CALIFORNIA FIRE SCIENCE CONSORTIUM

## *Research Brief for Resource Managers*


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# Using Stand Density Index (SDI) as a stocking guide in frequent fire forests


*Chivhenge, E., D.G. Ray, A.R. Weiskittel, C.W. Woodall, and A.W. D'Amato. 2024. Evaluating the development and application of stand density index for the management of complex and adaptive forests. Current Forestry Reports 10: 133-152 https://link.springer.com/article/10.1007/s40725-024-00212-w*


Quantification of competition levels in forest stands benefits assessments of stand health, vulnerability to stressors, and prediction of future stand dynamics. Because different forests have different carrying capacities that can be maintained given differences in site productivities, it is important to consider stocking in terms that are relative to these maximum levels. Stand Density Index (SDI) is a common metric of competition in temperate forests of Western North America, originating in 1933 and gaining widespread use within the field of forestry throughout the 20th century. SDI has notably been used in Density Management Diagrams (DMDs) for prediction of stand dynamics over time and plays a similar role as a key component of growth models. Recently, researchers working in frequent-fire forests have used Relative Density (RD), a direct estimate of competition derived from SDI, to demonstrate the low levels of competition that frequent fires maintained before fire suppression and have proposed its utility in treatments focused on resilience as a primary objective.

### Management Implications

- SDI is a robust and simple metric for estimating and comparing competition among forest stands that can inform treatments designed to restore fire-maintained structures.
- National- and regional-scale inventory datasets and robust statistical techniques such as hierarchical Bayesian modeling can increase accuracy and precision in $SDI_{MAX}$, which is estimated in order to calculate SDI for interpretation.
- A general understanding of SDI will help practitioners when interpreting reports and publications that use large datasets.
- With their own basic field measurements of stocking before and after treatments such as prescribed fire, practitioners can use SDI to interpret the impact of treatments on inter-tree competition and concepts of stand resilience.

This study is timely for those practitioners interested in using SDI directly or for those who want to interpret the applications of studies to their work. The authors synthesized the large body of published literature on SDI since its introduction in 1933. First, they provide a brief overview of key historical developments in the SDI concept, then evaluate statistical methods and necessary data for estimating the maximum size-density relationship, a key value used to calculate RD from SDI. Finally, the authors discuss the application of RD in forest management as a measure of competition. Overall, the authors find SDI and its extension as RD to be robust and useful in both science and forest management.

**SDI Overview and History**

SDI as originally introduced by Reineke in 1933 is a formula (Equation 1) that utilizes two easily-obtained metrics (measured from either fixed- or variable radius plots) to produce an estimate of competition at the stand level: the number of trees per unit area of the stand (N), and the quadratic mean diameter of the stand (QMD). The units of SDI are the N of a stand experiencing the same level of competition as the stand for which SDI is calculated, where this equivalent stand has QMD of 10 inches. For example, an even-aged stand with 150 trees per acre and 30 inch QMD would have an SDI of 875, indicating a high level of competition analogous to a stand with 10 inch QMD containing 875 trees per acre.

SDI was originally intended only for use in even-aged, single-species stands to compare levels of competition between stands of the same species, which limited its application in forest management. A key development in the history of SDI was the development of additive SDI (ASDI, Equation 2) in the 1960s and 1990s, which utilizes information about the individual trees in a stand to produce an SDI value that more accurately characterizes competition in stands with complex structures than is possible with the traditional SDI formula (Figure 1). This created opportunities to utilize SDI in frequent-fire forests, which often have complex and multiaged structures.

However, the relation of absolute competitive pressure (measured by SDI) to physiological stress and long-term outcomes is influenced by a variety of factors, including species and species mixing, site conditions, and environmental conditions. A second key development in the history of SDI was the Relative Density concept (RD, Equation 3) of the late 1970s, in which the SDI of a given stand is related to a theoretical maximum value of SDI ($SDI_{MAX}$), generating a value between no competition (0) and maximum competition (1). $SDI_{MAX}$ is the maximum N of stems of a given QMD, typically benchmarked like SDI to 10 inches, that can exist in a self-thinning environment, i.e. maximum density. Traditionally, $SDI_{MAX}$ was assumed to vary with species identity and be invariant to site conditions and environmental conditions, allowing values of RD to have equivalent meaning in stands across a range of species composition, site conditions, and environmental conditions. This also allows for generation of unique $SDI_{MAX}$ values in mixed-species stands by calculating a weighted average of the component species' $SDI_{MAX}$ values, thereby extending SDI from single-species to mixed-species stands. RD is generally utilized by categorization into four classes between 0 and 1, with each class corresponding to a stage of stand development characterized by well-understood processes and known outcomes in the next stage. While the values that delineate classes can differ, some authors characterize stands with RD <0.25 as open-grown and free from competition, with values >0.25 indicating some competition; similarly, some authors take RD of 0.35 to mark the onset of full site occupancy, with RD of 0.60 marking the onset of self-thinning (imminent density-dependent mortality), and the maximum physiologically possible density reached at an RD of 1.

Newer research summarized in this study shows that the $SDI_{MAX}$ achievable by a species varies with site and environmental conditions (Figure 3). Since RD is largely determined by the chosen value of $SDI_{MAX}$, accurate characterization of $SDI_{MAX}$ is necessary for RD values to have consistent meaning. In other words, RD as a metric of competition can be improved if $SDI_{MAX}$ can be calculated with data and models that more accurately take into account species composition and local environments, as described below.

**Determination of Self-Thinning Line**

Original development of SDI and innovations such as $SDI_{MAX}$ were focused around scatterplots of observed stand data with log(N) plotted against log(QMD), with each data point representing a single field plot or sampled stand. Often, such graphs seem to show the area of data being bounded by a negative linear upper boundary; this has been called the "self-thinning boundary", as stands near this line typically experience high density-dependent mortality where N decreases as QMD increases. $SDI_{MAX}$ is derived from this line; conceptually, the line represents maximum density, and RD shows how close a given stand is to the line. While quantification of the line's exact slope and intercept have been topics of debate, the traditional slope of -1.605 has been found to be very close to alternative slopes. This study summarizes how estimates of the self-thinning line's slope and intercept are affected by both the data utilized and statistical method chosen and details the advantages and disadvantages of the numerous methods found in the literature. This study concludes that large datasets, such as national or regional-scale inventories, especially those with repeated measurements over time, and statistical techniques such as hierarchical Bayesian estimation and linear quantile mixed modeling show promise for robust and informative estimation of the self-thinning line and consequently $SDI_{MAX}$ across a variety of species, sites, and environmental conditions.

**Application of Relative Density & Future Research Needs**

The study summarizes the wide variety of applications for RD, from a long history of use in silviculture as a component of Density Management Diagrams (DMDs) to potential use in carbon accounting by forecasting mortality and subsequent deadwood dynamics. However, while RD can be applied quite usefully to a variety of problems, knowledge gaps remain and hinder increased accuracy. Primarily, improvements in accuracy will come from $SDI_{MAX}$ values that are generated from regional- or national-scale datasets with robust statistical techniques that incorporate species, site, and environmental information. This will allow for RD estimates to be most precisely tailored to the conditions in which a given stand is growing, and to therefore be optimally comparable across varied conditions. Secondarily, relation of accurately characterized RD levels to growth and mortality dynamics, using similarly large datasets or remote sensing products, can improve the predictive ability of RD measurements, and allow for precise RD values to be utilized rather than fewer large classes. Finally, forest management tools such as DMDs and stocking charts often utilize estimates of SDI derived from data with small samples sizes collected in the 20th century, and accuracy could be increased by updating these estimates with large-scale data from contemporary stands experiencing modern environmental conditions.

SDI is an evolving tool underpinned with basic ecological relationships. It will likely continue to be a valuable tool for both timber and non-timber objectives. This value should improve and be broadly useful when applied to frequent fire forest, especially as its accuracy improves with the incorporation of emerging datasets and statistical methods.

**Equations:**

(Eq. 1) $SDI = N * (\frac{QMD}{10})^{1.605}$, where N = trees acre$^{-1}$ and QMD = quadratic mean diameter (inches) of the sampled area

(Eq. 2) $ASDI = \sum_i^N N_i * (\frac{DBH_i}{10})^{1.605}$, where N = number of trees sampled, $N_i$ = trees acre$^{-1}$ represented by the $i^{th}$ tree, and $DBH_i$ = DBH of the $i^{th}$ tree (inches)

(Eq. 3) $RD = \frac{SDI}{SDI_{MAX}}$, where SDI = SDI or ASDI of the area for which RD is calculated, and $SDI_{MAX}$ is matched to the species composition and possibly also the site and environmental conditions of the area

## Figures:

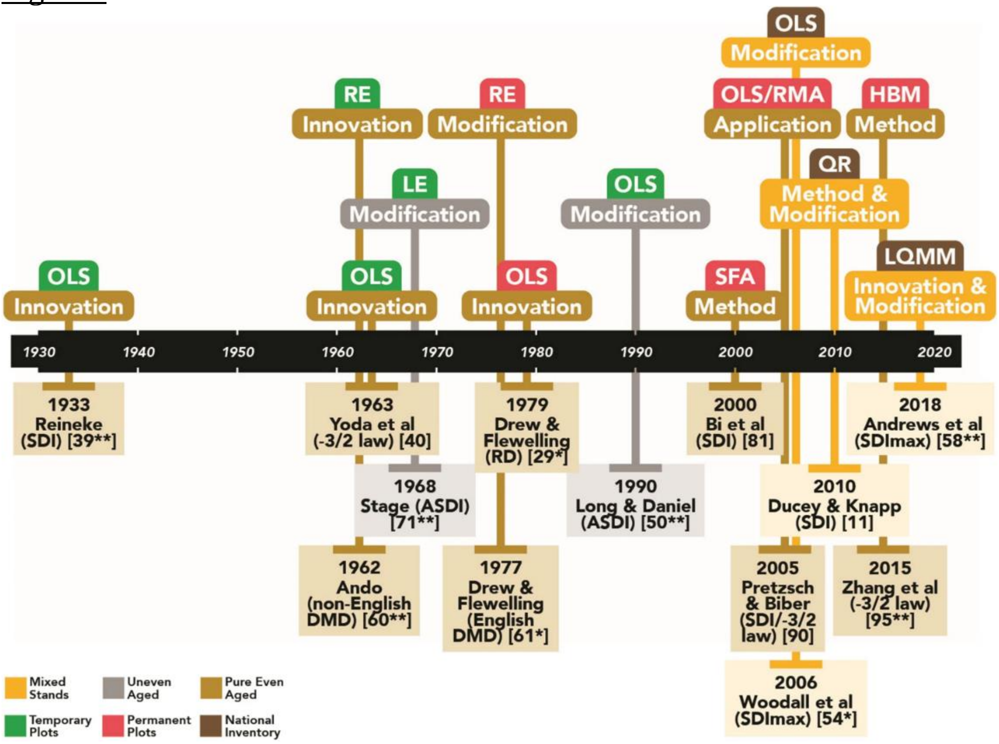


Figure 1. The development, modification, and application of Reineke's stand density index (SDI) through time with the specific statistical methods and type of forest stands examined. Authors who applied and modified SDI have been cited. Key abbreviations are OLS, ordinary least squares; RE, reciprocal equations; LE, linear equations; RMA, reduced major axis; QR, quantile regression; DMD, density management diagram; LQMM, linear quantile mixed models; SFA, stochastic frontier analysis; SDI, stand density index; ASDI, additive stand density index; RD, relative density; $SDI_{MAX}$, maximum stand density index

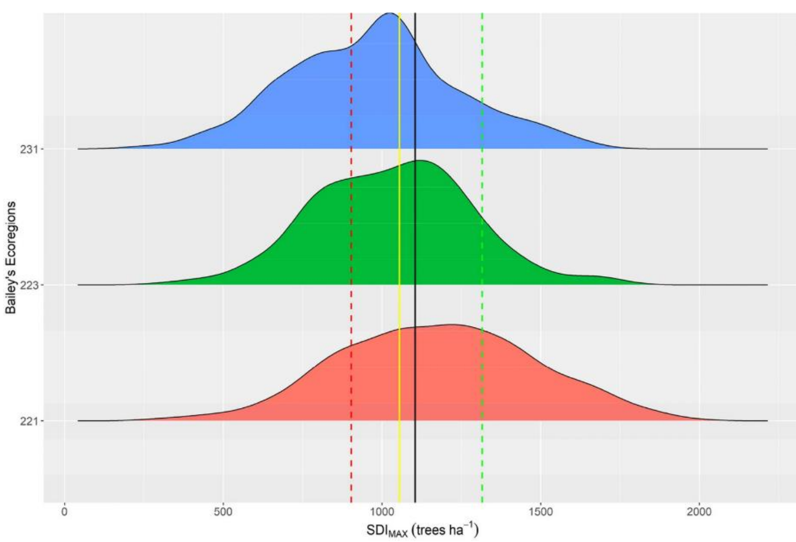


Figure 3. Comparison of the distributions of $SDI_{MAX}$ estimates for white oak (*Quercus alba* L.) / red oak (*Quercus rubra* L.) / hickory (*Carya* spp.) forest type across Bailey ecoregions of 221 (Eastern Broadleaf Forest, Oceanic), 223 (Eastern Broadleaf Forest, Continental), and 231 (Southeastern Mixed Forest) generated using US Forest Service, Forest Inventory & Analysis (FIA) data. The red dotted line shows the 25th percentile ($N$ = 903), solid black shows the median value ($N$ = 1,104), and the dotted green line shows the 75th percentile ($N$ = 1,316) of $SDI_{MAX}$ estimates for a subset of the white oak/red oak/hickory forest type across Bailey ecoregions. The solid yellow line shows the overall median value $N$ = 1,055 for white oak / red oak / hickory forest type from the whole FIA dataset.