

# THE DENSEST LOBLOLLY PINE STAND AND ITS SILVICULTURAL IMPLICATIONS

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**Abstract**—Estimation of stand density index has been based on the assumption that the only cause of mortality in fully stocked stands is diameter growth. For example, when average diameter increases by 1 percent, a fixed proportion (1.6 percent) of trees must die, regardless of age, average tree size, and other factors. This balance between growth and mortality entails the maximum limit of density index; for loblolly pine it is 1,140. We found a 10-year-old loblolly pine stand with density that is up to 59 percent greater than the maximum. The decisive factor of this exceptional density is the abundance of seeds shed by a row of mature pines. This finding requires reconsidering our understanding of stand dynamics. It is likely that, in addition to diameter growth, some internal factors contribute to mortality of trees. The proportion of mortality is not fixed but may change with age. Besides theoretical implications, further analysis of the reported finding can produce better methods of density estimation.

## INTRODUCTION

Growth and yield of forest stands depend on climate, site quality, tree species, age, competition control, stand density, rotation age, and other factors. There are two reasons why stand density occupies a special place among these factors. First, it is one of the most influential variables for predicting tree form, growth, and survival. In dense stands mature trees can be twice as tall but a third as thick as their open-grown conspecifics of the same age. Second, unlike climate and site quality, density can be controlled easily and often profitably. Therefore, control of density has been a major tool of forestry from its beginning.

## MEASURING STAND DENSITY

To control density we need to know how to measure it. We still do not have a reasonable and widely accepted definition of density. The proximity of trees and branches, their size and arrangement, distribution of foliage, form and depth of roots—all these and many other factors bear on stand density. Usually, density is characterized by fittingly vague adjectives such as “dense” or “understocked.”

Unlike ecologists who use number of organisms per unit area as measure of density, foresters have intuited the idea that, in addition to the number, stand density depends on tree size. Reineke's (1933) stand density index, the most reasonable, though not most common measure of density, uses both tree size and their number. It is based on the reciprocal relationship between average diameter,  $D$ , and number of trees per unit area,  $N_n$ , in fully stocked (normal) stands:

$$N_n = kD^{-r} \quad (1)$$

where  $k$  and  $r$  are parameters. Reineke believed that parameter  $r = 1.605$  is constant for all species and locations. This equation says that a certain increase in average diameter,  $dD/D$ , eliminates a fixed proportion of trees equal to  $r dD/D$ .

Reineke realized that the relationship between number of trees and diameter in fully stocked even-aged stands can be used as a standard for estimating density in stands of any degree of stocking. In the stand density index,  $SDI$ , that he proposed:

$$SDI = N \left( \frac{D}{25} \right)^r \quad (2)$$

the number of trees,  $N$ , needs not to be normal, as indicated by the absence of the subscript  $n$ , but parameter  $r$  must be found in normal stands. Stand density index has a clear meaning: it is the number of trees per unit area with a specified diameter of 25 cm in metric and slightly larger in English units (10 inches = 25.4 cm).

Faults of other measures of density are either poor choice of opposites or their inappropriate combination. The most popular measure of stand density, basal area of trees per unit area, has the same components as Reineke's index (number of trees and stem diameter). The difference is in the power of diameter: it is 2 for basal area and 1.6 for the index. As a result of this difference, basal area varies in equally dense stands. Thus, according to a well known density guide (Gingrich 1967) adopted as the U.S. Forest Service standard for stocking guides, when average diameter is 10 cm, a stand is fully stocked if its basal area reaches 11 m<sup>2</sup>/ha. However, for a stand with diameter 40 cm, basal area should be 60 percent greater than 11 m<sup>2</sup>/ha to qualify for the same full stocking. And conversely, the same basal area can be found in stands differing in stocking. Gingrich's guide considers a stand with a basal area of 17 m<sup>2</sup>/ha understocked when the average diameter is greater than 38 cm. When the diameter is less than 8 cm, the stand with the same basal area is classified as overstocked. For the intermediate diameters, it is fully stocked.

## Maximum Level of Density

The balance between growth and mortality in fully-stocked stands suggests the existence of maximum stand density index common to all stands of a given species, regardless of

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site quality, age, and tree size. Site quality or planting density may affect the time of reaching the maximum but not its value. Due to local disturbances caused by mortality of single trees, even in densest stands actual indices are always below the maximum. To establish a perfect maximum, Reineke (1933) drew a line above the cloud of points representing average diameters and numbers of trees in the fully stocked stands. The maximum he reported for loblolly pine was 450 in English units. In metric units, we use 25 cm instead of 25.4 (= 10 inches) as the basis. Since Reineke (1933) did not provide any justification for his highly precise value of  $r$  (= 1.605), it is commonly rounded to 1.6 (contrary to Reineke's belief, this value varies with the shade tolerance of a species). With these modifications in metric units the maximum per hectare is 1140 (=  $450 \times 2.471 \times (25.4/25)^{1.6}$ ). This density is about 60 percent greater than average (normal) density of 700 for his plots.

### PERFECTING REINEKE'S INDEX

Reineke's index is the best available measure of stand density because, unlike basal area, it does not confuse understocked stands with overstocked ones. Still, many researchers reported that number of trees drops faster than the power function of diameter (Zeide 2005). For this reason, Meyer (1938) used a curved-down (on the log-log scale) line to relate number and diameter of dense stands. Also it was found that  $r$  changes with age, being smaller in younger stands. In young (average age of 20 years) loblolly pine stands, Williams (1994) found  $r = 1.5$ . In older stands (from 19 to 77 years) of the same species in the same region (northern Louisiana), Meyer (1942) came up with the value of 1.9. These discrepancies suggest that, along with tree size, there are other nonrandom factors of tree mortality.

#### Internal Factors of Tree Mortality

Reineke's equation is built on the assumption that trees die as a result of single physical process: the increase in size of neighboring trees. The equation disregards internal physiological and morphological processes such as diminishing tolerance to shading, senescence, and impediments associated with increasing tree size. We know that younger trees generally tolerate deeper shade than older ones and that in mature stands age gap area becomes more pronounced. Since seed production increases with age and tree size, it is of selective advantage for older trees not to choke their progeny, but to loosen the canopy and let light in for advance regeneration. This knowledge should help us to design a better size-number relationship and improve density estimates.

Aging, diminishing tolerance, and other internal factors work in the same direction of continuously reducing tree vigor. Since stand density index denotes number of trees with diameter 25 cm, if they exist, internal factors would make the maximum (1,140) smaller in older stands with diameter greater than 25 cm, and larger than 1,140 in younger stands. These manifestations of internal factors can be tested experimentally.

#### Gap Accumulation in Older Stands

To account for aging, it was proposed to add to Reineke's equation a module describing diminishing canopy cover

(Zeide 2005). Observations that the number of trees falls faster than the power function suggest the exponential form of the module. Because diminishing cover is associated with increasing age and tree size, either of these variables could be used to derive the module of canopy cover. The augmented relationship between number of trees,  $N_n$ , and average diameter in fully stocked stands can be written as:

$$N_n = a \left( \frac{D}{25} \right)^{-b} e^{-\frac{25-D}{c}} \quad (3)$$

where  $a$  is normal stand density,  $b$  is the rate of tree mortality caused by the increase in crown size, and  $c$  is the parameter of mortality due to diminishing canopy cover. The resulting model accounts for the two factors of tree survival (or mortality): increase of tree size and accumulation of gaps particularly evident in older stands. This equation does not impose canopy gaps. If canopy cover is complete,  $c$  would tend to infinity and the equation would be reduced to Reineke's.

Equation 3 uncovers two components that are conflated in Reineke's equation. First is the effect of physical expansion of tree crown; its rate is  $b < r$ . The second component of tree mortality is caused by internal factors; it is described by the exponential module. For medium values of diameter, the combination of both components can be approximated by a power function with parameter  $r$ . The difference between Reineke's equation and equation 3 becomes more pronounced at the edges of diameter-number relationship.

#### Tenacity of Young Trees

According to Reineke's equation, when diameter increases by factor  $p > 1$ , the fixed  $(1 - p^{-r})$  proportion of trees must die, regardless of age, tree size, and other factors. This assumption does not agree with observations that younger trees can tolerate deeper shade. They are more tenacious than older ones. Since this age-related persistence is not accounted by Reineke's equation, we may expect deviations from the maximum density he reported. The action of internal factors can be manifested not only in a lower maximum in older stands but also in a greater maximum in young stands when initial number of trees is sufficiently high. This conclusion offers a simple way to confirm (or reject) the hypothesis that the proportion of trees dying in response to the same increase in diameter increases with age and tree size. If the hypothesis is correct, it should be possible to find young stands with a higher density index than Reineke's maximum of 1,140.

The hypothesis that initial number of trees may affect stand density index is not new. It was tested and rejected by Shouzheng and others (1995). They found that maximum density index is not significantly influenced by initial stand densities. On the other hand, VanderSchaaf (2006) showed that maximum density index depends on the time when trees close their canopies and competition begins. The index is higher for stands with larger initial number of trees because they start competing earlier.

## DOCUMENTING THE HIGHEST STAND DENSITY INDEX

The arguments presented above suggest that the younger the stand, the higher the maximum of density should be. The highest maximum is the earliest one. The maximum is limited by initial number of trees and seed supply because these limitations postpone the age and the level of the maximum. An ideal method to document the highest maximum is to grow seedlings in a nursery until density index culminates. The next best and quicker option is to locate young stands with plentiful regeneration.

### Stand Description

A tract of land, half a kilometer north of the Arkansas University School of Forestry, was clearcut in 1996 and planted 2.4 by 2.4 m (8 by 8 feet) with 1-year-old loblolly pine in February 1997. The ground was not prepared well and ten years later, about half of planted pines survived, interspersed with much hardwood ingrowth. The situation differed on the eastern side of the tract where a single row of mature pines, growing 10 to 15 m apart, bounds the stand. The pines are 30 to 60 cm in diameter and were not cut because they belong to a different owner. These pines heavily seeded the plantation where the soil was scarified by cutting and planting.

By 2006, the portion of the plantation adjacent to the row of pines was exceptionally dense. This strip, 15 to 25 m wide and 400 m long, starts at the edge of the crown projections of seed pines. It was composed of planted 10-year-old (from seed) trees and numerous pine volunteers with a few tiny hardwoods (< 1 percent by basal area). While the diameter of planted trees was 9 to 12 cm, the diameter of 9 year old volunteers was 6 to 8 cm; 8 year olds were still smaller. Dead trees were 3- to 5-years-old and mostly smaller than 3 cm in diameter. The average age of live pines, including planted and natural regeneration, was 9 years.

Besides the combination of soil scarification and abundant seed source, there is nothing unusual about the stand. It is situated in the midst of the loblolly pine region, on flat ground, and has a typical site index of 65 (base age 25 years). Soil analysis (pH, nitrogen, phosphorus, potassium, and carbon) did not reveal any irregularities.

### Density Profile

To document the extent of the dense strip, five point sampling transects were run with a BAF 4 (metric) prism starting from seed trees. Each transect was 100 m long and ran directly

west perpendicular to the strip around the areas where the plots were established. Basal area was estimated every 10 m. Also the distance to the end of crown projection and distance to the end of dense regeneration were noted.

These measurements showed that the average distance from the seed trees to the end of crown projection (half of crown width) was 5.6 m; the distance to the end of dense regeneration was 24.5 m. Average results of five point sampling transects demonstrate that at the beginning, under the canopy of the seed trees, basal area is approximately 25 m<sup>2</sup>/ha (fig. 1). By 10 m the basal area has increased to 37 m<sup>2</sup>/ha and at 20 m is nearly 40 m<sup>2</sup>/ha on average. At 30 m basal area drops back to 25 m<sup>2</sup>/ha. By this point, the area of dense regeneration has ended. At greater distances, basal area stays at about 20 to 25 m<sup>2</sup>/ha.

### Plot Measurements

On the dense strip, eight square plots were established and measured in January-February of 2006 and another one in January of 2007 when the original plots were remeasured. The area of each plot is 25 m<sup>2</sup>. Since we are interested in maximum and not average values, the plots are located in the middle of the dense strip with buffer zones, 4 to 6 m wide, of approximately equal density on both sides. Plots 1 through 5 are contiguous and oriented on a north/south bearing. Plots 3.1 and 3.2 are contiguous, perpendicular to, and directly to the west of plot 3. Plots 6 and 6.1 are located 70 m south from plots 1 through 5 and oriented directly to the north and south. In addition to diameter at breast height of all trees, total tree height, height to live crown, and crown width (at two perpendicular directions) were measured on a sample including all tree sizes. The position of each tree on the densest plot 1 was mapped.

## RESULTS

The results of plot measurements show that, given sufficient regeneration, Reineke's maximum can be exceeded by as much as 59 percent (table 1). We have not seen references

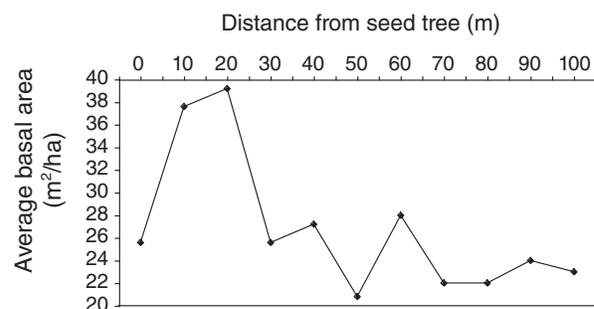


Figure 1—Average basal areas of five transects at 10 m intervals from seed trees.

**Table 1—Characteristics of loblolly pine plots measured in 2006 and 2007**

PN	Age	D	N	BA	SDI	Ratio
1	9	4.89	24400	45.82	1792.8	1.57
	10	5.37	21200	48.04	1810.6	1.59
2	9	4.82	22000	40.12	1579.1	1.39
	10	5.13	20400	42.17	1618.5	1.42
3	9	5	22000	43.2	1675.4	1.47
	10	5.31	20800	45.98	1741.4	1.53
3.1	9	6.23	12400	37.78	1341.9	1.18
	10	6.6	11600	39.66	1376.5	1.21
3.2	9	6.18	13600	40.84	1454.8	1.28
	10	6.73	12400	44.14	1519.7	1.33
4	9	5.13	15200	31.4	1205.4	1.06
	10	5.47	15200	35.68	1335.2	1.17
5	9	6.34	12400	39.09	1379	1.21
	10	6.81	12400	45.12	1546.8	1.36
6	9	4.74	22400	39.55	1566.6	1.37
	10	5.28	21600	47.33	1795.6	1.58
6.1	10	5.4	18000	41.28	1552	1.36

PN=plot number; Age=age in years; D=quadratic mean diameter in cm; N=number of trees per hectare; BA=basal area in m<sup>2</sup>/ha; SDI=stand density index; Ratio is ratio of SDI and Reineke's maximum of 1,140.

to so high a stand density index in literature. Out of 4 885 FIA plots, 12 have indices higher than Reineke's maximum with the highest being 1,384. Since the index has increased on all the plots from 9 to 10 years, it has not yet reached the highest value.

## DISCUSSION

The importance of stand density to forest management justifies continuing search for deeper understanding of density and better methods for its estimation. The finding of a stand with a substantially higher density index than the maximum established by Reineke (1933) suggests insufficiency of his equation. This finding indicates that some factors, other than physical expansion of tree sizes, are involved in the process of tree mortality. The reported discovery calls for a revision of existing methods for density estimation.

Most likely, these hypothetical factors are the internal physiological and morphological processes that detract from vitality as trees get older. Among these processes is diminishing tolerance to shading, and increasing tree size, which slow the growth by diverting resources to supporting structures and respiration. These factors contribute to tree mortality as is evident from the area of gaps, which becomes more pronounced with age.

The presented arguments suggest that the younger stand, the higher the maximum density. The highest maximum is the earliest one. The maximum is limited by initial number of trees and seed supply because these limitations postpone the age and the level of the maximum. These considerations provide suggestions for a model describing tree mortality. The model should use both external and internal factors for describing change in number of trees. In agreement with evidence, the predicted slope in the middle range of

diameters should be around -1.6 as in Reineke's equation. Unlike this equation, this slope would be a combination of two or more processes. The model should predict maxima higher than Reineke's for younger stands and lower maxima for older stands.

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