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Suggested Stocking Levels for Forest Stands in Northeastern Oregon and Southeastern Washington: An Implementation Guide for the Umatilla National Forest

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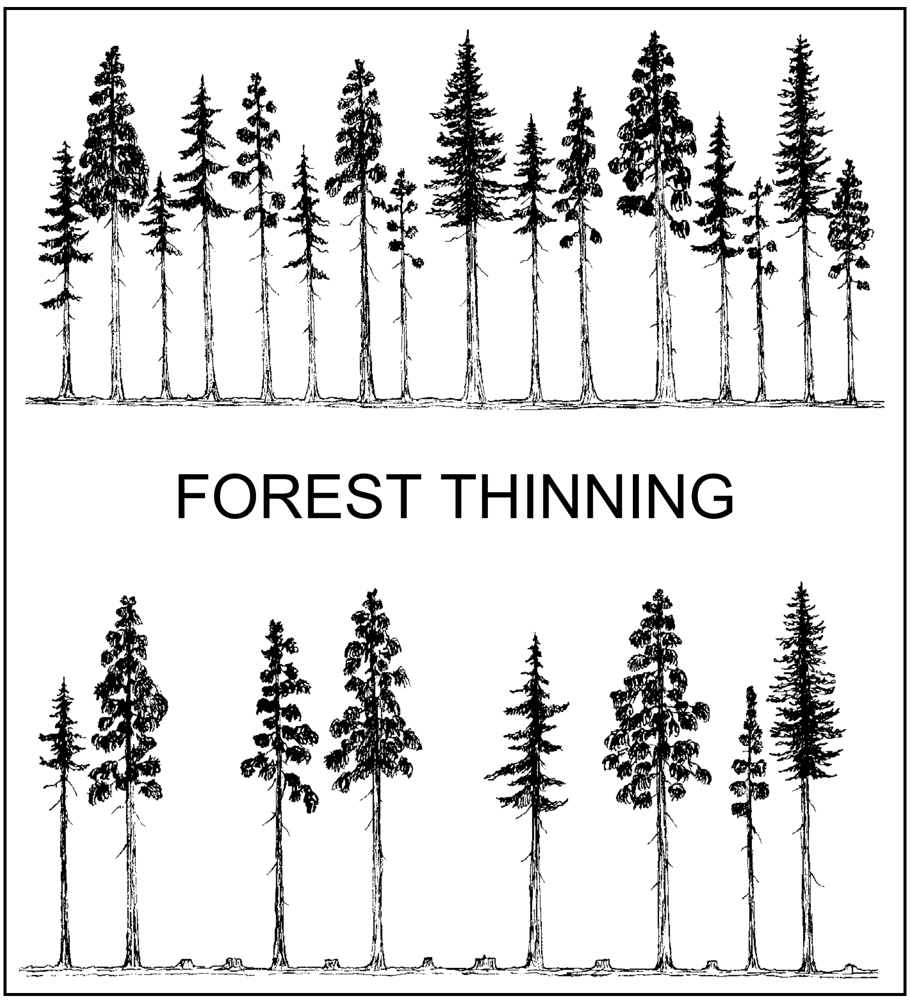

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Title Page Photograph

A low thinning in a high-elevation, mixed stand of Engelmann spruce and subalpine fir established on the subalpine fir/grouse huckleberry plant association (ABLA2/VASC). The area was planted with spruce seedlings in the early 1940s and thinned in the fall of 1981. The pre-treatment stand had a basal area of 101 square feet per acre, a quadratic mean diameter (QMD) of 6.1 inches and a stand density index (SDI) of 224. Cut trees averaged exactly 200 per acre, as determined from a post-thinning survey utilizing 1/20-acre fixed-area plots. The post-treatment stand had a basal area of 78 square feet per acre, a QMD of 7.1 inches and an SDI of 168. Before thinning, the stand was exactly midway between the upper and lower limits of the management zone for Engelmann spruce; after thinning, it was slightly below the suggested stocking level for the lower limit of the management zone (refer to the basal area values for an irregular stand structure in table 25).

Abstract

During the last 10 to 20 years, forests in the Blue, Ochoco and Wallowa Mountains of northeastern Oregon and southeastern Washington experienced increasing levels of damage from wildfires and tree-killing insects and diseases. Often, the high damage levels were assumed to be an indicator of impaired forest health. In response to concerns about forest health in the Blue Mountains, both from scientists and the general public, the value of minimizing insect and disease damage by maintaining high stand vigor is gradually being recognized. Perhaps no silvicultural approach can contribute as much to forest health as stocking-level control (stand density management). In 1994, a research note was published that established suggested stocking levels for forest stands in northeastern Oregon and southeastern Washington (Cochran and others 1994).

As practitioners began using the research note, it gradually became apparent that additional information would help implement the stocking recommendations (items such as calculated SDIs for the upper and lower limits of the management zone, basal area values for each of the stocking levels, stocking levels pertaining to stand structures that are not even-aged, stocking recommendations spanning a range of quadratic mean diameters, and translation of SDI-based stocking information into forest (tree) canopy cover percentages and inter-tree distances). This "implementation guide" provides the additional information; it is supplied as both a series of figures (appendix 2) and a set of tables (appendix 3).
Keywords: Forest health, stand density index, Blue Mountains, Ochoco Mountains, Wallowa-Snake province, stand density, stocking levels, forest insects, forest diseases.

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INTRODUCTION

In 1994, the Pacific Northwest Research Station published a research note establishing suggested *stocking levels*[1] for forest stands in the Blue Mountains of northeastern Oregon and southeastern Washington (Cochran and others 1994). That note, hereafter referred to as the Cochran paper, was unique because specific stocking levels were developed for seven tree species, and they varied by *plant association* and by ecological province (Blue-Ochoco and Wallowa-Snake). I am not aware that *stocking* or *stand density* recommendations have been developed to that level of detail anywhere else in North America.

The Cochran paper provided a single stocking level (*full stocking*) pertaining to one specific situation – even-aged stands with a *quadratic mean diameter* (QMD) of 10 inches. As practitioners began using the Cochran paper, it became clear that additional information would help with implementation of the stocking level recommendations. In particular, the following items were identified:

- *Upper limit of the management zone* and *lower limit of the management zone* values were needed for each tree species–plant association combination;
- Stocking levels were needed for two measures of stand density: *basal area* per acre and trees per acre;
- Stocking levels were needed for stand structures other than *even-aged*: *irregular* and *uneven-aged*;
- Stocking levels were needed for a range of quadratic mean diameters;
- Stocking levels also needed to be expressed as both forest (tree) canopy cover and inter-tree distance.

The Cochran paper developed the basic information to address those items; what was needed for implementation was not additional research or analyses, but an expansion of the existing information. This document is termed an "implementation guide" for that reason – it was designed to meet the needs described above by helping to implement the suggested stocking levels from Cochran and others (1994).

STAND DENSITY: CONCEPTS AND TERMS

The general term stand density is a measure of the amount of tree vegetation on a unit of land area. It can be the number of trees or the amount of basal area, wood volume, leaf cover, or any of a variety of other parameters (Curtis 1970, Ernst and Knapp 1985). Stocking is the proportion that any particular measurement of stand density bears to a standard expressed in the same units. In other words, stand density tells us what actually exists, whereas stocking tells us how it relates to an established standard of what ought to be (Smith and others 1997).

The relationship between an existing stand density and a *reference level* that could occur at the same average tree size is referred to as *relative density* (Helms 1998, Smith and others 1997). Since relative density relates an existing density to a reference level, it is similar in concept to stocking. In common usage, relative density is an expression of how existing density relates to either a biological *maximum density* for the species (Curtis 1982, Drew and Flewelling 1979), or to a *normal density* (MacLean 1979) that represents an "average-maximum" level of competition (Curtis 1970, Ernst and Knapp 1985).

STAND DENSITY INDEX – AN INDEX OF RELATIVE DENSITY

Silviculturists commonly use a relative density index to characterize stocking levels. A popular index in the western United States is *stand density index* (SDI), which is based on the relationship between tree size and the number of trees per acre (Daniel and others 1979b, Reineke 1933). Perhaps the greatest advantage of SDI and similar indexes is their independence from site quality and stand age. This means that stands with the same quadratic mean diameter and number of trees per acre are "more alike in every way than stands of the same site and age" (McArdle and others 1961).

[1] Any italicized term (except scientific names) is defined in the glossary.

Reineke (1933) discovered that any pure, fully-stocked, even-aged stand of a given average stand diameter had approximately the same number of trees per acre as any other pure, fully-stocked, even-aged stand of the same species and average stand diameter. Reineke plotted tree densities for fully-stocked, even-aged stands and then drew a freehand line that "skimmed" the outermost data values, resulting in a maximum density line for each species that he worked with. He observed that the lines for redwood *(Sequoia sempervirens)* and red fir *(Abies magnifica)* were identical and were higher than those for other species, so he proposed that their maximum density (an SDI of 1,000) be used as a reference level.

Reineke's work (1933) showed that the *growing space* occupied by trees growing in fully-stocked, even-aged stands increased at a constant exponential (straight line) rate as the quadratic mean diameter of the stand increased. This relationship between average size and density has been referred to as the *self-thinning* rule because some individuals in the population must eventually relinquish their growing space (e.g., die) if surviving trees are to continue increasing in size (fig. 1). Self thinning also occurs for life forms other than trees (Long and Smith 1984, Westoby 1984).

Reineke (1933) believed that the slope of the "self-thinning" line, which expresses the mathematical relationship between tree density and average diameter, was constant for all tree species. Recent evidence suggests that the slope of the line is more variable than previously thought, that straight lines may be the exception rather than the rule, and that the slope varies with the biology of the plant (Lonsdale 1990). For those reasons, the maximum size-density relationship tends to vary for conifers versus hardwoods, and for tolerant versus intolerant tree species (Daniel and others 1979a, Smith and others 1997).

EFFECTS OF STAND DENSITY ON INSECTS AND DISEASES

The suggested stocking levels in this guide delineate a management zone in which stand densities are presumed to be relatively resistant to insect and disease problems. To preclude serious tree mortality from mountain pine beetle, western dwarf mistletoe and perhaps western pine beetle, stand densities should be maintained below the upper limit of the management zone (fig. 2) (Barrett and Roth 1985, Cochran and others 1994). In recognition of that fact, considerations related to mountain pine beetle *susceptibility* resulted in adjustments to the upper and lower limits of the management zone for both lodgepole pine *(Pinus contorta)* and ponderosa pine *(Pinus ponderosa)*.

Steele and others (1996) recently developed a stand hazard rating system for central Idaho forests. Eleven disturbance agents were included in their system – six insects, one group of parasites (dwarf mistletoes), three diseases, and one abiotic agent (wildfire). Stand density had been found to exert a strong influence on forest susceptibility to insects and diseases, and it was used as a hazard rating factor for five of the eleven disturbance agents – Douglas-fir beetle, mountain pine beetle in lodgepole pine, spruce beetle, western pine beetle and mountain pine beetle in ponderosa pine, and western spruce budworm.

Mountain Pine Beetle. Many studies explored the relationship between lodgepole pine stand density and tree mortality caused by mountain pine beetle. McGregor and others (1981) noted that beetle-caused mortality decreased when the *crown competition factor* (Krajicek and others 1961) was greater than 200. Anhold and Jenkins (1987) observed a similar density threshold when using SDI. Amman and Anhold (1989) found a negative correlation between SDI and beetle-caused mortality. Anhold and others (1996) identified a zone of high susceptibility that consisted of relative densities between 20 and 35 percent of the maximum SDI for lodgepole pine, and quadratic mean diameters greater than 8 inches.

These studies seem to demonstrate that very dense lodgepole pine stands are unfavorable to mountain pine beetle, presumably because they have a high proportion of low-vigor trees with thin phloem, which is marginally suitable as habitat for beetle broods. Although a relationship between stand density and beetle-caused mortality apparently exists, it may have limited predictive value because risk rating must also account for the beetle's population phase (endemic versus epidemic), its population dynamics, and the spatial characteristics of beetle populations (Bentz and others 1993).

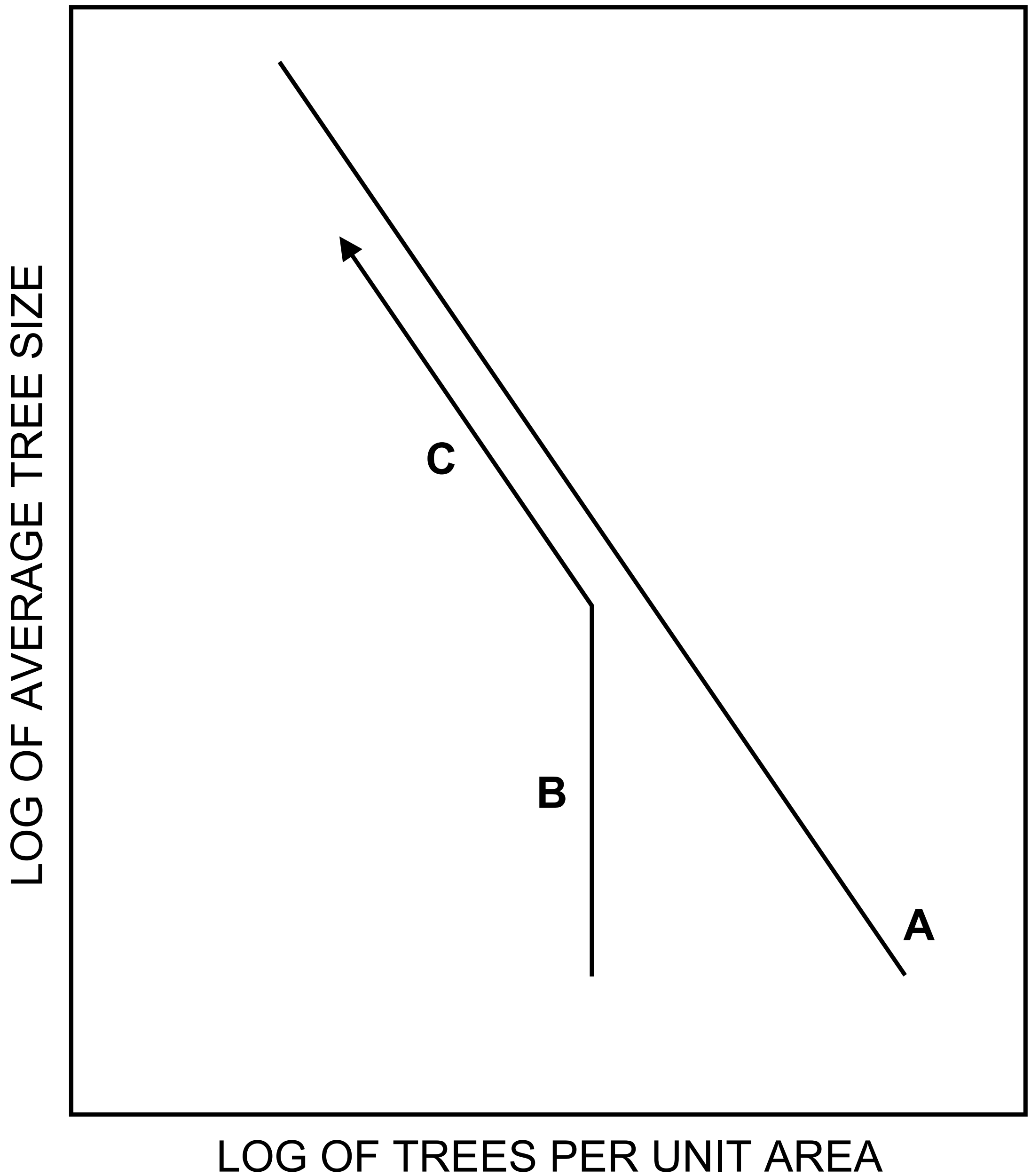

Figure 1 – Hypothetical development of an even-aged tree stand (adapted from Dean and Baldwin 1993). This figure shows two lines. Line "A" shows the maximum size-density boundary; in this document, it refers to the full-stocking density level. The maximum size-density relationship is a species-specific boundary line that forms the basis for indexing relative density, i.e., for stands without stockability limitations (MacLean and Bolsinger 1973), the ratio of actual SDI to the full-stocking SDI can be used as a stocking level. The full-stocking line is a logarithmic relationship with a negative slope (it's sloping downward rather than upward), which means that more trees are associated with a smaller size and less trees with a larger mean size. This negative relationship between mean size and density exists for all self-thinning plant populations, regardless of their life-form (tree, shrub, herb). The second line shows a hypothetical even-aged stand. Line segment "B" shows the period in stand development characterized by *free growth*, where trees are growing as fast as possible for prevailing site conditions. The early portion of this period, when trees fill unoccupied growing space prior to crown closure and the onset of competition, is known as "open growth" (Oliver and Larson 1996). Line segment "C" shows a change in trajectory after the stand enters the self-thinning zone and density-related competition causes tree mortality. After self-thinning begins, a stand is constrained by the full-stocking boundary (the "A" line) and its future trajectory will then remain below, but track along, that line. These developmental processes hold for all forests, although low-productivity sites progress at slower rates than high sites (Westoby 1984).

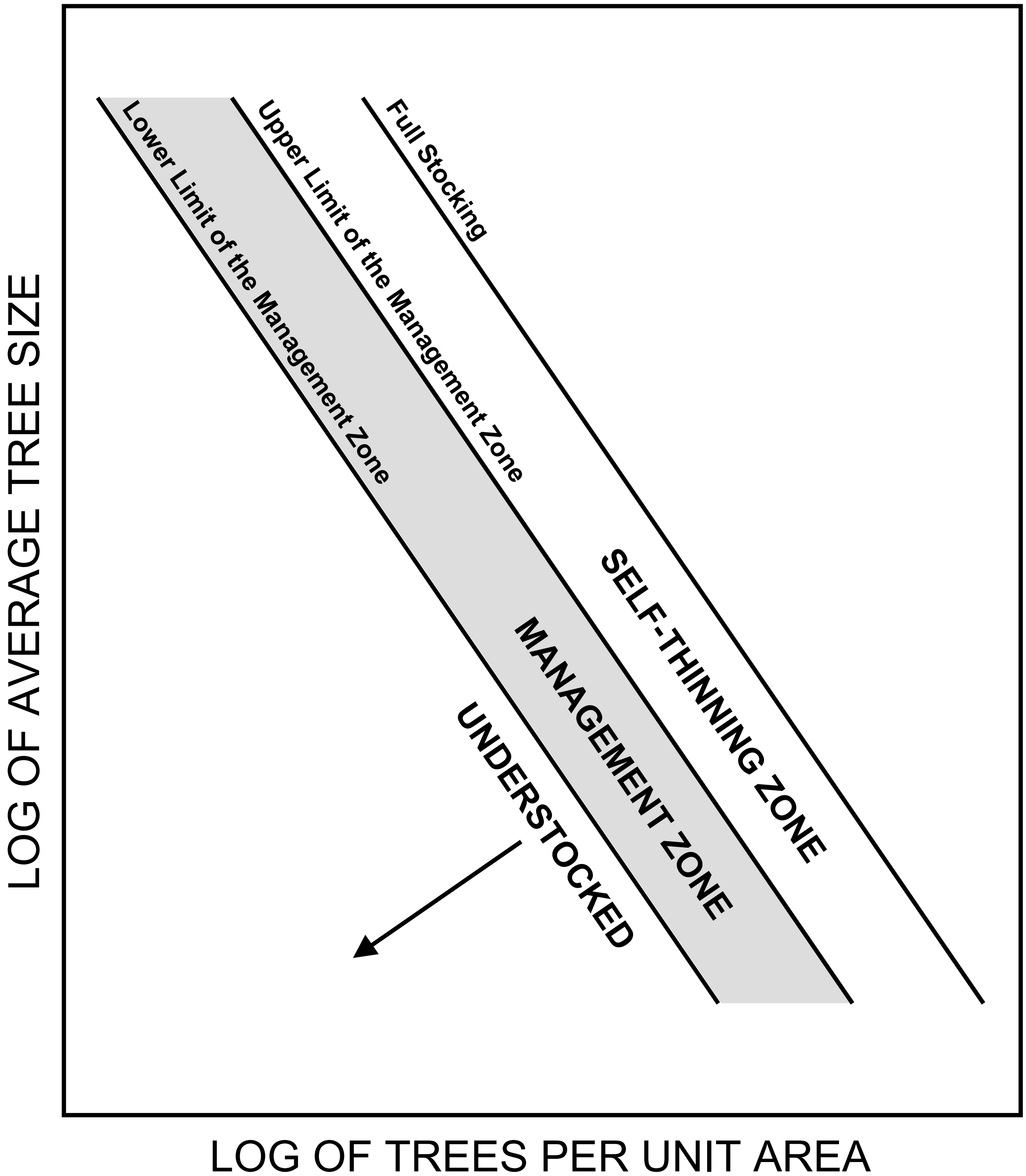

Figure 2 – Important stand density thresholds. This figure shows several important zones with respect to stand density management and development of stocking levels. The full stocking line corresponds to line "A" in figure 1. Full stocking is a species-specific boundary line that can be used to index relative density because the upper and lower limits of a management zone are often calculated as percentages of full stocking. The upper limit of the management zone (ULMZ) is 75% of the full-stocking line for Douglas-fir *(Pseudotsuga menziesii)*, western larch *(Larix occidentalis)*, Engelmann spruce *(Picea engelmannii)*, grand fir *(Abies grandis)*, and subalpine fir *(Abies lasiocarpa)*. For lodgepole and ponderosa pines, the recommended ULMZ is not calculated as a percentage of full stocking. The lower limit of the management zone (LLMZ) coincides with the "lower limit of full site occupancy;" it represents the point at which a significant portion of a site's resources can be captured as tree growth. For all seven tree species included in this document, the LLMZ was calculated as 67% of the ULMZ. For Douglas-fir, western larch, Engelmann spruce, grand fir, and subalpine fir, the LLMZ also represents 50% of the full-stocking density. Stand densities above the ULMZ are in the self-thinning zone where trees aggressively compete with each other for moisture, sunlight, nutrients, and the other essentials of life. Stands in the self-thinning zone experience density-related, competition-induced mortality, particularly for trees in the suppressed and intermediate crown classes. Mortality that occurs below the self-thinning zone is not related to stand density. Stand densities below the LLMZ could be considered understocked because growing space is not fully occupied (utilized) by the trees.

Several studies found that tree mortality due to mountain pine beetle was insignificant until a certain stand density was reached (Cochran 1992, Mitchell and others 1983). Peterson and Hibbs (1989) concluded, based on their analysis of previously-published data collected from both thinned and unthinned stands in the Blue Mountains (Mitchell and others 1983), that an SDI of 160-170 was the threshold density above which beetle-induced mortality became serious for lodgepole pine (table 1).

Thinning lodgepole pine increases tree vigor and resistance to mountain pine beetle (Mitchell and others 1983); fewer trees are killed in heavily-thinned areas as compared to lightly-thinned ones (Schmitz and others 1989). Waring and Pitman (1985) noted that the risk of beetle epidemics can be greatly reduced by periodic thinnings. Apparently, thinning causes an immediate alteration of stand microclimate such that beetles cannot mount a successful attack (Amman and others 1988, Bartos and Booth 1994). Once residual trees respond to a thinning (often 3-5 years after treatment), their improved vigor allows production of additional defensive chemical compounds that enhance beetle resistance (Christiansen and others 1987).

Mountain pine beetle also attacks ponderosa pine. When Sartwell (1971) examined mountain pine beetle effects on second-growth stands of ponderosa pine in eastern Oregon and eastern Washington, he found a significant and direct relationship between stand density and beetle-induced tree mortality. A correlation between site productivity and mortality from mountain pine beetle was also obvious (fig. 3).

Sartwell (1971) found that mortality caused by mountain pine beetle was least on the high-productivity areas (site class III), and that tree killing acted like a low thinning (thinning from below) in terms of its impact on stand structure (fig. 3). On moderate productivity areas (site class IV), beetle-caused mortality was greater than for the high-productivity sites and was also indiscriminate because it affected a wide range of diameter classes. For the low-productivity areas (site class V), mortality was extensive and resembled a heavy thinning from above (e.g., large trees were killed more often than small trees).

Sartwell (1971) believed that mountain pine beetle outbreaks could be attributed to two primary factors: second-growth ponderosa pine stands were even-aged and ecologically simplified when compared with the uneven-aged “virgin” forest; and man’s intentional suppression of wildfire effectively removed an important landscape-level thinning agent, which in turn caused an unnatural accumulation of stand density (basal area) as compared to virgin conditions.

Studies examining stand density in relation to beetle-induced mortality identified stocking thresholds below which mortality was minimal. For second-growth stands of ponderosa pine, it was recommended that stocking-level control be used to maintain densities below 150 square feet of basal area per acre, which would allow *vulnerable* stands to withstand at least moderate attack from mountain pine beetle (table 1; Larsson and others 1983, Sartwell 1971, Sartwell and Dolph 1976, Sartwell and Stevens 1975). Another study found that 150 square feet per acre may be too high, so it was recommended that basal area be maintained at 120 square feet per acre or less to minimize beetle risk (Schmid and Mata 1992).

Defoliating Insects. Two defoliating insects have been particularly important in the Blue Mountains – Douglas-fir tussock moth and western spruce budworm. Population eruptions of these defoliators are cyclic and tend to be influenced by weather conditions. Outbreaks are favored by a large component of climax tree species, particularly on warm dry sites, and by dense, multi-layered stand structures. Stress on host tree species caused by factors such as drought, inadequate nutrients, overcrowding (high stand density), and root disease is also believed to influence host-tree susceptibility (table 1; Carlson and Wulf 1989, Hadley and Veblen 1993, Powell 1994, Steele and others 1996).

Powell (1994) analyzed budworm-caused impacts (defoliation, top-killing, and mortality) for mixed-conifer forests in the south-central Blue Mountains. One of 17 factors used for the analysis was stand density. Although defoliation and top-killing exhibited little variation with changes in stand density, budworm-induced tree mortality was obviously greater for plots having an SDI of 151 or more as compared to those with an SDI or 150 or less, although the difference was not statistically significant when based on the standard error of the stratified mean estimate.

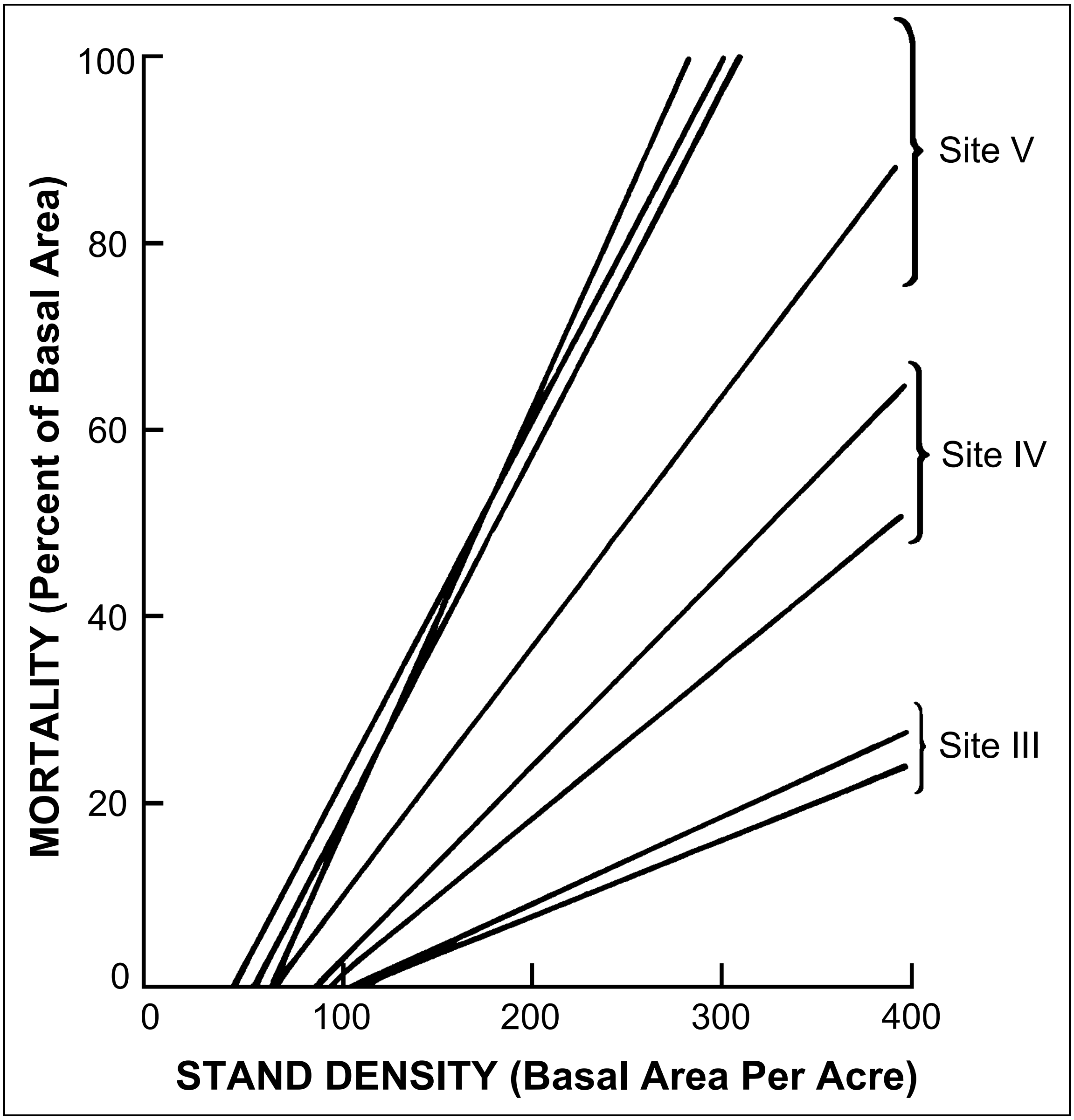

Figure 3 – Relationship of tree killing by mountain pine beetle to stand density and site productivity for eight pole-sized, second-growth ponderosa pine stands in eastern Oregon and eastern Washington (from Sartwell 1971). The plant associations in which ponderosa pine occurs (see table 2) were assigned to site classes as follows (assignments were based on information from Johnson and Clausnitzer 1992, and from Johnson and Simon 1987):

Site Class III: PSME/HODI.

Site Class IV: ABGR/LIBO2, ABGR/VAME, ABGR/SPBE, ABGR/CARU, ABGR/CAGE, PIPO/SYAL.

Site Class V: ABGR/VASC, PSME/ACGL-PHMA, PSME/PHMA, PSME/SYAL, PSME/VAME, PSME/CARU, PSME/CAGE, PSME/SPBE, PSME/SYOR, PIPO/SYOR, PIPO/CARU, PIPO/CAGE, PIPO/CELE/CAGE, PIPO/PUTR/CAGE, PIPO/PUTR/CARO.

Over the long run, thinning and other silvicultural practices may be the most effective way to deal with western spruce budworm. Research from Montana found that thinning improved budworm resistance by increasing stand vigor, increasing budworm larval mortality during their dispersal period, and by reducing the budworm-host species in mixed-conifer forests (table 1). Thinning provided short-term protection for treated stands, and would presumably contribute to long-term resistance once landscape-sized areas were treated (Carlson and Wulf 1989).

Similar studies in northeast Oregon had different results – when western spruce budworm populations were exceedingly large, thinning provided little benefit because budworm numbers were able to overwhelm the effects of any indirect treatment (Wickman and others 1992). In fact, it appeared that thinning may have actually favored budworm by allowing more sunlight into the forest canopy, thereby creating warmer microhabitats that allowed it to develop faster, eat more, and to possibly escape more natural predation while in the larval stage (table 1; Boyd Wickman, personal communication, 1994).

Forest Diseases. Three primary disease groups play important roles in the forests of the Blue Mountains: dwarf mistletoes, stem decays, and root diseases (Gast and others 1991). As described previously, bark beetles prefer densely-stocked stands (Filip and others 1996), so their populations vary somewhat predictably with stand density levels and in response to stocking control measures such as thinnings. That is not always the case for forest diseases because tree resistance or forest susceptibility appear to vary with stand density in some instances, but not in others (table 1; Schmitt 1999).

Perhaps no disease agent has a greater impact on Blue Mountain forests than a group of parasitic plants called dwarf mistletoes (Filip and others 1996, Gast and others 1991). In a study that included stands from the Malheur National Forest in the southern Blue Mountains, precommercial thinning increased the radial and height growth of Douglas-firs with light or moderate infections of dwarf mistletoe; stand density reductions did not produce a growth increase in heavily-infected trees (Knutson and Tinnin 1986).

The impacts of forest diseases are frequently overlooked because they tend to cause insidious changes occurring over decades. Oftentimes, the changes wrought by root diseases and similar disturbance agents have been so difficult for people to discern that they are termed “the invisible present” (Magnuson 1990).

Stand Density and Forest Health. During the last 10 to 20 years, Blue Mountain forests experienced increasing levels of damage from wildfire, insects, and diseases. Scientific assessments and studies documented the high damage levels and speculated about their underlying causes (Caraher and others 1992, Gast and others 1991, Lehmkuhl and others 1994, Powell 1994, Shlisky 1994). Partly in response to the scientific assessments, the Blue Mountains area attained national notoriety for its *forest health* problems (Boise Cascade Corporation 1992, Joseph and others 1991, Lucas 1992, McLean 1992, Petersen 1992, Phillips 1995, Wickman 1992). A recent survey conducted by Oregon State University found that many Blue Mountain residents perceive their forests to be unhealthy (Shindler and Reed 1996).

Schmitt and Scott (1993) discussed catastrophic stand conditions in the Blue Mountains and provided guidelines, based on an insect and disease perspective, to help determine whether stand damage levels should be considered catastrophic. They developed a stand classification rating system to estimate imminence of catastrophic damage; it incorporated six factors to derive a stand composite rating. One of the six factors involved an assessment of stand density, and it was based on the suggested stocking levels that were eventually published by Cochran and others (1994).

In response to concerns about forest health in the Blue Mountains, both from scientists and the general public, the value of minimizing insect and disease damage by maintaining high stand vigor is gradually being recognized (fig. 4). Perhaps no silvicultural approach can contribute as much to forest health as stand density management. Thinning and other density management treatments are an effective way to apply *integrated pest management*, which involves the use of silvicultural measures to reduce susceptibility or vulnerability to insects, diseases, parasites and other harmful agents (Nyland 1996).

Increased insect and disease problems are just one possible symptom of deteriorated forest health in the Blue Mountains; perhaps a more dramatic one was a proliferation of stand-replacing wildfires in the late 1980s and 1990s (Glacier, Canal, Corral Basin, Snowshoe, Sheep Mountain, Whiting Springs, Tepee Butte, Tower, Wheeler Point, and many others). Although stand-replacing wildfires are attributed to many different factors, it does appear that stand density can play a role (fig. 5). Agee (1996) recently developed stand density recommendations designed to minimize the potential for lethal crown fires.

Table 1a: Effects of stand density, and thinning as a density-management treatment, on selected forest insects of the Blue Mountains.

NAME OF INSECT	HOST TREES	DAMAGE CAUSED	EFFECTS OF STAND DENSITY OR THINNING
Douglas-fir beetle *(Dendroctonus pseudotsugae)*	Douglas-fir	Blue-staining of sapwood Tree mortality	High stand density was positively correlated with high susceptibility (Weatherby and Thier 1993); in high-density stands, younger trees are attacked and killed in addition to older ones (Furniss and others 1979).
Douglas-fir tussock moth *(Orgyia pseudotsugata)*	Douglas-fir Grand fir	Defoliation Top-killing Tree mortality	Outbreaks and damage levels are most severe on warm dry sites where host trees are under high stress due to competition for moisture and nutrients (Filip and others 1996, Hessburg and others 1994).
Fir engraver *(Scolytus ventralis)*	Grand fir Subalpine fir	Brown-stained sapwood Top-killing Tree mortality	Commonly attacks low-vigor trees weakened by overstocking (Hessburg and others 1994). Resin production, a common defense response of beetle-attacked firs, was significantly greater for high-vigor trees such as those in thinned areas (Filip and others 1989a).
Mountain pine beetle *(Dendroctonus ponderosae)*	Lodgepole pine Ponderosa pine	Blue-staining of sapwood Tree mortality	For lodgepole pine, tree mortality is significant once SDI exceeds 170 in stands containing trees 9" DBH and greater (Cochran and others 1994). Thinning lodgepole pine increases tree vigor and resistance to this beetle (Mitchell and others 1983). For ponderosa pine, maintaining basal areas below 150 square feet per acre was recommended for second-growth stands (Larsson and others 1983, Sartwell 1971).
Pine engraver *(Ips pini)*	Lodgepole Pine Ponderosa Pine	Top-killing Tree mortality	Often spills over into living trees after attacking green slash created by thinnings, particularly for thinnings completed between February and July. Slash created after July is seldom a problem (Sartwell 1970).
Spruce beetle *(Dendroctonus rufipennis)*	Engelmann spruce	Tree mortality	Stand density is related to spruce beetle risk (Schmid and Frye 1976). Research suggests that stand resistance can be enhanced by decreasing stocking to reduce competition and increase tree vigor (Hard 1985).
Western pine beetle *(Dendroctonus brevicomis)*	Ponderosa pine	Blue-staining of sapwood Tree mortality	Damage is strongly associated with low stand vigor, regardless of its source: root disease, drought, overstocking, fire damage, etc. (Keen 1950, Miller and Keen 1960, Whiteside 1951).
Western spruce budworm *(Choristoneura occidentalis)*	Douglas-fir Engelmann spruce Grand fir Subalpine fir	Defoliation Top-killing Reduced tree vigor/growth Reduced seed production Tree mortality	Stress on host trees caused by factors such as drought, inadequate nutrients, overstocking, and root disease influences susceptibility (Carlson and Wulf 1989, Filip and others 1996, Powell 1994). Fast-growing, healthy stands are less susceptible than stagnated, stressed stands (Carlson 1989). Thinning improved tree resistance to budworm and resulted in less defoliation damage (Carlson and others 1985).

Table 1b: Effects of stand density, and thinning as a density-management treatment, on selected forest diseases of the Blue Mountains.

NAME OF DISEASE	HOST TREES	DAMAGE CAUSED	EFFECTS OF STAND DENSITY OR THINNING
Annosus root disease *(Heterobasidion annosum)*	True firs Ponderosa pine	Decay in lower tree stem Tree mortality	Precommercial thinning (or thinning and fertilization) increases grand fir vigor and growth, thereby decreasing susceptibility to wound-associated stem decay from annosus root disease (Filip and others 1992).
Armillaria root disease *(Armillaria ostoyae)*	Douglas-fir Grand fir Pines (moderate)	Reduced tree vigor/growth Decay in lower tree stem Windthrow Tree mortality	A tendency toward greater tree mortality was observed for stands with high density (Filip and others 1989c). Thinning increases host vigor and resistance to *Armillaria*; it can also improve resistance by modifying the proportion of hosts to non-hosts in a stand (Schmitt 1999). In a study involving thinned, fertilized, and untreated stands, *Armillaria* infection rates were lowest in thinned stands, and highest in fertilized stands; infected Douglas-fir stands should be thinned when trees are small rather than large (Entry and others 1991).
Atropellis canker *(Atropellis piniphila)*	Lodgepole pine	Stem cankers Tree mortality	*Atropellis* severity, and tree mortality related to canker-caused girdling, are highest for stagnated stands on cool sites (Hessburg and others 1994, Schmitt 1999).
Dwarf mistletoes *(Arceuthobium douglassii)* *(Arceuthobium americanum)* *(Arceuthobium campylopodum)* *(Arceuthobium laricis)*	Douglas-fir Lodgepole pine Ponderosa pine Western larch	Reduced tree vigor/growth Top-killing Stem deformities; brooms Reduced seed production Stem cankers Tree mortality	Thinning increases inter-tree distance, so it can favor dwarf mistletoe seed dispersal and resultant spread rates. Stands thinned to a 12-foot spacing were almost optimal for mistletoe spread from tree to tree (Knutson and Tinnin 1980). Thinning can lessen impacts in stands with a low dwarf mistletoe rating by removing infected trees, encouraging height growth, and simplifying multi-layered stand structures (Baker 1988, Filip and others 1989b, Hawksworth and Johnson 1989).
Elytroderma blight *(Elytroderma deformans)*	Ponderosa pine	Needle lesions; brooms Reduced tree vigor/growth	Thinning or another stocking control treatment can be used as a preventive measure on high hazard sites (Schmitt 1999).
Indian paint fungus *(Echinodontium tinctorium)*	Grand fir	Stem decay	Precommercial thinning (or thinning and fertilization) increases grand fir vigor and growth, thereby decreasing susceptibility to wound-associated stem decay from Indian paint fungus (Filip and others 1992).
White pine blister rust *(Cronartium ribicola)*	Western white pine Whitebark pine	Tree mortality	Infection rates have been shown to increase dramatically following thinning, particularly on sites with high rust hazard (Schmitt 1999).

Sources/Notes: Table format based on Safranyik and others (1998). Forest insect information was derived primarily from Flanagan (1999). Forest diseases selected for inclusion in this table were based on Schmitt (1999). Host trees include those species that are native to the Blue Mountains and serve as a primary host of the insect or disease organism (Gast and others 1991).

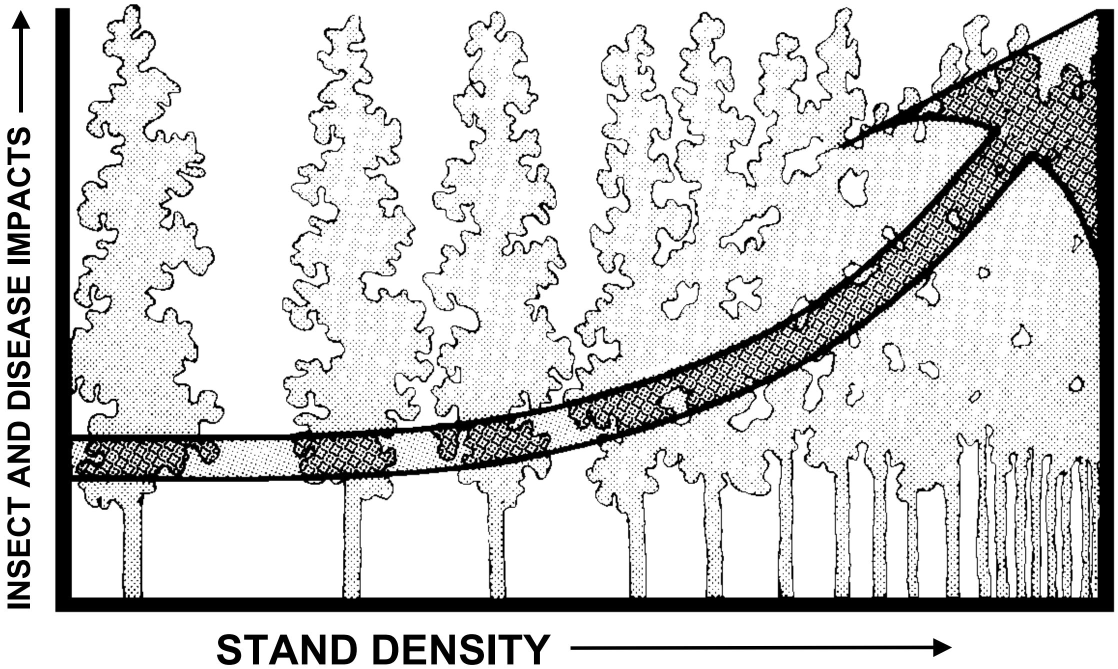

Figure 4 – Insect and disease impacts can vary with stand density (from Powell 1994). Because open stands generally have higher vigor levels than dense stands, they tend to be more resistant to insect and disease impacts. Maintaining a wide stand spacing results in a condition where the trees are not experiencing significant competition. Although not universally true, vigorous trees are better able to withstand attack from insects, pathogens and parasites (Safranyik and others 1998).

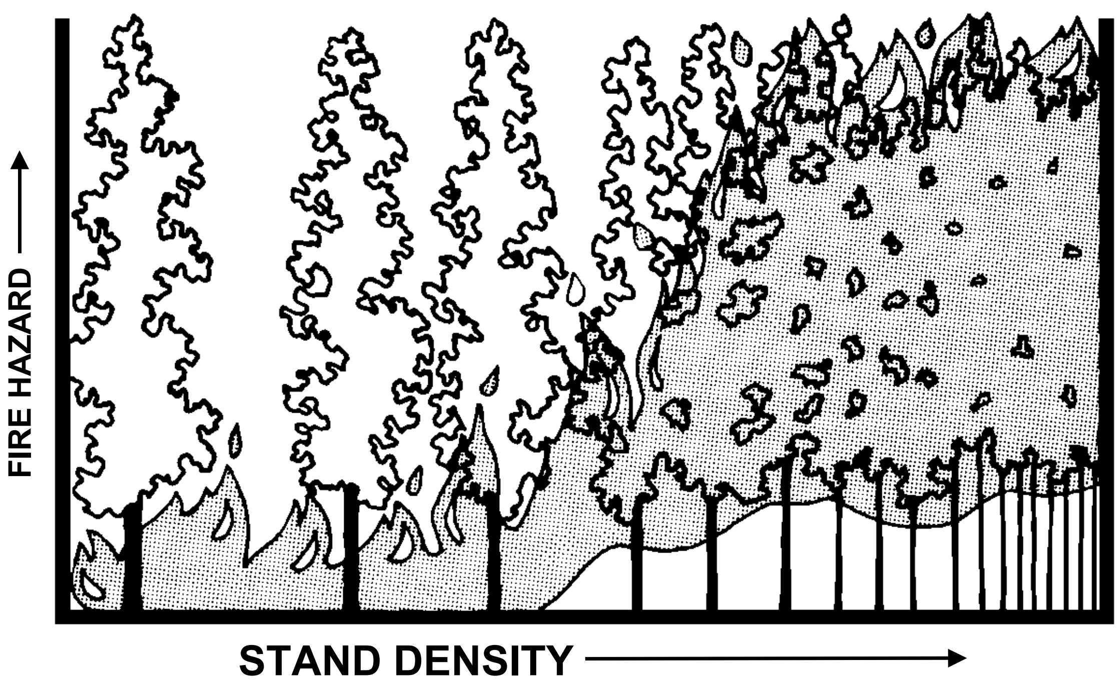

Figure 5 – Fire intensity can vary with stand density (from Powell 1994). When a fire moves through an open stand with widely-spaced trees, it generally stays on the ground as a low-intensity burn. But when it encounters a dense, closely-spaced stand, fire is much more likely to leave the ground and begin moving through the intermingled tree crowns as a lethal, high-severity burn. Agee (1996) recently developed stand density recommendations that were designed to minimize the potential for lethal crown fires.

DERIVATION OF THE STOCKING LEVEL INFORMATION

The remainder of this document provides information designed to meet the five objectives described on page 1 (see the introduction section). The information was developed as a series of figures and tables that characterize full-stocking stand densities, as well as suggested stocking levels for the upper and lower limits of the management zone. Appendix 2 portrays the stocking-level information in figures organized by tree species (a total of 28 figures, 4 each for 7 species). Appendix 3 provides the stocking-level information in tables grouped by forest *series* (one table for each of the seven tree species that occurs in the 44 upland-forest plant associations, for a total of 113 tables).

This section describes how appendixes 2 and 3 were developed, and provides further information to help users apply and interpret them. Stocking level information in the two appendixes was developed using the process described below.

1. The plant associations that occur on the Umatilla National Forest were identified. Since the stocking information contained in Cochran and others (1994) applies to upland forests only, plant associations for non-forested uplands or riparian forests were ignored. The upland forest plant associations occurring on the Umatilla National Forest were taken from Powell (1998) and are included in table 2.
2. Full-stocking SDI values were obtained for each of the upland-forest plant associations (table 2). They were derived from tables 1, 3 or 4 in Cochran and others (1994).
3. SDI values for the upper limit of the management zone (ULMZ) were calculated for each tree species occurring in each of the plant associations (table 2). ULMZ calculations were made according to instructions in Cochran and others (1994).
4. SDI values for the lower limit of the management zone (LLMZ) were calculated for each tree species occurring in each of the plant associations (table 2). Once again, LLMZ values were calculated using instructions from Cochran and others (1994).
5. SDI values for both the ULMZ and the LLMZ were expressed as two measures of stand density – trees per acre and basal area per acre. Those calculations were completed for a range of quadratic mean diameters (1 to 30 inches in variable increments) and for three stand structures – even-aged, irregular, and uneven-aged.
6. The trees per acre stand density values were used to calculate two measures of inter-tree distance – *equilateral spacing* and *square spacing*.
7. The basal area per acre stand density values were used to calculate two measures of forest canopy cover – unmanaged and managed.

Full Stocking Level. Full stocking refers to single-cohort (even-aged) stands where *differentiation* has resulted in a full range of *crown classes* – dominant, codominant, intermediate and suppressed trees are present (fig. 6). Full stocking implies high stand densities, at least within the context of a site's inherent capacity to support stocking (MacLean and Bolsinger 1973), so trees in fully-stocked stands compete with each other for water, sunlight, and mineral nutrients. If intense competition persists, density-related mortality eventually becomes serious, particularly for suppressed and intermediate trees (fig. 7).

Cochran and others (1994) developed full-stocking SDI values (see their tables 3 and 4) for each combination of tree species and plant association occurring in the Blue-Ochoco and Wallowa-Snake ecological provinces (Johnson and Clausnitzer 1992, Johnson and Simon 1987). The full-stocking SDIs were subsequently used to calculate the upper and lower limits of a management zone for each of the tree species except ponderosa pine and lodgepole pine.

In a few cases, the full-stocking SDI for a tree species–plant association combination was higher than the species maximum SDI shown in table 1 of Cochran and others (1994). In those instances, Cochran's full-stocking SDI was ignored and the species maximum SDI used in its place. Species maximum SDIs are shown in the column headings of table 2. The full-stocking SDI for each tree species–plant association combination occurring on the Umatilla National Forest is also provided in table 2.

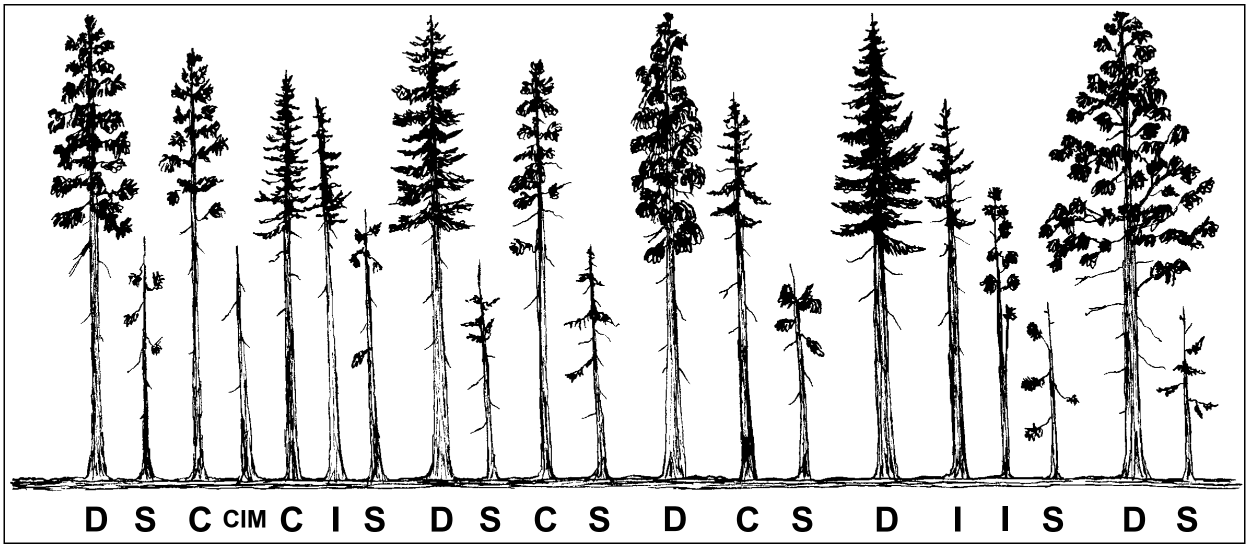

Figure 6 – Crown classes resulting from differentiation in a mixed-species, single-cohort stand (from Powell 1994). Crown classes classify a tree's position in the forest canopy. Dominant trees (D) have crowns that rise above the general canopy, where they enjoy full sunlight from above and, to a certain extent, from the sides. Codominant trees (C) are not quite as tall as dominants and their crowns may be hemmed in from the sides. Intermediate trees (I) occupy a subordinate position; they have competition from the sides, but usually receive some overhead sunlight through canopy holes. Suppressed trees (S) are overtopped entirely; if they can tolerate shade, they may survive on filtered sunlight for many decades (fig. 7). Suppressed trees of intolerant species quickly experience competition-induced mortality (CIM). Stratified (multi-storied) stands can also result from differential height growth rates, since intolerant species tend to grow faster than tolerant ones (Cobb and others 1992; O'Hara 1995).

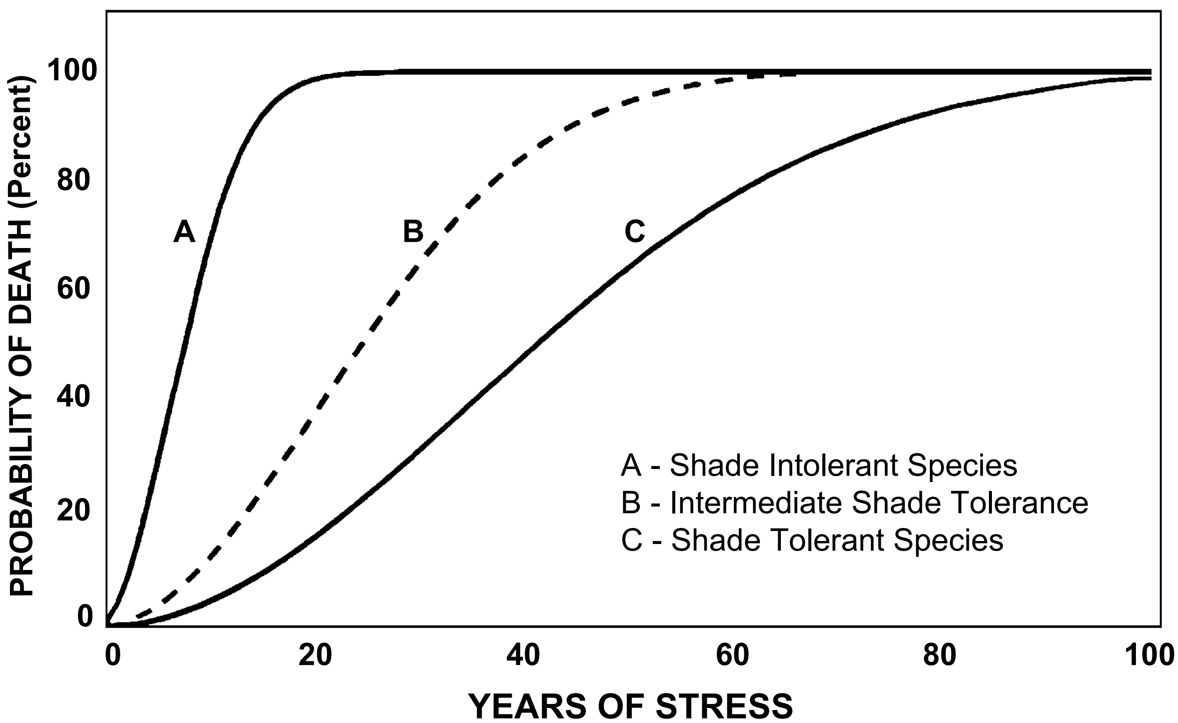

Figure 7 – Tree resistance to stress varies with shade tolerance (adapted from Keane and others 1996). Intolerant tree species (lodgepole pine, ponderosa pine, western larch) will die relatively quickly when exposed to the chronic stress associated with high stand densities. Trees with intermediate tolerance (Douglas-fir and western white pine) can withstand a longer period of stress without dying. Shade tolerant species (Engelmann spruce, grand fir, subalpine fir) can endure relatively long stress periods before experiencing mortality.

Table 2: Suggested stocking levels, by tree species, for upland-forest plant associations of the Umatilla NF (based on Cochran and others 1994).

PLANT ASSOCIATION	**PP** (MAX 365) FS	UZ	LZ	**DF** (MAX 380) FS	UZ	LZ	**WL** (MAX 410) FS	UZ	LZ	**LP** (MAX 277) FS	UZ	LZ	**ES** (MAX 469) FS	UZ	LZ	**GF** (MAX 560) FS	UZ	LZ	**SF** (MAX 416) FS	UZ	LZ
ABLA2/TRCA3										277	170♦	114♦	344	258	172				382	287	191
ABLA2/CLUN							410	308	205				469	352	235				416	312	208
ABLA2/LIBO2							410	308	205				379	284	190				335	251	168
ABLA2/MEFE																			416	312	208
ABLA2/VAME							382	287	191	255	170♦	114♦	382	287	191				265	199	133
ABLA2/VASC				366	275	183	380	285	190	277	170♦	114♦	366	275	183				365	274	183
ABLA2/VASC/POPU*				366	275	183	380	285	190	277	170♦	114♦	366	275	183				365	274	183
ABLA2/CAGE										277	170♦	114♦							372	279	186
ABGR/GYDR																553	415	277			
ABGR/POMU-ASCA3							350	263	175				469	352	235	486	365	243			
ABGR/TRCA3							398	299	199				388	291	194	554	416	277			
ABGR/ACGL				241	181	121	351	263	176				324	243	162	461	346	231			
ABGR/TABR/CLUN													426	320	213	560	420	280			
ABGR/TABR/LIBO2				380	285	190	302	227	151				299	224	150	560	420	280			
ABGR/CLUN				380	285	190	410	308	205	277	170♦	114♦	469	352	235	560	420	280			
ABGR/LIBO2	365	162	108	380	285	190	370	278	185	277	170♦	114♦	399	299	200	516	387	258	373	280	187
ABGR/VAME	292	139	93	380	285	190	410	308	205	238	170♦	114♦	341	256	171	455	341	228	412	309	206
ABGR/VASC-LIBO2				347	260	174	253	190	127	277	170♦	114♦	349	262	175	494	371	247	184	138	92
ABGR/VASC	172	101	68	274	206	137	304	228	152	277	170♦	114♦				368	276	184			
ABGR/SPBE	255	147	98	198	149	99										354	266	177			
ABGR/CARU	316	154	103	357	268	179	307	230	154	277	170♦	114♦				444	333	222			
ABGR/CAGE	210	109	73	301	226	151										560	420	280			
ABGR/BRVU							410	308	205				469	352	235	560	420	280			
PICO/CARU										223	167	112									
PSME/ACGL-PHMA*	281	189	127	277	208	139															
PSME/PHMA	274	167	112	225	169	113	256	192	128												
PSME/HODI	340	252	169	255	191	128															
PSME/SPBE*	353	226	152	371	278	186															
PSME/SYAL	273	151	101	247	185	124	205	154	103												
PSME/SYOR*	361	180	120																		
PSME/VAME	193	96	64	183	137	92															
PSME/CARU	263	122	82	264	198	132															
PSME/CAGE	222	86	58	281	211	141															
PIPO/SYAL	318	218	146																		
PIPO/SYOR	260	135	91																		
PIPO/CARU	365	154	103																		
PIPO/CAGE	201	82	55																		
PIPO/CELE/CAGE	232	82	55																		

Table 2: Suggested stocking levels, by tree species, for upland-forest plant associations of the Umatilla NF (CONTINUED).

	PP (MAX 365)			**DF** (MAX 380)			**WL** (MAX 410)			**LP** (MAX 277)			**ES** (MAX 469)			**GF** (MAX 560)			**SF** (MAX 416)		
PLANT ASSOCIATION	**FS**	**UZ**	**LZ**	**FS**	**UZ**	**LZ**	**FS**	**UZ**	**LZ**	**FS**	**UZ**	**LZ**	**FS**	**UZ**	**LZ**	**FS**	**UZ**	**LZ**	**FS**	**UZ**	**LZ**
PIPO/CELE/FEID-AGSP	157	32	21																		
PIPO/PUTR/CAGE	204	70	47																		
PIPO/PUTR/CARO	243	92	61																		
PIPO/PUTR/FEID-AGSP	185	66	44																		
PIPO/FEID	194	62	42																		
PIPO/AGSP	133	38	26																		

PLANT COMMUNITY TYPE (A SERAL OR SUCCESSIONAL STAGE OF A PLANT ASSOCIATION)	
ABGR/ACGL-PHMA*	Refer to stocking recommendations for the ABGR/ACGL plant association
ABGR/ARCO	Refer to stocking recommendations for the ABGR/CARU plant association
ABLA2/ARCO	Refer to stocking recommendations for the ABLA2/TRCA3 plant association
ABLA2/CARU*	No stocking recommendations are available for this community type
ABLA2/POPU*	Refer to stocking recommendations for the ABLA2/VASC/POPU plant association
ABLA2/STAM*	No stocking recommendations are available for this community type
ABLA2/STOC	Refer to stocking recommendations for the ABLA2/CAGE plant association
ABLA2-PIAL/POPU	No stocking recommendations are available for this community type
PICO(ABGR)/ALSI	Refer to stocking recommendations for the ABGR/CLUN plant association
PICO(ABGR)/ARNE	Refer to stocking recommendations for the ABGR/VAME plant association
PICO(ABGR)/VAME	Refer to stocking recommendations for the ABGR/VAME plant association
PICO(ABGR)/VAME/CARU	Refer to stocking recommendations for the ABGR/VAME plant association
PICO(ABGR)/VAME-LIBO2	Refer to stocking recommendations for the ABGR/LIBO2 plant association
PICO(ABGR)/VAME/PTAQ	Refer to stocking recommendations for the ABGR/VAME plant association
PICO(ABGR)/VASC/CARU	Refer to stocking recommendations for the ABGR/VASC plant association
PICO(ABLA2)/STOC	Refer to stocking recommendations for the ABLA2/CAGE plant association
PICO(ABLA2)/VAME	Refer to stocking recommendations for the ABLA2/VAME plant association
PICO(ABLA2)/VASC	Refer to stocking recommendations for the ABLA2/VASC plant association
PICO(ABLA2)/VASC/POPU	Refer to stocking recommendations for the ABLA2/VASC/POPU plant association
PIPO/SPBE*	No stocking recommendations are available for this community type
PSME/CELE/CAGE	No stocking recommendations are available for this community type

* Vegetation types from the Wallowa-Snake classification (Johnson and Simon 1987) whose stocking levels are based on Table 4 in Cochran and others (1994).

♦ ULMZ and LLMZ values were adjusted to account for mountain pine beetle risk in lodgepole pine (maximum SDI of 170 and a QMD of 9" or greater).

Column headings are:

PP	Ponderosa Pine	ES	Engelmann Spruce	UZ	Calculated SDI value for the upper limit of the management zone (ULMZ)
DF	Douglas-fir	GF	Grand Fir	LZ	Calculated SDI value for the lower limit of the management zone (LLMZ)
WL	Western Larch	SF	Subalpine Fir		
LP	Lodgepole Pine	FS	SDI value for the full stocking density (from table 3 or 4 in Cochran and others 1994)		

Notes: Maximum SDI values are provided next to each tree species code in the column headings (max values taken from table 1 in Cochran and others 1994). See appendix 1 for common and scientific plant names for the species codes that were used to name the plant associations and community types.

Upper Limit of the Management Zone (ULMZ). The word "management" implies that the management zone bears some relationship to land management objectives. That implication is correct; the management zone could vary depending on a manager's objectives and, in theory at least, a different zone could be established for each individual stand. The Cochran paper did not provide explicit SDI values for the limits of a management zone, although a process was described for how to calculate them.

Foresters would prefer to manage even-aged stands in a way that avoids the mortality typically associated with small trees in subordinate canopy positions. One way to accomplish that objective is to set an upper limit of the management zone that prevents development of a suppressed crown class. Cochran and others (1994) recommended just such a strategy since it would preclude significant amounts of self thinning (density-related) mortality.

Published research (Long 1985) has characterized certain stand development benchmarks or stocking thresholds as percentages of maximum density or full stocking. Those characterizations are summarized in table 3. Since the lower limit of the self-thinning zone is believed to be 75% of the full stocking density (table 3), the Cochran paper recommended that the upper limit of a management zone be set at the 75% level if a manager's objective is to avoid self-thinning mortality.

For five of the seven major tree species that occur in upland-forest plant associations of the Umatilla National Forest (Douglas-fir, western larch, Engelmann spruce, grand fir and subalpine fir), the upper limit of the management zone was calculated as 75% of the full-stocking density. The ULMZ values for those species are provided in table 2.

For the other two species (ponderosa and lodgepole pines), considerations related to mountain pine beetle susceptibility resulted in a different process for establishment of the ULMZ. For lodgepole pine, an absolute threshold was used – it consisted of an SDI of 170 for stands containing trees 9 inches or larger in diameter; see Cochran and others (1994), and the "effects of stand density on insects and diseases" section (page 2), for additional information related to this threshold. Table 2 includes the ULMZ values for lodgepole pine.

Table 3: Characterization of selected stand development benchmarks or stocking thresholds as percentages of maximum density and full stocking.

STAND DEVELOPMENT BENCHMARK OR STOCKING THRESHOLD	PERCENT OF MAXIMUM DENSITY	PERCENT OF FULL STOCKING
Maximum Density	100%	125%
Full Stocking (Normal Density)	80%	100%
Lower Limit of Self Thinning Zone*	60%	75%
Upper Limit of the Management Zone	60%	75%
Live Tree Crown Ratio of 40 Percent	50%	~63%
Lower Limit of the Management Zone	~40%	50%
Lower Limit of Full Site Occupancy	35%	~45%
Onset of Competition/Crown Closure	25%	~30%

* This threshold has also been referred to as the "zone of imminent competition mortality" (Drew and Flewelling 1979).

Sources/Notes: *Maximum density* is the maximum stand density observed for a tree species; although rare in nature, it represents an upper limit. *Full stocking* refers to "normal" yield table values published in sources such as Meyer (1961); it has also been termed "average maximum" density. "Percent of maximum density" values are based on Long (1985) or were calculated; "percent of full stocking" values are based on Cochran and others (1994) or were calculated.

An absolute threshold was not appropriate for ponderosa pine, and ULMZ calculations were based on site quality information (site index values) as described in Cochran and others (1994; see page 7). The methodology and results of those calculations are described in table 4. The ULMZ values for ponderosa pine are included in table 2.

Lower Limit of the Management Zone (LLMZ). As was described for the ULMZ, the lower limit of the management zone can also relate to land management objectives. For example, residual stocking levels for a commercial thinning might need to be less than the LLMZ to avoid logging-related tree damage or to facilitate slash treatment (Cochran and Oliver 1988). Once again, the Cochran paper did not provide explicit SDI values for the LLMZ, although a process was described for how to calculate them.

Stand density management typically represents a compromise between total volume production and individual tree growth because both objectives cannot be optimized simultaneously; in other words, maximum gross volume production is incompatible with maximum individual tree growth, and vice versa (Daniel and others 1979a, Long 1985). Although some objectives could be favored by the very low stand densities that maximize individual tree growth, many others are compatible with a stocking level that allows a substantial portion of a site's resources to be captured as tree growth. Because of a desire to maintain full site occupancy and maximize volume production, foresters have often been unwilling to cut enough trees in a thinning to allow the remaining trees to grow vigorously (Cochran and Barrett 1993, Oliver and Larson 1996).

The Cochran paper recommended that the lower limit of the management zone be established in such a way as to "capture a significant portion of the site resources in tree growth." Since that objective would be met by a stand development benchmark called the *lower limit of full site occupancy* (table 3), it was used as the basis for the LLMZ. Table 3 shows that the lower limit of full site occupancy is approximately 45% of full stocking; however, a value of 50% was actually used for the LLMZ calculations because it was recommended in the Cochran paper. [Even though the two percentages differ slightly, it must be emphasized that Cochran and others (1994) intended for the lower limit of the management zone to coincide with the lower limit of full site occupancy.]

For five of the seven major tree species that occur in upland-forest plant associations of the Umatilla National Forest (Douglas-fir, western larch, Engelmann spruce, grand fir and subalpine fir), the lower limit of the management zone was calculated as 50% of the full-stocking density. The LLMZ values for those species are provided in table 2.

For the other two species (ponderosa and lodgepole pines), the LLMZ values could not be calculated as a percentage of full stocking because that process was not used for the ULMZ calculations and it is important to maintain a consistent relationship between the two stocking levels. Since the LLMZ represents 67% of the ULMZ for the other five species, the calculations were made in the same way for lodgepole and ponderosa pines – the LLMZ values are 67% of the ULMZ values. The LLMZ values for lodgepole and ponderosa pines are included in table 2.

Adjustments Related to SDI Calculation Method. Reineke (1933) developed his stand density index using even-aged, fully-stocked, single-species stands. One of the advantages of SDI, however, is that it is directly proportional to site utilization and growing-space occupancy (Daniel and others 1979a) and can therefore be used with stands that are not even-aged or pure (Cochran 1992; Long 1995, 1996; Long and Daniel 1990; O'Hara and Valappil 1995, Stage 1968).

The original method of calculating SDI (Reineke 1933) is referred to as the Dq method (Diameter-quadratic) because it utilizes stand averages – all that is needed for the calculation is the total number of trees per acre and the quadratic mean diameter of a stand. But since it is legitimate to calculate SDI for individual stand components such as cohorts or diameter classes, and then add them together for an approximate stand total (Daniel and others 1979a, 1979b), an alternative calculation method was developed for stands without a normal (bell-shaped) diameter distribution – the Dsum method (Diameter-summation).

Table 4: Derivation of the upper and lower limits of the management zone (ULMZ; LLMZ) for ponderosa pine, calculated for each of the plant associations in which it occurs.

Plant Association	Meyer Site Index	Barrett Site Index	Apparent ULMZ	Full Stocking	Actual ULMZ	LLMZ
ABGR/CAGE	80	88.0	189.8	210	109	73
ABGR/CARU	77	84.7	177.8	316	154	103
ABGR/LIBO2	73	80.3	161.7	365	162	108
ABGR/SPBE	85	93.5	209.9	255	147	98
ABGR/VAME	76	83.6	173.7	292	139	93
ABGR/VASC	86	94.6	213.9	172	101	68
PSME/ACGL-PHMA	94	103.4	246.0	281	189	127
PSME/CAGE	68	74.8	141.6	222	86	58
PSME/CARU	75	82.5	169.7	263	122	82
PSME/HODI	107	117.7	270.1*	340	252	169
PSME/PHMA	88	96.8	221.9	274	167	112
PSME/SPBE	91	100.1	234.0	353	226	152
PSME/SYAL	83	91.3	201.8	273	151	101
PSME/SYOR	78	85.8	181.8	361	180	120
PSME/VAME	78	85.8	181.8	193	96	64
PIPO/AGSP	59	64.9	105.5	133	38	26
PIPO/CAGE	70	77.0	149.7	201	82	55
PIPO/CARU	71	78.1	153.7	365	154	103
PIPO/CELE/CAGE	65	71.5	129.6	232	82	55
PIPO/CELE/FEID-AGSP	51	56.1	73.4	157	32	21
PIPO/FEID	62	68.2	117.5	194	62	42
PIPO/PUTR/CAGE	64	70.4	125.6	204	70	47
PIPO/PUTR/CARO	67	73.7	137.6	243	92	61
PIPO/PUTR/FEID-AGSP	65	71.5	129.6	185	66	44
PIPO/SYAL	95	104.5	250.0	318	218	146
PIPO/SYOR	80	88.0	189.8	260	135	91

Plant Association	Abbreviation for the plant association name; from Table 3 or 4 in Cochran and others (1994).
Meyer Site Index	Site index value calculated using Meyer's curves (Meyer 1961); taken from Table 3 or 4 in Cochran and others (1994).
Barrett Site Index	Conversion of Meyer's site index value to Barrett's site index value (Barrett 1978); Meyer's site index multiplied by 1.1 = Barrett's site index.
Apparent ULMZ	Calculated SDI value for the ULMZ using equation 3 from Cochran and others (1994, page 4); values with an * are 74% of the species maximum SDI (365) and pertain to associations where Barrett's site index exceeds 110 (page 7 in Cochran and others 1994).
Full Stocking	SDI value from Table 3 or 4 in Cochran and others (1994).
Actual ULMZ	Obtained by multiplying the "Apparent ULMZ" SDI value by an adjustment fraction (Af), which is the full stocking SDI for a plant association (210 for ABGR/CAGE) divided by the species maximum SDI for ponderosa pine (365).
LLMZ	Although Cochran and others (1994) were moot about how to calculate the LLMZ SDI value for ponderosa pine, it was assumed to be 67% of the ULMZ SDI value.

Long (1995) recently evaluated the difference between the Dq and Dsum methods by using them to calculate SDI for three different stand structures – even-aged, a bi-modal or *two-storied structure*, and a balanced uneven-aged stand. The results of his analysis are provided in figure 8. It shows that an SDI value pertaining to an even-aged stand (calculated using the Dq method) should be reduced by a certain percentage before attempting to use it with irregular or uneven-aged stands because SDIs for those structures are best calculated using the summation (Dsum) method (Long 1995, 1996; Shaw In press).

Long's (1995) analysis involved hypothetical stand structures. On the Umatilla National Forest, very few stands fit his hypothetical structure for a two-storied stand, and yet there are many stands that are neither even-aged nor perfectly uneven-aged. To address that situation, an SDI analysis was completed for three historical, large-area plots from the central and northern Blue Mountains (Munger 1917). The results of that analysis are provided in figure 9. Munger's plots typify the irregular structure associated with mature, unmanaged stands on dry-forest sites in the Blue Mountains.[2]

The tables providing stocking levels by plant association and tree species (appendix 3) include a trees per acre and a basal area per acre value pertaining to an even-aged stand structure; they were calculated using instructions from appendix 2 of Cochran and others (1994). Appendix 3 also provides that information for irregular and uneven-aged stand structures, but it was calculated by reducing the even-aged values by one of the percentages shown in figures 8 and 9 (e.g., 6% or 7% for an irregular structure and 13% for an uneven-aged structure) to account for differences between the Dq and Dsum SDI calculation methods.

Note that when using SDI to regulate an irregular or uneven-aged stand structure, silviculturists should not make the calculations using the SDI equation from Cochran and others (1994, equation 2 on page 3) because it pertains to even-aged stands only. When working with irregular, two-storied, or uneven-aged stands, SDI can be approximated using the Dsum method as described by Cochran (1992), Long (1996), or Long and Daniel (1990). An example of the two SDI calculation methods is provided in table 5.

Basal Area Considerations. Stand density index is more sensitive to tree size than is basal area, a commonly used measure of absolute stand density (Daniel and others 1979a). For example, consider two even-aged ponderosa pine stands, each with an SDI of 200: one has a QMD of 8 inches, 298 trees per acre and 104 square feet per acre of basal area, whereas the other has a QMD of 22 inches, 50 trees per acre and 132 square feet per acre. Even though both stands represent equivalent site utilization or growing space occupancy (i.e., both have an SDI of 200), one has 28 more square feet of basal area than the other.

A steadily increasing amount of basal area for a constant SDI level is also exhibited in the tables in appendix 3. That phenomenon has been confusing to some users of SDI-based stocking level information. It can be explained this way: not all square feet of basal area are equal from a site occupancy perspective; a higher SDI (representing greater site utilization) is associated with a square foot of basal area when it occurs in small trees than in large ones (table 6). For example, table 6 shows that the SDI associated with one square foot of basal area in 4-inch Douglas-fir trees is more than twice that of a square foot of basal area in 24-inch trees (2.87 vs. 1.19; Douglas-fir SDI/Sq Ft. column in table 6).

Several reasons have been postulated for this relationship between basal area and SDI. Long and Smith (1984) believe that SDI is directly related to foliar biomass, which in turn is related to a stand's sapwood area (sapwood is the outer living portion of a tree bole that supplies the foliage with water). As trees develop, the proportion of sapwood to total basal area changes; small trees have a higher proportion of sapwood (and less heartwood) than large trees. This makes sense from a functional or physiological perspective because large trees require more mechanical support than small trees, and much of that support is provided by heartwood tissue with its high component of lignin, and because large trees tend to have less transpiring foliage (on a proportional basis) than small trees.

[2] Munger's data, which was collected in 1910-1911, provides a quantified characterization of historical or "presettlement" stand conditions. Current conditions, however, are markedly different following almost ninety years of fire suppression and at least fifty years of selective harvesting. For example, when two forest inventory plots located near Munger's Austin-Whitney sample area were measured in 1980, they showed dramatic increases in stand density (trees per acre) and stand density index, and substantial decreases in quadratic mean diameter and the number of large trees per acre, when compared with Munger's sample data (Powell 1994).

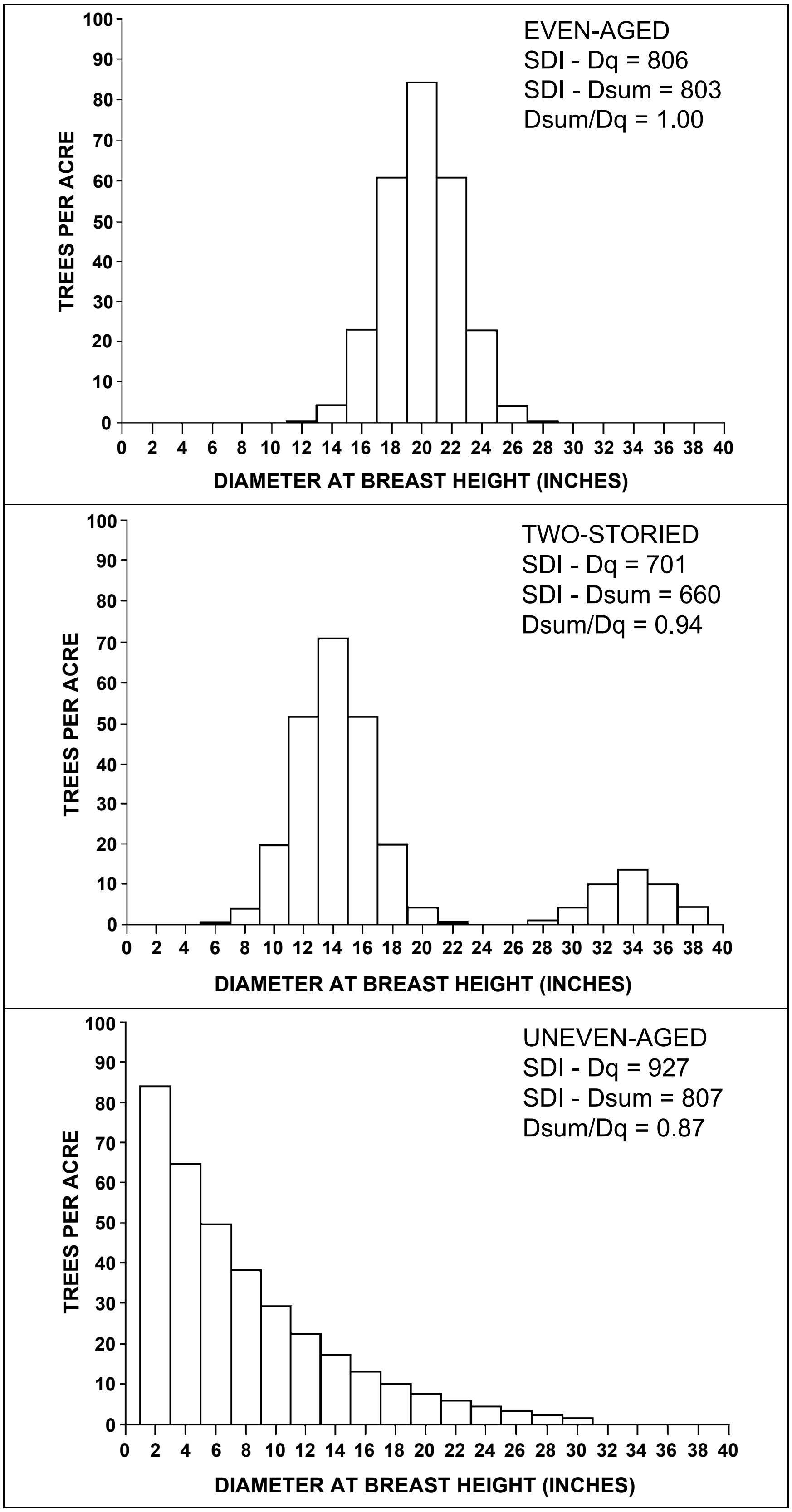

Figure 8 – SDI calculations for three hypothetical stand structures (adapted from Long 1995). This figure shows Dq and Dsum SDI calculations for three stand structures, and shows the Dsum/Dq fraction for each.

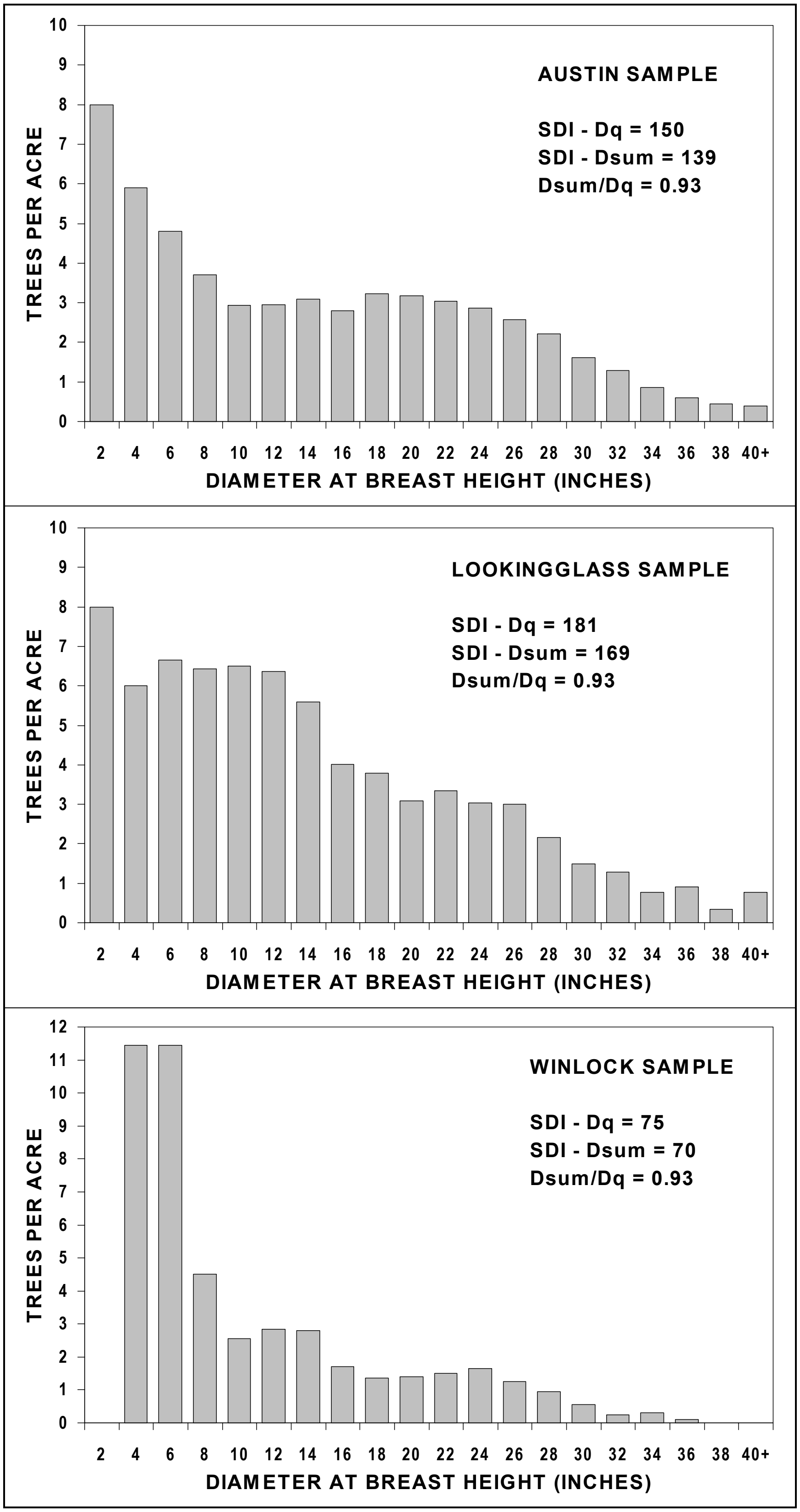

Figure 9 – SDI calculations for three sample areas in the Blue Mountains (data from Munger 1917). This figure shows Dq and Dsum SDI calculations for mature stands with an irregular structure; they were sampled in 1910-1911.

Table 5: SDI calculations, using the Dsum and Dq methods, for the Lookingglass sample.

1	2	3	4	5	6	7	8	9	10	11
DBH	**BA/**	**PONDEROSA PINE**			**OTHER SPECIES**			**GRAND TOTAL**		
CLASS	**TREE**	**TPA**	**BAA**	**SDI**	**TPA**	**BAA**	**SDI**	**TPA**	**BAA**	**SDI**
2	0.02	4.0	0.1	0.2	4.0	0.1	0.4	8.0	0.2	0.6
4	0.09	3.0	0.3	0.6	3.0	0.3	0.8	6.0	0.5	1.3
6	0.20	3.1	0.6	1.3	3.6	0.7	1.6	6.7	1.3	2.9
8	0.35	5.0	1.8	3.4	1.4	0.5	1.0	6.4	2.2	4.4
10	0.55	5.1	2.8	5.1	1.4	0.8	1.4	6.5	3.5	6.5
12	0.79	5.3	4.1	7.3	1.1	0.9	1.4	6.4	5.0	8.7
14	1.07	4.5	4.8	8.2	1.1	1.1	1.8	5.6	6.0	10.0
16	1.40	3.4	4.8	7.9	0.6	0.8	1.2	4.0	5.6	9.1
18	1.77	3.3	5.9	9.5	0.5	0.8	1.1	3.8	6.7	10.5
20	2.18	2.5	5.5	8.6	0.6	1.2	1.6	3.1	6.7	10.2
22	2.64	2.9	7.5	11.5	0.5	1.3	1.6	3.3	8.8	13.1
24	3.14	2.8	8.6	13.0	0.3	0.9	1.1	3.0	9.6	14.0
26	3.69	2.7	9.9	14.5	0.3	1.2	1.4	3.0	11.1	15.9
28	4.28	2.1	8.9	12.8	0.1	0.4	0.4	2.2	9.2	13.2
30	4.91	1.4	6.9	9.9	0.1	0.4	0.5	1.5	7.4	10.3
32	5.59	1.2	6.8	9.5	0.1	0.4	0.4	1.3	7.1	9.9
34	6.30	0.7	4.3	5.9	0.1	0.6	0.6	0.8	4.9	6.5
36	7.07	0.8	5.7	7.7	0.1	0.8	0.8	0.9	6.4	8.5
38	7.88	0.3	2.0	2.7	0.1	0.7	0.7	0.3	2.7	3.3
40	8.73	0.4	3.1	4.2	0.0	0.0	0.0	0.4	3.1	4.2
42	9.62	0.1	1.3	1.8	0.0	0.0	0.0	0.1	1.3	1.8
≥43	10.56	0.3	2.9	3.7	0.0	0.0	0.0	0.3	2.9	3.7
TOTAL		54.8	98.5	149.2	18.8	13.8	19.6	73.6	112.3	168.8
SDI–Dq Method				**157.5**			**23.5**			**181.0**

COLUMN	DESCRIPTION (NOTE THAT * WHEN USED BELOW REFERS TO MULTIPLICATION)
1	Midpoint of the diameter class, in inches; used as a QMD for Dsum SDI calculations.
2	Basal area per tree, in square feet (column 1 squared * 0.00545415).
3	Trees per acre (TPA) for ponderosa pine; from Munger (1917), page 20.
4	Basal area per acre (BAA) for ponderosa pine (column 2 * column 3).
5	Stand density index (SDI) for ponderosa pine (col. 3 * Power(10/QMD,-1.77)).
6	Trees per acre for other species; from Munger (1917), page 20.
7	Basal area per acre for other species (column 2 * column 6).
8	Stand density index for other species (col. 6 * Power(10/QMD,-1.51)).
9	Trees per acre for all species combined; column 3 + column 6.
10	Basal area per acre for all species combined; column 4 + column 7.
11	Stand density index for all species combined; column 5 + column 8.
SDI–Dq	SDI–Dq was calculated: Total TPA (54.8) * Power(10/QMD,-1.77) for ponderosa pine (PP); Total TPA (18.8) * Power(10/QMD,-1.51) for other species (OS); and PP SDI + OS SDI for Grand Total. The Douglas-fir SDI coefficient was used for other species. QMD calculations for both PP and OS: Power(Total BAA/Total TPA,0.5) * 13.54.

Sources/Notes: This data pertains to a plot measured in 1910 or 1911 in the Lookingglass Creek area of Union County, Oregon (Munger 1917). The plot area covered 44 acres and was described as "stands with about 5 percent of other species, growing in coves and on gentle slopes at an altitude of 3,200 feet. Climate: more humid than is usual at that elevation in the Blue Mountains. Soil: good, deep, loamy, decomposed lava." The top half of this table shows SDI calculations using the Dsum method (SDI calculated by DBH Class with the class mid-point used as a QMD); the middle of the table shows SDI values calculated by the Dq approach (using stand totals).

Table 6: SDI per tree, and per square foot (Sq Ft.) of basal area, by tree species and 2-inch diameter classes.

DBH	PONDEROSA PINE		DOUGLAS-FIR		WL/GF/SF/ES		LODGEPOLE PINE	
CLASS	SDI/Tree	SDI/Sq Ft.	SDI/Tree	SDI/Sq Ft.	SDI/Tree	SDI/Sq Ft.	SDI/Tree	SDI/Sq Ft.
2	0.06	2.65	0.09	4.03	0.06	2.83	0.06	2.79
4	0.20	2.26	0.25	2.87	0.20	2.35	0.20	2.33
6	0.40	2.06	0.46	2.35	0.41	2.10	0.41	2.09
8	0.67	1.93	0.71	2.05	0.68	1.95	0.68	1.94
10	1.00	1.83	1.00	1.83	1.00	1.83	1.00	1.83
12	1.38	1.76	1.32	1.68	1.37	1.75	1.37	1.75
14	1.81	1.70	1.66	1.55	1.79	1.67	1.80	1.68
16	2.30	1.65	2.03	1.46	2.25	1.61	2.27	1.62
18	2.83	1.60	2.43	1.37	2.76	1.56	2.78	1.57
20	3.41	1.56	2.85	1.31	3.32	1.52	3.34	1.53
22	4.04	1.53	3.29	1.25	3.91	1.48	3.94	1.49
24	4.71	1.50	3.75	1.19	4.55	1.45	4.59	1.46
26	5.43	1.47	4.23	1.15	5.22	1.42	5.27	1.43
28	6.19	1.45	4.73	1.11	5.94	1.39	6.00	1.40
30	6.99	1.42	5.25	1.07	6.69	1.36	6.76	1.38

Sources/Notes: Adapted from Fiedler and Cully (1995). This data shows that not all square feet of basal area are equal from a site utilization standpoint because a higher SDI is associated with a square foot of basal area when it occurs in small trees than in large ones. Note that "WL/GF/SF/ES" refers to western larch, grand fir, subalpine fir, and Engelmann spruce; those species are combined because they have the same exponent coefficient for the SDI equation (see table 1 and equation 2 on page 3 in Cochran and others 1994). Ponderosa pine, Douglas-fir and lodgepole pine have unique coefficients, so their values for SDI/Tree and SDI/Sq Ft. differ from those for the other four species. "DBH Class" refers to tree diameter at breast height (4½ feet), in inches.

If SDI is more sensitive to site utilization and growing-space occupancy than basal area, then why was basal area included in appendixes 2 and 3? Basal area was calculated for both the upper and lower limits of the management zone because it is a density measure familiar to foresters and in common usage; it is easily applied and estimated in the field; it may be the only estimate of stand density available for some types of inventory data (low-intensity stand exams, etc.); and it is commonly used to monitor or evaluate stand treatment marking.

Calculation of Inter-Tree Distance. Silviculturists generally use stocking level recommendations when preparing a *silvicultural prescription* and an associated *marking guide* for a thinning or another intermediate stand treatment (Mahoney and others 1980). One item often included in a prescription or marking guide is an estimate of inter-tree distance, an important attribute of the post-treatment (residual) stand. To meet that need, two measures of inter-tree distance were calculated so that users could visualize the average tree spacing associated with the suggested stocking levels for any particular quadratic mean diameter; however, it was not intended that spacings could be followed sequentially during management because that would require physically moving the trees.

Square spacing assumes that tree crowns occupy the center of adjoining squares (fig. 10). This model of tree arrangement is most compatible with young stands (those comprised mostly of seedling- and sapling-sized trees) and, consequently, recommended tree planting densities for the Pacific Northwest have generally assumed a square-spacing distribution (Cleary and others 1978). The regular geometric pattern resulting from the square-spacing approach also provides certain operational advantages, such as easier administration and inspection of tree planting contracts.

Equilateral spacing assumes that trees occupy adjacent hexagons (fig. 10). This model of tree distribution is most representative of mature stands (those with pole-sized trees and larger). As tree stands develop, even those originating as plantations on a square-spacing pattern, tree spacing gradually evolves to an equilateral arrangement because it best represents normal crown architecture (Oliver and Larson 1996). Under a hexagonal spacing arrangement, imaginary lines connecting the centers of three adjacent trees form an equilateral triangle (fig. 10), so equilateral spacing is also referred to as triangular spacing.

The tables providing suggested stocking levels by plant association and tree species (appendix 3) include an equilateral spacing distance for both the ULMZ and the LLMZ. For lodgepole pine, a square spacing was also calculated because lodgepole stands are often managed at small quadratic mean diameters and the square spacing figures are helpful for thinning prescriptions. Spacing calculations were always based on an even-aged stand structure because it presumably has the most consistent tree spacing relationship; the spacing values would not apply to trees left in clumps or other irregular arrangements.

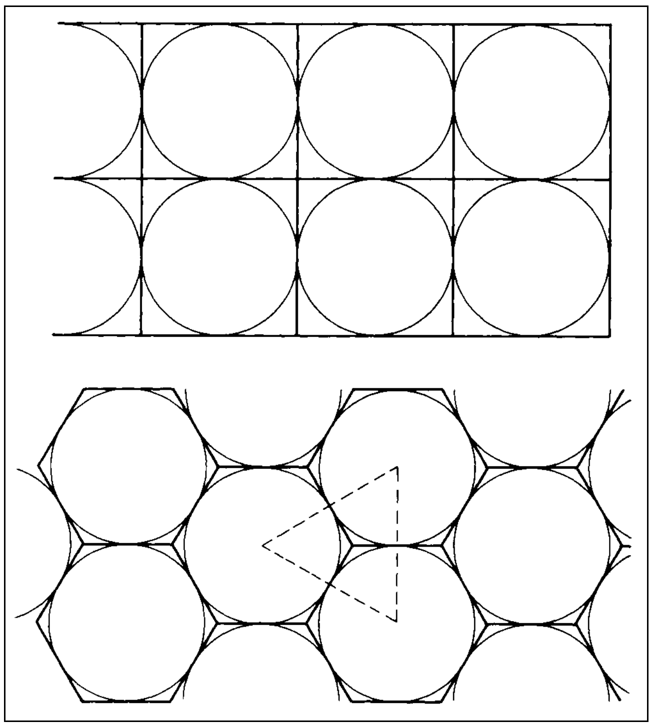

Figure 10 – Two measures of tree spacing (from Smith and others 1997). The top portion shows a square spacing arrangement where each tree crown (the circles) occupies the center of an adjacent square. The bottom portion shows an equilateral spacing arrangement where each crown occupies the center of an adjacent hexagon. When imaginary lines are used to connect the centers of three adjoining, similar-sized trees in an hexagonal arrangement, an equilateral triangle is the result (depicted by the dashed lines).

Calculation of Forest (Tree) Canopy Cover Percentages. When a density management objective is formulated for a stand, it is typically described in absolute terms such as trees per acre or basal area per acre. Often, it is helpful to be able to translate a stand density objective into an equivalent amount of forest canopy cover. For example, many wildlife objectives have been articulated as forest canopy cover percentages, particularly those relating to elk or deer habitat (Thomas 1979). Recent recommendations regarding landscape-level connectivity corridors for an old-growth forest network in the Blue Mountains were also expressed as canopy cover percentages (Noss and Cooperrider 1994).

Inventory information is used to prepare assessments of watersheds, landscapes, entire National Forests, and other mid- or broad-scale land areas. Dating back to the early 1990s, inventory budgets have been steadily declining, quickly resulting in increased use of low-resolution, broad-scale data sources. Fewer stand examinations or other high-resolution surveys were available, so assessment efforts relied increasingly on interpretation of aerial photography, satellite imagery, and other remotely-sensed data.

Ground-based surveys generally provide detailed information about stand density (trees per acre, basal area per acre, etc.), whereas remote-sensing sources do not. Remote-sensing sources, however, do provide canopy cover information that can be used as a surrogate for stand density. Therefore, if stocking-level recommendations could be translated into their corresponding canopy cover percentages, then it would be possible to conduct a stand density analysis during mid- or broad-scale assessments.

To meet the need described above, equations developed during an elk thermal cover study (Dealy 1985) were used to calculate forest (tree) canopy cover percentages for the suggested stocking levels. Dealy (1985) sampled 609 unmanaged tree stands throughout the Blue and Ochoco Mountains; "no evidence of tree removal" was his only criterion for identification of unmanaged stands. He stratified the sample into five broad "cover type" groups and then developed mathematical formulas (one for each group) that related basal area per acre to a forest (tree) canopy cover percentage.

The tables providing suggested stocking levels by plant association and tree species (appendix 3) include forest (tree) canopy cover percentages for both the ULMZ and the LLMZ. For lodgepole pine, two canopy cover values were calculated for each limit of the management zone – one pertaining to unmanaged stands, and another for managed stands (defined as those thinned early in life, before attaining an average height of nine feet). The managed-stand canopy cover calculation was based on results from a research study involving young, thinned lodgepole pine in the Anthony Lakes area of the Blue Mountains (Cochran and Dahms 1998).

For Douglas-fir, ponderosa pine, Engelmann spruce, grand fir, and subalpine fir, forest canopy cover values pertain to an irregular stand structure because it best reflects the unmanaged stands that Dealy (1985) sampled. For lodgepole pine and western larch, canopy cover values pertain to an even-aged stand structure because unmanaged stands tend to be even-aged for those two species.

APPLICATION OF STOCKING LEVEL INFORMATION

Thinning and Other Density-Management Treatments. To grow well, a tree needs a place in the sun and some soil to call its own. As a stand of trees occupies all of its growing space, competition causes the death of some trees and then the survivors compete for growing space relinquished after the demise of their neighbors (Long and Dean 1986). Thinnings mimic this natural tendency for a few large trees to ultimately occupy the space that once supported many small trees. Thinnings that anticipate density-related (competition-induced) mortality by removing trees from beneath the main canopy are called a *low thinning* or thinning from below (Smith and others 1997).

Thinnings were being used in some parts of Germany as early as the sixteenth century. They became a common silvicultural practice throughout much of Europe by the latter half of the eighteenth century. Hartig and other early German foresters were "intensely conservative" in their application of thinning (in terms of the number of trees being removed); unfortunately, that same conservatism eventually carried over into American forestry (Hubbard 1904).

As the twentieth century began, it was widely recognized in the United States that "light thinning neither gives a very paying intermediate yield, nor greatly improves the growth and quality on the final stand." It was also recognized that maintaining overly-dense stands in order to stimulate juvenile height growth, which had long been a commonly-held belief, was unnecessary because "a reasonable amount of room [between trees] not only increases the diameter, but also the height" (Hubbard 1904).

By reducing the number of trees on a site and opening up a stand, more sunlight, water and nutrients are made available for the residual trees. Research from the Blue Mountains consistently found substantial increases in tree growth following a low thinning. This result was obtained for thinned stands of western larch (Seidel 1987), ponderosa pine (Cochran and Barrett 1993, 1995) or lodgepole pine (Cochran and Dahms 1998). Research from central Oregon showed a similar response for thinned stands of Douglas-fir, grand fir, western white pine *(Pinus monticola)* or Engelmann spruce (Seidel and Cochran 1981).

Thinning can reduce stand susceptibility to certain insects and diseases (Hessburg and others 1994, Oliver and others 1994, Pitman and others 1982). Trees respond to a thinning by producing more foliage and by developing a higher level of root reserves, both of which improve their ability to resist and recover from insect and disease problems. For example, trees remaining after a thinning have increased vigor, which allows them to produce more resin and better repel bark beetle attacks (Safranyik and others 1998).

Log quality and product merchantability can also be influenced by *density management* decisions. Although thinnings cannot eliminate branches or their resultant knots, they can be used to control their size. For lodgepole pine, branch sizes of two inches or less are produced by stand densities of at least 120 trees per acre, whereas branches of one inch or less result from an initial stand density of 500 trees per acre or more. This means that silviculturists can exert some control on branch size by how they prescribe *pre-commercial thinnings* and other silvicultural treatments (Ballard and Long 1988).

Prescribed fire has recently been proposed as a possible replacement for mechanical thinning. A recent survey by Oregon State University, however, showed a stronger public preference for thinning (79% of respondents) than for prescribed fire (20%) as a way to address forest health concerns in the Blue Mountains (Shindler and Reed 1996). On forest sites in eastern Washington, residual trees increased growth following surface fires which killed intermediate and suppressed trees, but growth increases were greater when the forest was thinned by manual cutting. Unlike fire, manual thinning did not damage roots, so residual trees reoccupied the growing space quickly. After *overstory* trees appropriated the additional growing space provided by a thinning, grasses did not readily invade (Oliver and Larson 1996).

Silvicultural Planning. When reduced to its essence, silviculture is little more than application of ecological leverage – it provides an opportunity to favor one tree species or genotype over another, to produce a desired configuration of vertical or horizontal stand structure, or to influence a variety of stand development processes in order to achieve land management objectives. Manipulation of stand density may well be the most powerful tool available to the silviculturist for applying that ecological leverage.

Silviculturists have historically used SDI or another relative-density index when prescribing treatments for even-aged stands, but SDI is also a practical option for regulating other types of stand structure (Cochran 1992, Long 1996). The SDI concept assumes that relative density is directly proportional to site utilization (Curtis 1970), so it is legitimate to calculate SDI for individual components (diameter classes, *cohorts*, etc.) and then sum them to derive an approximate stand total (Daniel and others 1979a, 1979b). If SDI was not additive, it would be inappropriate to use it with stand structures other than those with an even-aged diameter distribution (Long and Daniel 1990).

Stocking level information has always been central to the practice of silviculture and to forest management in general. Clear, easily-applied information about size–density interactions, indexes of stand density, growth–growing stock relationships, and stand density management can help silviculturists prepare prescriptions that best meet the vegetation management objectives of an area. Four examples of how silviculturists could use the stocking level information in this guide are described below.

1. **Formulation of tree planting densities.** The suggested stocking levels vary by plant association, which means they reflect the ecological "carrying capacity" of a site to support tree density. Traditionally, silviculturists have tended to be conservative, often planting more trees than are necessary in order to "hedge their bets" for the future (Oliver and Larson 1996). But when a silviculturist uses ecologically-based stocking information to develop reforestation recommendations, it is much more

likely that they will be closely matched to the inherent stockability of a planting site. Such an approach would also reduce the risk of planting more or fewer trees than are needed to fully occupy the growing space. An example of how a stocking level (the lower limit of the management zone) could be used to formulate tree planting densities is provided in table 7.

2. **Avoidance of stagnation.** When ideal site and environmental conditions happen to coincide with abundant seed production, extremely dense tree stands are often the result (Mowat 1953). In a dense stand established on a uniform site, the trees grow normally until crown closure and full site occupancy occurs. At that point, most trees are about the same size and one tree is not able to take growing space away from another because neither of them has a competitive advantage. Eventually, all of a tree's *photosynthate* is consumed for its own respiration and growth essentially ceases. Stands where this has occurred, and yet the trees are still alive, are considered to be stagnant. *Stagnation* is particularly prevalent for lodgepole pine and ponderosa pine in the Blue Mountains of northeastern Oregon and southeastern Washington (Hall 1984). Stagnation potential is highest for poor (low productivity) sites and in stands with very high tree densities (Oliver and Larson 1996). Lodgepole pine stands with high densities should be thinned early (by age 10) to avoid stagnation (Lotan and Critchfield 1990). Delaying or bypassing an early thinning could result in unreleasable stagnation and improper stand development from that point onward. Ponderosa pine, however, is more apt than lodgepole pine to remain physiologically young; stagnated ponderosa pine stands have responded to release at ages of 70 to 100 years with no apparent ill effect (Oliver and Ryker 1990). Perhaps the best way to prevent stagnation, particularly for susceptible species growing on poor, droughty sites prone to insect outbreaks and wildfires, is to maintain stand densities at a level below the upper limit of the management zone (Oliver and others 1994).
3. **Maintenance of a balanced height to diameter ratio.** A tree allocates photosynthate to different needs in an order of priorities. Height growth has a higher priority than diameter growth (Oliver and Larson 1996). This means that high-density, low-vigor stands may eventually develop tall, spindly trees because height growth continues even after diameter growth slows or stops. Such trees have an unbalanced height to diameter ratio and are called "wet noodles" because they can't support themselves and tend to experience snow breakage or just fall over if adjacent support trees are removed or die. In the Inland Northwest United States, trees with a height to diameter ratio of 80 or more are at risk of becoming wet noodles. Perhaps the best way to avoid an unbalanced height to diameter ratio is to use thinning or another density management treatment to maintain stand densities at a level below the upper limit of the management zone, thereby ensuring that sufficient photosynthate is available for diameter growth (Oliver and others 1994).
4. **Production of merchantable timber volume.** Stand density management typically represents a compromise between total volume production and individual tree growth; maximum cubic-foot volume production is incompatible with maximum individual tree growth (Daniel and others 1979a, Long 1985). Low-density stands yield high volumes of usable timber (Sassaman and others 1977). If wood continues to be a valuable commodity desired by human societies, then high yields of merchantable (usable) timber will be beneficial in the future. Figure 11 shows board-foot and cubic-foot volume yields for ponderosa pine stands (site class IV) at age 45 for a range of initial stand densities (Barrett 1971). It shows that cubic-foot yields were remarkably consistent across the range of initial tree densities; board-foot volumes, however, were highest at low densities and lowest at the highest density. Since board-foot volume represents sawtimber and similar products better than cubic-foot volume, figure 11 shows that maintaining low stand densities (at the lower limit of the management zone or even lower) will provide the greatest dividends in terms of usable wood volume.

Wildlife and Range Management. The stocking-level information in this guide is potentially useful for wildlife management purposes. The habitat for many wildlife species is closely tied to the structure of the forest vegetation that they utilize (Hunter 1990, Thomas 1979). In the Blue Mountains, roost trees used by big brown bats *(Eptesicus fuscus)* occur in an open forest structure, whereas those used by silver-haired bats *(Lasionycteris noctivagans)* are found in denser forest stands (Betts 1996). Another example is satisfactory elk *(Cervus elaphus)* cover, a wildlife habitat component defined as "a stand of coniferous trees at least 12 m (40 ft) tall and exceeding an average of 70 percent crown closure" (Thomas 1979).

Table 7: An example of how the lower limit of the management zone stocking level could be used to help formulate tree planting densities for ponderosa pine.

Plant Association	LLMZ	Trees/Acre (9" QMD)	Pre-Certification Mortality	Post-Certification Mortality	Planting Density
ABGR/CAGE	73	88	31	5	124
ABGR/CARU	103	124	44	7	174
ABGR/LIBO2	108	130	46	7	183
ABGR/SPBE	98	118	41	6	166
ABGR/VAME	93	112	39	6	157
ABGR/VASC	68	81	28	4	114
PSME/ACGL-PHMA	127	152	53	8	213
PSME/CAGE	58	69	24	4	97
PSME/CARU	82	98	34	5	138
PSME/HODI	169	202	71	11	284
PSME/PHMA	112	134	47	7	188
PSME/SPBE	152	181	64	10	254
PSME/SYAL	101	121	43	6	170
PSME/SYOR	120	145	51	8	204
PSME/VAME	64	77	27	4	108
PIPO/AGSP	26	31	11	2	44
PIPO/CAGE	55	66	23	3	93
PIPO/CARU	103	124	44	7	174
PIPO/CELE/CAGE	55	66	23	3	93
PIPO/CELE/FEID-AGSP	21	26	9	1	37
PIPO/FEID	42	51	18	3	72
PIPO/PUTR/CAGE	47	56	20	3	79
PIPO/PUTR/CARO	61	74	26	4	104
PIPO/PUTR/FEID-AGSP	44	53	19	3	74
PIPO/SYAL	146	175	61	9	246
PIPO/SYOR	91	108	38	6	152

Plant Association — Abbreviation for the name of each plant association in which ponderosa pine occurs; taken from Table 3 or 4 in Cochran and others (1994).

LLMZ — SDI value associated with the Lower Limit of the Management Zone; taken from Table 4. The LLMZ stocking level was selected as a target planting density because it represents the lower limit of full site occupancy; selecting a higher stocking target would have presumed that precommercial thinning was necessary.

Trees/Acre (9" QMD) — The trees per acre associated with the LLMZ stocking level for an even-aged ponderosa pine stand with a quadratic mean diameter (QMD) of 9 inches; taken from the tables in appendix 3 (each of the ponderosa pine tables by plant association).

Pre-Certification Mortality — An estimate of the number of seedlings that would die in the first three years after planting (e.g., between planting and certification of stand establishment). For this example, a survival percentage of 74% was assumed at the end of the third growing season, based on long-term Umatilla National Forest data.

Post-Certification Mortality — An estimate of the number of seedlings that would die (5% used) between the time of plantation certification (3 years) and when the stand reached a 9" QMD, when it was assumed a commercial entry could be made to adjust stand density, if needed.

Planting Density — The total number of seedlings that would need to be planted to ensure that the tree density target (Trees/Acre at 9" QMD) could be achieved, based on the assumptions used for this analysis. The "Planting Density" value is the mathematical sum of the previous three columns.

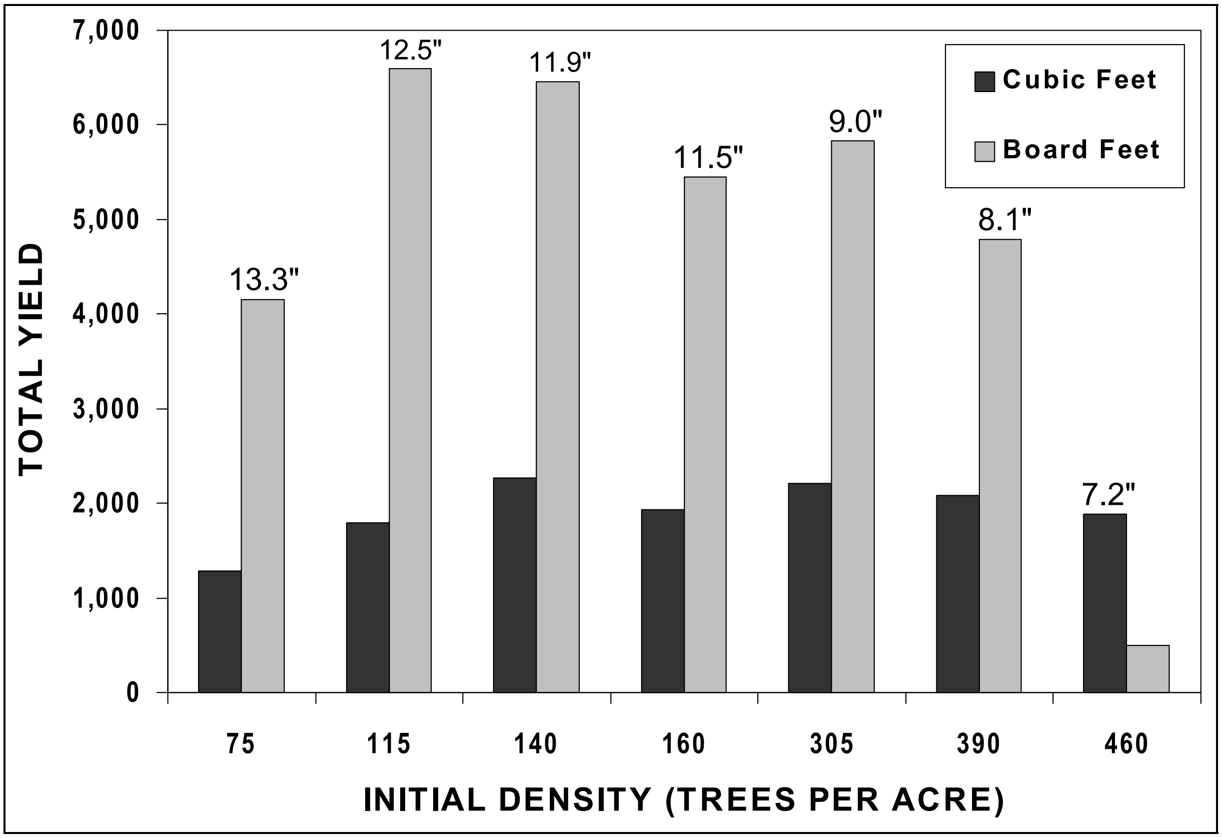

Figure 11 – Total yield of site class IV ponderosa pine at age 45 for various initial tree densities (from Barrett 1971). The quadratic mean diameter, in inches, is shown directly above each set of yield bars and illustrates the effect of initial tree density on diameter growth. This figure demonstrates that 140 trees per acre can produce as much or more usable wood (board feet) as three times that many trees.

Perusing the canopy cover figures in appendix 2 (figs. 14, 18, 22, 26, 30, 34, 38) clearly shows which tree species–plant association combinations have the biological capability to support a 70 percent canopy cover stocking level, which means they could provide satisfactory elk cover. The instances in appendix 2 where 70 percent canopy cover occurs within the management zone, or within the "understocked" portion of a figure, indicate species–association combinations where satisfactory elk cover is not only feasible but is ecologically sustainable (e.g., 70% canopy cover could be sustained for a reasonably long time period).

Thinning and other density management treatments can be used to shift a site's growth potential to fewer stems so that the large-diameter trees often desired as wildlife habitat are produced more quickly (Cochran and Barrett 1993, 1995; Mowat 1953; Oliver and others 1994; fig. 11). In fact, stocking-level and density management information has been used for a variety of wildlife and range management purposes:

- SDI was used to characterize northern goshawk *(Accipiter gentilis)* nesting habitat in Douglas-fir stands of the northern Rocky Mountains (Lilieholm and others 1993, Lilieholm and others 1994).
- SDI was used to characterize elk hiding or thermal cover for ponderosa pine stands in the southwestern United States, including preparation of a stocking chart and several examples of its use (McTague and Patton 1989).
- Smith and Long (1987) used SDI to prepare elk hiding and thermal cover guidelines for even-aged stands of lodgepole pine in southeastern Wyoming, including a *density management diagram* showing separate zones of thermal and hiding cover. They developed a thinning prescription which delayed self-pruning and allowed the lodgepole pine trees to retain full crowns for a substantial portion of their lifespan.

- SDI was used to propose a silvicultural prescription for management of Mexican spotted owl *(Strix occidentalis lucida)* habitat in mixed-conifer and ponderosa pine forests of the southwestern United States (Fiedler and Cully 1995). Their prescription provided increased stand densities, patchy openings for owl feeding and regeneration of seral species, and desirable vertical and horizontal structure.
- SDI was found to be a useful predictor of understory forage production (graminoid, forb, and current-year shrub) on the Kaibab Plateau of northern Arizona (Moore and Deiter 1992).
- Studies examining overstory-*understory* relationships indicated that overstory (tree) canopy cover can have a significant influence on understory plant composition and production. In northeastern Oregon, for example, shrub crown cover declined rapidly once overstory canopy cover exceeded 50 percent (Hedrick and others 1968). Other research found that understory plant biomass may actually be limited more by water and nitrogen availability, which was related to root competition from the overstory trees, than from a lack of sunlight caused by overstory shading (Riegel and others 1991, 1992).

Stocking Levels for Mixed-Species Stands. How should suggested stocking levels be selected for mixed-species stands? On the Umatilla National Forest, many plant associations have the ecological capability to support five, six or even seven tree species (see table 2). A decision about the mixture of species to emphasize on any particular site should be based on land management objectives ("maintain 60% or more of the stand composition as non-host species in order to minimize future susceptibility to western spruce budworm," for example). Once that decision has been made, a silviculturist has several alternatives for selecting stocking levels for mixed-species stands, depending on the circumstances:

1. It wouldn't matter which stocking levels were selected because the species being considered have nearly the same ULMZ and LLMZ values;
2. It wouldn't matter because one or more of the species will eventually be removed during cultural operations such as precommercial and commercial thinnings;
3. A weighted average could be calculated for two or more species, although that strategy should be used with caution when the stocking levels deviate widely between species. This approach was described in Seidel and Cochran (1981);
4. The lowest stocking-level recommendations could be selected. This strategy assumes that the species with the lowest SDI values has the most restrictive stocking requirements, and that other species would develop acceptably under the lower densities established for the limiting species. This is the strategy recommended by Cochran and others (1994).

Western White Pine Considerations. Western white pine, a mid-*seral* tree species, is occasionally found on cool moist, cool wet, and warm moist sites in the upper montane and lower subalpine vegetation zones (Powell 1998). It was characterized as having a restricted geographical distribution in the Blue Mountains (Haig and others 1941). In actuality, western white pine has a relatively wide distribution as a minor species in mixed-conifer forests, although it seldom comprises a plurality of the basal area in any individual stand. Due to changes wrought by fire suppression, bark-beetle outbreaks, white pine blister rust *(Cronartium ribicola)* and other factors, it is believed that white pine in the Blue Mountains was more abundant historically than at present.

Over the last 15 years, western white pine has increasingly been used in reforestation plantings because it survives well and has rapid juvenile growth. Interest in planting white pine has existed for quite some time. For example, when an extensive reconnaissance of the Wenaha National Forest was completed in 1913 (the Wenaha is now the northern half of the Umatilla National Forest), it was thought that "white pine would be an excellent tree to plant on all the burns found on the higher altitudes," where the examiner believed it should be encouraged to the same extent that western yellow (ponderosa) pine was encouraged at lower altitudes (Bright and Powell 1994).

In the near future, mixed-conifer plantations containing western white pine will need to be thinned. How should stocking levels be determined for managed stands with a substantial component of white pine? Since white pine was seldom encountered on the sample plots that were used to develop a plant association classification for the Blue and Ochoco Mountains (Johnson and Clausnitzer 1992), stocking levels for white pine could not be derived by using the productivity information from the ecological classification (as was done for the seven tree species included in this guide).

Seidel and Cochran (1981), however, used data from the northern Rocky Mountains to develop stocking level curves for western white pine. Their white pine curves compare closely to those developed for Douglas-fir in eastern Oregon and eastern Washington, so they recommended that Douglas-fir stocking levels also be used for western white pine (Seidel and Cochran 1981).

When western white pine occurs in mixed-species stands, which is almost always the situation for the Blue Mountains, it is important to manage mountain pine beetle risk in order to ensure their survival. White pines are particularly susceptible to mountain pine beetle attack in stands where lodgepole pine is present in sufficient numbers to serve as a beetle attractant. If low-vigor lodgepole pines do succeed in attracting beetles to a mixed-species stand, it is very likely that any associated white pines will also be killed because their thick phloem provides ideal beetle habitat (Mitchell 1989).

Customizing the Stocking-Level Information. Most of the information in this implementation guide pertains to two stocking levels – the upper and lower limits of the management zone. The suggested stocking levels associated with those limits were developed using a methodology described in Cochran and others (1994). But some practitioners would like the flexibility to establish different limits of the management zone than the ones recommended by Cochran and others (1994). To provide users with the capability to generate "customized" stocking-level information, including density management diagrams to analyze prescription options (Jack and Long 1996), a computer program was developed called SDI.[3]

The SDI computer program will produce tabular reports in a format similar to the tables in appendix 3, and it can also create density management diagrams or stocking-level curves in two formats: a curved-line "Gingrich" format (Ernst and Knapp 1985) that relates basal area per acre and trees per acre, and a straight-line, logarithmic ("Reineke") format that relates trees per acre and quadratic mean diameter.

GLOSSARY

The definitions in this glossary are from Helms (1998) unless noted otherwise, although some were modified slightly. The definitions are not the only valid ones for these terms.

Basal area. The cross-sectional area of a single tree stem, including the bark, measured at breast height (4½ feet above the ground); also, the cross-sectional area of all stems in a stand and expressed per unit of land area (basal area per acre).

Canopy cover. The proportion of ground or water covered by a vertical projection of the outermost perimeter of the natural spread of foliage or plants, including small openings within the canopy. Total canopy cover can exceed 100 percent because of the layering of different vegetative strata.

Cohort. A group of trees developing after a single disturbance, commonly consisting of trees of similar age, although one cohort can include a considerable span of ages ranging from seedlings or sprouts to trees that predated the disturbance (Helms 1998). Stands are often characterized as "single-cohort" or "multicohort" depending on whether they contain one or several cohorts (Oliver and Larson 1996).

Competition. The extent to which each organism maximizes fitness by both appropriating contested resources from a pool that is not sufficient for all, and adapting to an environment altered by all participants in the community or population. For trees, competition results in a density-related scarcity of certain environmental factors that are related to tree growth.

[3] SDI was programmed by Alan Ager, operations research analyst for the Umatilla National Forest. It is a Windows 95 application, and can be downloaded from the Forest's web site at http://www.fs.fed.us/r6/uma/ager/sdi.htm

Crown classes. A categorization or classification of trees based on their crown position relative to adjacent trees within the same canopy stratum; four primary crown classes are recognized:

Dominant – a tree whose crown extends above the general level of the main canopy, receiving full light from above and partial light from the sides.

Codominant – a tree whose crown helps to form the general level of the main canopy, receiving full light from above and limited light from the sides.

Intermediate – a tree whose crown extends into the lower portion of the main canopy but is shorter than the codominants, receiving little direct light from above and virtually none from the sides.

Suppressed (overtopped) – a tree whose crown is completely overtopped by the crowns of one or more neighboring trees, occurring in a subordinate or submerged position relative to the main canopy.

Crown closure. The point in stand development where the vertical projections of crown perimeters within a canopy touch (Helms 1998). The period when branch growth first begins to slow down due to lateral confinement caused by adjacent trees (Oliver and Larson 1996).

Crown competition factor. The sum of maximum crown area values for all trees in a stand, divided by its area in acres (Krajicek and others 1961).

Density management. The cutting or killing of trees to increase spacing and accelerate growth of remaining trees (Helms 1998); the manipulation and control of growing stock to achieve specific management objectives (Long 1985). Density management is often used to improve forest health, to open the canopy for selected trees, to maintain understory vegetation, or to promote late-successional characteristics for biological diversity.

Density management diagram. A graphical aide developed for use in designing and evaluating alternative density management regimes. Diagrams have been developed for different purposes and for a range of species, so each one tends to include slightly different stand attributes (McCarter and Long 1986).

Differentiation. A divergence in growth patterns of individual trees due to redistribution of growing space during stand development. Differentiation leads to formation of *crown classes*.

Equilateral spacing. An expression of inter-tree distance that assumes that tree crowns occupy adjoining hexagons. Calculated as the square root of: 50,300.23 divided by the number of trees per acre.

Even-aged stand structure. A *stand* of trees composed of a single age class in which the range of tree ages is no more than ±20 percent of the rotation age.

Forest health. The perceived condition of a forest based on concerns about such factors as its age, structure, composition, function, vigor, presence of unusual levels of insects or disease, and resilience to disturbance. Note that perception and interpretation of forest health is influenced by individual and cultural viewpoints, land management objectives, spatial and temporal scales, the relative health of stands that comprise the forest, and the appearance of the forest at a particular point in time.

Free growth. A period in stand development where trees expand to fill unoccupied growing space without direct competition (called open growth when occurring prior to *crown closure*), or with limited competition leading to initiation of crown *differentiation* but without tree mortality (Oliver and Larson 1996).

Full stocking. A point in the development of *even-aged stands* in which *differentiation* has resulted in *crown classes* (Cochran and others 1994); at full stocking, high *stand density* levels are causing inter-tree competition and resultant mortality of the weaker, less-vigorous trees (*self thinning* is occurring). Also see *normal density* and *reference level*.

Growing space. An intangible measure of the total resources of a site (sunlight, moisture, nutrients, etc.) that are available to a plant.

Integrated pest management. The maintenance of destructive agents, including insects, at tolerable levels by the planned use of preventive, suppressive, or regulatory strategies (including silvicultural treatments) that are ecologically and socially acceptable.

Irregular stand structure. A *stand* of trees characterized by variation in age structure or in the spatial arrangement of trees; stands without a uniform age or size structure.

Low thinning. The removal of trees from the lower *crown classes* to favor those in the upper crown classes; often referred to as thinning from below.

Lower limit of full site occupancy. The *stocking level* associated with the point in stand development where the site is fully occupied by trees that are interacting (competing) with each other. This developmental point is marked by *differentiation* into *crown classes*; total volume production for the stand is maximized beyond this point, although individual tree growth is less than the potential for the site.

Lower limit of the management zone (LLMZ). A *stocking level* objective used to establish the lower limit of a management zone; for the suggested stocking levels described in this document, the LLMZ was always set at 67 percent of the *upper limit of the management zone* for a given tree species–plant association combination (Cochran and others 1994).

Management zone. A *stocking level* zone established by setting upper and lower limits. The upper limit is often established in such a way as to avoid competition-induced mortality (*self thinning*). The lower limit generally maintains sufficient *stocking* to allow a significant portion of a site's resources to be captured as tree growth – a threshold also referred to as the *lower limit of full site occupancy* (Cochran and others 1994, Long 1985).

Marking guide. Written instructions describing the trees or *stands* that are to be cut, left, or otherwise treated during silvicultural operations (Smith and others 1997); an implementation plan for a silvicultural prescription.

Maximum density. The maximum *stand density* that can exist for a tree species for a given mean size in *self-thinning* populations (Long 1996).

Normal density. The *stand density* that is assumed to represent full site occupancy but which allows room for the development of crop trees; assumed to represent "average-maximum" competition or the average density of natural, undisturbed, fully-stocked stands. Normal density is assumed to be about 80% of maximum density. Normal density levels are typically derived from publications such as McArdle and others (1961) and Meyer (1961).

Overstory. That portion of the trees, in a forest of more than one story (layer), forming the uppermost canopy layer; in a two-storied forest, the tallest trees form the overstory, the shortest trees the *understory*.

Photosynthate. The organic compounds, particularly carbohydrates, that result from photosynthesis, a process whereby the chlorophyll cells of plants use carbon dioxide, water, enzymes, and sunlight (as an energy source) to produce photosynthate.

Plant association. A plant community with similar physiognomy (form and structure) and floristics; commonly it is a climax community (Allaby 1994). It is believed that 1) the individual species in the association are, to some extent, adapted to each other; 2) the association is made up of species that have similar habitat requirements; and 3) the association has some degree of integration (Kimmins 1997). Plant association is often considered to be synonymous with "habitat type" or "potential natural community" (Powell 1998).

Plant community type. An aggregation of plant communities with similar structure and floristic composition. A vegetation classification unit with no particular successional status implied (Dunster and Dunster 1996).

Precommercial thinning. The removal of trees not for immediate financial return but to reduce *stocking* and thereby concentrate growth on the more desirable trees.

Quadratic mean diameter. The diameter corresponding to the mean *basal area*; the diameter of a tree of average basal area in a stand.

Reference level. The absolute stand density that would normally be expected in a stand of given characteristics under some standard condition such as average maximum competition (Ernst and Knapp 1985). For the suggested *stocking levels* described in this document, *full stocking (normal density* or an "average-maximum" level of competition) was used as the reference level.

Relative density. The ratio, proportion or percent of absolute stand density to a *reference level* defined by some standard level of competition.

Self thinning. Plant mortality caused by intraspecific (inter-plant) competition in crowded, even-aged stands. For self-thinning populations, increasing average size is associated with a progressive diminution in tree density (Long and Smith 1984). Self thinning is also known as the –3/2 power rule, since the self-thinning zones for many plant species have a slope of –3/2 on a logarithmic graph (Westoby 1984).

Seral status: a stage of secondary successional development; also called seral stage. Four seral stages are recognized: potential natural community, late seral, mid seral, and early seral (Hall and others 1995).

Early Seral: clear dominance of seral species (western larch, ponderosa pine, lodgepole pine, etc.); PNC species are absent or present in very low numbers.

Mid Seral: PNC species are increasing in the forest composition as a result of their active colonization of the site; PNC species are approaching equal proportions with the seral species.

Late Seral: PNC species are now dominant, although long-lived seral species (ponderosa pine, western larch, etc.) may still persist in the plant community.

Potential Natural Community (PNC): the biotic community that one presumes would be established and maintained over time under present environmental conditions; seral species are scarce or absent in the plant composition.

Series. A level in the potential natural vegetation hierarchy that represents major environmental differences reflected by distributions of tree species at climax. A series is named for the projected climax tree species – the subalpine fir series includes all plant associations where subalpine fir is presumed to be the dominant tree species at climax (Pfister and Arno 1980).

Silvicultural prescription. A planned series of treatments designed to change current stand structure to one that meets the goals and objectives established for a stand (Helms 1998). A written statement or document defining the objectives to be attained from silvicultural treatments. The objectives are generally expressed as acceptable ranges of the various indices being used to characterize stand development (Dunster and Dunster 1996).

Square spacing. An expression of inter-tree distance that assumes that tree crowns occupy the center of adjacent squares. Calculated as the square root of: 43,560 divided by the number of trees per acre.

Stagnation. Stands of trees whose growth and development have been repressed or almost stopped due to poor site conditions or excessive *stocking* (Dunster and Dunster 1996).

Stand. A contiguous group of trees sufficiently uniform in age-class distribution, composition, and structure, and growing on a site of sufficiently uniform quality, to be a distinguishable unit.

Stand density. A quantitative measure of stocking expressed absolutely in terms of number of trees, basal area, or volume per unit area.

Stand density index. A widely used measure developed by Reineke (1933) that expresses *relative density* as the relationship between a number of trees per acre and a stand's *quadratic mean diameter*.

Stocking. The amount of anything on a given area, particularly in relation to what is considered optimum; in silviculture, an indication of growing-space occupancy relative to a pre-established standard.

Stocking levels. *Stand density* objectives expressed as constant or uniform amounts of *stocking* (Cochran and others 1994).

Susceptibility. The probability of an infestation (of bark beetles, defoliators, etc.) based on inherent or intrinsic stand characteristics (composition, density, etc.); contrast susceptibility with *vulnerability*.

Two-storied stand structure. A *stand* with trees of two distinct age classes (*cohorts*), or an even-aged (single *cohort*) stand in which differential height growth rates between tree species (for mixed-species stands) has resulted in two distinct canopy strata (an overstory and an understory).

Understory. All of the vegetation growing under a forest *overstory*. In some applications, understory is only considered to be small trees (e.g., in a forest comprised of multiple canopy layers, the taller trees form the overstory, the shorter trees the understory); in other instances, understory is assumed to include herbaceous and shrubby plants in addition to trees. When understory is assumed to refer to trees only, other plants (herbs and shrubs) are often called an undergrowth to differentiate between the two.

Uneven-aged stand structure. A stand with trees of three or more distinct age classes *(cohorts)*, either intimately mixed or in small groups.

Upper limit of the management zone (ULMZ). A *stocking level* objective used to establish the upper limit of a management zone. For the suggested stocking levels described in this document, the ULMZ was set at 75 percent of *full stocking (normal density)* for each of the tree species except ponderosa and lodgepole pines, whose ULMZ values were determined differently to account for their susceptibility to mountain pine beetle (Cochran and others 1994).

Vulnerability. The probability of tree or stand damage resulting from an infestation (of bark beetles, defoliators, etc.); contrast vulnerability with *susceptibility*. Susceptibility reflects the influence of forest or stand conditions on hazard (e.g., are lodgepole pines in a stand larger than 9 inches in diameter); vulnerability refers to the probability that damage will occur (e.g., is a beetle population in close proximity).

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APPENDIX 1: PLANT SPECIES CODES

This appendix provides scientific and common plant names for the species codes that were used to name the plant associations and plant community types in table 2 (from Johnson and Clausnitzer 1992 or Johnson and Simon 1987).

Code	Scientific Name	Common Name
ABGR	*Abies grandis*	Grand (white) fir
ABLA2	*Abies lasiocarpa*	Subalpine fir
ACGL	*Acer glabrum*	Rocky Mountain maple
AGSP	*Agropyron spicatum*	Bluebunch wheatgrass
ALSI	*Alnus sinuata*	Sitka Alder
ARCO	*Arnica cordifolia*	Heartleaf arnica
ARNE	*Arctostaphylos nevadensis*	Pinemat manzanita
ASCA3	*Asarum caudatum*	Wild ginger
BRVU	*Bromus vulgaris*	Columbia brome
CAGE	*Carex geyeri*	Elk sedge
CARO	*Carex rossii*	Ross sedge
CARU	*Calamagrostis rubescens*	Pinegrass
CELE	*Cercocarpus ledifolius*	Curlleaf mountain-mahogany
CLUN	*Clintonia uniflora*	Queencup beadlily
FEID	*Festuca idahoensis*	Idaho fescue
GYDR	*Gymnocarpium dryopteris*	Oakfern
HODI	*Holodiscus discolor*	Creambush oceanspray
LIBO2	*Linnaea borealis*	Twinflower
MEFE	*Menziesia ferruginea*	Fool’s huckleberry
PHMA	*Physocarpus malvaceus*	Mallow ninebark
PIAL	*Pinus albicaulis*	Whitebark pine
PICO	*Pinus contorta*	Lodgepole pine
PIPO	*Pinus ponderosa*	Ponderosa pine
POMU	*Polystichum munitum*	Sword fern
POPU	*Polemonium pulcherrimum*	Polemonium
PSME	*Pseudotsuga menziesii*	Douglas-fir
PTAQ	*Pteridium aquilinum*	Bracken fern
PUTR	*Purshia tridentata*	Bitterbrush
SPBE	*Spiraea betulifolia*	Birchleaf spirea
STAM	*Streptopus amplexifolius*	Twisted stalk
STOC	*Stipa occidentalis*	Western needlegrass
SYAL	*Symphoricarpos albus*	Common snowberry
SYOR	*Symphoricarpos oreophilus*	Mountain snowberry
TABR	*Taxus brevifolia*	Pacific yew
TRCA3	*Trautvetteria caroliniensis*	False bugbane
VAME	*Vaccinium membranaceum*	Big huckleberry
VASC	*Vaccinium scoparium*	Grouse huckleberry

APPENDIX 2: STOCKING LEVEL FIGURES

This appendix portrays suggested stocking levels in a series of figures organized by tree species. Each of the seven tree species has four figures – one summarizing stocking levels using stand density index (SDI), a second expressing them as basal area, a third showing canopy cover, and a fourth that characterizes the management zones using equilateral spacing. Note that these figures differ from the stocking-level tables in appendix 3 because they include the full-stocking level in addition to the upper and lower limits of the management zone.

The figures in this appendix show plant associations in a different order than was used in table 2, which follows the same order used by Cochran and others (1994). The order used here relates to plant association groups (PAG), a mid-scale ecological unit developed for ecosystem analyses at the watershed scale and for project planning (Powell 1998). Ordering associations by PAG allows users to easily visualize stocking level variations between and within PAGs.

One figure per tree species shows the suggested stocking levels using stand density index (SDI; see figs. 12, 16, 20, 24, 28, 32, 36). By definition, the SDI values also represent a trees per acre stand density, but only for stands with a quadratic mean diameter (QMD) of 10 inches. For stands with a QMD that is not 10 inches, users should consult the tables in appendix 3 to determine the trees per acre associated with either the upper or lower limits of the management zone. SDI values in this appendix pertain to an even-aged stand structure; trees per acre information for an irregular or uneven-aged structure is also provided for the upper and lower limits of the management zone in appendix 3.

One figure per tree species shows the suggested stocking levels using basal area (see figs. 13, 17, 21, 25, 29, 33, 37). The basal area values were calculated for the trees per acre associated with the SDIs, so they pertain to stands with a quadratic mean diameter (QMD) of 10 inches. For stands with a QMD that is not 10 inches, users should consult the tables in appendix 3 to determine the basal area per acre associated with either the upper or lower limits of the management zone. Basal area values in this appendix pertain to an even-aged stand structure; basal area information for an irregular or uneven-aged structure is also provided for the upper and lower limits of the management zone in appendix 3.

One figure per tree species shows the suggested stocking levels using forest (tree) canopy cover (see figs. 14, 18, 22, 26, 30, 34, 38). The canopy cover calculations were based on the basal area per acre values associated with the SDIs, so they pertain to stands with a quadratic mean diameter (QMD) of 10 inches. For stands with a QMD that is not 10 inches, users should consult the tables in appendix 3 to determine the canopy cover percentages associated with either the upper or lower limits of the management zone.

Forest (tree) canopy cover values in the figures for Douglas-fir, ponderosa pine, Engelmann spruce, grand fir, and subalpine fir pertain to an irregular stand structure because it best reflects the unmanaged stands that were used to derive the mathematical formulas (Dealy 1985). For lodgepole pine and western larch, canopy cover percentages pertain to an even-aged stand structure because unmanaged stands tend to be even-aged for those two species.

One figure per tree species shows the management zones expressed as equilateral tree spacing (see figs. 15, 19, 23, 27, 31, 35, 39). The equilateral spacing calculations were based on the trees per acre associated with the SDIs, so they pertain to stands with a quadratic mean diameter (QMD) of 10 inches. For stands with a QMD that is not 10 inches, users should consult the tables in appendix 3 to determine the equilateral spacings associated with either the upper or lower limits of the management zone. Spacing calculations were always based on even-aged stands because that structure presumably has the most consistent inter-tree distances; the spacing values would not apply to trees left in clumps or in other irregular arrangements.

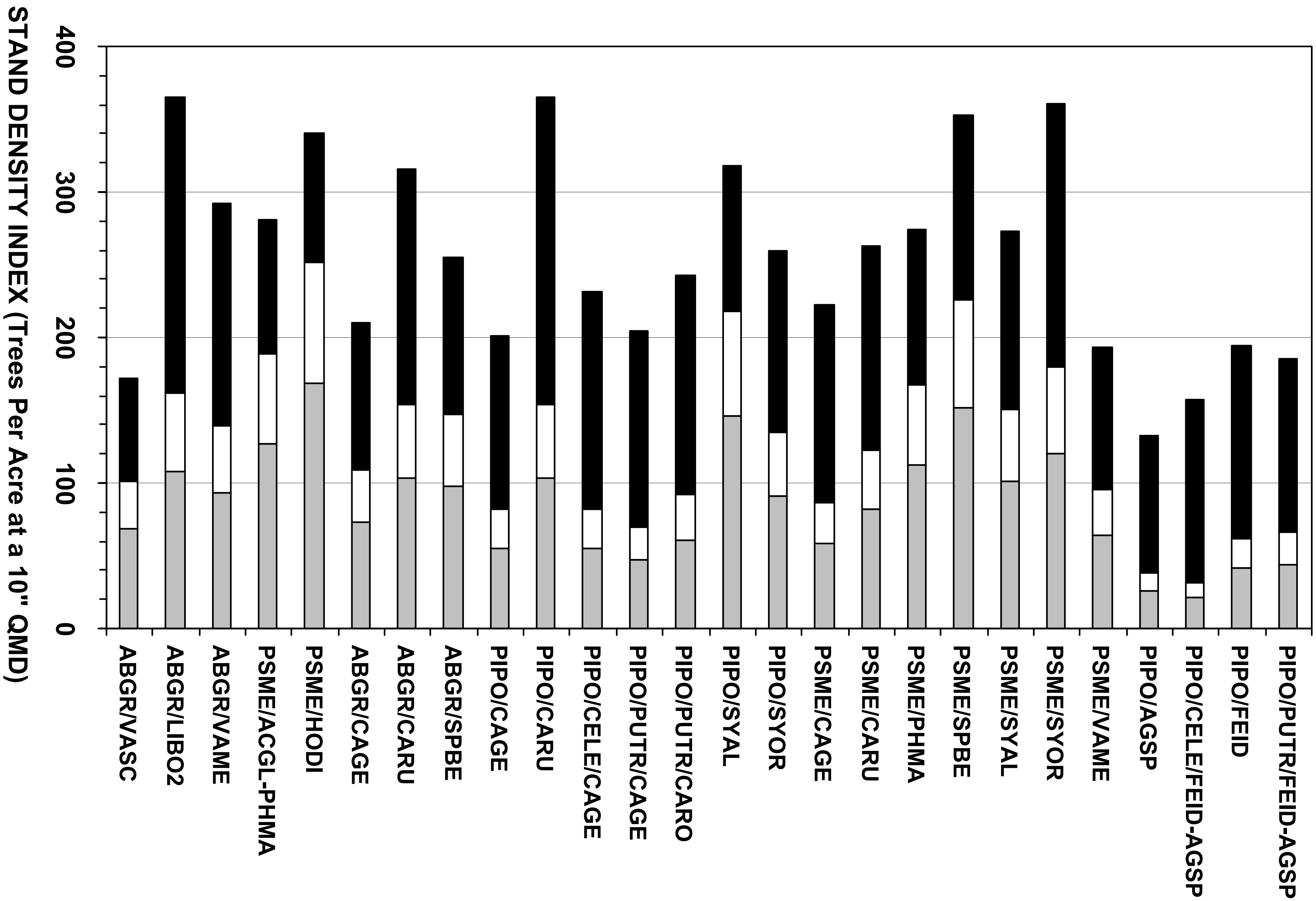

Figure 12 – Suggested stocking levels for ponderosa pine, expressed as SDI (gray: less than full site occupancy; white: management zone; black: overstocked).

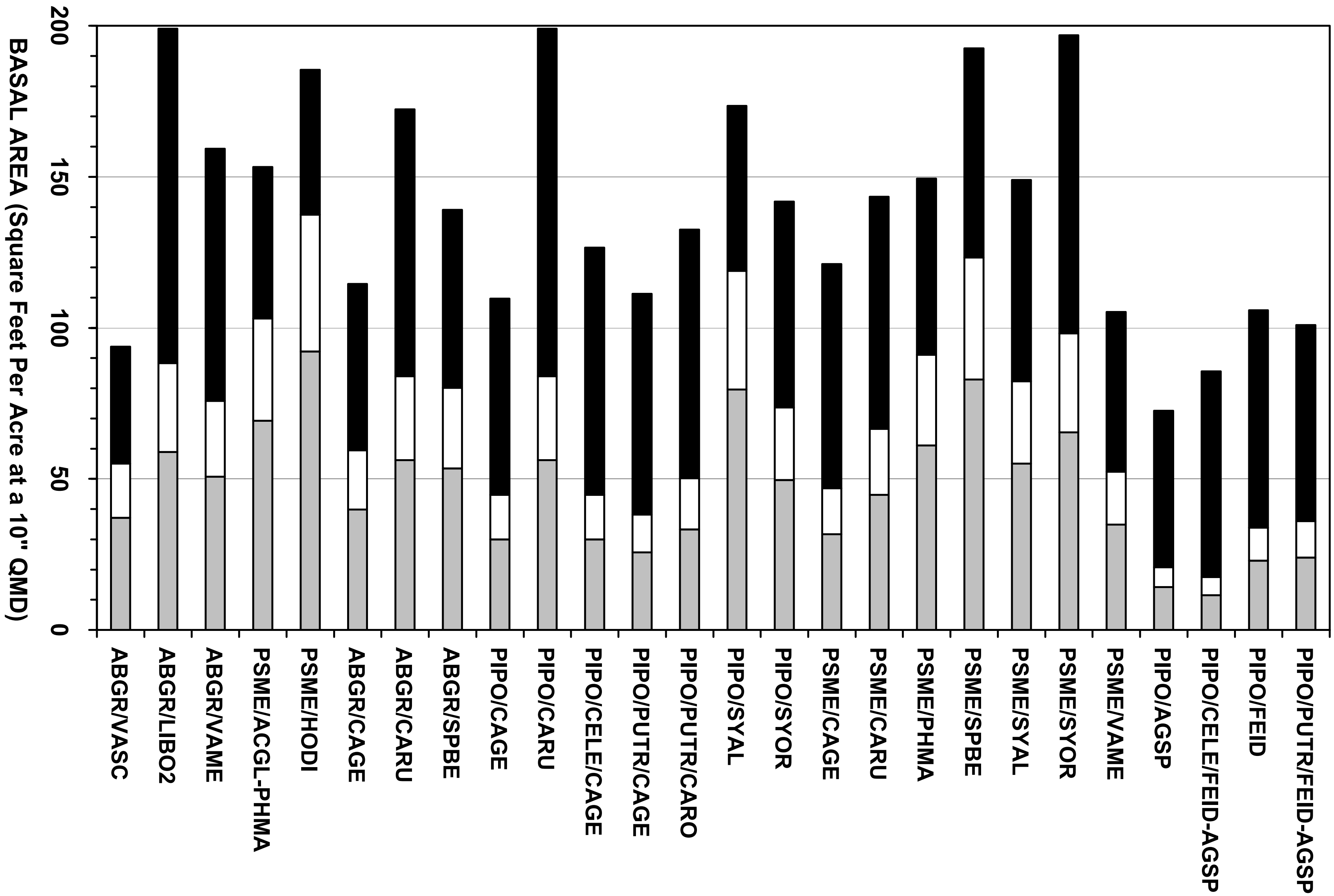

Figure 13 – Suggested stocking levels for ponderosa pine, expressed as basal area (gray: less than full site occupancy; white: management zone; black: overstocked).

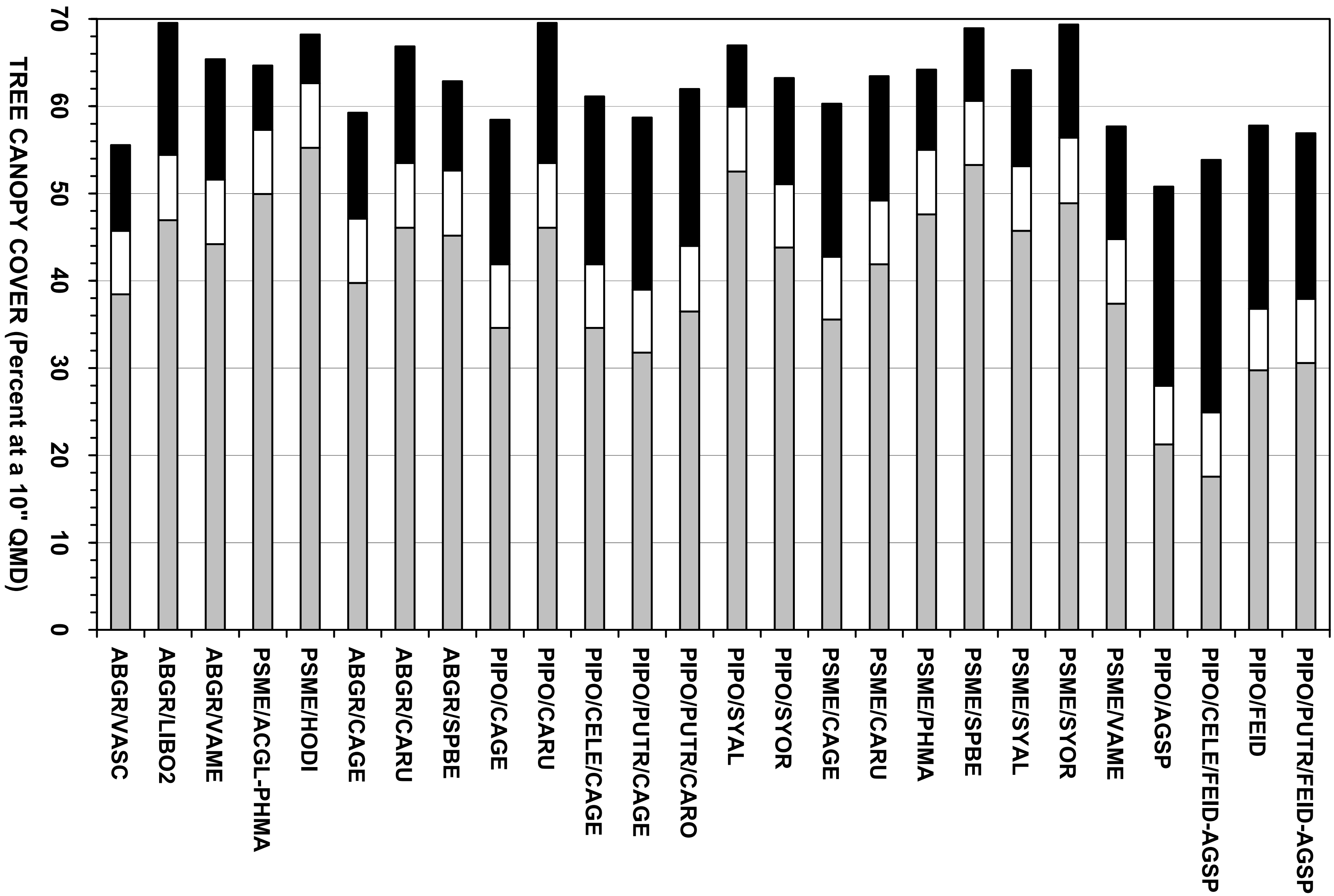

Figure 14 – Suggested stocking levels for ponderosa pine, expressed as canopy cover (gray: less than full site occupancy; white: management zone; black: overstocked).

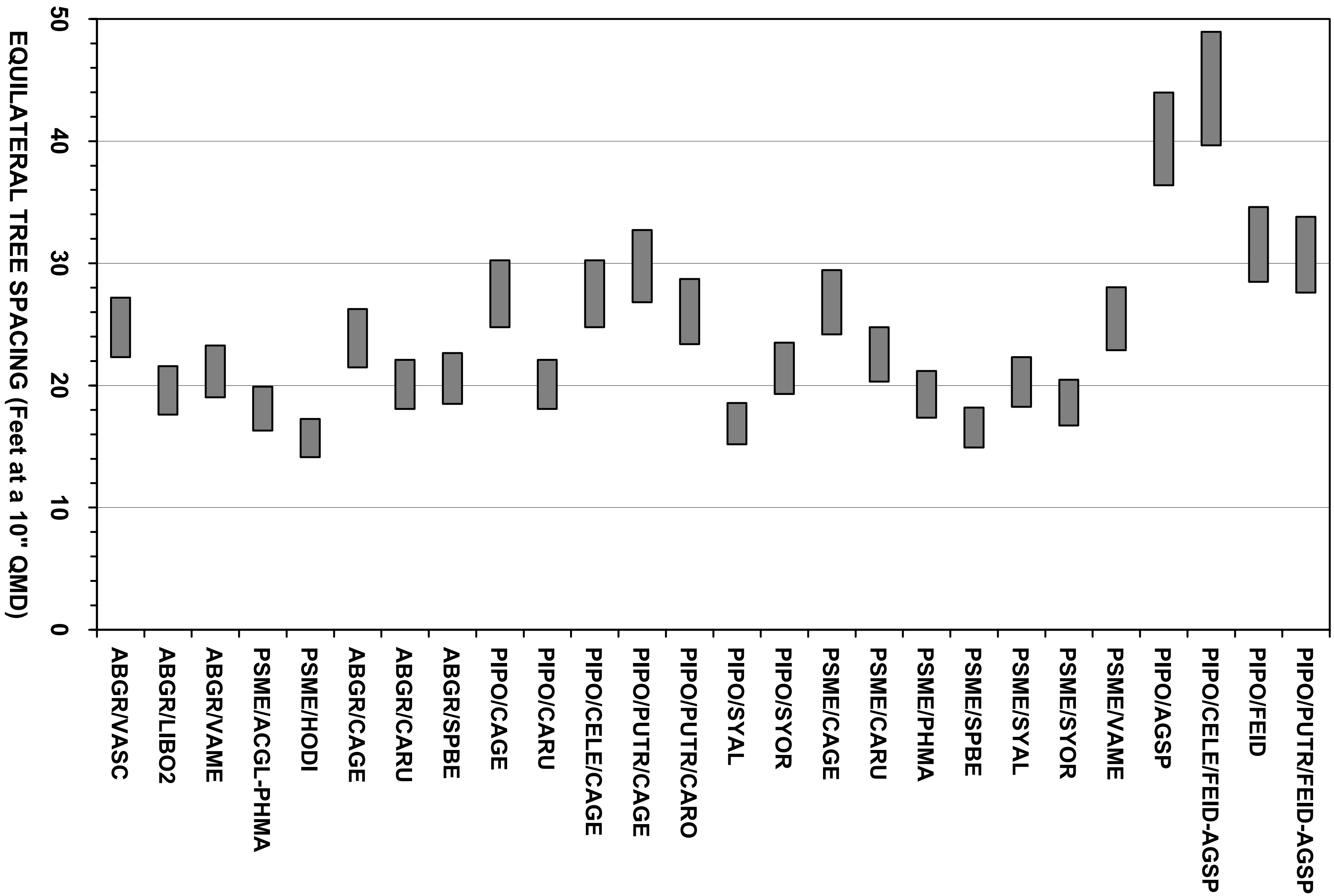

Figure 15 – Management zones for ponderosa pine, expressed as equilateral spacing.

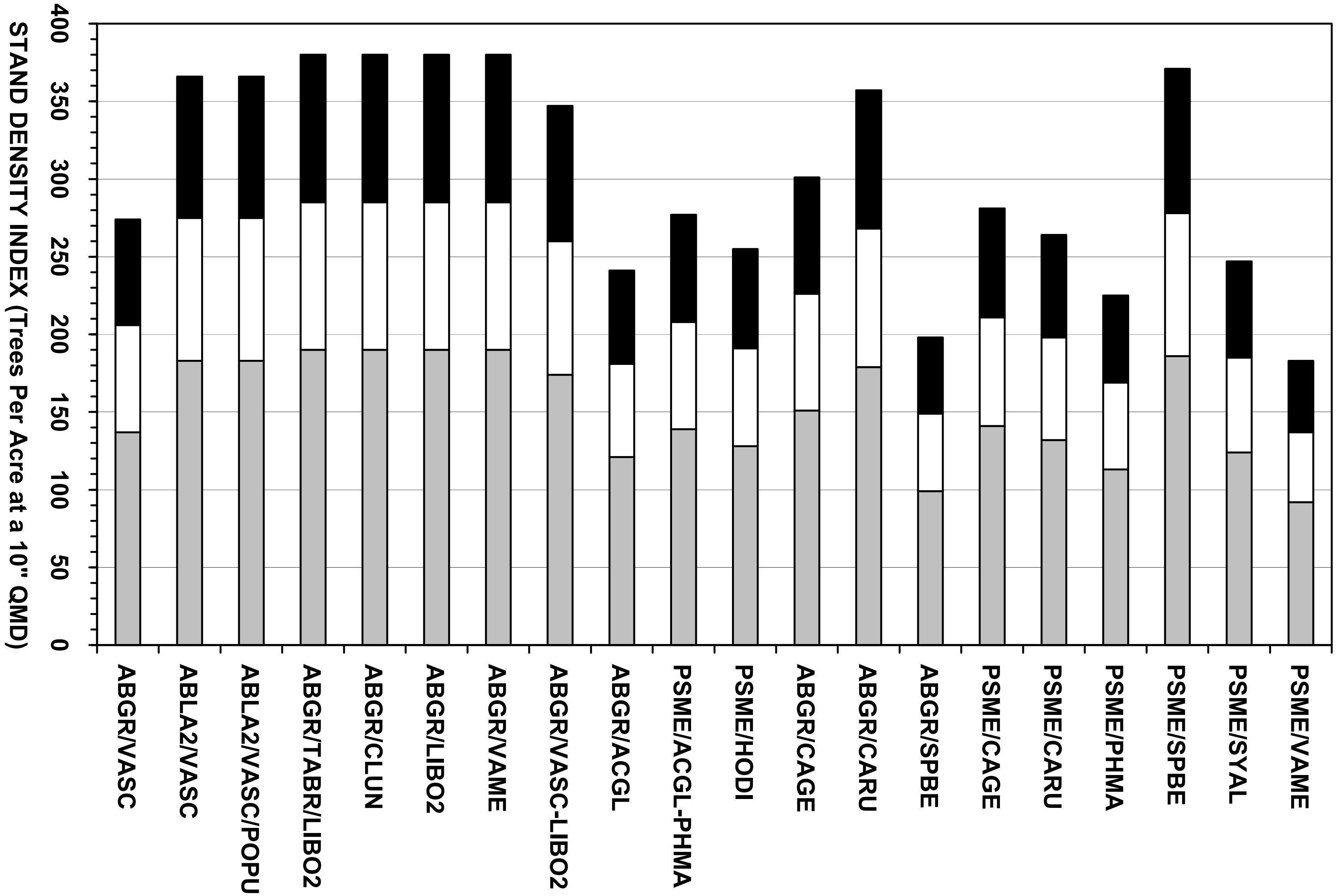

Figure 16 – Suggested stocking levels for Douglas-fir, expressed as SDI (gray: less than full site occupancy; white: management zone; black: overstocked).

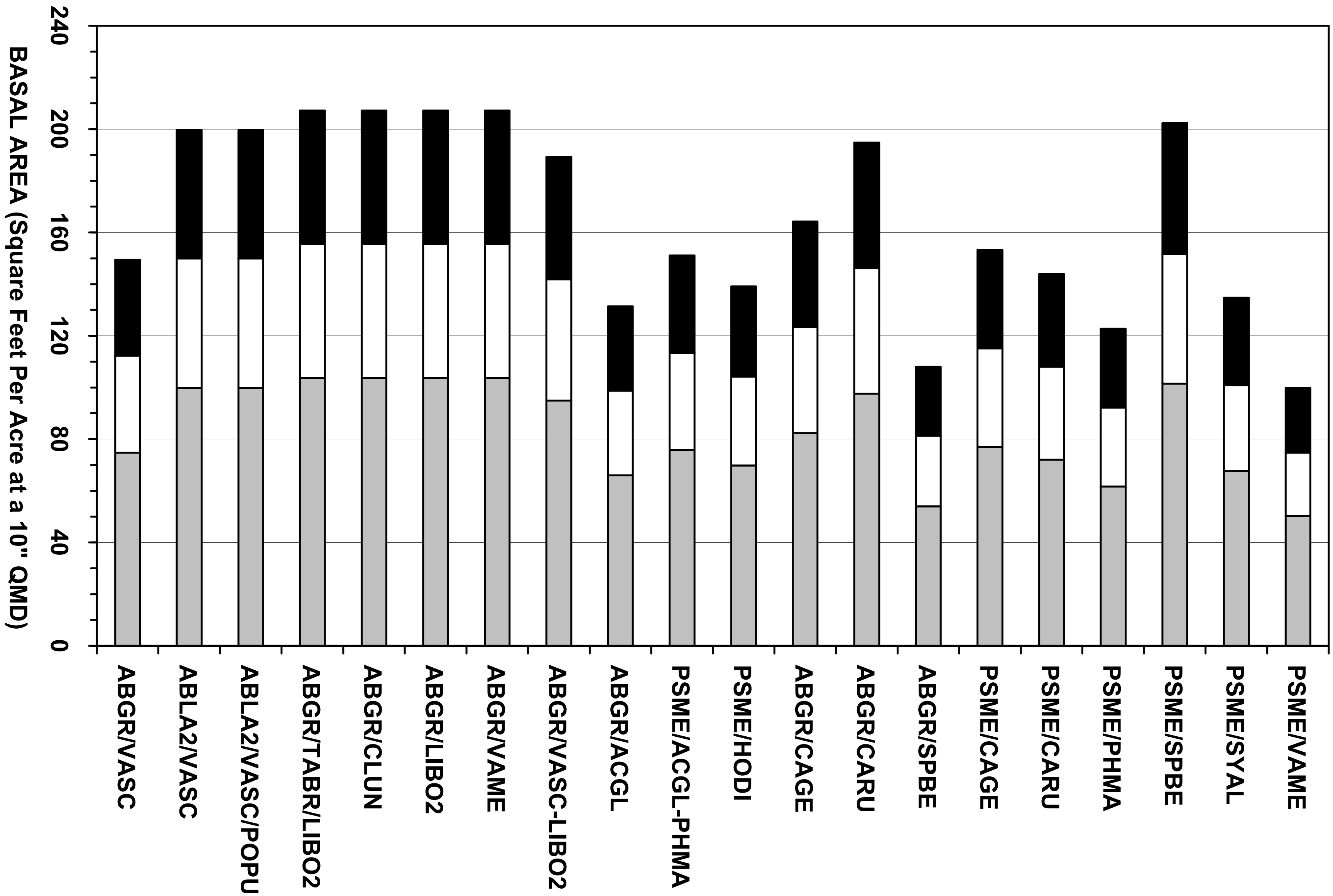

Figure 17 – Suggested stocking levels for Douglas-fir, expressed as basal area (gray: less than full site occupancy; white: management zone; black: overstocked).

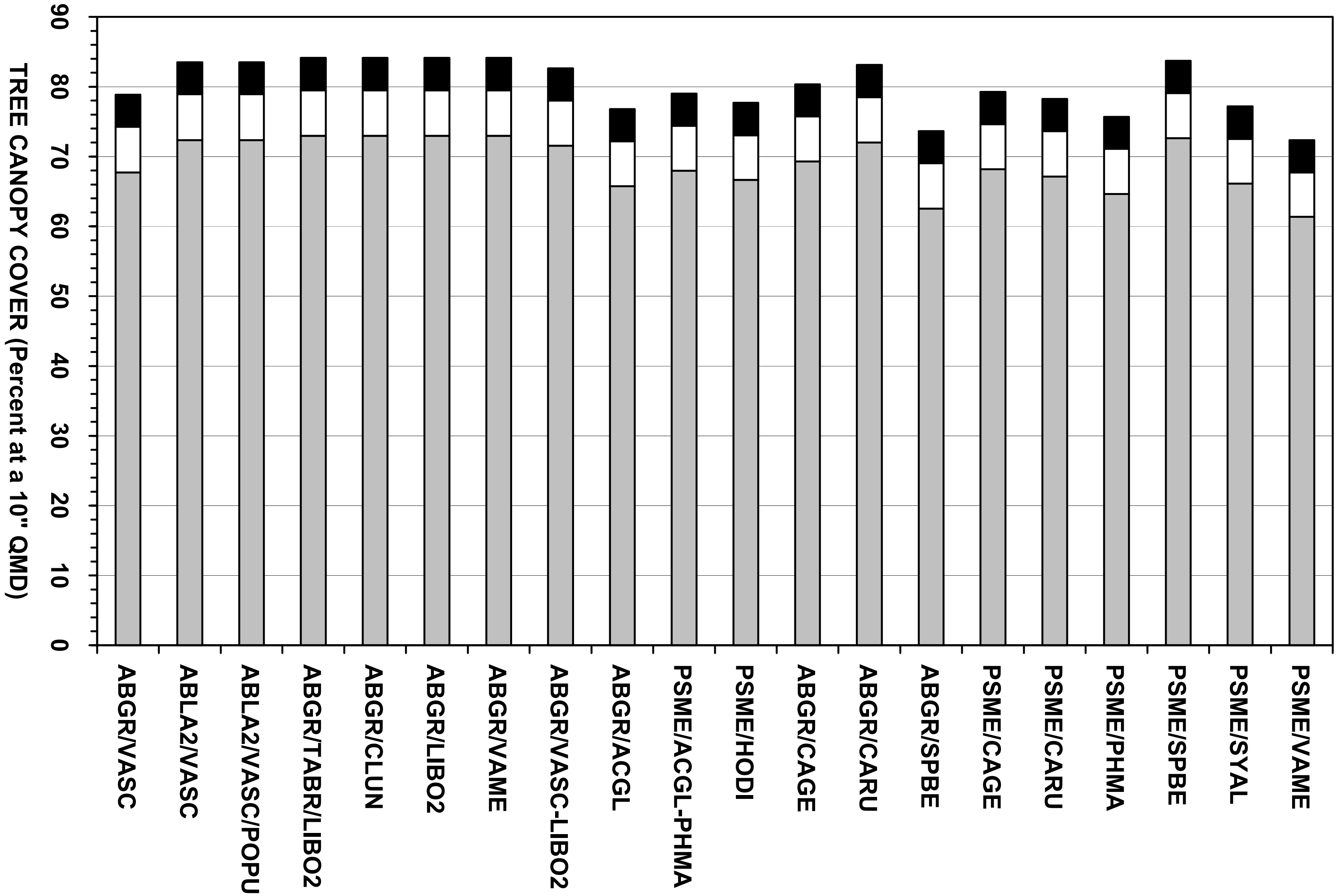

Figure 18 – Suggested stocking levels for Douglas-fir, expressed as canopy cover (gray: less than full site occupancy; white: management zone; black: overstocked).

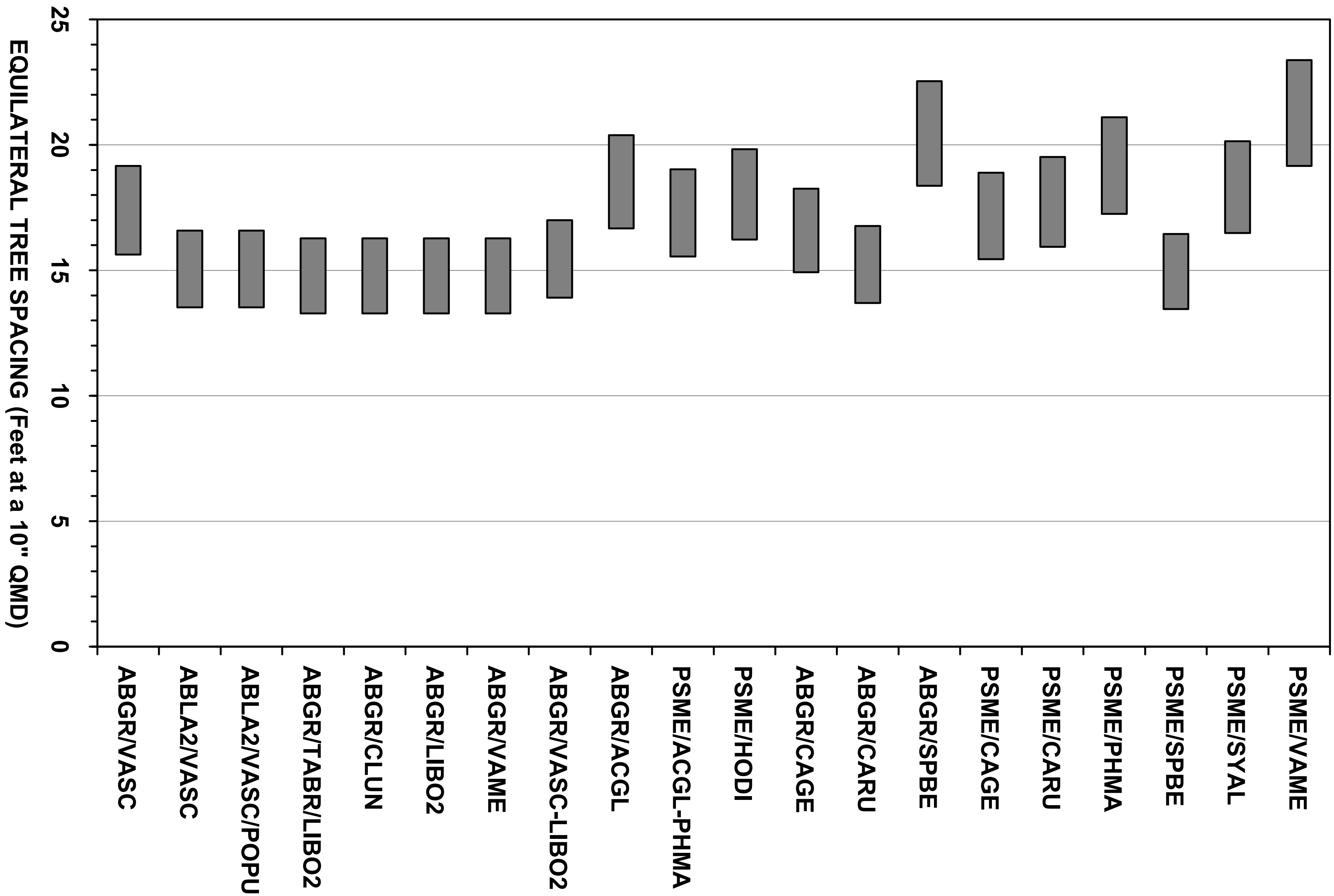

Figure 19 – Management zones for Douglas-fir, expressed as equilateral spacing.

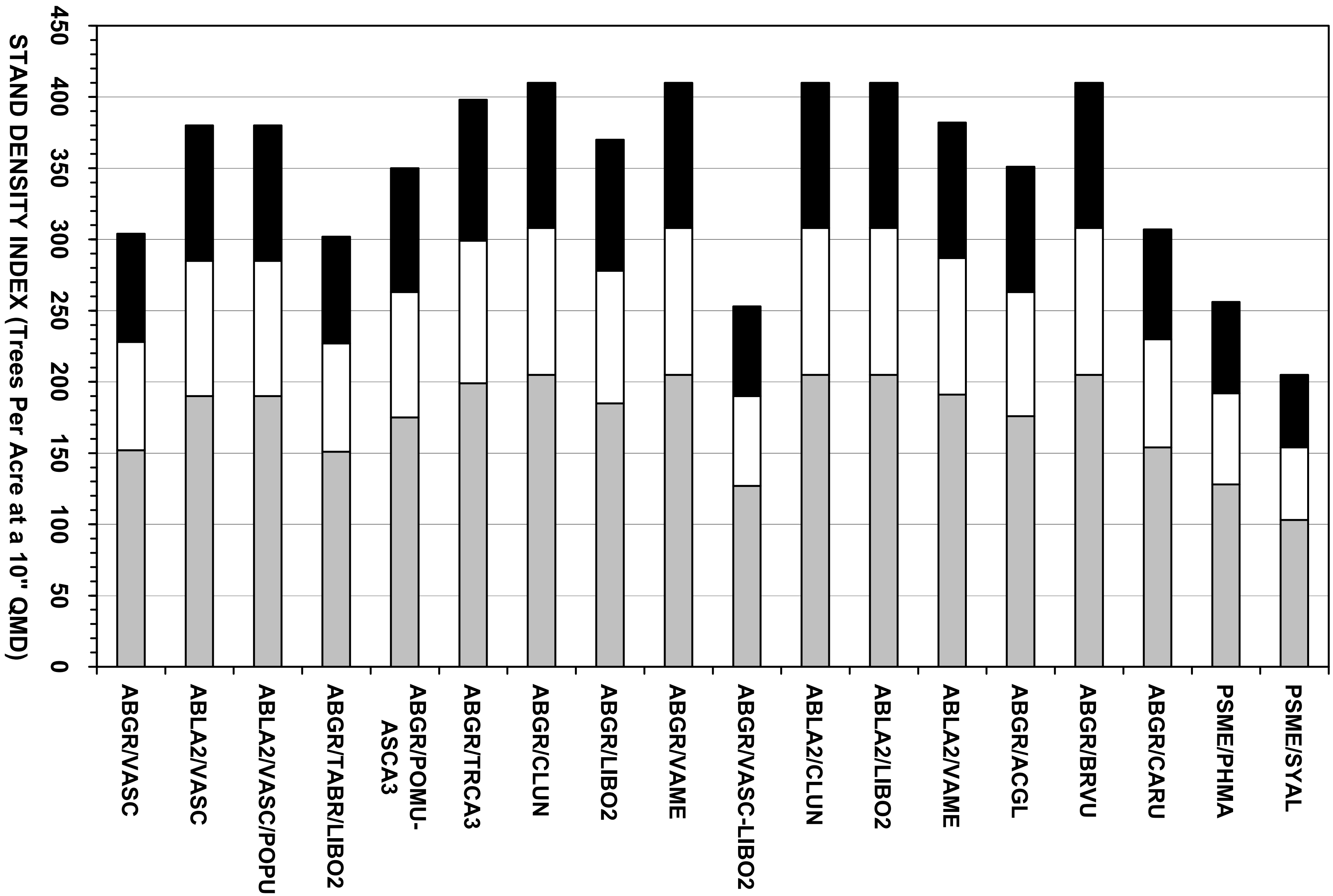

Figure 20 – Suggested stocking levels for western larch, expressed as SDI (gray: less than full site occupancy; white: management zone; black: overstocked).

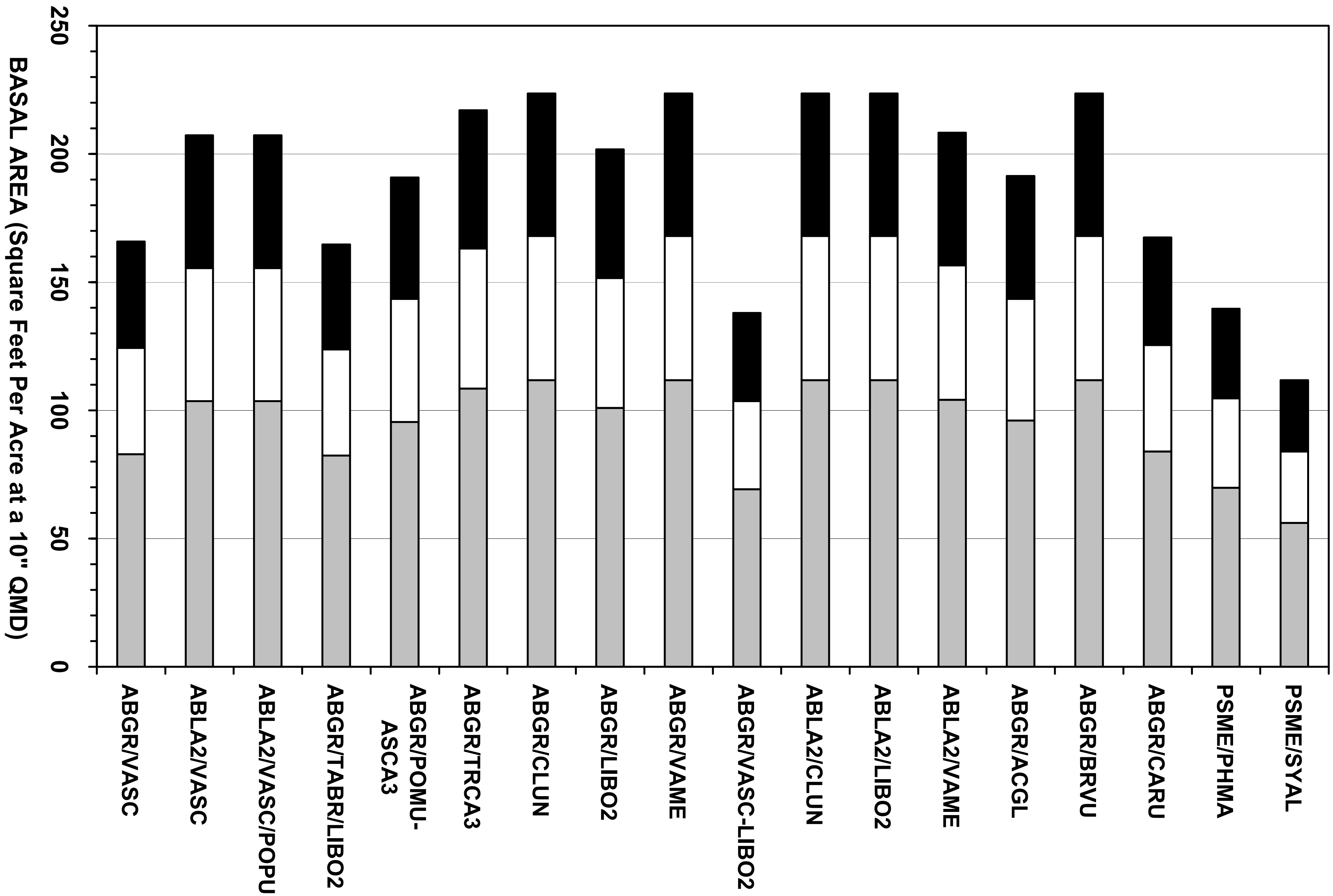

Figure 21 – Suggested stocking levels for western larch, expressed as basal area (gray: less than full site occupancy; white: management zone; black: overstocked).

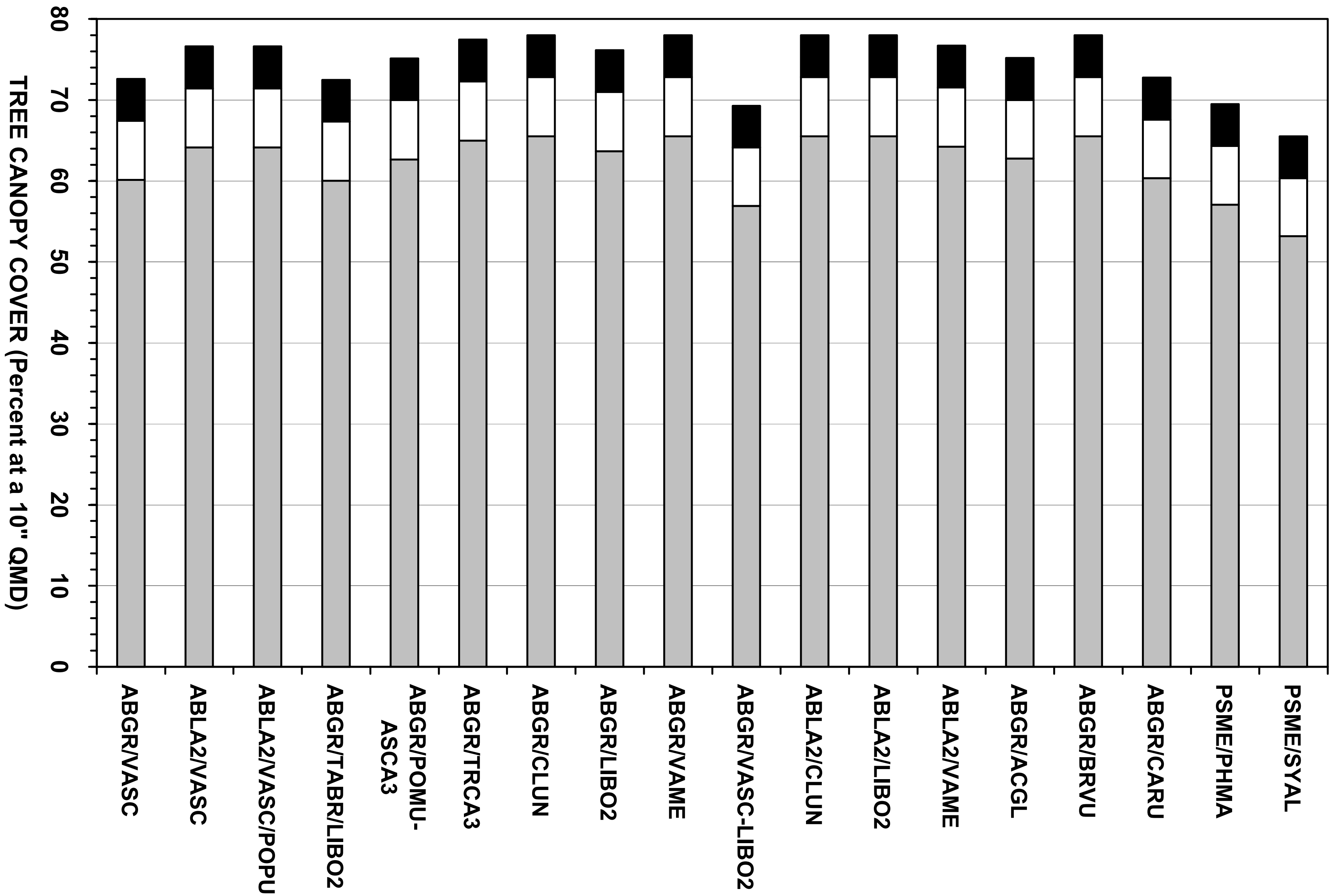

Figure 22 – Suggested stocking levels for western larch, expressed as canopy cover (gray: less than full site occupancy; white: management zone; black: overstocked).

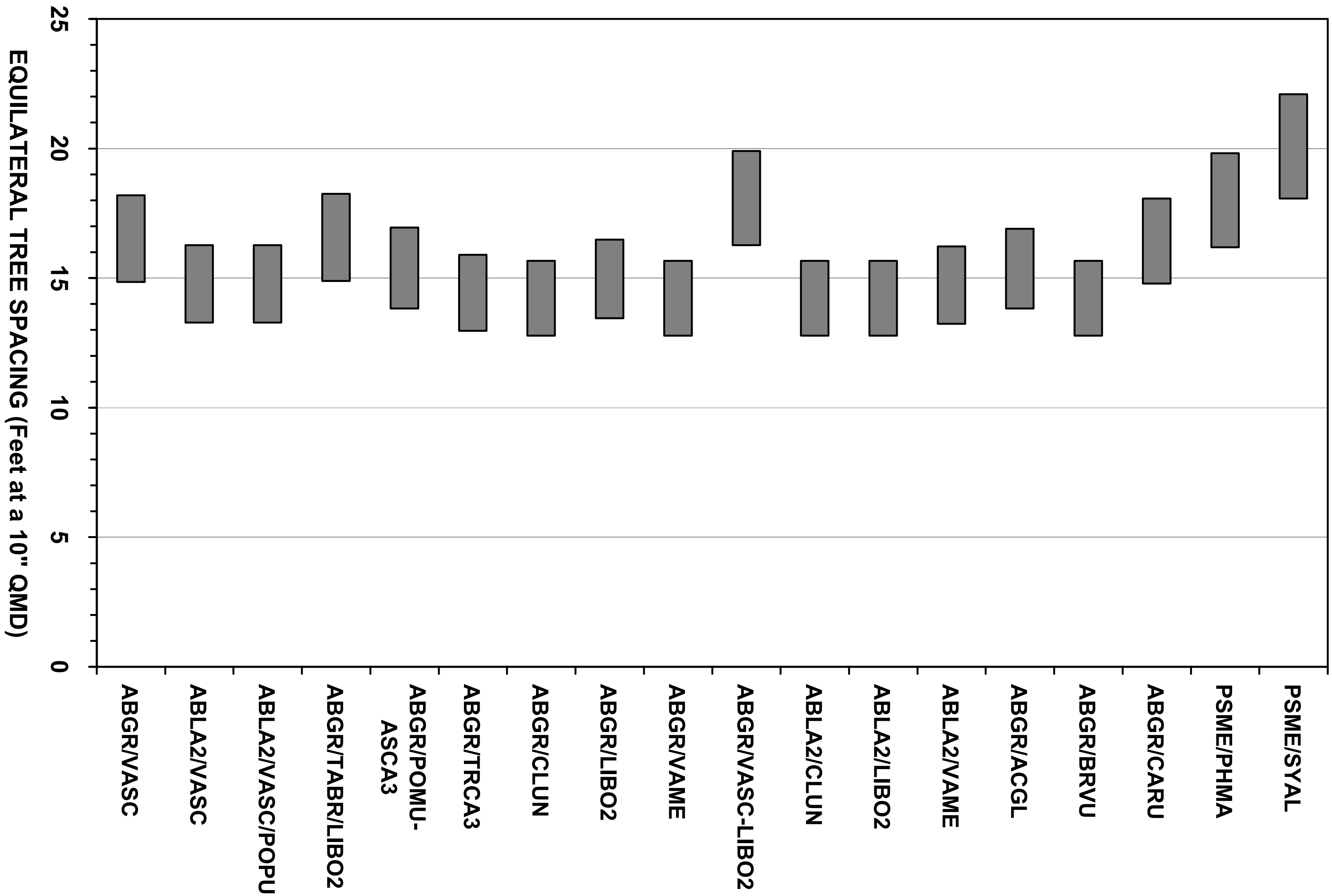

Figure 23 – Management zones for western larch, expressed as equilateral spacing.

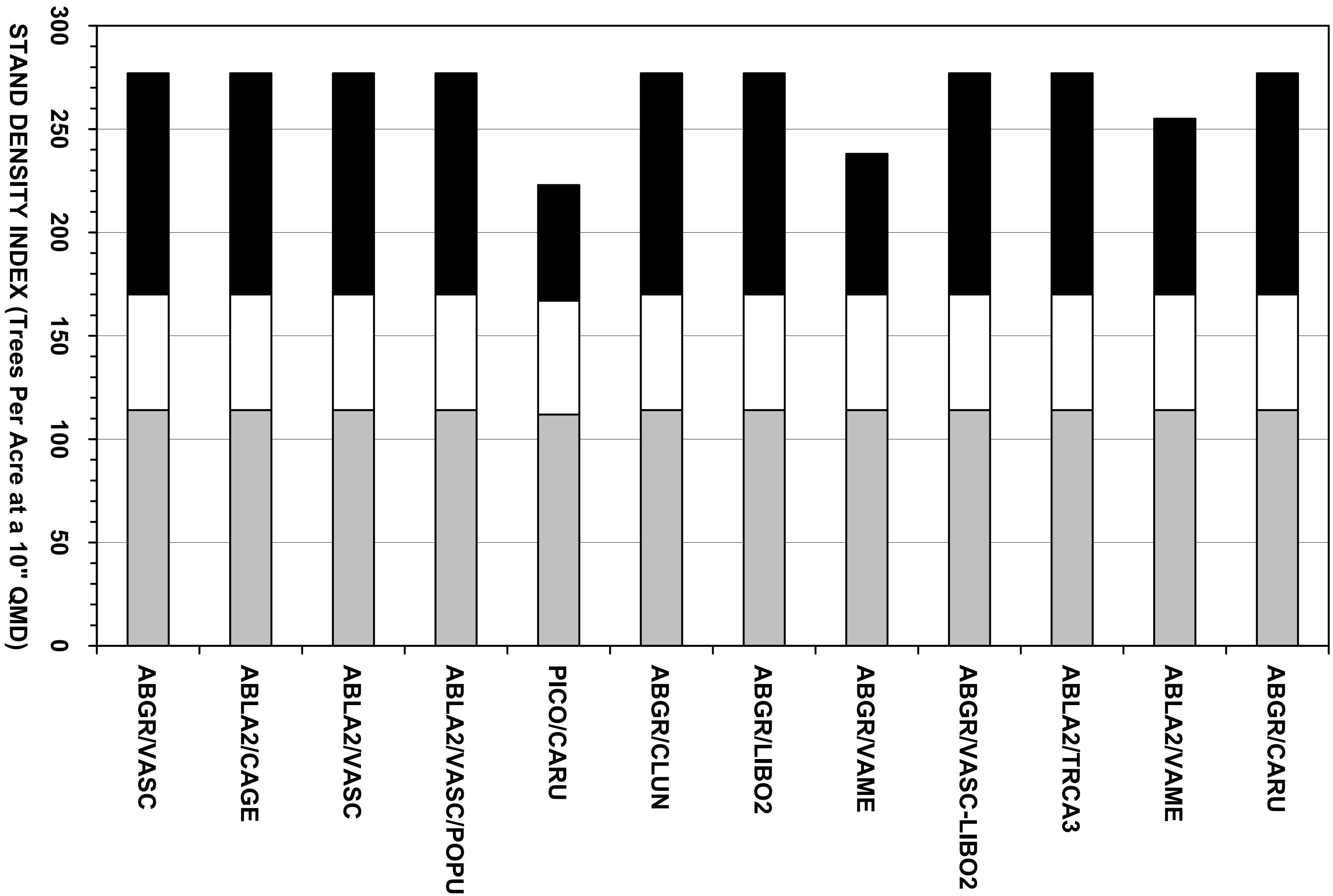

Figure 24 – Suggested stocking levels for lodgepole pine, expressed as SDI (gray: less than full site occupancy; white: management zone; black: overstocked).

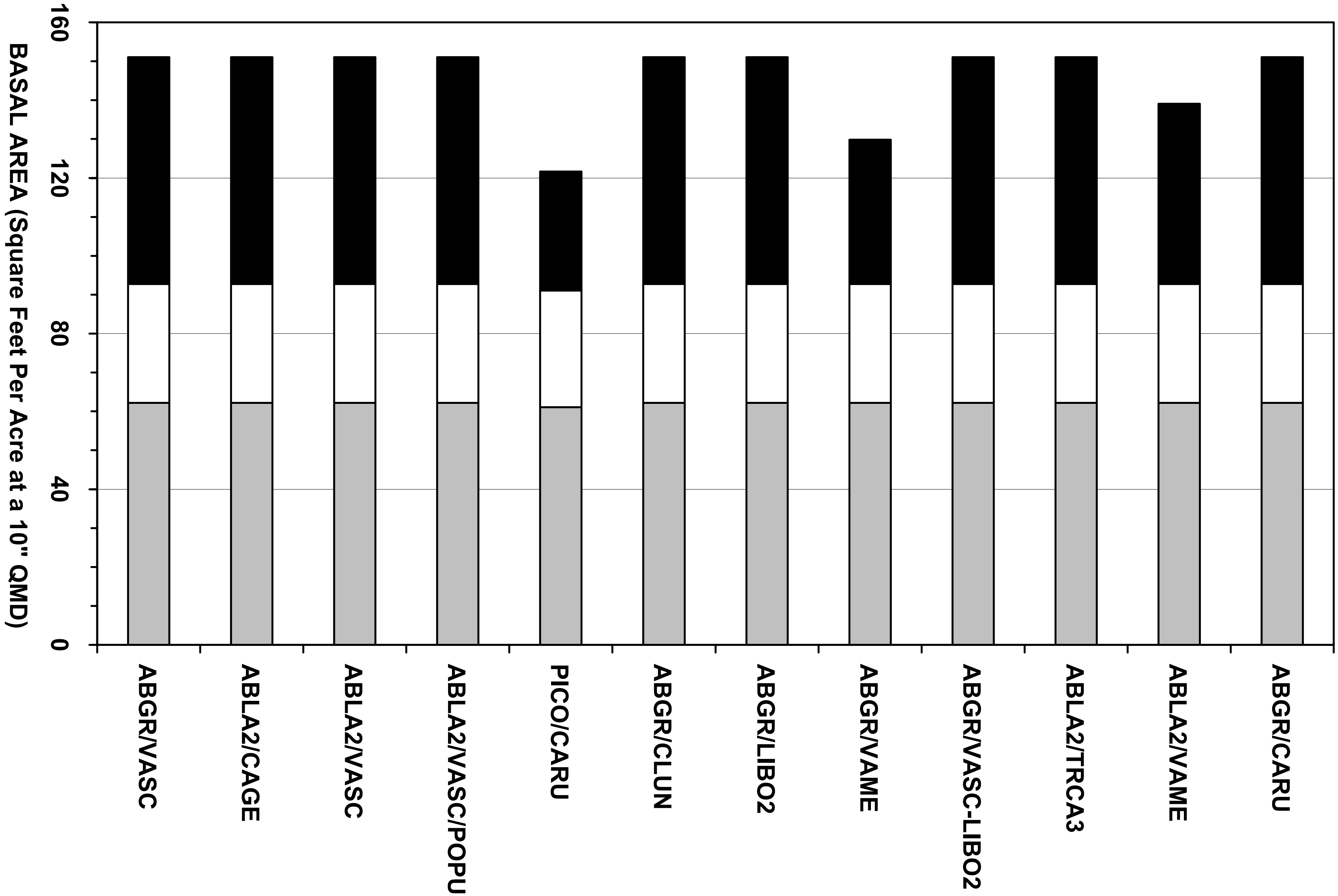

Figure 25 – Suggested stocking levels for lodgepole pine, expressed as basal area (gray: less than full site occupancy; white: management zone; black: overstocked).

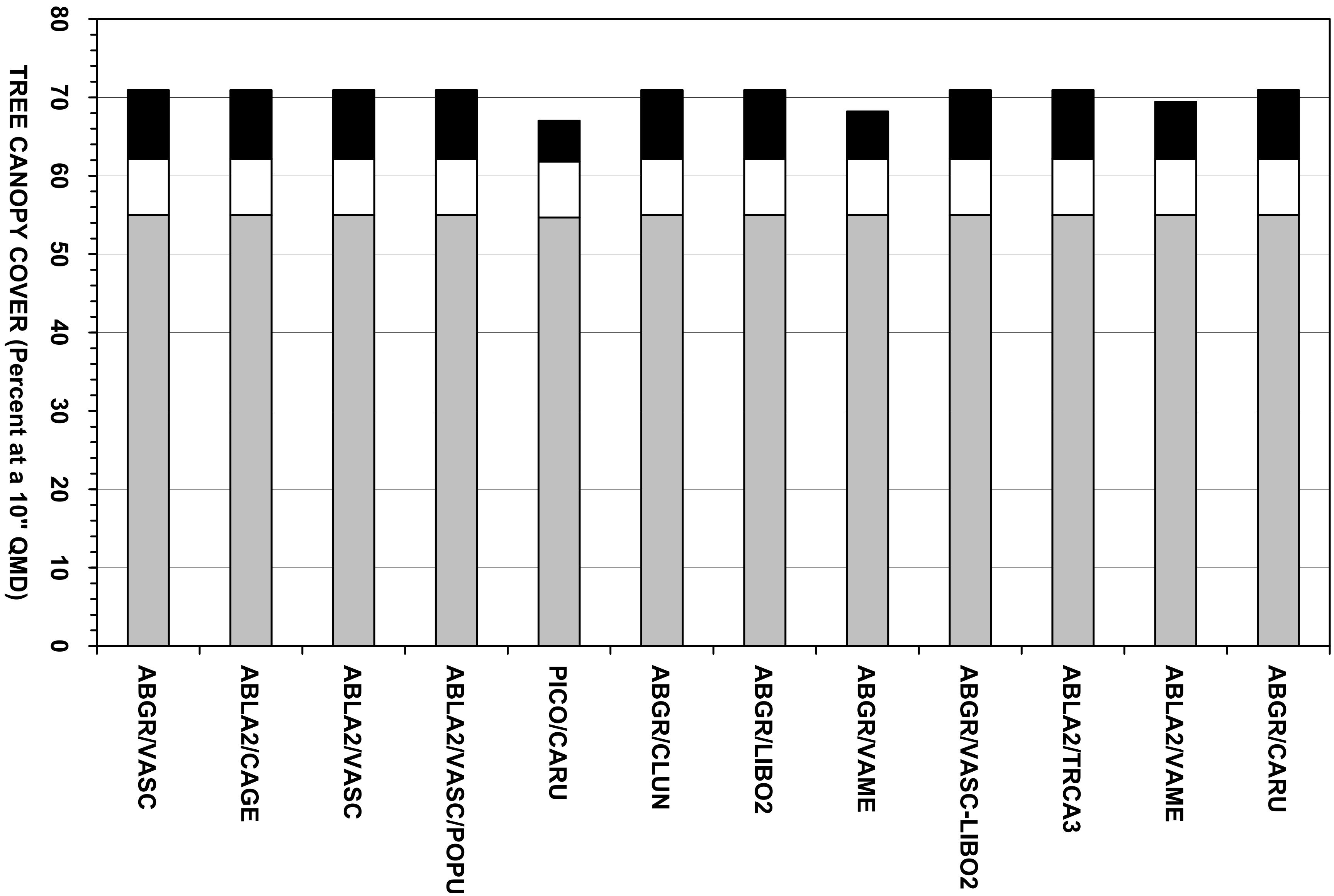

Figure 26 – Suggested stocking levels for lodgepole pine, expressed as canopy cover (gray: less than full site occupancy; white: management zone; black: overstocked).

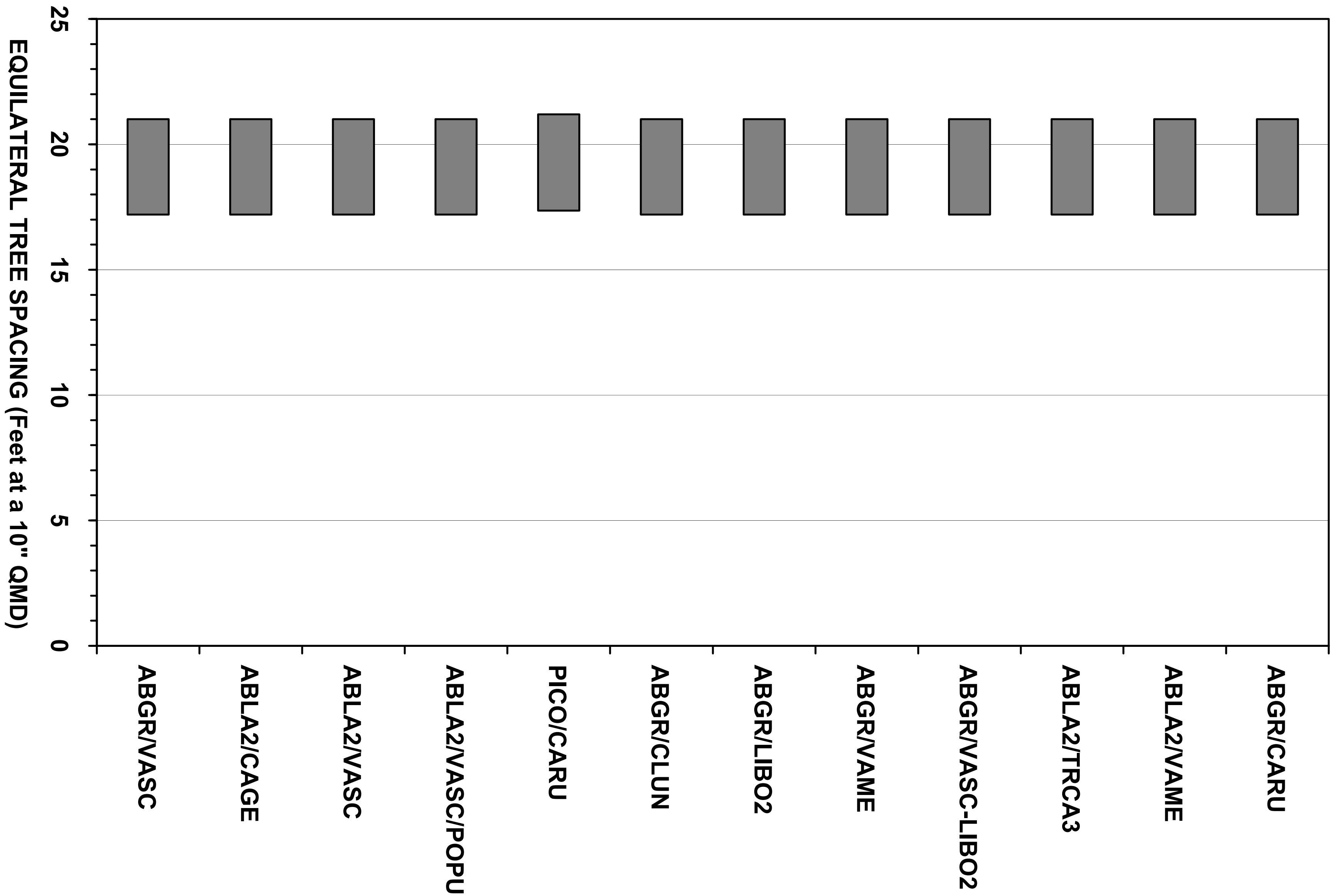

Figure 27 – Management zones for lodgepole pine, expressed as equilateral spacing.

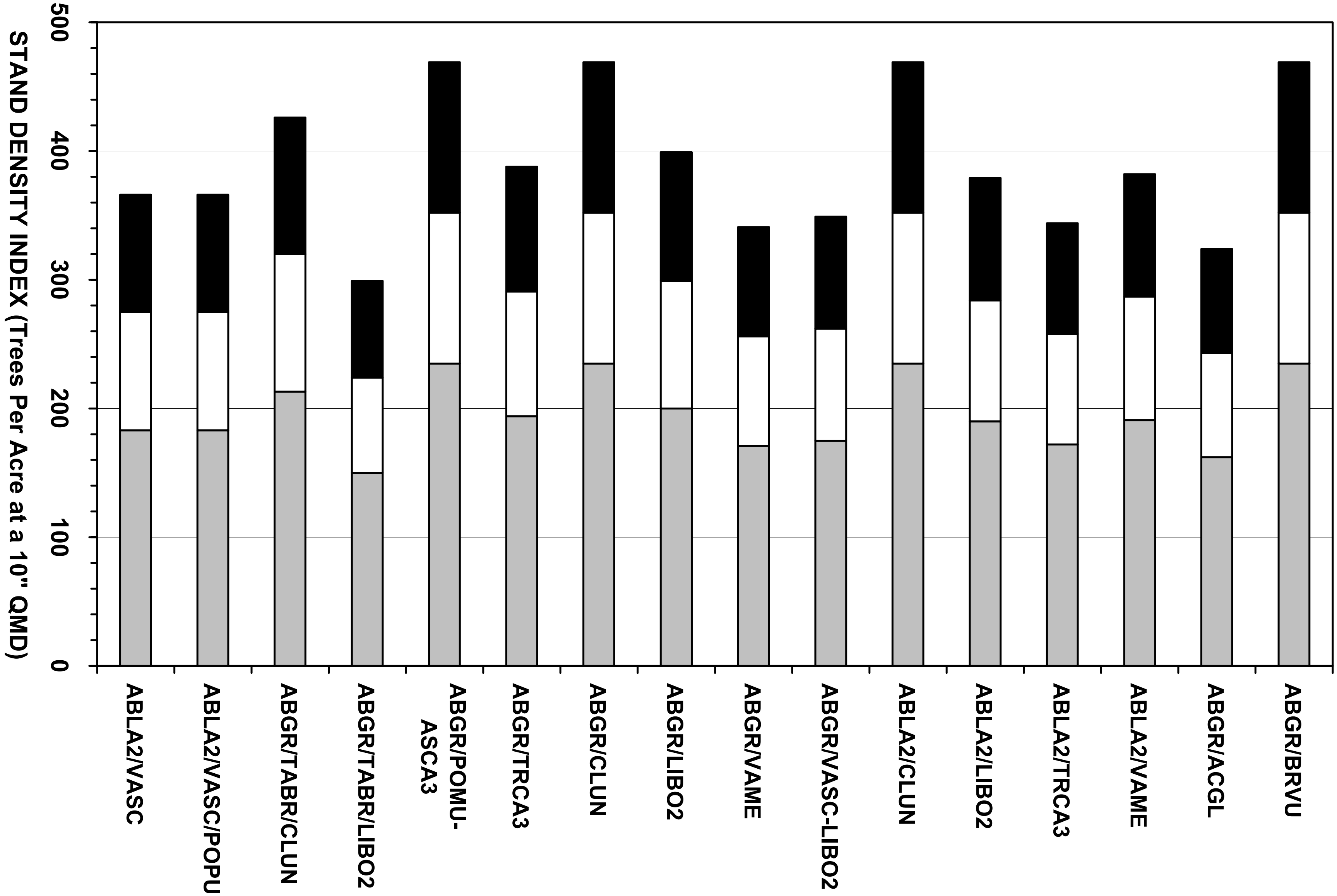

Figure 28 – Suggested stocking levels for Engelmann spruce, expressed as SDI (gray: less than full site occupancy; white: management zone; black: overstocked).

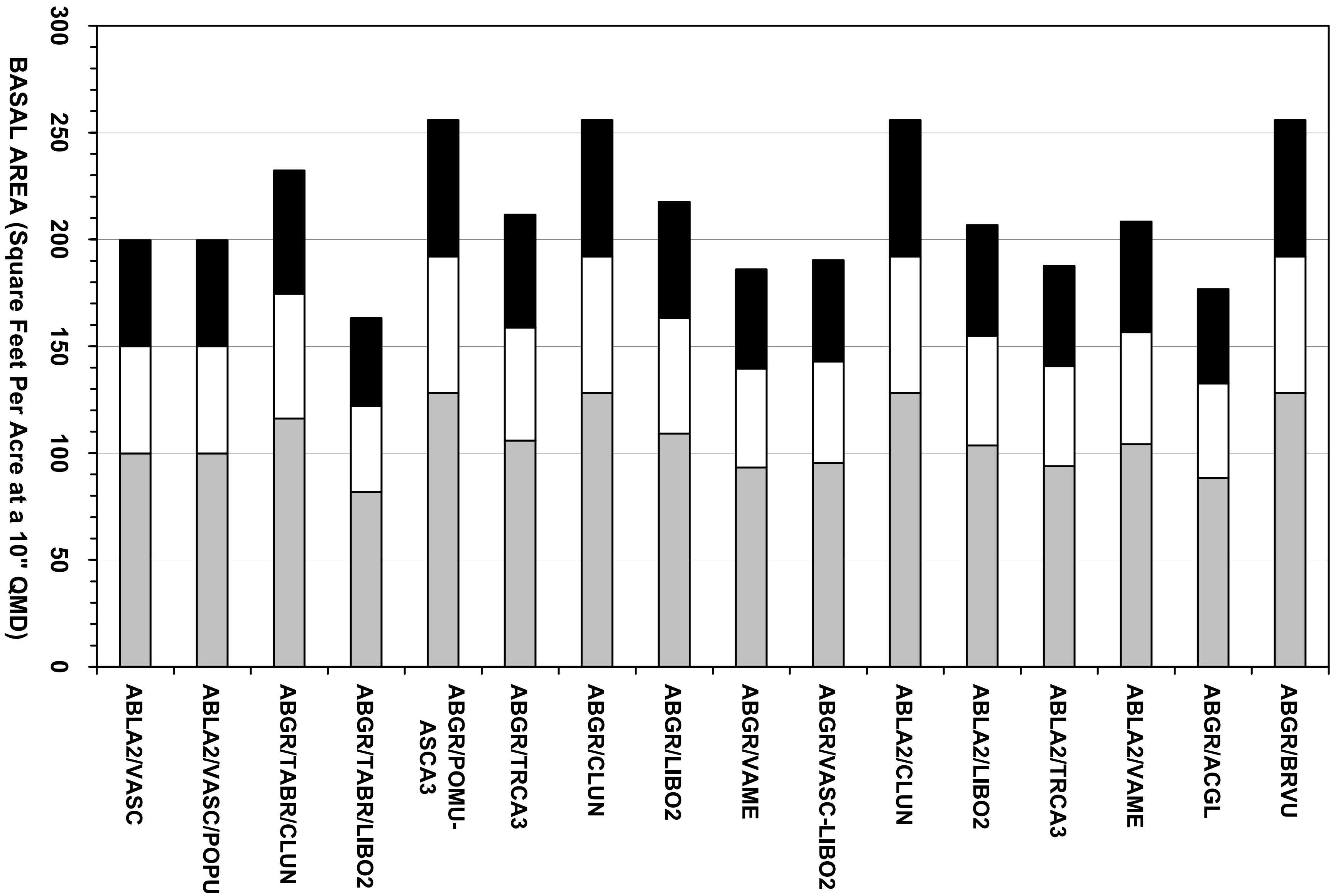

Figure 29 – Suggested stocking levels for Engelmann spruce, expressed as basal area (gray: less than full site occupancy; white: management zone; black: overstocked).

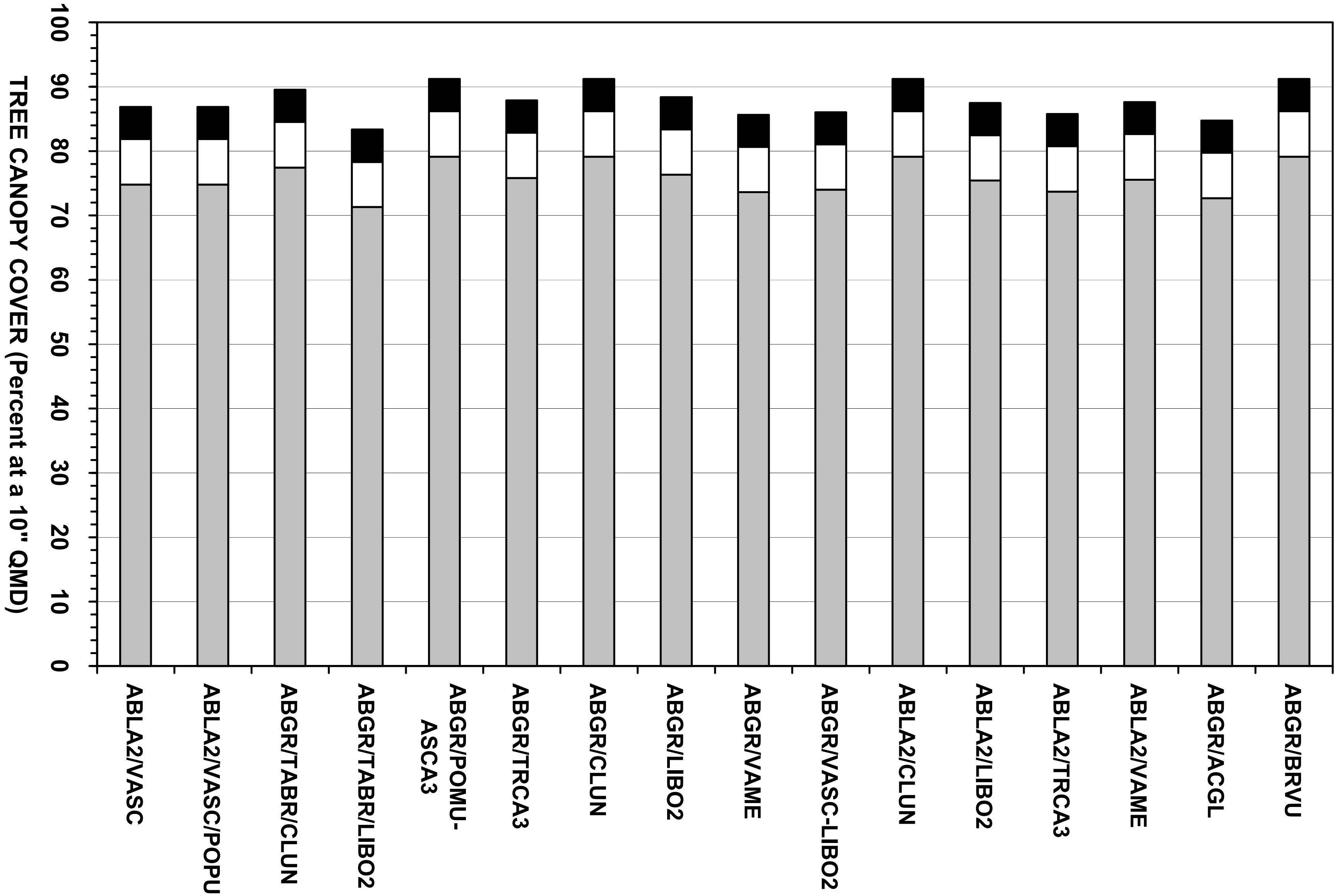

Figure 30 – Suggested stocking levels for Engelmann spruce, expressed as canopy cover (gray: less than full site occupancy; white: mgmt. zone; black: overstocked).

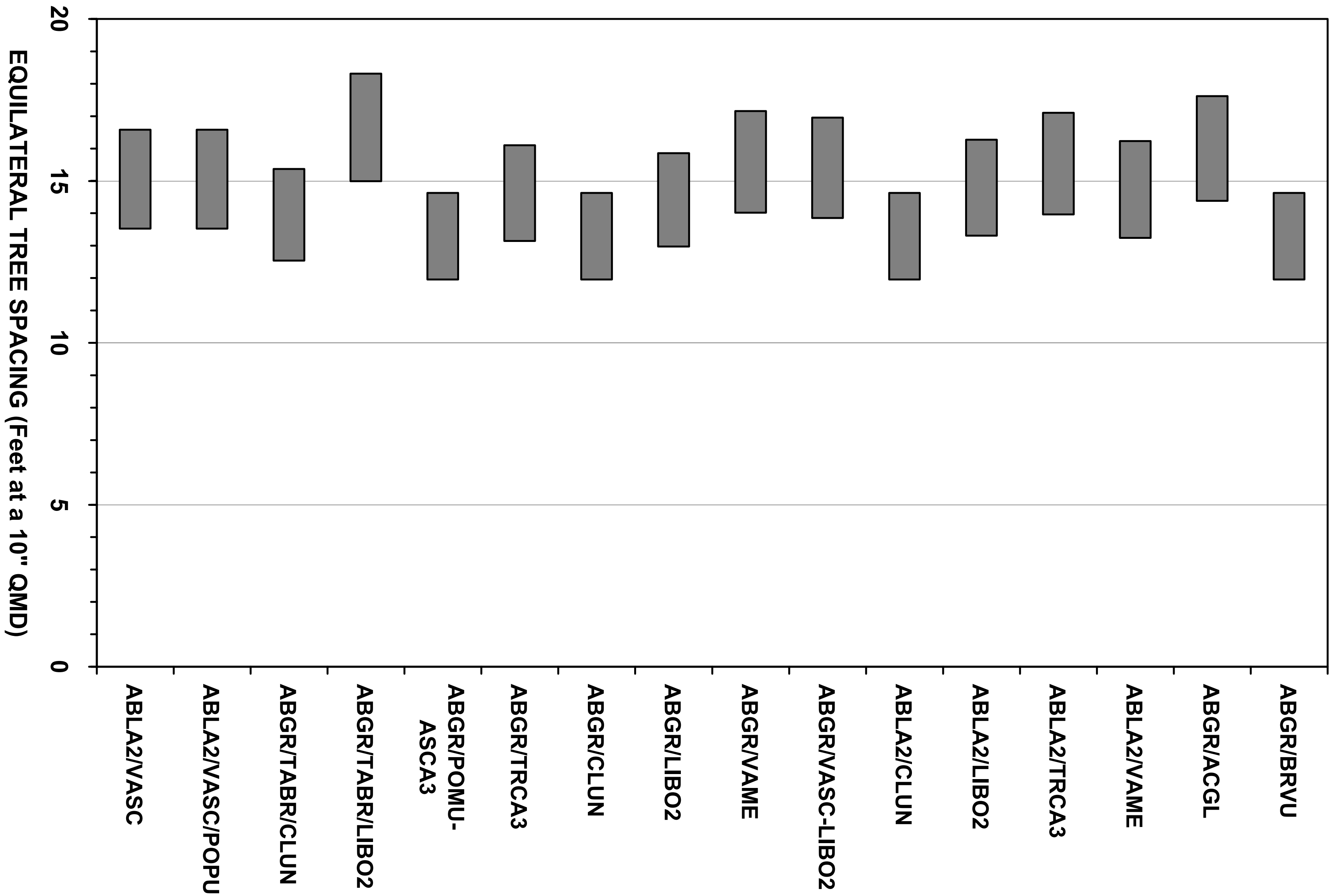

Figure 31 – Management zones for Engelmann spruce, expressed as equilateral spacing.

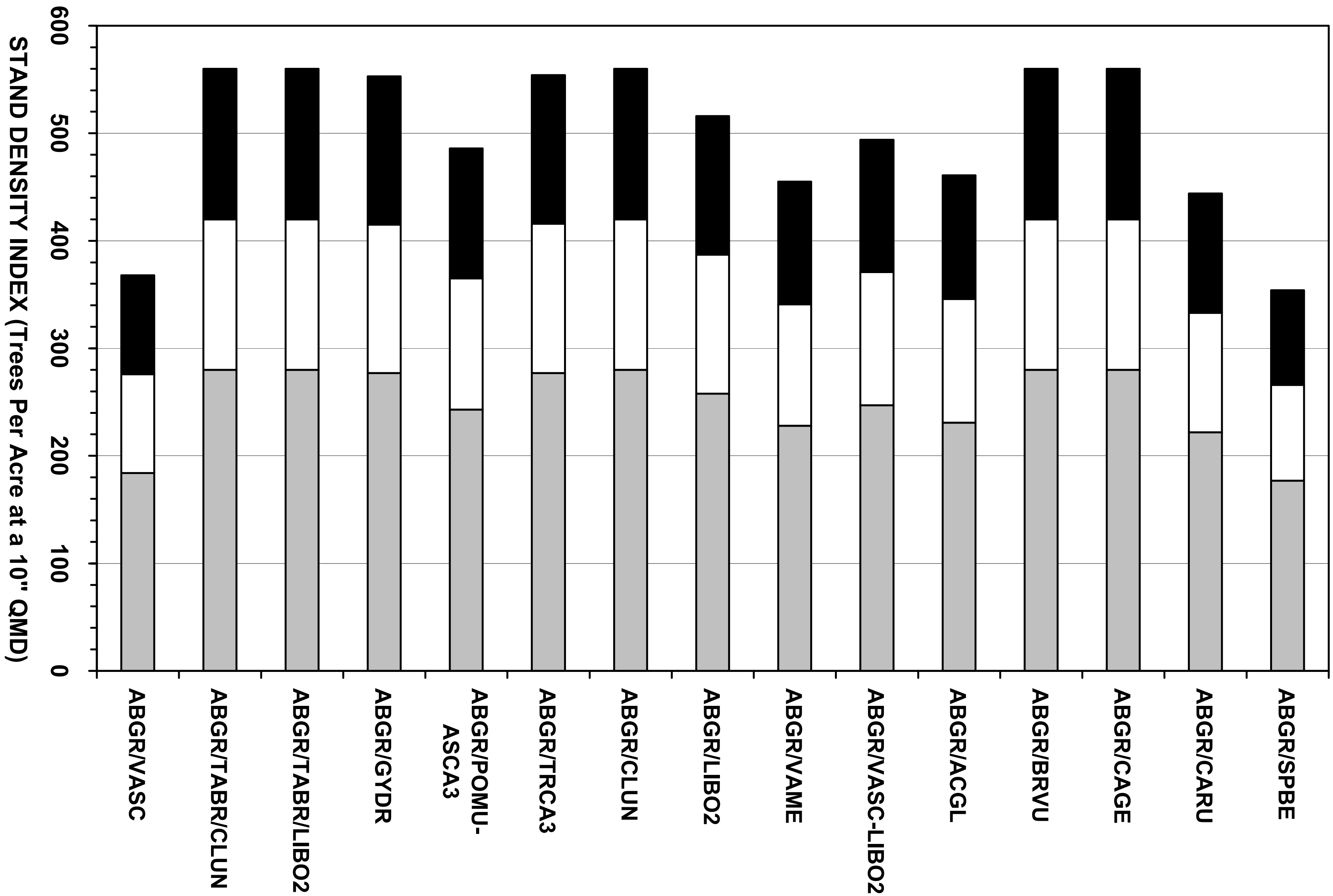

Figure 32 – Suggested stocking levels for grand fir, expressed as SDI (gray: less than full site occupancy; white: management zone; black: overstocked).

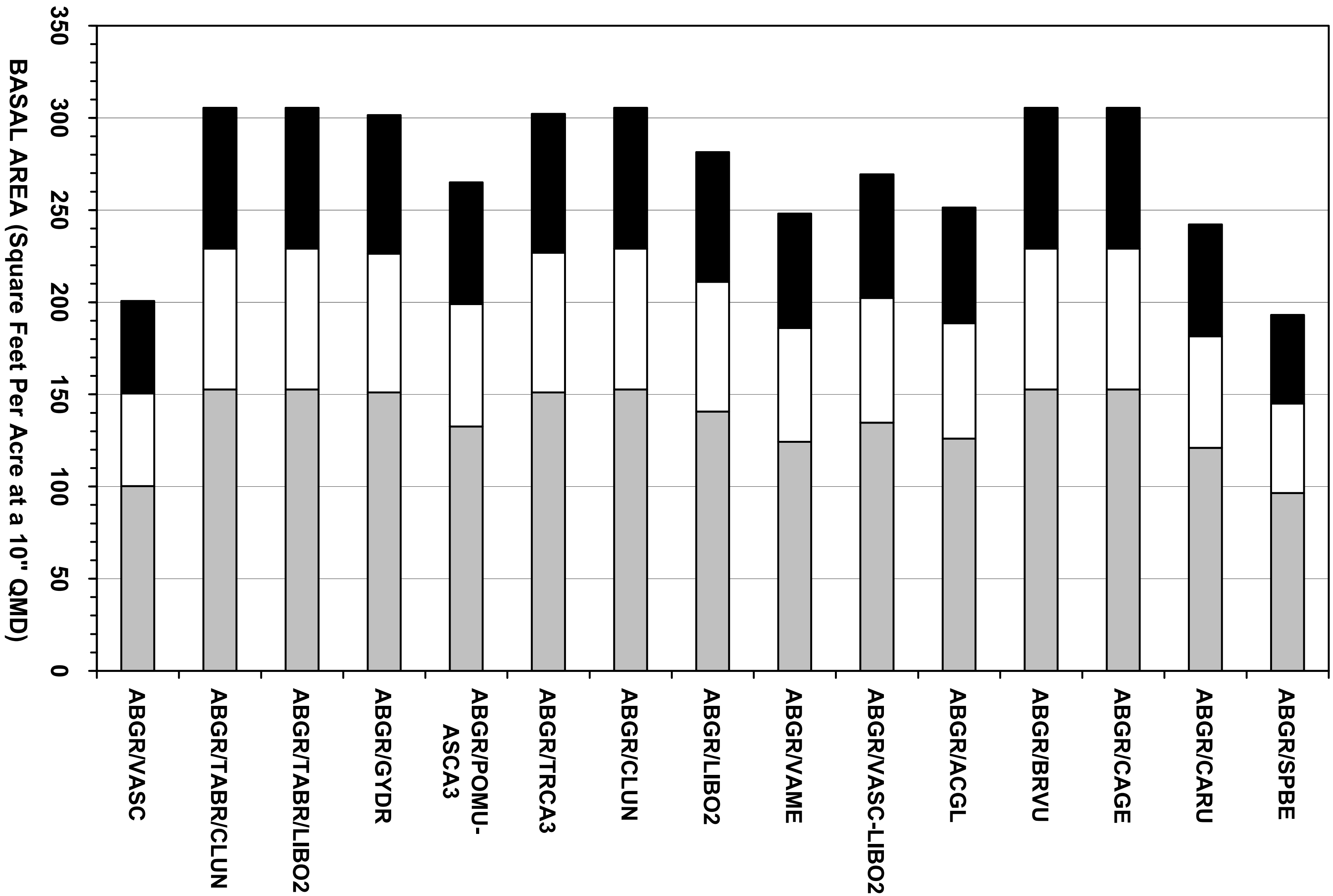

Figure 33 – Suggested stocking levels for grand fir, expressed as basal area (gray: less than full site occupancy; white: management zone; black: overstocked).

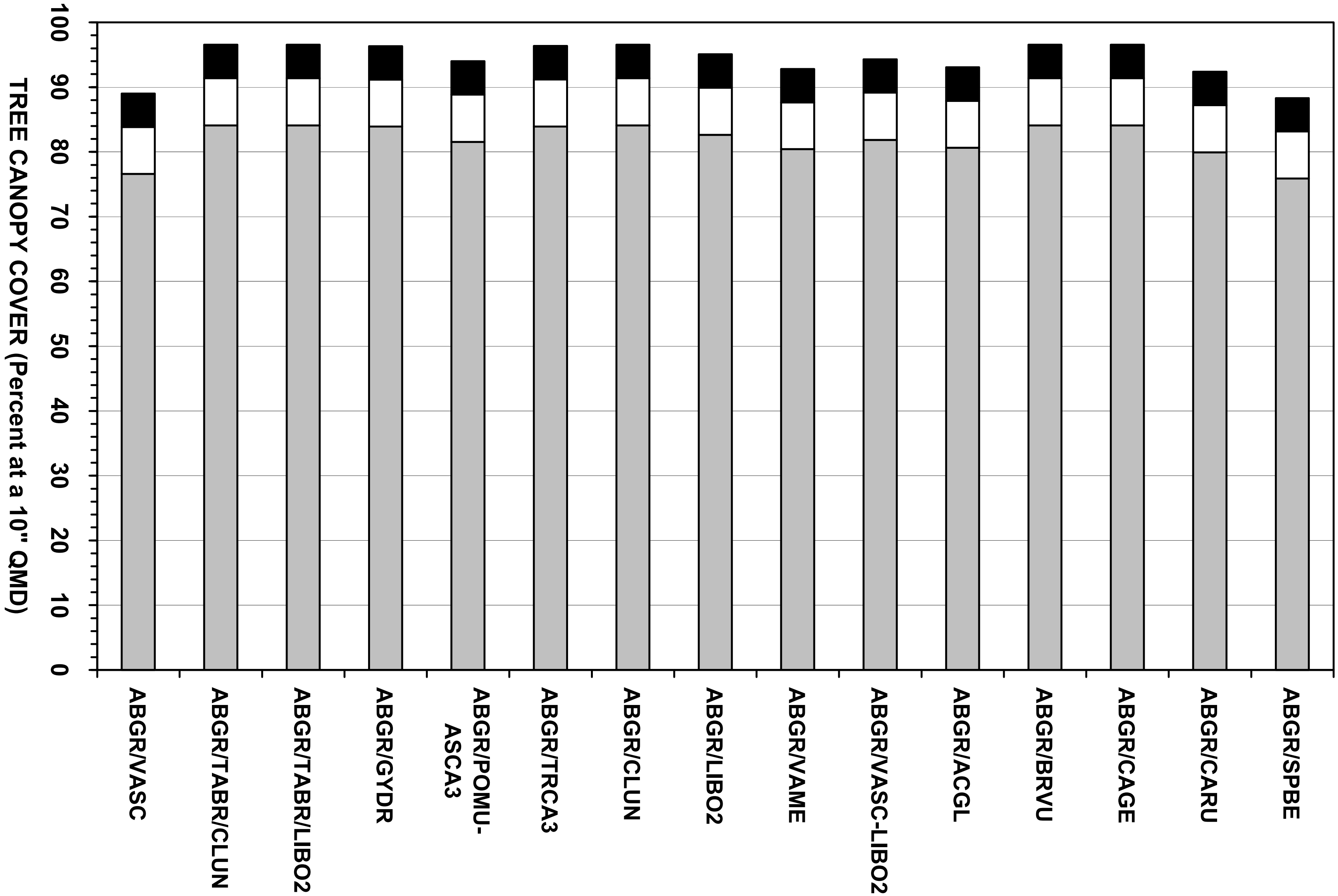

Figure 34 – Suggested stocking levels for grand fir, expressed as canopy cover (gray: less than full site occupancy; white: management zone; black: overstocked).

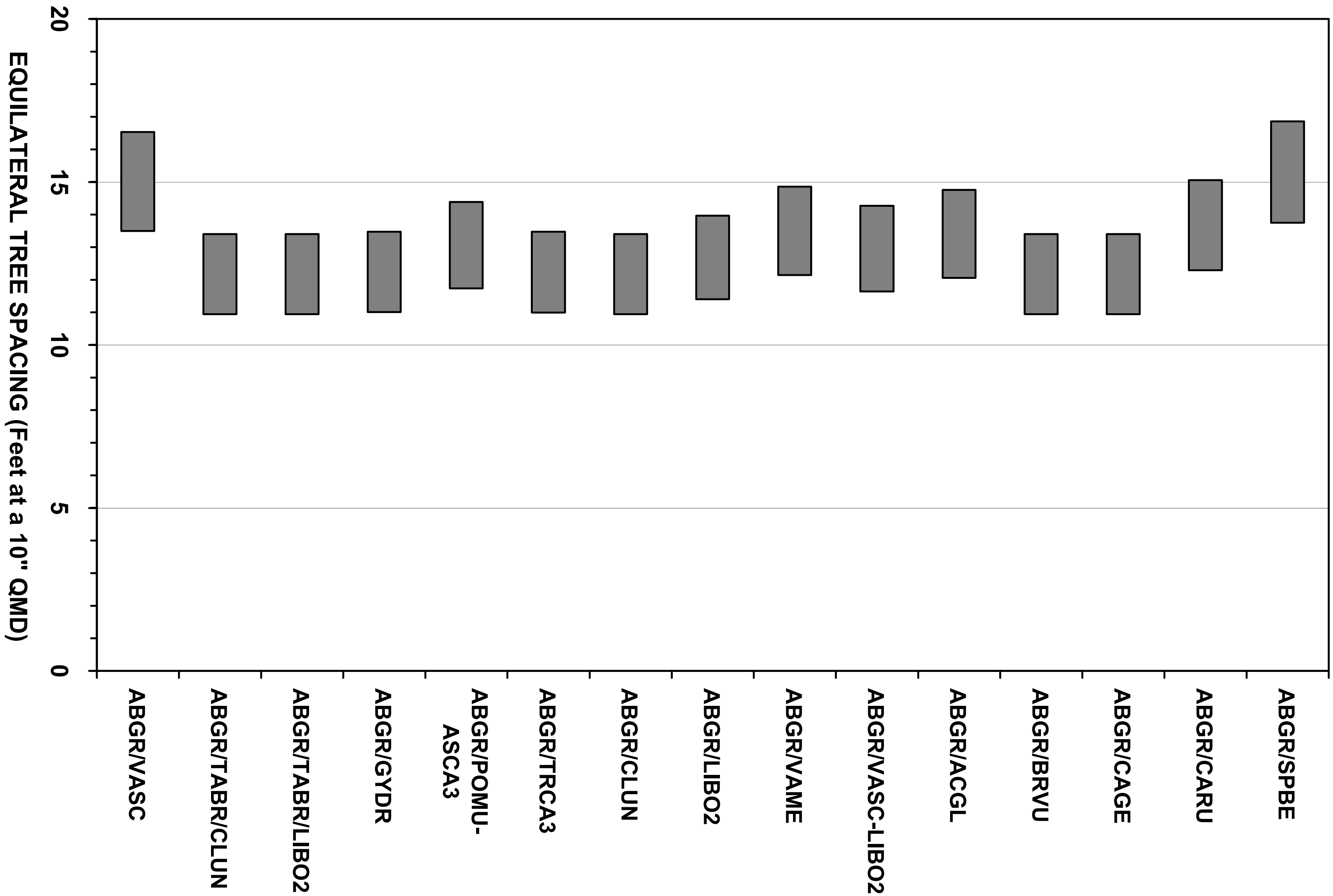

Figure 35 – Management zones for grand fir, expressed as equilateral spacing.

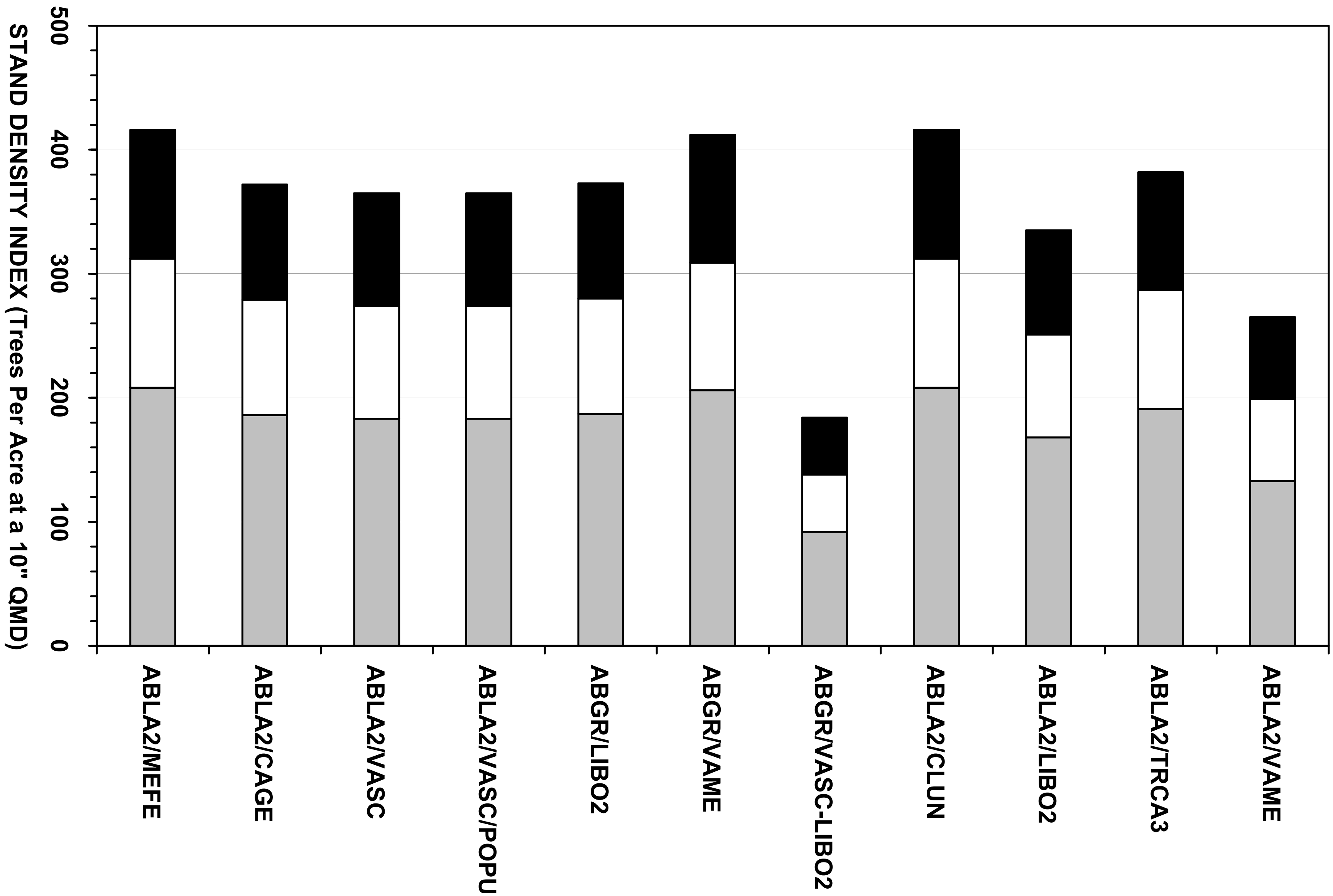

Figure 36 – Suggested stocking levels for subalpine fir, expressed as SDI (gray: less than full site occupancy; white: management zone; black: overstocked).

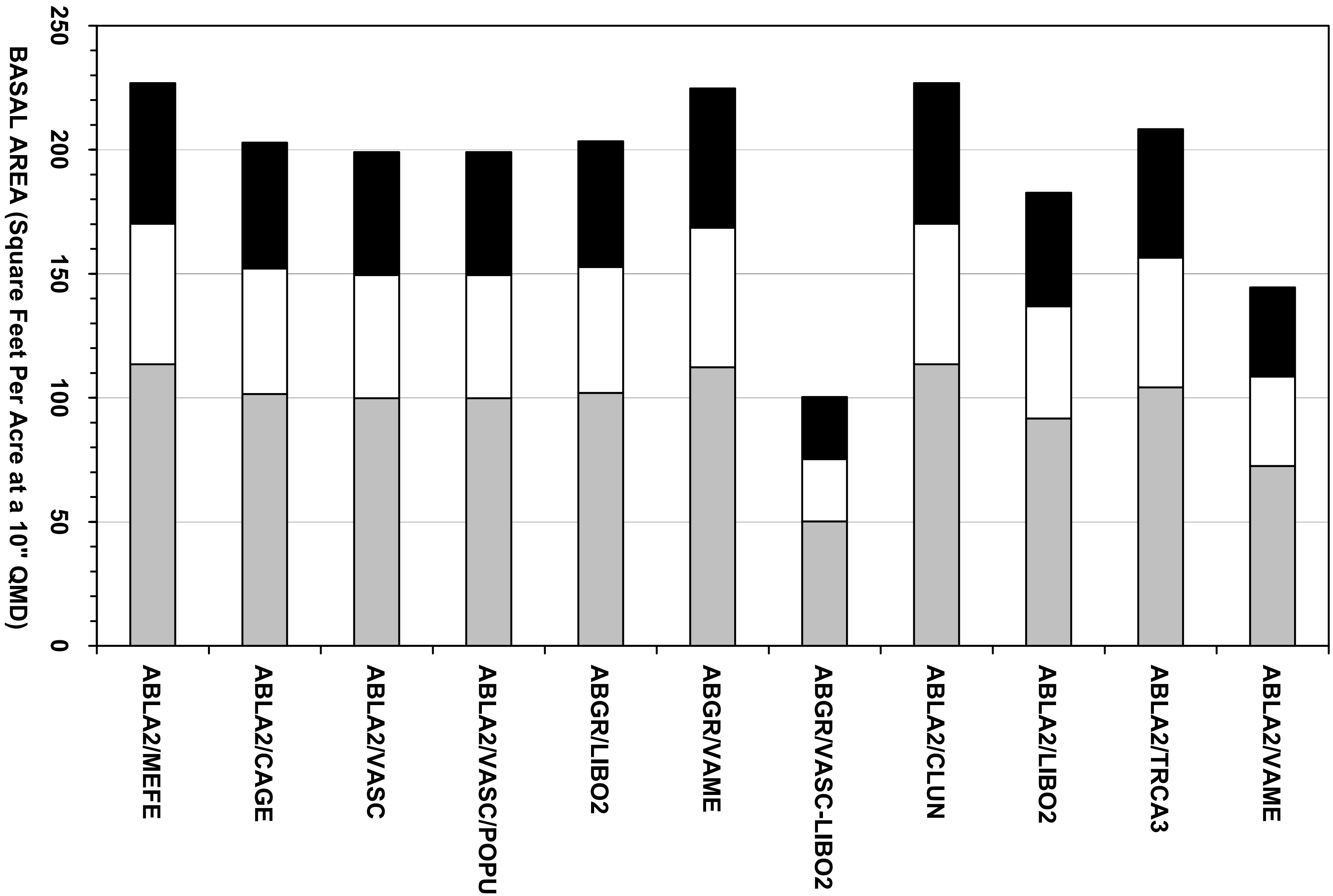

Figure 37 – Suggested stocking levels for subalpine fir, expressed as basal area (gray: less than full site occupancy; white: management zone; black: overstocked).

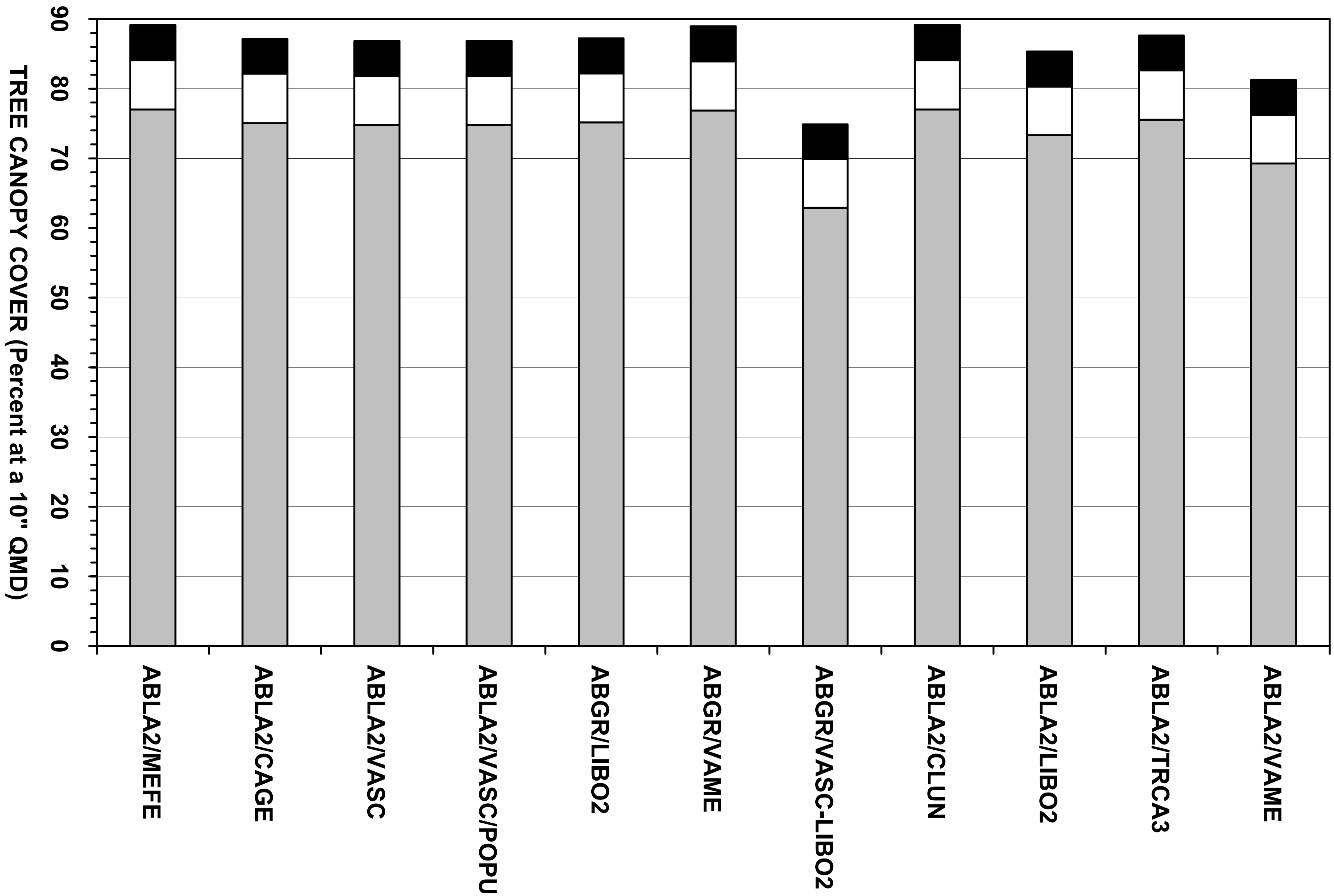

Figure 38 – Suggested stocking levels for subalpine fir, expressed as canopy cover (gray: less than full site occupancy; white: management zone; black: overstocked).

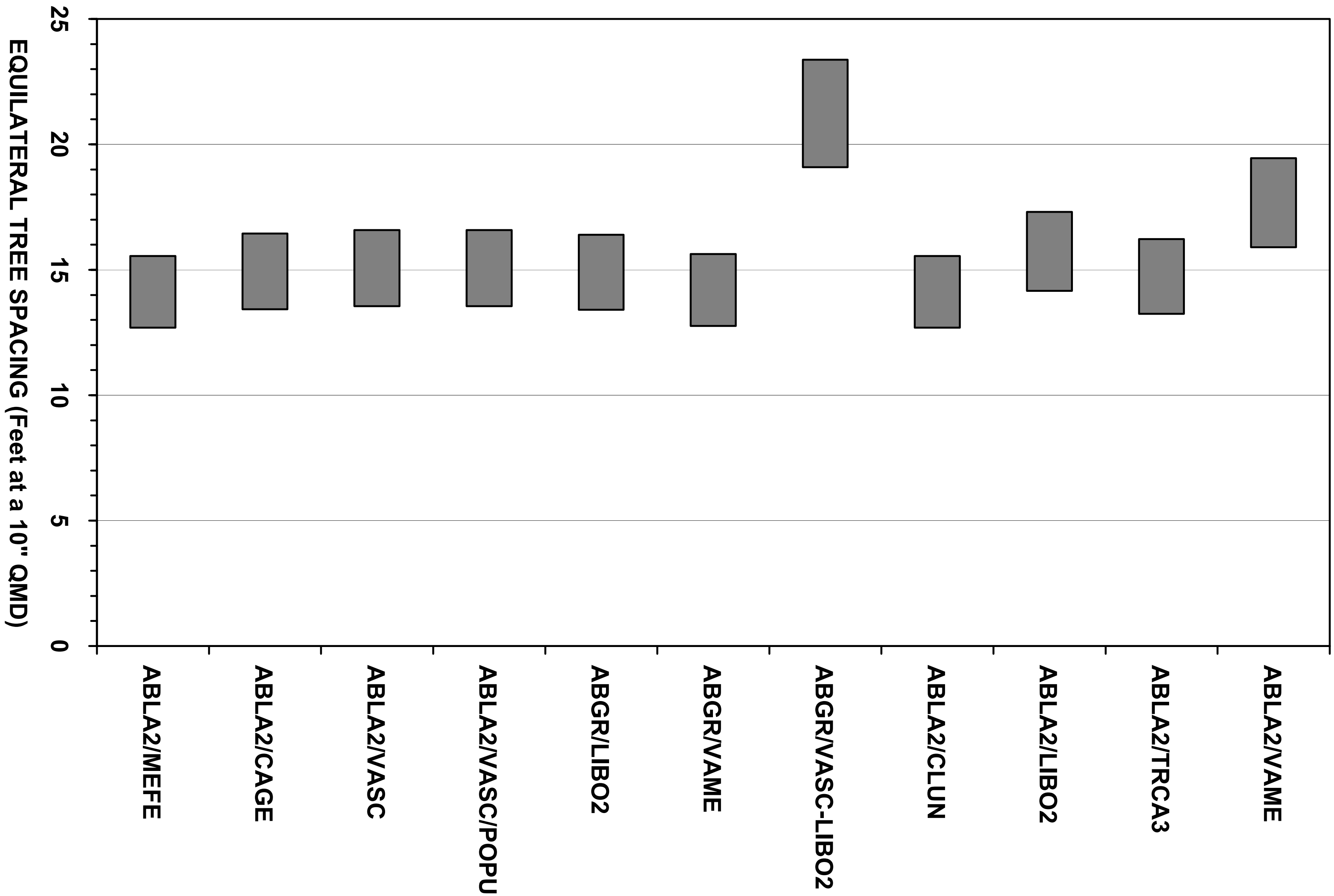

Figure 39 – Management zones for subalpine fir, expressed as equilateral spacing.