

Maximum Stand Densities for Ponderosa Pine and Red and White Fir in Northern California

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Introduction

Why are forest managers interested in quantifying maximum stand density? Nearly all conceivable management objectives dictate a stand density less than a biological maximum. Certainly, the notion that thinning dense stands increases growth on the remaining trees and reduces mortality is well-established in the literature. The interest in quantifying maximum stand density arises from the need to estimate mortality in growth and yield projection systems. Mortality estimates are the weakest link in all of these systems because it is extremely difficult to predict. Mortality tends to be episodic and often even catastrophic, especially if it is caused by external forces such as bark beetles, root disease, or wind. Mortality arising from intertree competition, on the other hand, tends to be much more uniform and constant. Fortunately, a method is available to predict this non-episodic and non-catastrophic mortality arising from intertree competition. This method has been variously termed the $-3/2$ Power Rule or the Self-Thinning Rule.

The Self-Thinning Rule and Stand Density Index

The Self-Thinning Rule was proposed some 30 years ago by Japanese scientists as a universal size-density relationship (Yoda et al. 1963). Very simply, it proposes that all environments with finite resources whether that be a goldfish pond or an acre of ground can support a finite amount of living biomass. Therefore, as individuals grow in size the number of individuals decline--an intuitive relationship. However, what is less intuitive is the proposal that this rate of decline is the same for all organisms, again, whether they be goldfish in a pond or trees in a stand. The universal exponent describing this rate of decline is a negative $3/2$ or -1.667 . Only the elevation of the line, not the slope, is organism dependent.

Interestingly, Reineke (1933) some 60 years ago introduced this rule for forest stands, naming it Stand Density Index (SDI). Stand Density Index is calculated as

$$SDI = 10^{(\log N + 1.605 \cdot \log D - 1.605)}$$

in which

log = logarithm to the base 10

N = number of trees per acre

D = average stand diameter at breast height in inches

Reineke gave a slope for the maximum stand density line of -1.605 which he proposed as universal for all tree species. A slope of -1.77 , however, has been found to be a better fit for ponderosa pine data sets both in California (Oliver and Powers 1978) and in central Oregon and Washington (DeMars and Barrett 1987). Slope differences, assuming they are real, don't necessarily negate the Self-Thinning Rule. Instead, differences may be because:

- a) In forestry average stand diameter is used as a surrogate for total biomass (Obviously, total above- and below-ground biomass, including fine feeding roots, of a stand of trees would be nearly impossible to obtain); and,
- b) Data are usually fitted to less than the full range of sizes. Such may be the case with the ponderosa pine data sets which were focused on young-growth stands.

The acceptance of the Self-Thinning Rule has breathed new life into Stand Density Index. It's commonly used now to control mortality in growth and yield projection systems and by managers to measure stand density in the field. Although difficult to measure in the field, SDI has a distinct advantage over basal area as a measure of stand density because it is not significantly affected by age and site quality. Unfortunately, no direct conversion from SDI to basal area per acre is possible because many combinations of mean stand diameter and number of trees per acre will produce identical SDIs but different basal areas per acre.

A Limiting Stand Density for Ponderosa Pine

Interest in maximum SDI has centered on ponderosa pine here in the West because of its susceptibility to attack and killing by *Dendroctonus* bark beetles. Managers have become acutely aware of the influence of bark beetles in limiting stand density of ponderosa pine because of the recent drought and the rapid build up of stand density common in even-aged stands, especially in plantations. Eaton (1941) was probably the first to recognize the importance of thinning in "bug proofing" ponderosa pine stands. Unfortunately, fire destroyed his research plots in the Warner Mountains of northeastern California before results were achieved. Thirty years later a threshold value of 150 ft² per acre of basal area was established above which stands east of the Cascades in Oregon and Washington became susceptible to bark beetle attack (Sartwell 1971, Sartwell and Stevens 1975, Sartwell and Dolph 1976). This value has since become well accepted in practice there, as well as in California.

In California, and especially on the productive sites on the westslope of the Sierra Nevada and Cascade Range, bark beetle-stand density relationships are less well-known. Clements (1953) was the first to recognize the relationship between stand density and mountain pine beetle (*Dendroctonus ponderosae* Hopkins) mortality. Most entomological investigations, however, have been concerned with the western pine beetle (*D. brevicomis* LeConte) in large, mature trees, because of their high economic and aesthetic value. The influence of stand density on bark beetle mortality of young, even-aged stands of ponderosa pine on the westside is less well-known. Information that does exist is anecdotal because no formal studies have been undertaken.

Sartwell's work suggests that bark beetles are ubiquitous regulators of stand density in young, even-aged stands of ponderosa pine. If this is true, does the Self-Thinning Rule apply? Can a bark-beetle-limiting SDI be defined? Also, a question remains as to whether Sartwell's threshold value of 150 ft² per acre of basal area applies to California and especially to the productive westside sites.

Over the years I have assembled and maintained a large number of long-term growth and yield plots. Forty-three plots are in ponderosa pine stands, both in plantations and in natural stands, which defined 234 size-density trajectories. Twenty-three percent of these plots suffered bark beetle mortality. A size-density relationship is demonstrated with a bark-beetle-limiting SDI of 365 (fig. 1A). This value is considerably below the SDI of 485 used in Region 5 for the Forest Vegetation Simulator (FVS) which is actually 85 percent of the maximum SDI of 571 (Dixon 1992, 1994).

It could be argued that a SDI of 365 is the result of increased bark beetle activity during the recent drought. Though this is reasonable, it is refuted by the fact that SDI 365 is identical to the SDI value derived from a least squares fit of the natural stand data used to construct Meyer's (1938) normal yield tables.

My contention that bark beetles and ponderosa pine stand development are inexorably linked seems to be supported by the Meyer's basal area-age relationship. Basal area of most other species rises continuously, albeit progressively more slowly, throughout the range of ages presented. In contrast, Meyer shows basal area building up rapidly and then plateauing sharply at age 60 which is about the age when maximum stand density is reached. This is the age at which Sartwell claims mountain pine beetle outbreaks begin. Actual stand data would, of course, trace a sawtooth pattern after age 60 as episodes of beetle kills reduce the basal area and growth of surviving trees subsequently builds back the basal area.

Stands that approach SDI 365 usually suffer large losses from bark beetle epidemics--losses that equal or exceed periodic growth. However, less dense stands often experience low levels of mortality from endemic populations. Figure suggests that beetle kills from endemic populations can begin when stands reach SDI 230. This stand density could be characterized as the beginning of a "zone of imminent bark beetle mortality". It should be noted, also, that bark beetle epidemics often continue to reduce stand density to levels far below the density that triggered the epidemic and well into this zone of imminent mortality.

The size-density trajectories shown often break off sharply when trees die, rather than forming a gently curving asymptote (fig. 1A). In bark beetle epidemics, many trees are killed in a season, large as well as small. Because beetle kills do not cause an increase in average diameter of the residual trees, as when death is concentrated in the subordinate crown classes, the size-density trajectory tends to form a 90° angle.

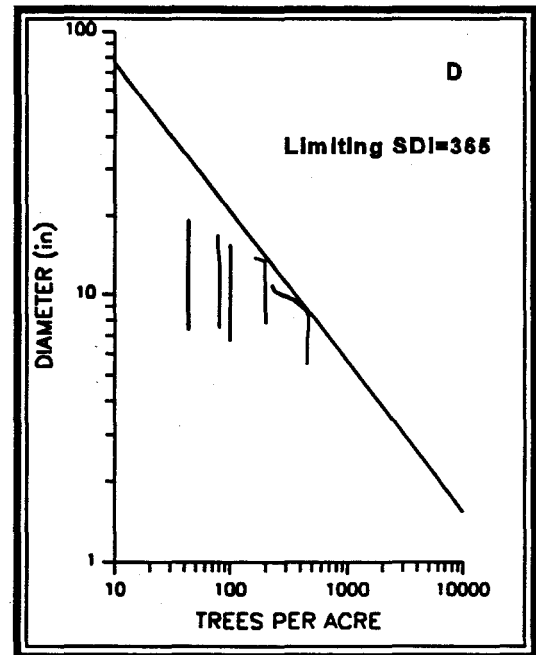
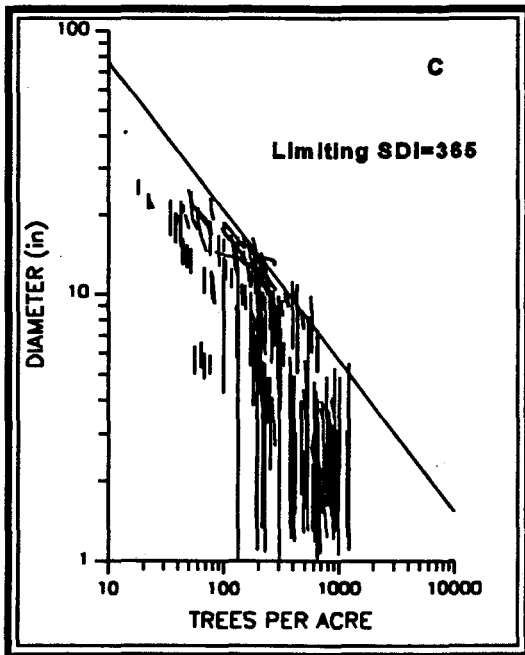
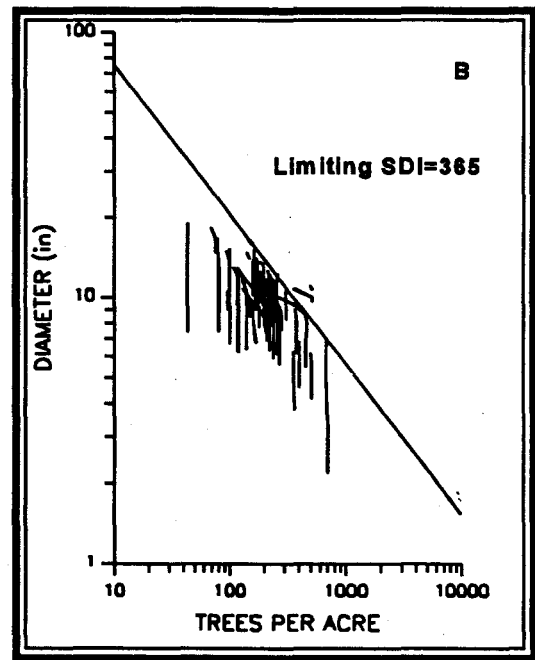
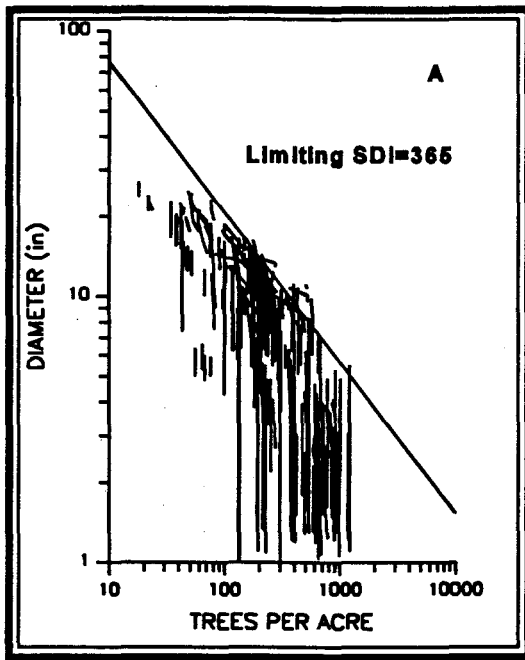


Figure 1. Size-density trajectories plotted on log-log scales for permanent plots in ponderosa pine stands (A) throughout northern California, (B) east and (C) west of the Sierra Nevada and Cascade Range, and (D) a levels-of-growing-stock study at Sugar Hill on the eastside.

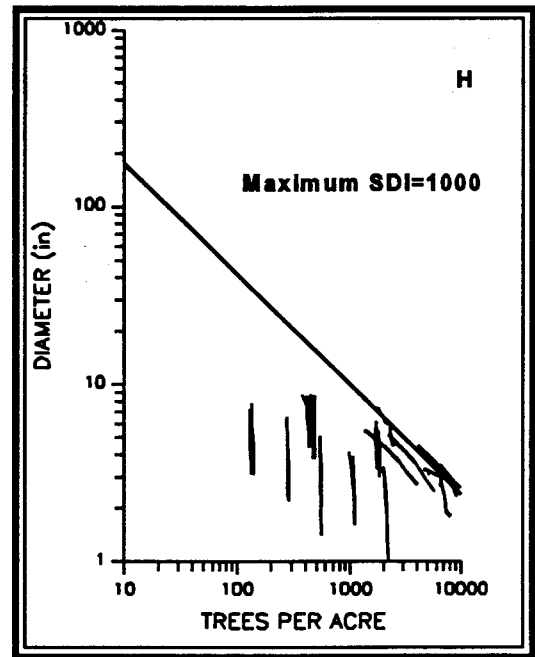
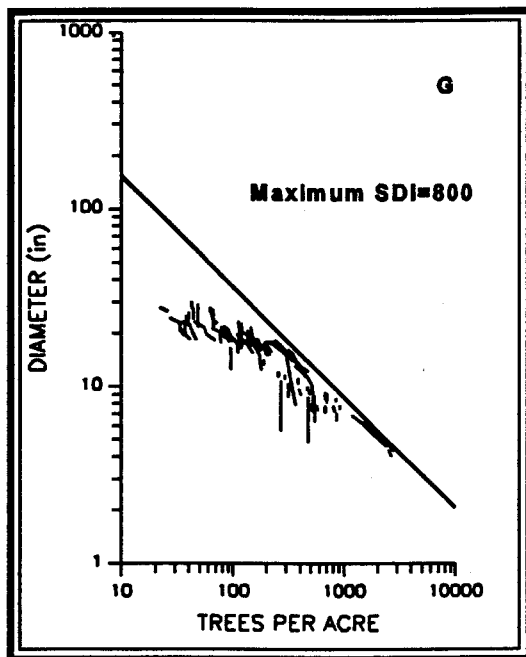
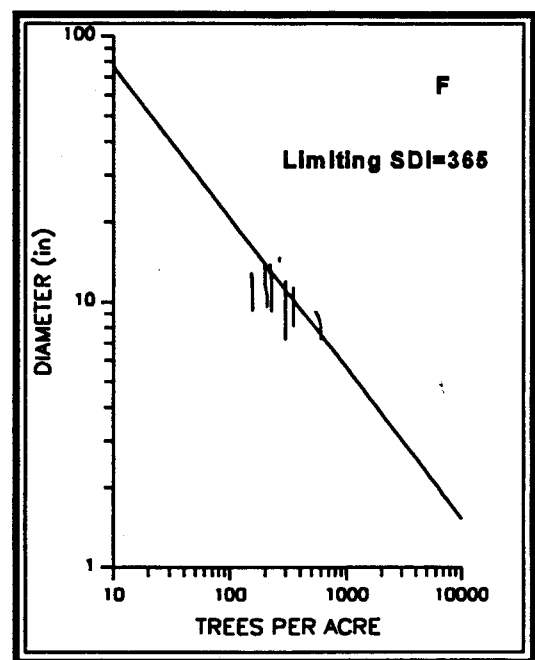
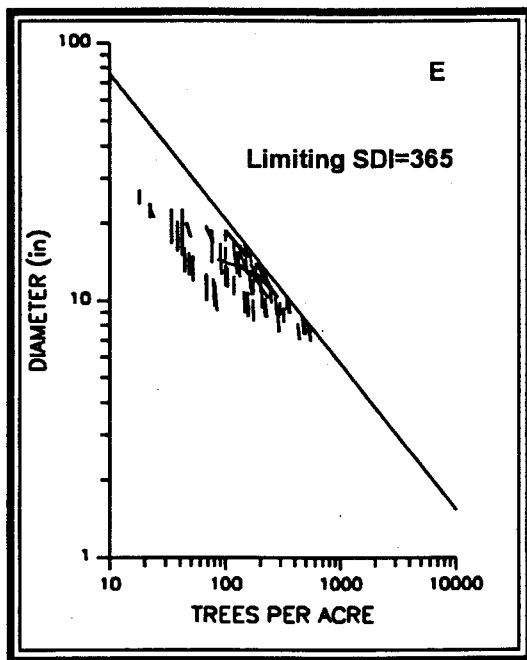


Figure 1 (continued). Size-density trajectories plotted on log-log scales for permanent plots in (E) a-levels-of-growing-stock study in ponderosa pine at Elliot Ranch on the westside, (F) Jeffrey pine, (G) white fir, and (H) red fir.

Because plots are located both east and west of the Sierra Nevada and Cascade Range crest, difference in limiting SDI can be examined between these regions (fig. 1B, 1C). It appears that limiting SDI for eastside stands may be a little lower than that for westside stands, but more data are needed to be certain.

Examples from levels-of-growing-stock studies

Bark beetle-stand density interactions in two level-of-growing-stock studies, one east and the other west of the Sierra Nevada and southern Cascade Range crest, suggest reasons why differences in limiting SDI between east and west sides may be minor.

Four growing stock levels are under test in the extensive plantations at Sugar Hill in the Warner Mountains east of the Cascade Range (Oliver 1979a) near where Eaton attempted his pioneering study 50 years ago. The site index of 95 (Barrett 1978) is better than average for the area. Trees were planted to a 8- by 8-ft spacing in spring 1932. Early survival and growth were good for those days. By 1959, when the study began, the plantation was 28 years old, 6 in. in diameter at breast height (dbh) and 18 ft tall. Four plots were thinned to a wide range of SDIs--25, 50, and 128 and the unthinned control of 157. Plots have not been rethinned in the intervening 36 years.

At Sugar hill stand density in the unthinned plot built steadily to SDI 327 at which time the mountain pine beetle began killing large numbers of trees. The killing began at age 48 and has continued to the present, killing half the trees and reducing SDI to 264 (fig. 1D). Killing began 10 years later in the plot thinned to SDI 128, when that plot reached SDI 331. Beetles in this plot have killed 23 percent of the trees; reducing SDI to 291. Similar patterns were found in a nearby natural stand at Joseph Creek and in several plantations and natural stands in Oregon (fig. 2).

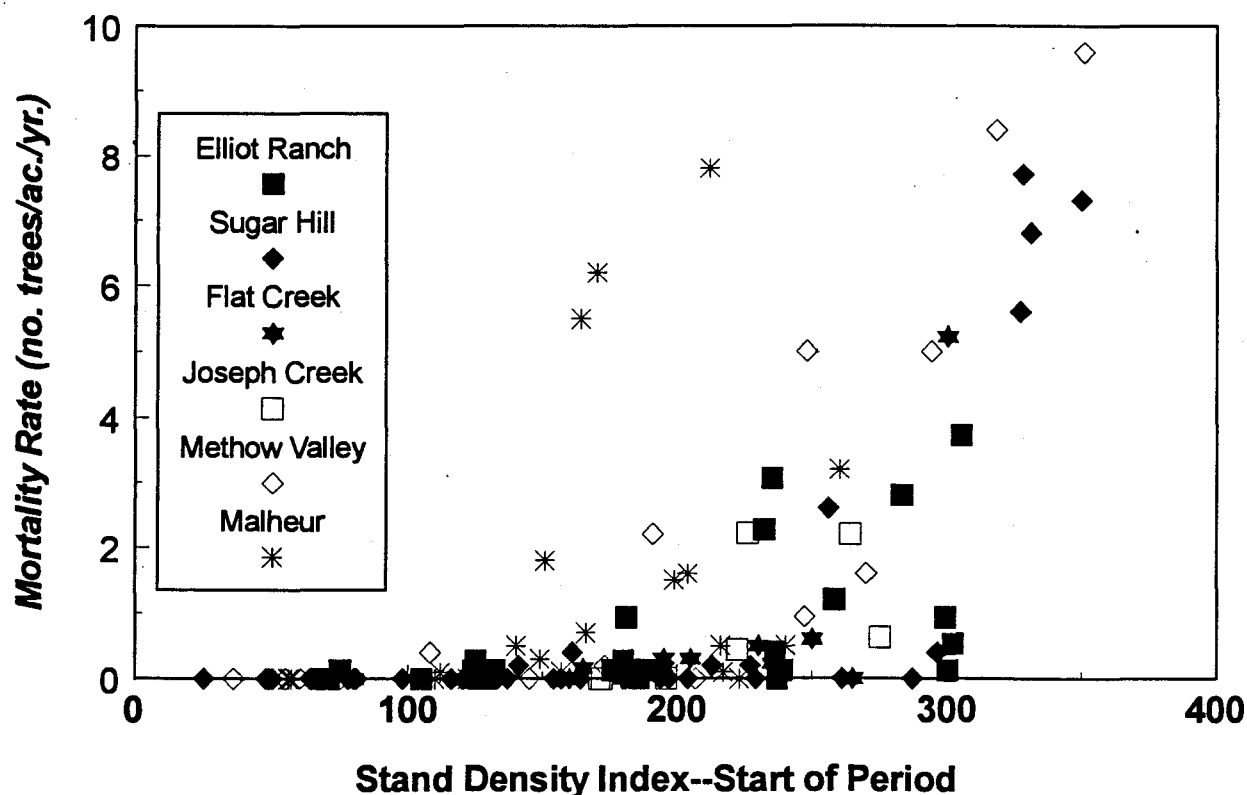


Figure 2. The relationship of stand density to rate of mortality from *Dendroctonus* bark beetles did not differ between even-aged ponderosa pine stands east and west of the Sierra Nevada and Cascade Range. Flat Creek data from Cochran and Barrett (1993), Methow Valley data from Cochran and Barrett (in press), and Malheur data from Cochran and Barrett (1995).

Five growing stock levels are under test in the Elliot Ranch Plantation on the west slope of the Sierra Nevada (Oliver 1979b). This plantation has a site index of 115 ft (Powers and Oliver 1978). Trees were planted to a 6- by 8-ft spacing in spring 1950. By age 20, when the study began, SDI averaged 307 and occasionally exceeded 350. The average tree was 7 in. dbh and 33 ft tall. Plots were thinned to SDIs of 73, 128, 183, 238, and 293. Plots have been rethinned three times in the intervening 25 years.

The western pine beetle and occasionally the red turpentine beetle (*D. valens* LeConte) are at work in this plantation. Again, stocking level had a profound influence on mortality, but surprisingly, the threshold of bark beetle susceptibility seems no higher than at Sugar Hill. Plots with SDIs above 230 suffered low or endemic levels of bark beetle mortality--97 SDI units lower than at Sugar Hill. Epidemic levels, however, were reached when stand densities reached an SDI of 300--similar to the pattern found at Sugar Hill (fig. 1E, 2).

What could account for this startling result? Startling because the site index at Elliot Ranch is twice that of Sugar Hill, and the general belief is that good sites will support a greater stand density than will poor sites. Bark beetle species differences and/or climate may be involved. Three generations of the western pine beetle are often produced during the warm summers on the westside of the Sierra Nevada. In contrast, only one generation is usually produced by the mountain pine beetle during the cooler, shorter summers in the Warner Mountains.

The most important factor, however, may be the repeated presence of volatile resins which attract bark beetles. Western pine beetle populations have been high, historically, in the Elliot Ranch area. Also, the plots have been rethinned three times, each time releasing these resins. Indeed, a few trees were killed by beetles after each thinning--a common phenomenon.

Stem breakage from winter storms is a major source of volatile resins and is a major cause of mortality at Elliot Ranch. Stem breakage and bark beetle mortality would seem to be linked. Most stems broke in the lower crown, leaving a few whorls of living branches--sufficient only to sustain life for a few years. These weakened stems were an ideal substrate for bark beetles and probably sustained a high population which attacked undamaged trees. And, of course, the exposed wood in the break released volatile resins. Like beetle kills, snow breakage was confined almost exclusively to the higher stand densities--SDIs of more than 183 (fig. 3). Snow breakage was particularly severe in the winter of 1981-82. Plots with the highest stand density, SDI 293, suffered the most damage. Twenty-eight percent of the trees lost portions of their boles. The proportion of damaged trees fell to 19 percent for plots with SDI 238 and to 7 percent for SDI 183. More lightly stocked plots received virtually no damage. The Sugar Hill plots suffered no stem breakage from winter storms. Indeed, such damage is virtually unknown in northeastern California.

In the absence of bark beetle attacks what would be the maximum SDI for ponderosa pine? Bark beetles seem to kill ponderosa pines at stand densities lower than would mortality from intertree competition. This may be suggested by a few Jeffrey pine data, if we assume that Jeffrey pine's tolerance of intertree competition is the same as ponderosa pine's tolerance. My files contain only seven stands yielding eight size-density trajectories (fig. 1F). All were plantations in areas devoid or with low populations of the Jeffrey pine beetle (*D. jeffreyi* Hopkins). Several trajectories cross the bark-beetle-limiting SDI of 365 for ponderosa pine without noticeable mortality, suggesting that in the absence of bark beetles maximum SDI for ponderosa pine might be higher than 365. I assume that the maximum SDI of 570 used in Region 5 for the local variants of FVS was established for stands without bark beetle mortality.

Maximum Stand Densities for True Firs

In true firs in contrast to ponderosa pine, the final cause of mortality in dense stands tends to be intertree competition rather than bark beetles. The genus, *Scolytus*, is not nearly as aggressive a killer as are *Dendroctonus* beetles. As a result, size-density trajectories tend to form a gently curving asymptote with the maximum SDI line because mortality is concentrated in the smaller size classes--a more classic example of the Self-Thinning Rule. I have far fewer data than for ponderosa pine--only six natural stands yielding 78 size-density trajectories (fig. 1G). Nevertheless, these limited data suggest a maximum SDI of 800, just a bit higher than that used in local variants of FVS, and a bit higher than that shown in Schumacher's (1926) normal yield tables, as well.

Again, I have a meager sample of red fir data--only three stands tracing 40 size-density trajectories (fig. 1H). These data suggest a maximum SDI of 1000, considerably higher than SDI 800 used in the local variants of FVS and higher than that suggested by Schumacher's (1928) normal yield tables.

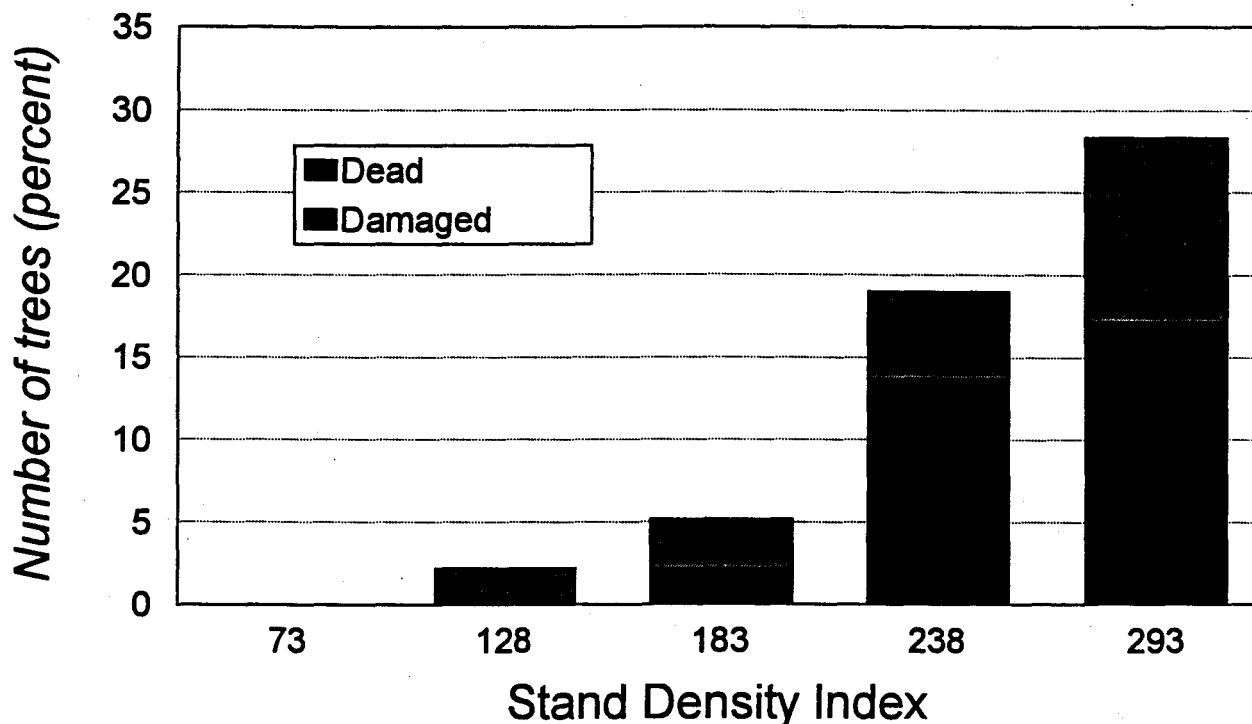


Figure 3. Storm damage to ponderosa pine in winter 1981-82 was related to Stand Density Index in the Elliot Ranch Levels-of-Growing-Stock Study.

Conclusions

Several conclusions seem evident from these observations:

A) Sartwell's threshold of 150 ft² per acre of basal area above which dense stands are susceptible to attack by bark beetles appears to be a reasonable average value for California. The eastside plots at Sugar Hill reached a SDI of 329, without disturbance, but then suffered catastrophic losses. The basal area per acre equivalent to SDI 329 is 170 for 332 trees per acre 9.7 in. d.b.h. The westside plots at Elliot Ranch, in contrast, were continually disturbed, either by cutting or storm damage, reaching a SDI of 245 before bark beetles began killing trees. The basal area per acre equivalent to SDI 245 at Elliot Ranch is 135 ft² of basal area per acre for 168 trees 12.3 in. d.b.h.. Losses at Elliot Ranch reached epidemic levels, however, at a stand density similar to that found at Sugar Hill--SDI 309. The basal area per acre equivalent to SDI 309 is 174 ft².

B) Self-thinning in even-aged ponderosa pine stands does seem to be ruled by *Dendroctonus* bark beetles. The Self-Thinning Rule usually thought to describe suppression-induced mortality applies equally well to bark-beetle-induced mortality. This outcome is not so surprising when one considers that the root cause of both mortality factors is competition for a fixed amount of site resources. In the absence of bark beetles, data from Jeffrey pine (a species similar to ponderosa pine) suggest that maximum SDI would be higher. The limiting SDI for ponderosa pine stands in northern California as defined by *Dendroctonus* bark beetles is 365. SDI 230 defines a threshold for a zone of imminent bark beetle mortality within which endemic populations kill a few trees but net growth is still positive.

C) Bark-beetle-limiting SDI differs little between eastside and westside stands of ponderosa pine. Even though SDI is reported to be insensitive to site quality, the similarity in limiting SDI between the distinctly different eastside and westside growing conditions is surprising. Two mortality agents are more active on the westside and seem to cancel productivity differences. Western pine beetle populations are more explosive on the westside because more generations

are produced in a single season. And stem breakage from winter storms, a regular density-related feature of westside stands, is virtually absent in eastside stands.

D) True firs have a maximum stand density much higher than ponderosa pine. My data suggest that maximum SDI for white fir may be 800 and for red fir 1000. The evidence is insufficient, however, to recommend changes to the somewhat lower values used by the local FVS variants. The reasons for such high maximums are the inherently greater shade tolerance of these species and the absence of bark beetles as aggressive as is the genus *Dendroctonus*.

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