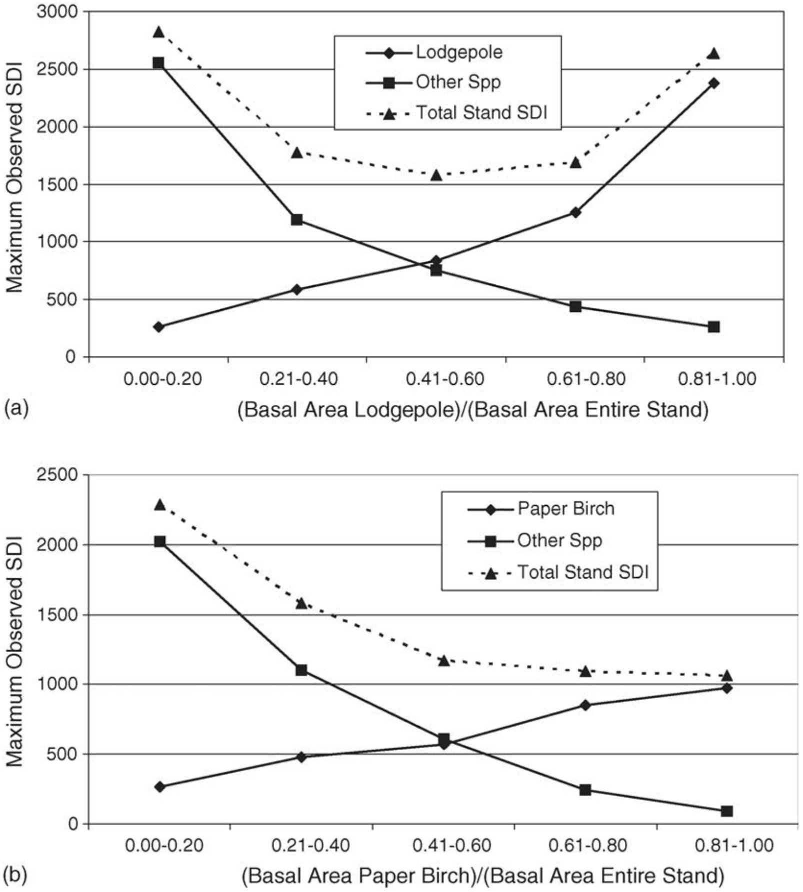

Fig. 1. (a) Maximum observed SDI from mixed to pure species composition for lodgepole pine, the combined SDI for all the other species, and total stand SDI. (b) Maximum observed SDI in mixed to pure species composition stands for paper birch, the combined SDI for all other species, and total stand SDI.

SDI_{max} (study species SDI + others species SDI) was examined for trends in stocking (Fig. 1a and b, Table 1). For stands that contained at least one shade intolerant study species tree (loblolly pine, aspen, and lodgepole), SDI_{max} was usually found at the extremes of species composition, either almost no study species in the stand or almost pure (Table 1). For stands that contained at least one shade tolerant species (Douglas-fir, paper birch, white oak, and red maple), SDI_{max} never occurred when the species composition was pure or nearly pure with study species (Table 1). Additionally, SDI_{max} was typically found for shade tolerant species in stands where these species were minimal stand components. The exception to these trends was ponderosa pine, a species that is rather shade tolerant when young but more shade intolerant when older (Steele, 1988).

The SDI_{max} for plots of what might be reasonably considered a lodgepole pine forest type (>50% stand basal area in lodgepole) was found to be 2640 (Fig. 1a). If this measure is applied to all lodgepole pine forest type stands in this study, then a stand with only 51% lodgepole basal area would be assigned a 2640 SDI_{max}, although the SDI_{max} for its corresponding lodgepole pine:other species mix is 1582 (Fig. 1a). A strategic assessment of stocking of mixed species lodgepole pine stands, basing SDI_{max} on pure lodgepole pine stands, would deviate by more than 1000 from what occurs in the environment for lodgepole-dominated mixed-species stands. For other

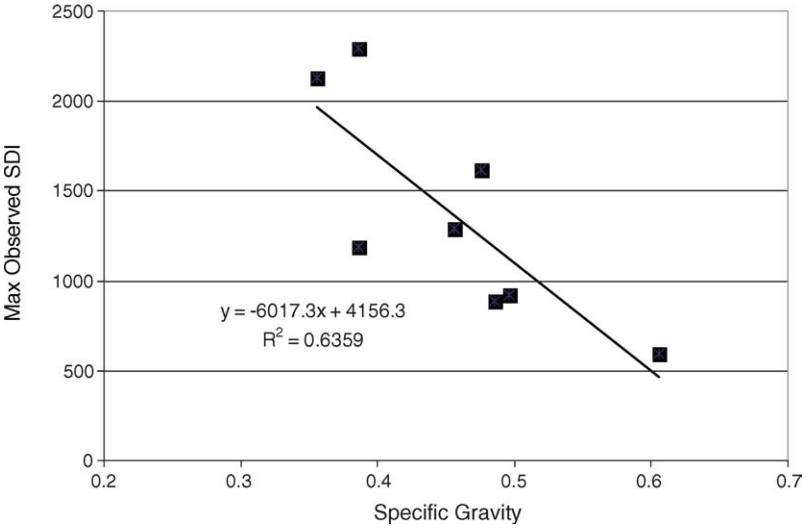

Fig. 2. Maximum observed SDI's for eight study species in relation to the species' specific gravity.

study species, such as paper birch (Fig. 1b), mixed-species composition had little effect on determination of SDI_{max}.

Because it appears that SDI_{max} is dependent on the unique combination of tree species in study stands, a stand-specific SDI_{max} methodology using individual tree's specific gravities was explored. A negative linear relationship between the SDI_{max} for all study species and their corresponding specific gravities was found ($r^2 = 0.6359$, RMSE = 395.2, p-value = 0.02) (Eq. (3)) (Fig. 2). To include all possible combinations of species beyond that of mostly pure stands in the initial regression model, the ability of SG_m to predict SDI_{max} was evaluated for the 99th percentile of the distribution of SDI (SDI_{99}) within classes of SG_m (Table 2). For predictions of SDI_{99}, SG_m explained 92% of the variation (p-value < 0.001, RMSE = 53.1, $\hat{b}_0 = 2057.3$, $\hat{b}_1 = -2098.6$) (Fig. 3). If SDI_{max} had been used as the dependent variable with inclusion of all outliers, parameter estimates would have been larger ($\hat{b}_0 = 3546.7$, $\hat{b}_1 = -3927.3$) with a substantial decrease in r^2 (0.62).

The model for predicting SDI_{99} was validated using the validation dataset. Analysis of the relative residuals for the 13 SG_m classes indicates a slight bias of the estimated linear relationship so that the SDI_{99} may be overpredicted (Table 3; Fig. 4). The mean of the relative residuals was 0.05 (Table 3). The absolute mean of relative residuals for the 13 classes of SG_m was 0.08 (Table 3).

4. Discussion

The application and interpretation of SDI is guided by the species composition of individual stands (Reineke, 1933; Long, 1985; Stout and Nyland, 1986). SDI_{max} information is available for numerous common species of the United States, particularly for western U.S. species (for examples, see Long, 1985; Cochran et al., 1994). However, for stands with two species there is even less available SDI_{max} information (for examples, see Stout and Nyland, 1986; Sturtevant et al., 1998) and for most multi-species stands there is an absence of any maximum relative density information. The lack of mixed-species maximum SDI guidance has impeded the wider application of SDI because vast acreages of forests of the United States are covered by mixed species stands. The results of our study, supported by similar findings in other studies (Stout and Nyland, 1986; Cochran et al., 1994), indicate that SDI_{max} depends on the species composition of any particular stand. A study by the USDA Forest Service (2005) used broad forest types to set maximum SDI in a large-scale assessment of fire-hazards. Our study's results indicate that using

Table 2
Maximum observed and 99th percentile stand SDI's for 116,067 RPA plots by classes of mean stand specific gravity

Mean SG classes	Number of sample plots	Maximum observed stand SDI	99th percentile observed stand SDI
0.3126–0.3250	855	2819	1413
0.3251–0.3375	1697	1908	1529
0.3376–0.3500	3546	1814	1252
0.3501–0.3625	4894	2285	1242
0.3626–0.3750	5884	1775	1275
0.3751–0.3875	11056	2640	1288
0.3876–0.4000	6084	1883	1210
0.4001–0.4125	5470	1951	1145
0.4126–0.4250	5290	2162	1190
0.4251–0.4375	5149	1718	1134
0.4376–0.4500	5750	2075	1062
0.4501–0.4625	4678	1811	1095
0.4626–0.4750	8478	1704	1120
0.4751–0.4875	7030	1396	1087
0.4876–0.5000	6491	1309	1026
0.5001–0.5125	6150	1347	1009
0.5126–0.5250	5928	1266	951
0.5251–0.5375	5592	1299	921
0.5376–0.5500	4891	1507	923
0.5501–0.5625	3961	1403	848
0.5626–0.5750	3133	1417	876
0.5751–0.5875	2514	1439	834
0.5876–0.6000	1546	1404	865

forest type as a means to predict SDI_{max} may be too general. As found in our study, a stand with a basal area of 51% lodgepole pine would have its SDI_{max} over predicted by 67%. Likewise, using the maximum observed SDI for pure paper birch stands in this study as SDI_{max} might be appropriate for all levels of paper birch occupancy in paper birch forest types (paper birch basal area >50%). The effect of species composition on SDI_{max} is highly species composition-specific, a finding supported by this and

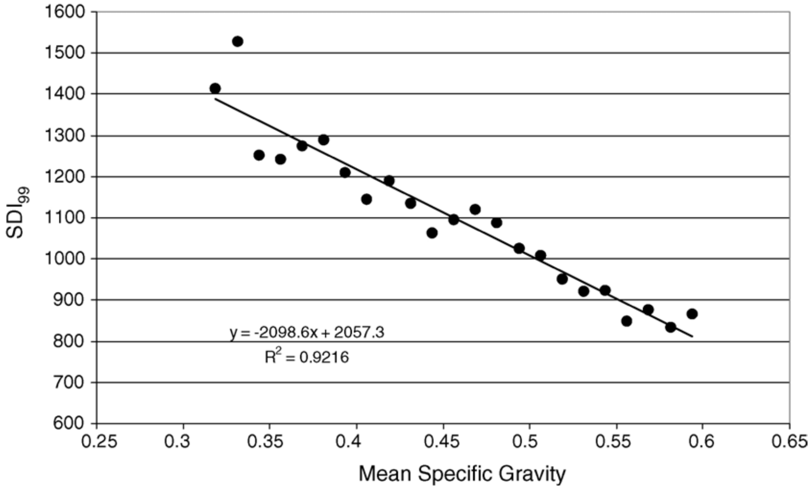

Fig. 3. 99th percentile SDI's by mean stand SG for 119,235 RPA plots.

Table 3
Observed and predicted 99th percentile SDI's for 29,307 RPA plots for 13 classes of mean stand specific gravity

Weighted mean SG classes	Number of sample plots	Observed 99th percentile SDI	Predicted 99th percentile SDI	Relative residuals[a]
0.3001–0.3250	1637	1310	1401	0.07
0.3251–0.3500	1214	1191	1349	0.13
0.3501–0.3750	1987	1284	1297	0.01
0.3751–0.4000	1714	1144	1244	0.09
0.4001–0.4250	2210	1339	1192	−0.11
0.4251–0.4500	1367	1019	1139	0.12
0.4501–0.4750	2780	1156	1087	−0.06
0.4751–0.5000	2606	929	1034	0.11
0.5001–0.5250	2994	872	982	0.13
0.5251–0.5500	5445	864	929	0.08
0.5501–0.5750	3245	817	877	0.07
0.5751–0.6000	1602	794	824	0.04
0.6001–0.6250	506	807	772	−0.04

[a] Relative residuals = (observed − predicted)/observed.

numerous other studies (Stout and Nyland, 1986; Puettman et al., 1993; Cochran et al., 1994; Binkley, 1984).

The variation in SDI_{max} is not easily explained by shade tolerances or growth dynamics of individual trees within study stands. There is a general trend of this study's species attaining greater species-specific SDI's in more pure stands. This should be expected due to the lack of intra-specific competition in pure stands allowing individual species to realize a maximum stocking. The total stand SDI_{max} (study species SDI + other species SDI) is not nearly so predictable. For some species, such as aspen and lodgepole pine, total stand SDI is maximized at extremes of species composition, either almost no lodgepole/aspen in the stand or nearly pure lodgepole/aspen stands. For other species such as red maple, white oak, paper birch, Douglas-fir, and ponderosa pine, stand SDI is maximized when study species are only one component of a diverse stand (mixed species composition). Site quality could be affecting some observed SDI_{max}'s where stockability could be limited by very poor forest sites (Cochran et al., 1994). The trends in maximum SDI and self-thinning are most certainly due to the inter-specific differences among species unique to each stand. These inter-specific differences may be attributed to competition responses such as the ability to re-allocate foliage in the upper

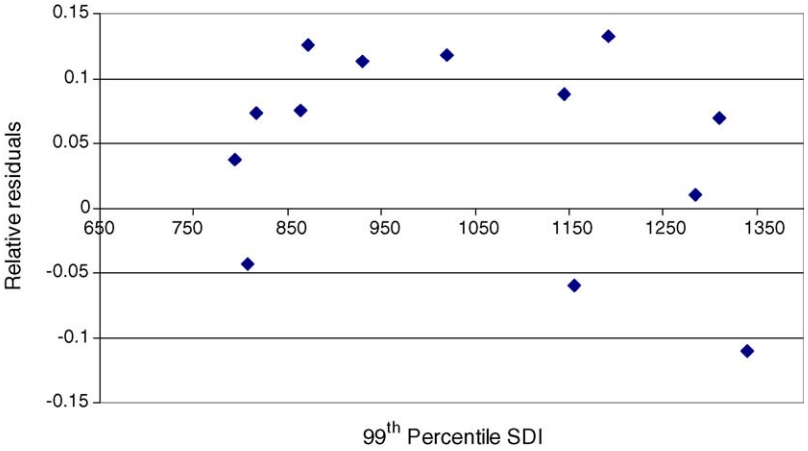

Fig. 4. Relative residuals for predictions of SDI_{99} for SG_m classes.

crown (Dean and Baldwin, 1986; Long and Smith, 1984) or other allometric responses (White, 1981; Mohler et al., 1978; Dean and Long, 1992).

A species' specific gravity has been identified by previous work by Dean and Baldwin (1996) as a species-specific characteristic that may help explain differences in maximum size-density limits during self-thinning in mixed species stands. Generally speaking, the higher a species' specific gravity, the more elastic its bole (Panshin and de Zeeuw, 1970), the more foliage that can be supported in its canopies, and the less trees per unit area needed to support a site-limited (Waring and Schlesinger, 1985) amount of leaf area. While most attempts to determine SDI_{max} for mixed species stands have involved empirical observations (for example, see Cochran et al., 1994), Dean and Baldwin's finding (1996) affords the opportunity to explore a more mechanistic rationale for determining SDI_{max} in mixed species stands.

Dean and Baldwin (1996) found that a species' specific gravity was inversely related to its SDI_{max}. The same result was found in this study for eight study species. However, beyond replicating Dean and Baldwin's finding, we attempted to take this premise a step farther and determine the mean specific gravity for all trees in a stand. Could the mean of all specific gravities in any mixed-species stand somehow indicate the limitation of the stand's species to allocate leaf area to constituent boles? Would a higher mean specific gravity indicate that less trees are needed per unit area to support site-limited leaf area? Using the 99th percentile of maximum observed SDI in order to eliminate extreme outliers, our study's results indicated a strong relationship between SG_m and SDI_{99} for classes of SG_m. Validation of our model to predict a stand's SDI_{99} based on its SG_m indicated a slight bias toward over predicting SDI_{99} (8%). However, other strictly empirical techniques to estimate maximum SDI based on forest types (USDA Forest Service, 2005) would have over predicted SDI_{max} in excess of 60%. Secondly, the nearly 29,000 plots in the validation dataset represent unique combinations of uncommon tree species across the United States (i.e., Osage-orange [*Maclura pomifera*] and Ohio buckeye [*Aesculus glabra*]), a situation where trying to determine a forest type and SDI_{max} would be nearly impossible. Stout and Nyland (1986) found that sugar maple and black cherry mixed species stands had a 57% increase in SDI_{max} as species composition shifted from sugar maple to black cherry dominated. Based on this study's findings; black cherry has a lower specific gravity (0.47) than sugar maple (0.56) so stands predominantly occupied by black cherry should have a higher SDI_{max}. Using this study's SDI_{99} model, black cherry stands would have a 21% increase in maximum SDI over sugar maple. This SDI_{max} difference (21%) is less than found by Stout and Nyland (1986) (57%), however our model used SDI_{99} as the response variable and was calibrated using a larger dataset.

Methodologies for assessing maximum relative stand density in strategic-scale assessments may be augmented by the results of this study. By using the summation method to determine current stand SDI and the SG_m to predict SDI_{99} as a surrogate for SDI_{max}, the opportunity exists to quantify relative stand density across the U.S. regardless of the character of individual stands (species and tree size combinations). SDI methodologies presented in this study warrant future refinement and application in strategic-scale density assessment situations such as found in national fire hazard reduction efforts.

References

Bechtold, William A., Patterson, Paul L. (Eds.), 2005. The enhanced Forest Inventory and Analysis program, national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 85 p.

Binkley, D., 1984. Importance of size-density relationships in mixed stands of Douglas-fir and red alder. For. Ecol. Manage. 9, 81–85.

Cochran, P.H., Geist, J.M., Clemens, D.L., Clausnitzer, R.R., Powell, D.C., 1994. Suggested stocking levels for forest stands in northeastern Oregon and Southeastern Washington. U.S. Dept of Agr. For Ser., Pacific Northwest Research Station, Portland, OR (PNW-RN-513).

Curtis, R.O., 1970. Stand density measures: an interpretation. For. Sci. 16, 403–414.

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

Dean, T.J., Long, J.N., 1992. Influence of leaf area and canopy structure on size-density relations in even-aged lodgepole pine stands. For. Ecol. Manage. 49, 109–117.

Ducey, M.J., Larson, B.C., 2003. Is there a correct stand density index? An alternate interpretation. West. J. Appl. For. 18, 179–184.

Drew, T.J., Flewelling, J.W., 1979. Stand density management: an alternative approach and its application to Douglas-fir plantations. For. Sci. 25, 518–532.

Fiedler, C.E., Keegan, C.E., Woodall, C.W., Morgan, T.A, 2004. A Strategic Assessment Of Crown Fire Hazard in Montana: Potential Effectiveness and Costs of Hazard Reduction Treatments. Gen. Tech. Rep. 622, U.S. Dept. of Agr. For. Serv., Pacific Northwest Research Station, Portland, OR.

Fiedler, C.E., Cully, J.E., 1995. A silvicultural approach to develop Mexican spotted owl habitat in Southwest forests. West. J. Appl. For. 10, 144–148.

Gingrich, S.F., 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in central states. For. Sci. 13, 39–53.

Krajicek, J.E., Brinkman, K.A., Gingrich, S.F., 1961. Crown competition—a measure of density. For. Sci. 7, 35–42.

Larson, P.R., 1963. Stem form development of forest trees. For. Sci. Monogr. 5, 42.

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

Long, J.N., 1995. Using Stand Density Index to regulate stocking in uneven-aged stands. In: O'Hara, K. (Ed), Uneven-Aged Management—Opportunities, Constraints, and Methodologies, vol. 56. Montana Forest and Conservation Experiment Station, pp. 110–122, Misc. Pub.

Long, J.N., 1996. A technique for the control of stocking in two-storied stands. West. J. Appl. For. 11 (2), 59–61.

Long, J.N., Daniel, T.W., 1990. Assessment of growing stock in uneven-aged stands. West. J. Appl. For. 5, 93–96.

Long, J.N., Smith, F.W., 1984. Relation between size and density in developing stands: a description and possible mechanism. For. Ecol. Manage. 7, 191–206.

Mar:Moller, C., 1947. The effects of thinning, age, site on foliage, increment, and loss of dry matter. J. For. 393–404.

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

Panshin, A.J., de Zeeuw, C., 1970. Textbook of Wood Technology, 1. McGraw-Hill, New York, 705pp.

Puettman, K.J., Hann, D.W., Hibbs, D.E., 1993. Evaluation of the size-density relationships for pure red alder and Douglas-fir stands. For. Sci. 39, 7–27.

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

Shaw, J.D., 2000. Application of stand density index to irregularly structured stands. West. J. Appl. For. 15, 40–42.

Smith, W.B., Miles, P.D., Vissage, J.S., Pugh, S.A., 2004. Forest Resources of the United States, 2002. Gen. Tech. Rep. NC-241, U.S. Dept. of Agr., For. Serv., North Central Res. Station, St. Paul, MN.

Stage, A.R., 1968. A tree-by-tree measure of site utilization for grand fir related to Stand Density Index. U.S. Dept. of Agr., For. Serv., Intermountain Forest and Range Experiment Station, Res. Note 77, Ogden, UT.

Steele, R., 1988. Ecological relationships of ponderosa pine. In: Baumgartner, D.M., Lotan, J.E. (Eds.), Ponderosa Pine: the Species and its Management. Sym. Proc., pp. 71–76.

Sterba, H., Monserud, R.A., 1993. The maximum density concept applied to uneven-aged mixed-species stands. For. Sci. 39, 432–452.

Stout, S.L., Nyland, R.D., 1986. Role of species composition in relative density measurement in Allegeny hardwoods. An. J. For. Res. 16, 574–579.

Sturtevant, B.R., Bissonette, J.A., Long, J.N., 1998. Stand density management diagram for mixed balsam fir—black spruce stands. North J. Appl. For. 15, 17–22.

Torres-Rojo, J.M., Martinez, A., 2000. Relative stand density index for mixed even-aged stands. Agrociencia 4, 497–507.

U.S. Department of Agriculture, 1999. Wood Handbook—Wood as an Engineering Material. Gen. Tech. Rep. 113, U.S. Dept. of Agr., Forest Products Laboratory Madison, WI.

U.S. Department of Agriculture, 2005. A Strategic Assessment of Forest Biomass and Fuel Reduction Treatments in Western States. Gen. Tech. Rep. RMRS-GTR-149, U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 17 pp.

Vissage, J.S., Miles, P.D., 2003. Fuel-reduction treatment: a west-wide assessment of opportunities. J. For. 101 (2), 5–6.

Waring, R.H., Schlesinger, W.H., 1985. Forest Ecosystems: Concepts and Management. Academic Press, New York, NY, 340 pp.

Westoby, M., 1984. The self-thinning rule. Adv. Ecol. Res. 14, 167–225.

White, J., 1981. The allometric interpretation of the self-thinning rule. J. Theor. Biol. 89, 475–500.

White, J., 1985. The Self-Thinning Rule and its Application to Mixtures of Plant Population Studies of Demography. Academic Press, London.

Williams, R.A., 2003. Use of stand density index as an alternative to stocking percent in upland hardwoods. North. J. Appl. For. 20, 137–142.

Wilson, D.S., Seymour, R.S., Maguire, D.A., 1999. Density management diagram for northeastern red spruce and balsam fir forests. North. J. Appl. For. 16, 48–56.

Woodall, C.W., Fiedler, C.E., Milner, K.S., 2003. Stand density index in uneven-aged ponderosa pine stands. Can. J. For. Res. 33, 96–100.

Woodall, C.W., Fiedler, C.E., 2005. Simulating silvicultural prescriptions using forest inventory and analysis data. In: McRoberts, R.E. (Eds.), 2002 FIA Science Symposium Proceedings. Gen. Tech. Rep. 252, U.S. Dept. Agr., For. Serv., North Central Research Station, St. Paul, MN, pp. 203–207.