

AN ABSTRACT OF THE THESIS OF

Doug B. Mainwaring for the degree of Master of Science in Forest Resources presented on April 21, 2000. Title: Growth Analysis of Heterogeneous Stands of Ponderosa Pine and Lodgepole Pine in Central Oregon

Abstract approved: _____

Douglas A. Maguire

Basal area and height growth were analyzed for individual trees in uneven-aged ponderosa and lodgepole pine stands in central Oregon. Basal area growth was modeled as a function of other stand and tree variables to address five general objectives: 1) to compare the predictive ability of distance-dependent versus distance-independent stand density variables; 2) to determine the degree to which small trees negatively affect the growth of overstory trees; 3) to compare attributes of trees demonstrating varying levels of growth efficiency, and differences imposed by species and by the index of spatial occupancy used to define efficiency; 4) to determine how estimates of growth and growth efficiency change when multiple spatial occupancy indices and more functional variables are used within the model; and 5) to compare changes in growth and growth efficiency following alternative silvicultural treatments simulated on the basis of the fitted growth model.

Distance-dependent variables were found to improve growth predictions when added to models with only distance-independent variables. However, this improvement was not considered sufficient to warrant the necessary labor-intensive collection procedures.

Small trees were found to have a quantifiably negative effect on the growth of larger trees. However, the volume growth gained as a result of removing them was small enough to question the utility of doing so for improving overstory growth.

The growth efficiency of a given tree was found to depend on the index of growing space by which that efficiency was defined. Likewise, growth efficiency patterns differed by species. While volume growth efficiency (VGE) declined with increasing levels of spatial occupancy for lodgepole pine, ponderosa pine VGE was greatest at the highest levels of crown base sapwood area and crown projection area.

A single index of spatial occupancy was found to be an insufficient description of a tree's spatial occupancy from the standpoint of growth—inclusion of multiple indices of spatial occupancy and more functional variables to growth models improved growth predictions significantly.

When different types of harvests were simulated on these plots, the growth responses depended on removal size class. Growth response within a given size class was greatest when basal area removal across the plot was concentrated among the largest trees. Stand growth response followed the opposite trend. Growth efficiency of residual trees was most dependent on the arrangement and characteristics of individual plot trees.

Growth Analysis of Heterogeneous Stands of Ponderosa
Pine and Lodgepole Pine in Central Oregon

by

Doug B. Mainwaring

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APPROVED:

Major Professor, representing Forest Resources

Head of Department of Forest Resources

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Doug B. Mainwaring, Author

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Growth Analysis of Heterogeneous Stands of Ponderosa Pine and Lodgepole Pine in Central Oregon

Chapter One: Introduction

Introduction

Many interior *Pinus ponderosa* ponderosa pine forests are presently in a multi-age condition as a result of prevailing disturbance patterns. The disturbance factors, including but not limited to fire, insects, diseases, and logging, create growing space within a stand, thus making possible the establishment of new cohorts.

This multi-age condition may be desirable for a number of reasons. Multi-age stands can provide landowners with a predictable supply of mature timber, extractable at predetermined cutting cycles. Some level of continuous ground cover provides a number of advantages, such as a more reliable and well dispersed source of seed for natural regeneration, amelioration of site climatic conditions, and what many feel is an enhanced visual character. The complexity of vertical structural in a multi-age stand is believed to provide for biological diversity, increasingly recognized to be a valuable social commodity. In addition, maintenance of large, old growth pines, presently a mandate for the Forest Service, reflects the aesthetic appeal of their orange colored bark as well as their value as a genetic and biological resource.

Harvesting within multi-age stands, while removing volume, is capable of simultaneously producing a structure capable of at least sustaining growth and vigor in residual trees. The residual size class distribution in a managed uneven-aged stand has been commonly described by the BDq approach to characterizing a reverse J-shaped curve, specifically by defining a residual basal area, a maximum diameter class, and a q-factor. The q-factor, (generally between 1 and 2 in an operational setting) is the ratio of trees per unit area in one diameter class to the trees per unit area in the next larger diameter class (Smith 1997). The reverse J-shaped curve described by the q-value thus describes the relative numbers of trees in successive diameter classes.

Even with relatively small q-values, the smallest diameter class in a stand has a large number of trees--made up of eventual replacements for the larger diameter classes.

This approach has been criticized in water limiting environments such as central Oregon. Cochran (1992) believed this approach delegated too many trees to smaller diameter classes. High numbers, though made up of small trees, constitute a large drain on site resources, and through it, greater competition for the larger diameter classes. Likewise, the intense inter-tree competition among small trees produces trees that enter into the minimum merchantable classes with poorer vigor than necessary. Rather than strict submission to a J-shaped curve, a better approach might be to have only as many trees as necessary to replace those harvested from the larger diameter classes.

In a study which was partially based on data from central Oregon, O'Hara (1996) looked at the effects of stocking levels among cohorts in multi-age ponderosa pine stands. From the measured growth and growth efficiency of individual cohorts, a model was developed to predict volume increment of a stand, given differences in growing space allocation among cohorts. Individual tree leaf area and the inferred leaf area index (LAI) of individual cohorts was assumed to represent an index of occupied growing space for trees. Though comparisons of LAI (per cohort or size class) to stand maximum LAI does give an indication of that fraction of growing space occupied, this may not necessarily be most practical for the land manager. Actual ground space occupancy is conceptually easier to understand for both the manager and the crew implementing the thinning.

For a multi-age stand to maintain productivity and maximal resistance to insect attack and disease, silvicultural treatments and systems must address both volume production and residual structure. Usually, these two goals require different kinds of manipulations, such that the final prescription is a balance between these considerations.

By virtue of the cutting cycle, multi-aged stands are subject to more frequent entries than a comparably productive even-aged stand. Due to the resulting shorter periods of compounded cost, there is some incentive to treat non-merchantable material under the expectation of a return on that investment. However, long range decisions, and in this case, investments, require some knowledge as to the costs and benefits of different management procedures.

To at least cover the costs of a harvesting operation, some large and valuable trees must be harvested. This can leave a stand overstocked with small trees, many more than are needed as future replacements, and many more than would be optimal to enhance

understory growth and vigor of the small trees themselves. Harvest prescriptions for these stands typically call for a minimum residual density, but don't address how this density is to be distributed across the range of size classes. This distribution is of critical importance, because the way the density is distributed among size classes can have enormous implications for stand and individual tree growth, growth efficiency (growth per unit site occupancy), and vigor. This study seeks to develop an understanding of how distribution of growing space influences individual tree and stand growth, growth efficiency, and vigor. This enhanced understanding will facilitate design of prescriptions for distributing residual stand density among size classes and by implication, across the ground area of a stand in order to meet particular objectives.

Past Work

Influence of residual stand structure on growth

In water limited environments, the ability of small plants or trees to hinder the growth of their larger neighbors has been documented. (Barrett, 1963; Barrett, 1970, Oren et. al. 1987, Riegel et. al. 1992, Hanson 1997). This fact has brought suggestions that for uneven-aged ponderosa pine stands, strict submission to a traditional J-shaped diameter distribution is likely to retard stand growth by allocating too much growing space and soil resources to small size classes whose numbers are unnecessarily high for crop tree replacement (Cochran 1992). In fact, many of these trees will be lost due to self-thinning.

Size class distribution in a multi-age stand will have a large impact on how leaf area is distributed among trees in a stand. Leaf area, the source of photosynthetic production and transpirational potential, is important both in its quantity, and its arrangement within and between trees. It is through this leaf area arrangement that actual allocation of growing space among size classes serves as a major determinant of future stand growth.

A study comparing two different species in medium-aged, even-aged stands, *Abies lasiocarpa* subalpine fir and *Pinus contorta* lodgepole pine, found that the relation between growth efficiency (GE) and leaf area of the two species differed, and that these

differences were explained by canopy structure and shade tolerance (Roberts et al. 1993). In the case of the more vertically stratified and shade tolerant fir, GE increased with increasing leaf area, though only to a point. This was believed due to the direct relationship between leaf area and height—increases in GE continue as long as increased height improves a tree's canopy position; however, above certain sizes, costs associated with increased size diminish GE. For lodgepole pine, GE decreased with increasing leaf area. Similarly explained by canopy structure and shade tolerance, the change in relative height associated with increased leaf area in lodgepole pine does not appreciably improve the light environment of the shade intolerant pine.

Previous studies looking at multi-age stands ponderosa pine stands have found that leaf area index (LAI) per cohort decreases with decreasing age of cohort (O'Hara 1996). These differences, related to structure, translate into large differences in the distribution of growth among cohorts. While this study found that the oldest cohorts, containing the most leaf area, were, on average, growing most efficiently (as defined by leaf area), this may be highly dependent on the characteristics of an individual tree. Although this species is, like lodgepole, classed as shade intolerant, the vertical stratification of uneven-aged ponderosa pine may cause it to behave similarly to subalpine fir stands. However, this result is not universal—within uneven-aged stands of the shade tolerant *Picea rubens* (red spruce), GE was found to decrease with increasing leaf area (Maguire et al. 1998). In these stands, any apparent association of greater leaf area with an improved light environment was not enough to overcome the associated costs of greater leaf area. Even when growth efficiency was corrected for tree size and degree of past suppression, efficiency still decreased with increasing leaf area..

In a study in even-aged Douglas-fir, the most efficient trees in unthinned stands were tall trees with large sized crowns. In stands thinned years prior, the most efficient trees were tall and had medium sized crowns (O'Hara 1988). Significantly, the large crowns prior to thinning were similar in size to the medium crowns following thinning (following a period of growth). This information, coupled with the limits to high GE with increased leaf area found in subalpine fir, may suggest that although large ponderosa pines may be most efficient as an entire cohort, individual trees may not display this efficiency once their crown becomes too large. For example, the long branches of large

ponderosa pine crowns are believed to display diminished hydraulic conductance, resulting in diminished diurnal photosynthesis relative to needles from short branches (Yoder et al. 1994).

Indices of growth efficiency

Growth efficiency most typically is a measure of production per unit growing space or some other basis of production. In the case of individual trees, it is generally defined by stemwood production per unit of site occupancy. Because site occupancy can be defined in a variety of ways, growth efficiency can and has been defined in several different ways. Among the typical measures of site occupancy are leaf area, crown projection, and area potentially available (O'Hara 1996, O'Hara 1988, Daniels and Burkhart 1986).

There is a clear relation between leaf area and productivity; leaves are the primary photosynthetic organs of a tree. Leaf area of forest stands varies a great deal between sites (Grier and Running 1977), and is often used as an indicator of potential stand productivity. Because a fully occupied site exhibits an approximately equilibrium leaf area (Grier and Running 1977), this maximum can be considered to be representative of maximum potential growing space, and any fraction of this maximum as actual occupied growing space (O'Hara 1988). Leaf area thus becomes a useful and biologically appealing measure of site occupancy for calculating growing efficiency--its use in this capacity has already demonstrated the efficiencies of different cohorts in multi-age ponderosa pine (O'Hara 1996).

The correlation between leaf area and sapwood cross-sectional area has been utilized extensively (Grier and Waring 1974). While leaf area itself is a difficult characteristic to measure, the ease of measuring sapwood area has led to its adoption as a surrogate. Site-specific or region-specific and species-specific relationships between these two characteristics are developed with linear regression techniques, and the relationship has been found to be similar among even-aged or uneven-aged structures in ponderosa pine (O'Hara and Valappil 1995). Nevertheless, taper of the sapwood between crown base and breast height, and the wide range of lengths between these two points in an uneven-aged stand, suggests that sapwood cross-sectional area at crown base would be

the better estimator of leaf area (Waring et. al. 1982). The existence of taper equations developed specifically for sapwood make it possible to adjust breast height sapwood cross-sectional area to crown base sapwood area (Maguire and Batista 1995).

Ground space occupancy has merit as a measure of site occupancy for efficiency calculations because applications seeking optimal spacing of residual trees by this variable are conceptually simpler, and thus more operationally practical, than would be distribution by leaf area. Also, leaf area may not reflect the total amount of site resources available to a tree, particularly in repeatedly entered stands. Ultimately, leaf area would have to be translated into size and spacing guidelines that could be practically implemented.

For stands at full crown closure, the ground occupancy of an individual tree is closely approximated by the ground area of its horizontal crown projection (Assman 1970). This has been applied to closed-canopy stands where crown overlap is negligible (O'Hara 1988). For sites where a fully stocked stand does not necessarily exhibit a closed-canopy, the extent of the root system would be a better indicator of ground space occupancy. In such sites, root spread has been found to greatly exceed crown projection (Hall 1989). The ground occupancy of the tree under these latter conditions is represented by the sum of crown projection area and a portion of the open area between trees. For open-canopy, fully-stocked stands, Area Potentially Available (APA) (Assman 1970), is a useful surrogate for ground space occupied. This measure considers a tree's share of horizontal ground space as determined by size and distance of neighbors (Assman 1970).

Various means of calculating area potential available have been used (Alemdag 1978, Daniels et. al. 1986). Among these is a distance-dependent procedure whereby polygons are attributed to each tree by establishing boundaries between the subject tree and its neighbors (Moore et. al. 1972). The location of these boundaries is determined by taking into account the comparative sizes of the subject and neighboring tree. By dividing stem increment of the subject tree by the determined APA, it is possible to calculate the growth efficiency of that tree, leading to references about how best to distribute ground area among stems.

Implications of individual tree vigor

It is believed that mountain pine beetle resistance in ponderosa and lodgepole pine can be tied to a particular threshold of tree vigor, particularly between epidemics. Vigor, as measured by weight of stemwood produced per unit canopy leaf area, has been used as a measure of a tree's carbon uptake and physiological status (Waring and Pitman 1985), and an indicator of their ability to resist attack by pests. Trees with greater than 100 g of annual stemwood growth per square meter of leaf surface area suffered very few attacks, and very little mortality (Larsson et. al. 1983). In lodgepole pine, it was found that at less than 20 g stemwood production per square meter of leaf surface area per year, no pitch was exuded during attacks. Meanwhile, like ponderosa pine, those trees putting on more than 100 g per square meter of leaf surface area per year were rarely killed, regardless of the attack density (Mitchell et al. 1983).

Trees have developed two lines of defense, called the constitutive defense system and the induced defense system (Berryman 1972). In pines, the constitutive defense system is based on resin ducts located throughout the xylem and phloem. Upon being wounded, these passive resin ducts are physically opened, and the toxin-containing resin is released as pitch (Berryman 1972). Because a tree's defense system is usually of lowest priority for internal resource allocation (Chung and Barnes 1980), its ability to allocate energy to this defense requires that the quantity of photosynthetic energy produced was sufficient to meet all other energy requirements first.

The second line of defense is called the induced defense system. Stimulated biochemically, this response seeks to contain an invasion through self-inflicted necrosis of host tissue (Berryman 1972). In addition, the area affected undergoes an increase in terpene and phenolic concentrations, constituting a chemical assault on the invader (Berryman 1972). By being so localized, this defensive response both conserves energy and limits the death of tissues responsible for translocation. However, while the induced system is efficient in its ability to limit its action to only those areas being attacked, it is very energy intensive (Raffa and Berryman 1982).

In the case of the lodgepole pine, response of the induced (secondary) defense system to bark beetle attack was found to be the most important difference between susceptible and resistant trees (Raffa and Berryman 1982). The constitutive (primary)

defense system was found to be most important where it slowed beetle activity by plugging galleries to mining or impeded pheromone emission, thus giving the induced system more time to react. Successful defense requires quick response, with the major feature said to be the quantity of stored energy available for the rapid synthesis of beetle and fungal toxins. (Raffa and Berryman, 1982). This being the case, in order to effectively defend against attack, the tree must have copious amounts of stored energy, i.e. photosynthetically derived carbohydrates. It has been hypothesized that a tree's defensive capacity is intimately tied to the amount of carbohydrates utilizable by defense systems (Waring and Pitman 1985), and that any factor which lowers photosynthate production or efficiency would ultimately compromise a tree's resistance to beetles and disease (Christiansen et. al., 1987).

Where bark beetle activity is a concern, measure of relative tree vigor will indicate what structures are likely to have trees capable of a strong defensive response. However, many studies showing beetle resistance after thinning have focused on even-aged stands, and have implicated the ensuing microclimatic changes as a major beetle deterrent (Amman et al. 1988, Bartos and Amman 1989, Schmid et al. 1991, Schmid et al. 1995). While these latter findings are potentially relevant within well-spaced uneven-aged structures, applicability would depend on the type of silvicultural treatment employed. Therefore, results from studies in even-aged stands, while indicative of a tree's potential defensive response and local environment, can't necessarily be extrapolated to predict an uneven-aged stand's resistance to bark beetles.

Summary of existing information

In dry east-side forests, where growth is limited by belowground resources, growth of stands and individual trees will be greatly influenced by stand density. Where stands are non-uniform in size and spatial distribution, their ability to capture site resources will affect their ability to compete, and hence, will influence the dynamics of the stand.

While there is much known about how site, stand structure, and canopy architecture affect the growth and growth efficiency of trees, calculation of growth efficiency requires more practical measures of growing space than current studies have

used. Similarly, an assessment of the consistency among growth efficiencies, based on alternative site occupancy measures has apparently received no attention. In central Oregon, where operational thinnings generally apply spacing as a means to mark residuals, efficiency as defined by ground space occupancy may be a more useful measure than leaf area.

Generally speaking, it is accepted that higher (pre-stagnation) stand densities produce more stand stemwood gross growth over the course of time. However, this increased stemwood production is not without trade-offs. The smaller crowns and correspondingly lowered vigor of individual trees means that they are less able to ward off endemic or periodic agents of mortality. This is of particular concern in regions, like the interior west, where growing conditions are marginal, where site resources are limited, and where many insect and disease pathogens are endemically present, and thus able to take advantage of trees that are physiologically susceptible.

Identification of the trade-offs between volume growth and individual tree vigor is straightforward. Identifying the exact implications of striking a particular balance is not. Because this project does not address any particular management prescription, it will not seek an optimum. Rather, it will attempt to identify the growth and growth efficiency effects of different types of structures, and speculate as to the trade-offs these structures might entail, particularly between total volume production per unit of area and individual tree vigor.

Objectives

The target population for this study is a large industrial land base in central Oregon, the majority of which comprises unevenaged or multicohort stands of ponderosa and lodgepole pine. This structure has resulted from repeated commercial entry, exclusion of fire, and other disturbance agents.

This study seeks to develop a connection between the distribution of growing space and individual tree and stand growth, growth efficiency, and vigor. This enhanced understanding will facilitate design of prescriptions for distributing residual stand density among size classes and, by implication, spatially within the stand in order to meet particular objectives. Specific objectives of this thesis research include:

- 1) Test hypotheses about stand structural variables and tree attributes that control growth and growth efficiency in heterogeneous stands of ponderosa pine and lodgepole pine, and to identify the trees or stand components exhibiting the greatest growth and growth efficiency (Chapter two).
- 2) To determine whether conclusions reached about patterns in growth efficiency depend on the indices of occupied growing space and the interactions among alternative occupancy indices (Chapter three).
- 3) Investigate the implications of various residual stand structures on subsequent growth and growth efficiency (and by implication resistance to certain insect and disease pests) by simulating various silvicultural treatments and predicting the tree and stand growth responses (Chapter four).

The final section of the thesis summarizes the operational context, major results and management recommendations from the described research.

Chapter Two: The Effect of Local Stand Structure on Growth and Growth Efficiency in Heterogeneous Stands of Ponderosa Pine and Lodgepole Pine in Central Oregon

Introduction

Many interior ponderosa pine forests in western North America are presently in a multi-age condition as a result of past and current disturbance patterns. The disturbance factors, including but not limited to fire, insects and diseases, and logging, create growing space within a stand, thus making possible the establishment of new cohorts. The spatial heterogeneity of each of these disturbance types, augmented by that of any subsequent regeneration, can lead to stands whose structural conditions may or may not be optimal for the objectives at hand, be it timber production or others. The spatial distribution of trees and other stand components will have profound implications for individual tree and stand growth, as well as for the growing space efficiency of the trees within the stand. The density of trees within the stand will greatly affect the allocation of growth among individual trees, as well as the total growth of the stand; in fact, the trade offs between individual tree and stand growth are well known under variations in stand density manipulation. Decisions about the specific balance desired may be facilitated by knowing the growing space efficiency (growth divided by occupied space) of different stand components under a given stand structure.

Stand density, being both an important descriptor of inter-tree competition and stand structure, is a key component of growth models. Density is typically sampled and computed as an overall plot or stand density. Previous studies in ponderosa pine have shown that where basal area per unit area was the measure of stand density, correlations between stand density and growth were highest if sampling was conducted with a small BAF prism; that is, if sampling a greater area around a subject tree was sampled in determining stand density (Lemmon et al. 1962). In contrast, other studies, also in ponderosa pine, have demonstrated that a high degree of inter-tree competition associated with areas where stand density is locally high is an important descriptor for assessing bark beetle attack risk (Olsen et al. 1996). The high degree of spatial heterogeneity in many central Oregon pine stands suggests the need to determine the relative importance

of average stand density and local stand density as descriptors of environment and predictors of growth. Determination of the relative importance of average stand density and local stand density may be addressed by careful formulation and relative performance of statistical models describing individual tree growth. Specifically, the marginal effect of adding spatially explicit competition measures to a distance-independent equation can be tested.

Predicting growth from spatially explicit competition indices has been explored in past studies. These studies have generally compared alternative competition indices to determine the best predictors of growth—in doing so, these indices are assessed both for their utility within growth models, and for their ability to enhance understanding of dynamics resulting from between-tree competition. The most often used types of indices include: distance-weighted size ratio indices; crown or influence zone overlap indices; and area occupancy indices. The performance of these indices in models depends on the index selected, and the forest system described. They have been found to add statistically significant predictability to growth models in a variety of forest types, including mixed conifer (Biging and Dobbertin 1992), northern hardwoods (Holmes and Reed 1991), red pine (Martin and Ek 1984), and eucalyptus (Tome and Burkhart 1989). However, because collecting data necessary to compute such variables is expensive, the marginal value of this extra predictability has been questioned in the context of growth and yield models (Daniels et al. 1986).

One consequence of and reason for the spatial heterogeneity of central Oregon pine forests is the copious natural regeneration that is found in some stands. Competition in such forests is often thought to be one-sided; that is, the overstory trees inhibit the growth of the understory as a result of shading, but the reverse is not true. However, while establishment and growth of natural regeneration is important to the maintenance of multi-age stands, too much regeneration beyond that necessary for future replacements may be deleterious to the growth of older cohorts as a result of their belowground resource utilization. The question as to whether the understory trees have a deleterious effect on the growth of the overstory needs quantification, to allow assessment of the worth of removing them. A related question as to whether brush control would have a similar effect, or whether brush expansion would erase the benefits of understory

thinning, were not addressed in this study. The potential deleterious effect of small understory trees on the overstory can be tested by isolating the competition effects of different groupings of the smallest trees through regression analysis, particularly on sites where variation in understory density has been imposed by removals during past logging. Decisions about the desirability of removing small trees would require a rigorous economic analysis, but must be based on estimates of growth effects. Therefore, quantification of growth lost to small trees will provide insight as to whether precommercial thinning is cost effective.

Statistical models developed to test the first two hypotheses can also lend insight into relations between residual stand structure and the relative growth efficiency of the constituent trees. Unfortunately, growing space has been measured in numerous ways (Waring 1983, Roberts 1993, O'Hara 1988), so growth efficiency patterns may vary from study to study depending on the growth dimension and the measure of growing space or site occupancy. Three general alternatives are leaf area, crown projection area, and area potentially available.

There is a clear relation between leaf area and productivity; Leaves are the primary photosynthetic organs of a tree. Because a fully occupied site exhibits an approximate equilibrium leaf area (Grier and Running 1977), this maximum can be considered to be representative of maximum potential growing space, and any fraction of this maximum as actual occupied growing space (O'Hara 1988). Leaf area thus seems a biologically appealing measure of site occupancy for calculating growing efficiency. This measure has been made practical by the correlation between leaf area and sapwood cross-sectional area (Grier and Waring 1974); that is, it is possible to use sapwood area as a surrogate for leaf area.

Volume growth efficiency was found to be greatest for the oldest cohorts in multi-aged ponderosa pine stands (O'Hara 1996). The high efficiency of the largest trees was believed to result from the better light environment inherent to their stand social position. The increase in growth efficiency with increasing leaf area for lower crown classes in even-aged subalpine fir stands was attributed to the same mechanism (Roberts et al. 1993). Roberts et al. (1993), however, found that lodgepole pine behaved differently. Lodgepole was found to exhibit decreasing volume growth efficiency with increasing leaf

area. This was ascribed to the shade intolerance and relative lack of stratification in lodgepole pine, and, hence, the lack of correlation between a tree's relative height in the stand, and leaf area.

Ground space occupancy has merit as a measure of site occupancy because applications seeking optimal spacing of residual trees are directly related to this variable. It is also simpler, and thus more operationally practical, than would be regulating distribution by leaf area. In repeatedly entered stands, ground space being utilized may often not be proportional to the tree's leaf area. However, for stands at full crown closure, the ground occupancy of an individual tree is closely approximated by the ground area of its horizontal crown projection (Assman 1970). This approach has commonly been applied to closed-canopy stands where crown overlap is negligible (O'Hara 1988).

For sites where a fully stocked stand does not necessarily exhibit a closed-canopy, the extent of the root system would be a better indicator of ground space occupancy. In such sites, root spread has been found to greatly exceed crown projection (Hall 1989). The ground occupancy of the tree under these latter conditions is represented by the sum of crown projection area and a portion of the open area between trees. For open-canopy, fully-stocked stands, Area Potentially Available (APA) (Assman 1970), is a useful surrogate for ground space occupied. This measure requires determination of a tree's share of the open ground between trees (Assman 1970).

Growth efficiency based on area potentially available, leaf area, and horizontal crown projection area are expected to lead to slightly different conclusions. Viewed in a different way, however, different growth efficiencies in combination may improve understanding of stand structural effects on growth and growth efficiency. Analysis of the tree and stand structural characteristics of trees with low and high growth efficiency can then lend insight into design of silvicultural systems.

For the relatively dry interior forests of ponderosa and lodgepole pine, stand density (and brush cover) is of particular concern given the limited belowground resources for tree growth. The associated decreases in tree vigor are amplified by increasing stand density. Three hypotheses, pertaining to the spatial structure of different components of these multi-aged stands, are of interest:

- 1) Spatially explicit measures of local stand structure provide significant gains in predictive power over stand- or plot-average variables.
- 2) Understory trees have a deleterious effect on the overstory tree growth, and the effect is large enough to warrant investing in precommercial thinning of smaller trees.
- 3) Relative growth efficiency of individual trees depends on the basis by which site occupancy is measured: leaf area, crown projection area, or available ground area.

Methods

The above hypotheses were tested using multiple linear regression techniques. Accordingly, growth was described by construction of a basal area growth model. Basal area growth can be attributed to various tree and stand attributes, including tree size, tree vigor, tree position, stand density, and site productivity (Hann and Larsen 1991).

In constructing this model, previous models of stem diameter growth were scrutinized (Hann 1980, Ritchie and Hann 1985, Dolph 1988, Wykoff 1990, Hann and Larsen 1991, Dolph 1992). Variables required for the growth model included both covariates which adjust for differences in individual tree and stand characteristics, and covariates whose associated parameter estimates were necessary for hypothesis testing. The number and scope of variables (and necessary measurements) reflected the broad questions this study sought to answer.

Study Sites

Data were collected in the summer of 1998. Nine square, 0.4-ha plots were established within Crown Pacific's central Oregon tree farm, centered approximately at Gilchrist, Oregon (43°28' N, 121°42' W). These nine plots, split between two sites, are in the *Pinus ponderosa/Purshia tridentata* plant association (Franklin and Dyrness 1973).

The two sites represented two different stand types. The first, termed the Timbers site, consisted primarily of multi-aged ponderosa pine (Pipo) (87% of basal area is Pipo). The second site, called Blackrock, also contains primarily ponderosa pine (55% of basal area is Pipo), but a significant component of lodgepole pine (Pico) also is present. Much of the lodgepole pine occurs in single, patchy cohorts. Nevertheless, the presence of many large, old ponderosa pine stumps testifies to previous stand conditions and previous disturbance types. Evidence of more recent disturbance includes numerous skid trails,

often free of regeneration, which in many places partitions the plots into small patches of trees. The understory of both sites is dominated by bitterbrush (*Purshia tridentata*).

This portion of central Oregon, like much of the interior west, is characterized by cold winters, warm and dry summers, and limited precipitation falling mostly as snow during the winter months. The dry summers are further characterized by periodic drought. Over the last 30 years, the mean January minimum was -8°C and the mean July maximum was 27°C . Total annual precipitation during this time averaged 54 cm, with approximately 70% of this falling as snow (<http://www.ocs.orst.edu/>).

These sites, chosen from among many candidates, were subjectively selected for their fitness in meeting the objectives of the model. The target population for construction of the model consisted of multi-cohort ponderosa/lodgepole pine stands. Square, 0.4 ha plots were subjectively sampled to meet the following requirements:

- Variability in local stand density, vertical stratification, diameter range, and presence of small trees and regeneration.
- No large treeless areas or large areas of high stem densities prohibitive to mapping.
- No management activity for the past five to ten years.
- Common aspect and no obvious differences in soil type, plant association, or landform.

Although, like trees, brush acts as a drain on belowground resources, its impact was not addressed by this study. Its distribution throughout the study plots was approximately uniform, and was assumed to draw on belowground resources in a spatially uniform manner. Furthermore, whereas Crown Pacific sometimes removes small trees (by mechanical crushing or manual PCT), they do not carry out mechanical or chemical site prep or release treatments specifically targeting brush. As a result, the effect of brush presence on overstory trees was not addressed in this study, but may have an influence on maximum growth rates attainable on these sites.

Basal area by species (fig 2.1) and plot diameter distributions (figs. 2.2 – 2.10) are shown below, illustrating density, size class distribution, and species composition graphically. Individual plots ranged in basal area and trees per hectare from 7.3 to 24.3 m^2 and 306 to 2684, respectively. Plot attributes are detailed in table 2.1.

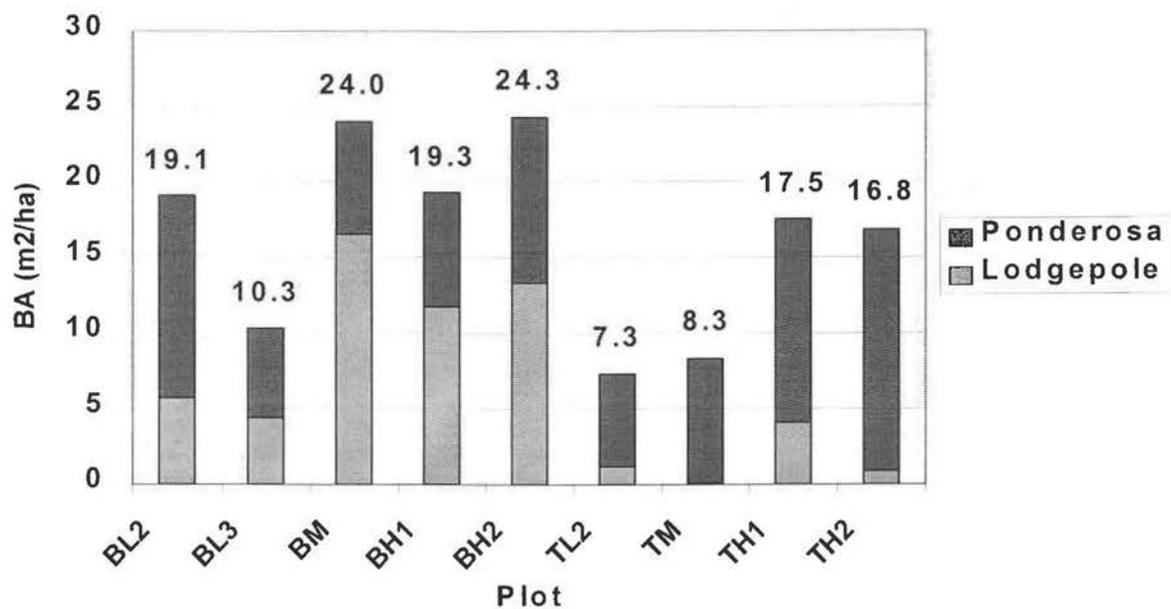


Figure 2.1 Basal area for each study plot, by species

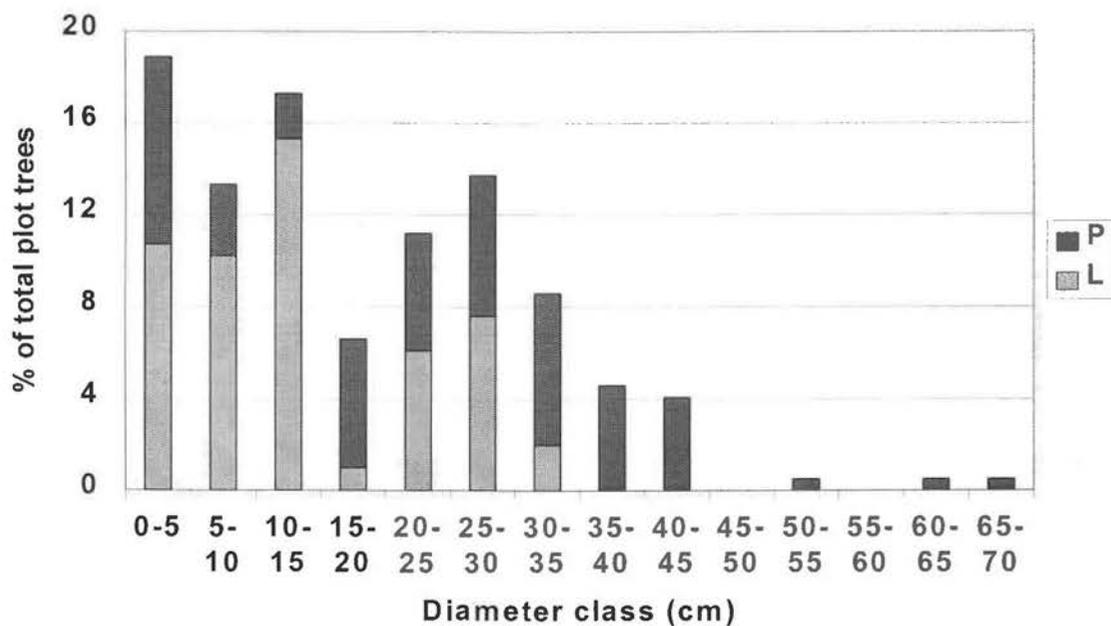


Figure 2.2 Diameter distribution, plot BL2

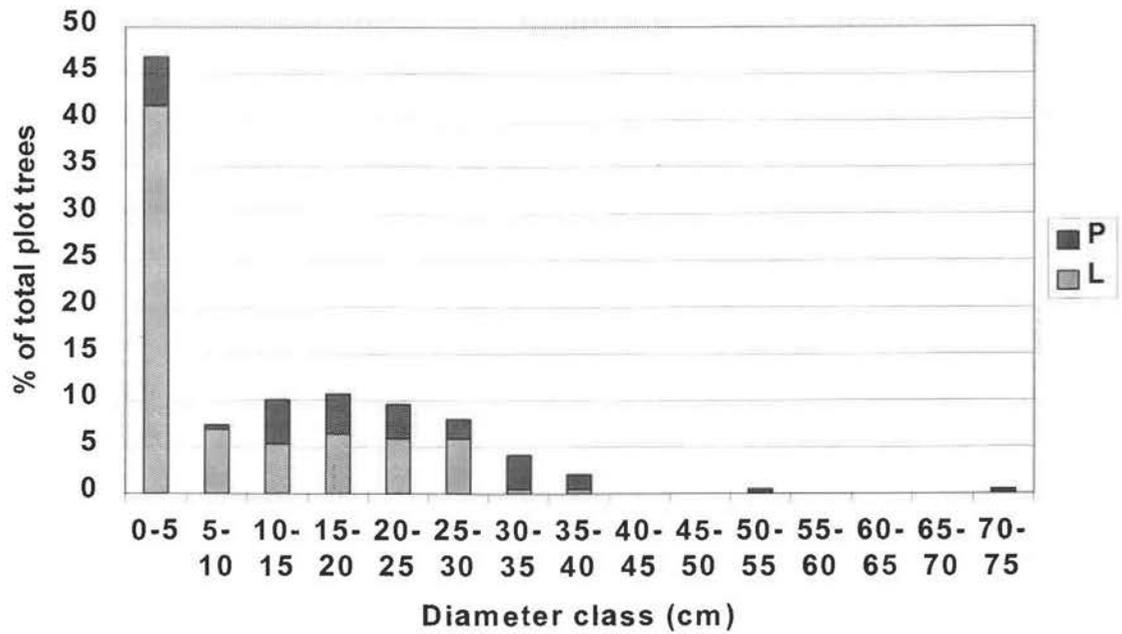


Figure 2.3 Diameter distribution, plot BL3

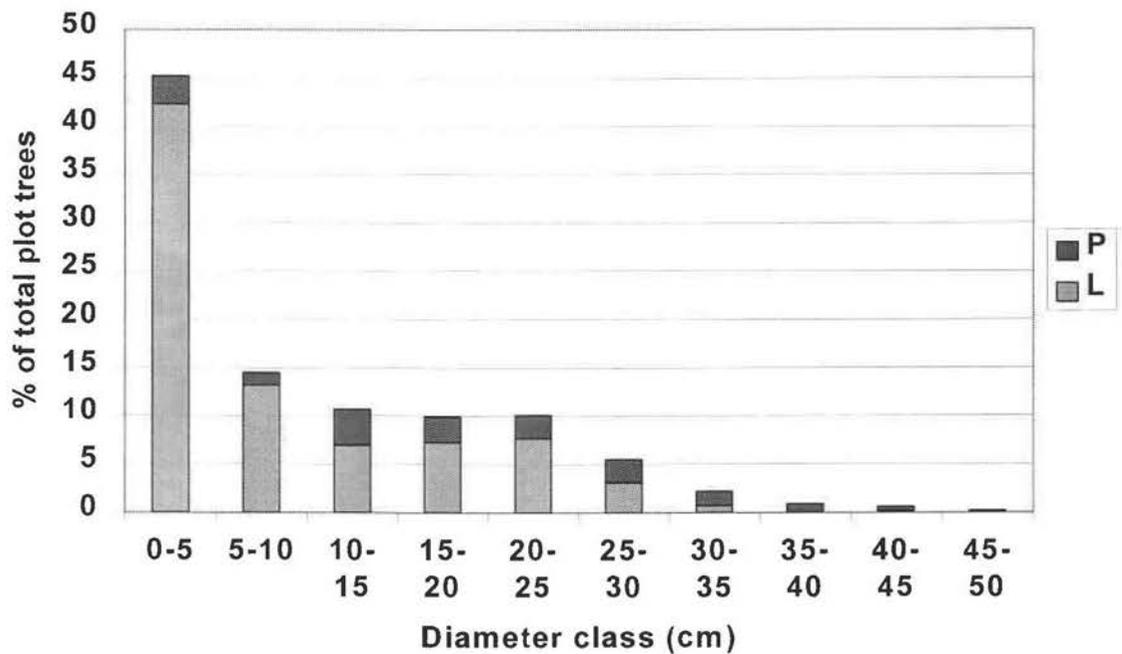


Figure 2.4 Diameter distribution, plot BM

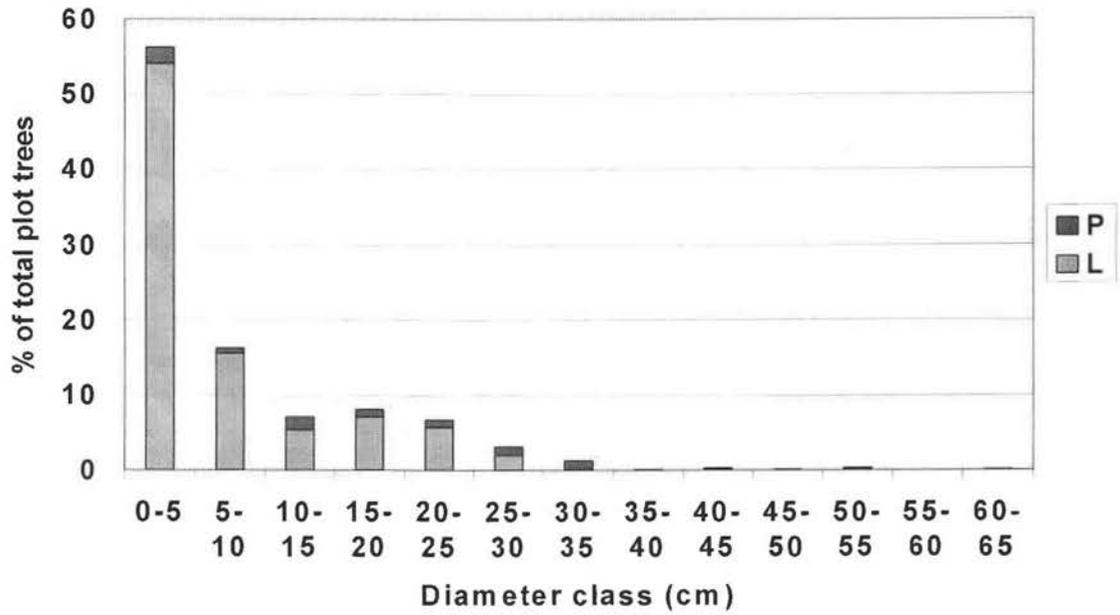


Figure 2. 5 Diameter distribution, plot BH1

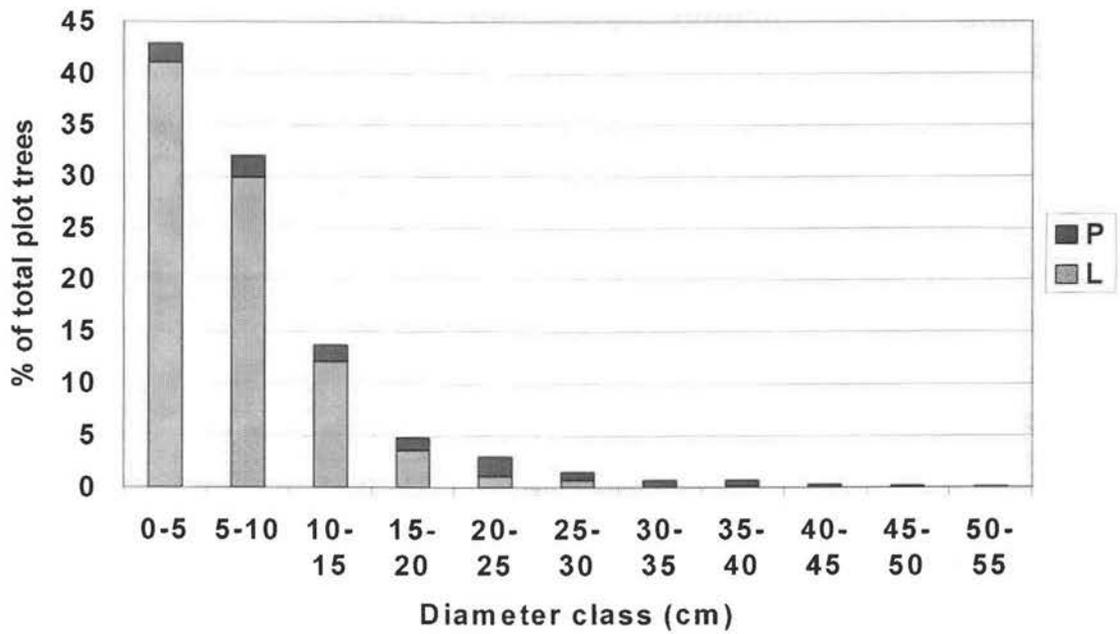


Figure 2. 6 Diameter distribution, plot BH2

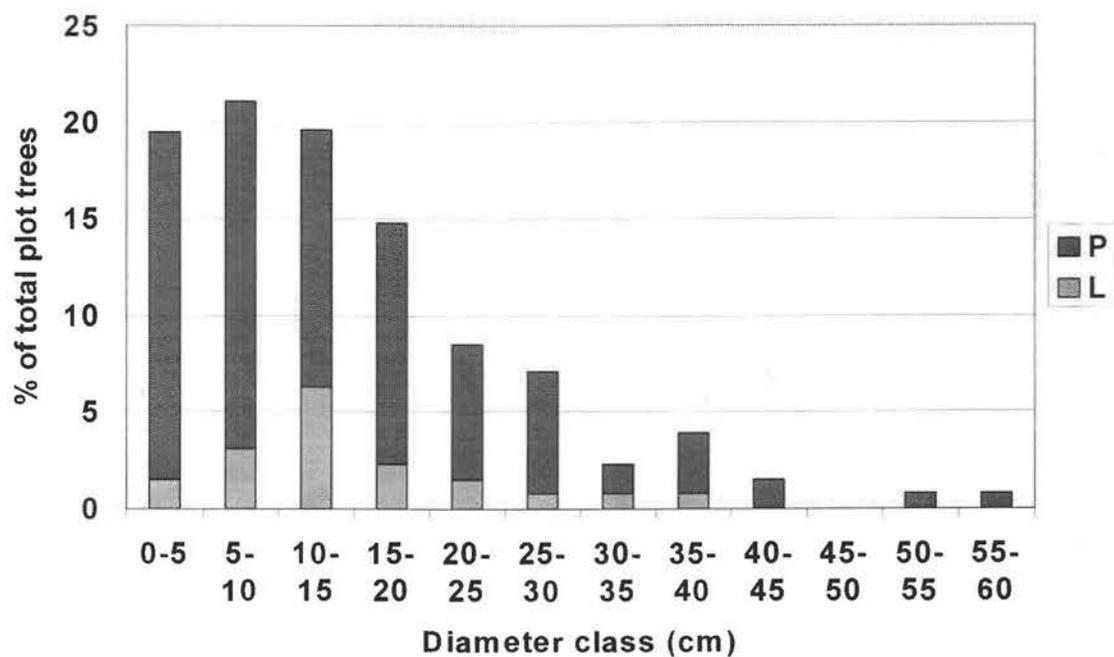


Figure 2. 7 Diameter distribution, plot TL1

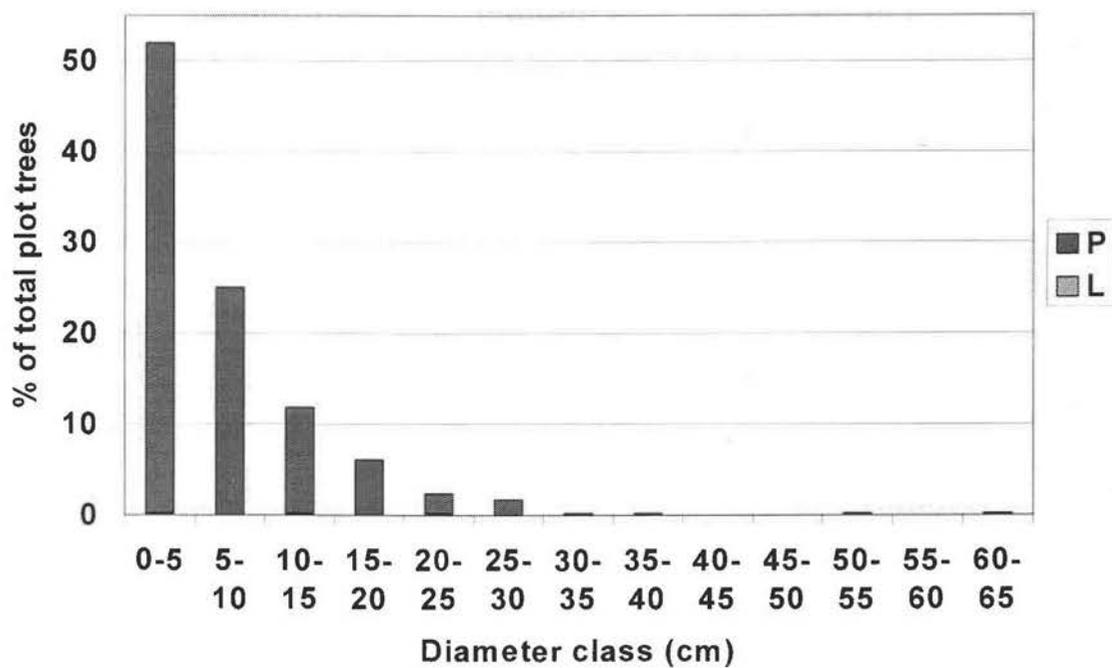


Figure 2. 8 Diameter distribution, plot TM

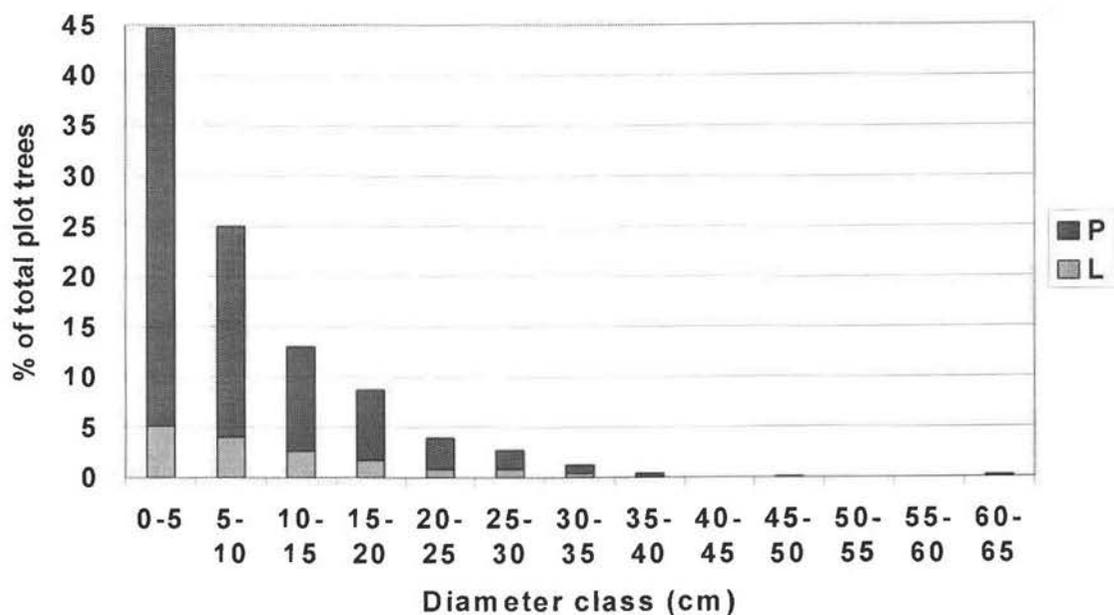


Figure 2. 9 Diameter distribution, plot TH1

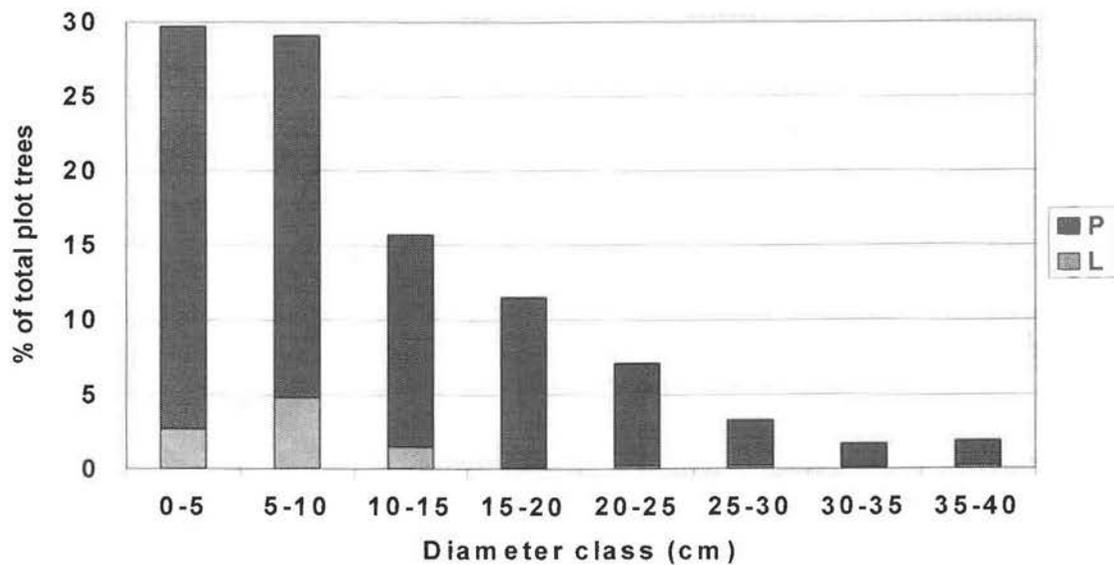


Figure 2. 10 Diameter distribution, plot TH2

Table 2. 1 Attributes of the nine 0.4 ha study plots from the pumice region of central Oregon

Plot	All trees # of trees	Ponderosa Pine									Lodgepole Pine								
		Number of trees		5-yr basal area growth/tree (cm ²)		DBH (cm)		Height (m)		Basal area (m ² /0.4 ha) All trees	Number of trees		5-yr basal area growth/tree (cm ²)		DBH (cm)		Height (m)		Basal area (m ² /0.4 ha) All trees
		>10 cm dbh	< 10 cm dbh	mean	range	mean	range	mean	range		>10 cm dbh	< 10 cm dbh	mean	range	mean	range	mean	range	
BL 2	195	69	22	73.6	11.9-186.5	29.4	11.9-67.0	13.7	5.9-23.3	5.43	63	41	52.5	16.0-111.3	19.7	10.1-34.8	11.7	6.8-18.1	2.30
BL 3	188	40	11	83.7	13.0-278.6	24.6	10.2-73.5	11.9	4.5-28.5	2.40	48	89	59.2	15.5-149.4	18.1	5.2-37.4	13.1	4.8-20.0	1.76
BM	454	65	19	46.8	5.4-150.2	25.4	10.3-47.1	12.2	5.4-26.6	3.05	118	252	46.2	6.6-166.1	19.5	10.2-42.7	13.9	6.3-21.3	6.67
BH 1	687	49	20	56.8	7.3-200.2	25.4	10.3-60.2	13.1	5.4-26.6	3.07	140	478	40.9	11.5-101.2	18.5	10-32.5	13.5	6.1-19.0	4.73
BH 2	108 6	81	43	53.5	7.4-194.0	24.6	10.1-50.5	12.7	4.4-22.7	4.44	192	770	25.2	7.2-82.7	14.4	10.0-33.0	11.1	5.1-20.5	5.37
T L1	124	57	45	56.6	14.5-180.6	18.0	5.9-50.2	7.8	2.6-21.5	2.45	16	6	65.1	23.2-171.1	18.3	10.2-35.2	8.5	4.9-14.3	0.52
T M	412	96	313	39.3	9.2-213.1	17.0	10.0-60.7	8.1	3.7-28.7	3.30	2	1	32.8	16.8-48.8	16.0	11.2-20.8	9.5	7.6-11.3	0.04
T H1	753	148	475	24.6	5.7-91.9	18.0	10.1-61.9	10.6	4.3-30.8	5.43	53	77	42.6	10.8-134.5	17.7	10.2-30.4	10.9	5.0-22.9	1.63
T H2	478	190	242	34.0	6.8-193.0	18.5	10.0-39.7	8.1	4.2-21.2	6.43	10	36	41.1	23.2-74.5	18.1	10.3-35.7	8.2	4.9-14.2	0.37

Sampling Design and Field Measurements

Each of the three specified hypotheses required stem mapping, both for calculation of distance-dependent competition indices and APA polygons. Hypothesis three, in seeking to test growth efficiency as defined by numerous spatial occupancy indices, required measurement and calculation of these indices.

Following establishment of plot corners, all trees > 1.37 m in height were numbered and mapped by recording distance and azimuth to an appropriate plot corner using a Criterion 400 (Laser Technologies). On most plots tree density was such that some trees needed to be referenced to interior points, that in turn were referenced to a plot corner. All tagged trees were measured for dbh to the nearest 0.1 cm.

For each plot tree greater than 10 cm dbh, the following additional attributes were measured:

Ht: Height from ground to tree tip, representing height at the end of the 1998 growing season (nearest 0.1 m).

Ht₅: Height from ground to the fifth whorl from the tip of the tree, representing total height at the end of the 1993 growing season (nearest 0.1 m).

HCB: Height to live crown base (nearest 0.1 m). Where crown base was uneven, crown base was defined as the lowest whorl in which 75% of the branches were still alive.

CW: Geometric mean of two crown widths, representing the greatest width in the north-south and east-west direction.

ΔR : Radial increment for the past five years (nearest 0.5 mm). Each tree over 10 cm dbh was randomly assigned a number, 1-4, indicating the initial location for coring (1-south side, 2-southwest, 3-west, 4-northwest). Each tree was cored twice—the second core was made at a location 180° from the first. Where scars were located in the part of the tree to be cored, the coring location was advanced to the next number (1-4) until a suitable location was found.

From these measurements, numerous variables were calculated:

APA: Area Potentially Available was calculated as constrained, tree-weighted polygons for each tree (Nance et al. 1988).

$H(\theta)$: Point relative height (with θ = angle), was calculated by determining the height of the subject tree as a fraction of neighboring trees. Neighboring trees were defined as those trees whose height penetrated an inverted cone produced by a 360° sweep made with a fixed angle θ from the tip of the subject tree (figure 2.11). The subject tree's point relative height was based on the height of the tallest tree entering this inverted cone. Two angles were tested: 30 and 45 degrees.

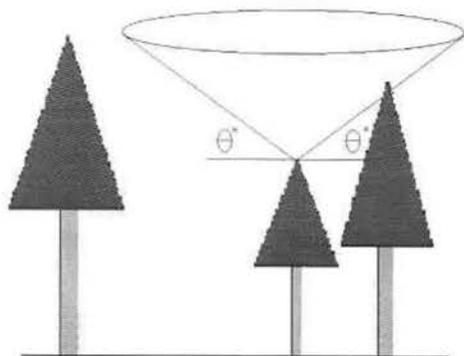


Fig 2.11 Point relative height

ST : Total basal area of small trees with diameter less than 10 cm, was calculated within zones surrounding subject trees. These circular zones had radii equal to multiples of the crown width of each tree, where the multiples were 1.5, 2, 2.5, 3 and 3.5 times the crown width of the subject tree.

BT (*Bark thickness*): Distance to pith was measured (nearest 1 mm) on approximately 60 trees of each species, covering a range of diameters, from the cores taken to determine diameter growth rates. Double bark thickness was assumed equal to the difference between dbh (as measured by d-tape) and twice the radius inside bark (from the cores). A bark thickness equation was then constructed for application to the subject trees.

SAP : Breast height sapwood radii were measured from each of the increment cores (nearest 1 mm). Sapwood cross-sectional area (SAP) was computed as:

$$SAP = \pi(R^2 - (R - SR)^2)$$

where $R = DIB/2$

$SR =$ Geometric mean of two sapwood radii

$DIB = b_1 DOB^{b_2}$

$DIB =$ diameter inside bark at 1.37 m

$DOB =$ diameter outside bark at 1.37 m

CSAP: Crown base sapwood cross sectional area was estimated from the sapwood cross sectional area at breast height assuming that the relative sapwood taper for ponderosa and lodgepole pine was similar to relative sapwood taper in coastal Douglas-fir (Maguire and Batista 1995). The crown base sapwood area should theoretically better represent actual leaf area, particularly among stands and plots of widely differing stand densities and, hence, differing heights to crown base (Waring et al. 1982). Empirical studies have confirmed this expectation (Dean and Long 1986).

Trees which had some type of defect were noted. Observed defects included broken tops, scars, leaners (with large amounts of compression wood), misshapen stems, and trees exhibiting signs of disease.

Backdating

Numerous tree and stand-level variables were computed for regression analysis of growth and growth efficiency (Table 2.2).

Backdating of variables was necessary in order to base the past five year growth on initial growth period conditions. During the course of field measurements, 1993 height was measured directly at the fifth whorl below the tree tip, and 1993 diameters were determined using the five-year diameter increments and the calculated bark thickness equation. Where possible, all subsequent individual tree and stand variables were calculated using these backdated values. Sapwood cross-sectional area, crown width measurements, and crown ratios were assumed to have been unchanged.

Small tree ($dbh < 10$ cm) basal area growth rates over the previous five years were computed by assuming small trees had relative basal area growth equivalent to the average for large trees on the same plot. Because understory trees often exhibit less growth than their overstory counterparts, this assumption may underestimate the small tree basal area at the start of the five year growth period. If so, the parameter value of the small tree basal area variable may be overestimated.

Table 2. 2 Table of Variables used for Model Construction

(Model 1 = Distance Independent, Model 2 = Distance Dependent)

Variable	Abbr.	Units	Model	Notes
<i>Dependent variable</i>				
Basal Area Growth	BAG	cm ²	1,2	
<i>Independent variables</i>				
Diameter	D	cm	1,2	
Volume	V	m ³	2	From equation by Cochran (1985)
Crown Ratio*	CR	m/m	1,2	
Crown Ratio—diameter adj.	CRID	(m/m) ² /[ln(D)]	1	From Dolph (1988)
Basal Area in Larger trees	BAL	m ² /0.4 ha	1,2	
Basal Area in Taller trees	BAT	m ² /0.4 ha	1,2	
Basal Area	BA	m ² /0.4 ha	1,2	
Point Relative Height	H(30,45)	m/m	2	Height relative to tallest nearest neighbor. Values in parentheses indicate defining angle in degrees.
Plot Relative Height	RH	m/m	1	Height relative to tallest plot tree
Plot Average Height	HAVG	m/m	1	Height relative to plot average
Area Potentially Available	APA	m ²	2	Calculated using program detailed by Nance et al. (1988)
Horizontal Crown Proj. Area*	CPA	cm ²	2	
Basal area of small trees	ST	m ² /0.4 ha	2	Defined by subject tree crown width
Timbers	T	indicator	1,2	Site indicator variable = 1 if Timbers = 0 if Blackrock

*Variable was assumed to be constant over the last five years

Statistical Analysis

Two basic model types were explored: 1) distance-independent, and 2) distance-dependent. Both models were constructed separately for the two species. Both logarithmically transformed and untransformed forms of the independent variables were explored using scatterplots. Variables were logarithmically transformed where this was deemed appropriate. Once the log-linearized form of the models had been fit, the implied nonlinear model was fit using the linear model parameter values as starting values.

Initial screening for the appropriate variables was based on variance inflation factor (VIF), Mallow's C_p statistic, correlation coefficients, compatibility with existing models, biological understanding, ease of variable interpretation, and consistency in model forms for both species.

Model checking was performed by examining residuals for homogeneity of variance and normality, and by performing outlier analysis with Cook's Distance and standardized residuals. Identified outliers were checked to ensure proper variable values, and the possible influence of tree defects. Where unusual data values were found through this check, some field remeasurement was required for confirmation.

The distance-independent model was based on variables obtained or easily calculated from standard timber cruise or stand exam information. The distance-dependent model was formed as an expansion of the distance-independent form. The variables considered during the construction of this model included variables describing ground occupancy (APA and CPA), relative height, and the presence of trees less than 10 cm dbh (table 2.3).

Growth efficiencies were analyzed by exploration of the distance-dependent growth model. The distance-dependent model was refit with successive replacement of the site occupancy variable (CSAP, APA, CPA). Both the right and left hand sides were divided by the measure of occupancy, yielding growth efficiency on the left hand side of the equation. The implied GE was calculated for classes of the corresponding occupancy index, with the value of the other variables fixed at the mean value for each class of occupancy index. Trends in growth efficiency over other model variables were analyzed graphically. Rather than attempting to convert CSAP into leaf area, CSAP was regarded as a direct surrogate for leaf area.

Results

Growth

Basal area growth has been best represented in non-linear models in the past, primarily due to non-normality of the residuals on the logarithmic scale (Ritchie and Hann 1985). Visual inspection of the normality plots for this model did not support non-normality on the transformed scale. (Furnival's index (Furnival 1961) suggested that the log-transformed model was marginally better.)

The final distance-independent model for both ponderosa and lodgepole pine was:

Equation 2. 1

$$\text{Ln(BAG)} = \alpha_0 + \alpha_1 \text{Ln(DBH)} + \alpha_2(\text{CR}) + \alpha_3(\text{BA}) + \alpha_4(\text{BAL}) + \alpha_5(\text{T}) + \varepsilon$$

This model explained 79% and 66% of the variation in the logarithm of ponderosa pine and lodgepole pine basal area growth, respectively, and yielded an RMSE of 0.360 and 0.342, respectively. Parameter estimates indicated positive effects of increasing initial diameter and crown ratio, but negative effects of increasing basal area and BAL (Tables 2.3 and 2.4). Residual plots indicated close conformity to constant variance and normally distributed residuals (Figures 2.12-2.15).

Table 2. 3 Parameter estimates for ponderosa pine, distance-independent model

Variable	Parameter estimate	Standard error
α_0	0.383177	0.21319463
α_1	0.871805	0.05850279
α_2	2.293532	0.13994082
α_3	- 0.032001	0.01333483
α_4	- 0.134225	0.01735397
α_5	- 0.334053	0.03297478

Table 2. 4 Parameter estimates for lodgepole pine, distance-independent model

Variable	Parameter estimate	Standard error
α_0	1.144059	0.25200686
α_1	0.713304	0.07124842

Table 2.4 (continued)

α_2	1.906438	0.10669908
α_3	- 0.064859	0.01498577
α_4	- 0.065951	0.02237707
α_5	- 0.209805	0.05070873

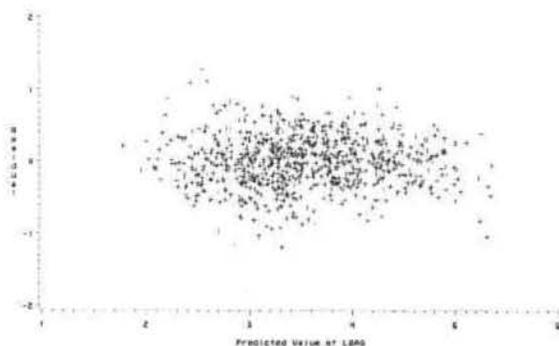


Figure 2.12 Residual plot for the distance-independent ponderosa pine model

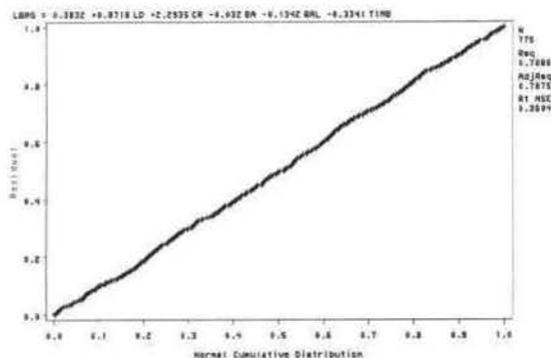


Figure 2.13 Normal probability plot for the distance-independent ponderosa pine model

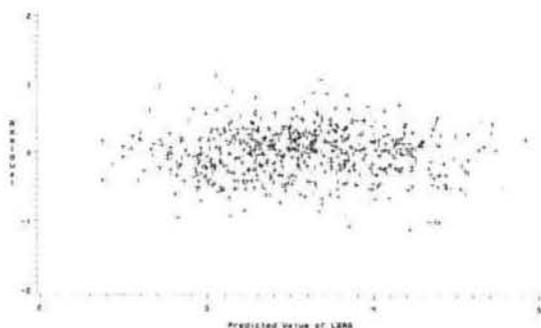


Figure 2. 14 Residual plot for the distance-independent lodgepole pine model

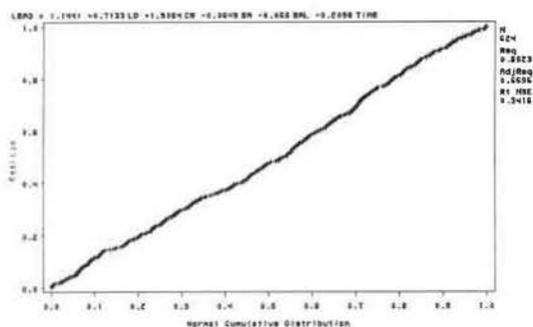


Figure 2. 15 Normal probability plot for the distance-independent lodgepole pine model

The best distance-dependent model for both ponderosa and lodgepole pine was:

Equation 2. 2

$$\text{Ln(BAG)} = \beta_0 + \beta_1 \text{Ln(DBH)} + \beta_2(\text{CR}) + \beta_3 \text{Ln(APA)} + \beta_4(\text{BAL}) + \beta_5(\text{H}\Theta) + \beta_6(\text{ST}) + \beta_7(\text{T}) + \varepsilon$$

This model explained 83% and 71% of the variation in the logarithm of ponderosa pine and lodgepole pine basal area growth, respectively, and yielded an RMSE of 0.329 and 0.320, respectively. Parameter estimates indicated positive effects of increasing initial diameter, crown ratio, APA and point relative height, but negative effects of increasing BAL and basal area of small stems (Tables 2.5 and 2.6). Although H45 was a more powerful predictor than H30 for ponderosa pine, the reverse was true for lodgepole pine. Residual plots indicated close conformity to constant variance and normally distributed residuals (Figures 2.16-2.19).

Table 2. 5 Parameter estimates for ponderosa pine, distance-dependent model

Variable	Parameter estimate	Standard error
β_0	1.099418	0.19447585
β_1	0.485935	0.05212912
β_2	1.762887	0.13539446
β_3	0.171185	0.01468925
β_4	- 0.133276	0.01141408
β_5	0.208438	0.05317825
β_6	- 0.421100	0.25166008
β_7	- 0.290214	0.03038249

Table 2. 6 Parameter estimates for lodgepole pine, distance-dependent model

Variable	Parameter estimate	Standard error
β_0	1.734346	0.24199558
β_1	0.274063	0.07601025
β_2	1.663325	0.10755936
β_3	0.183244	0.02141236
β_4	- 0.093950	0.01547749
β_5	0.156119	0.07567528
β_6	- 1.539712	0.31544625
β_7	- 0.118937	0.04986244

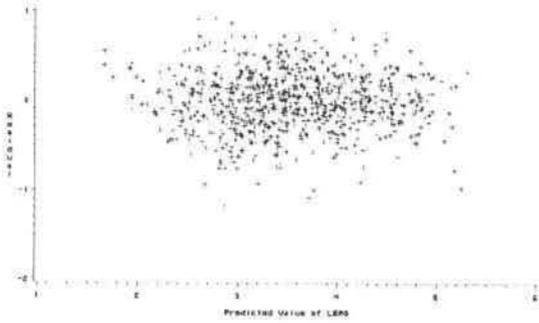


Figure 2.16 Residual plot for the distance-dependent ponderosa pine model

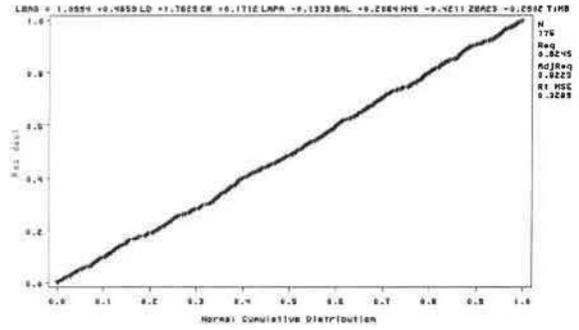


Figure 2.17 Normal probability plot for the distance-dependent ponderosa pine model

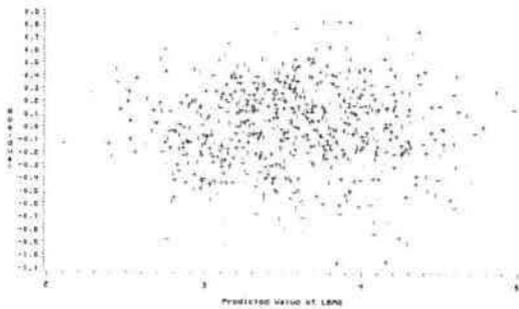


Figure 2. 18 Residual plot for the distance-dependent lodgepole pine model

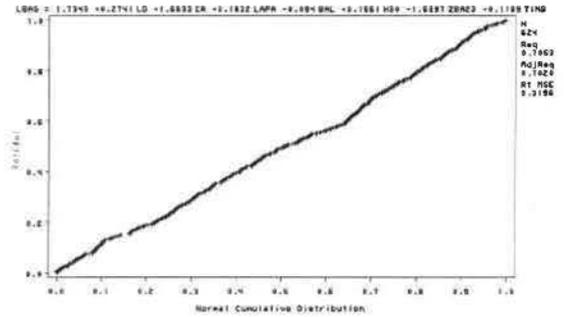


Figure 2. 19 Normal probability plot for the distance-dependent lodgepole pine model

Growth Efficiency

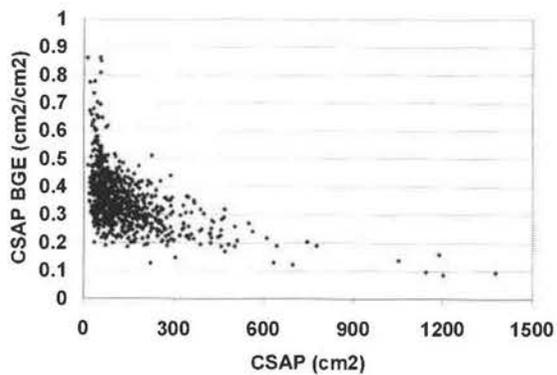
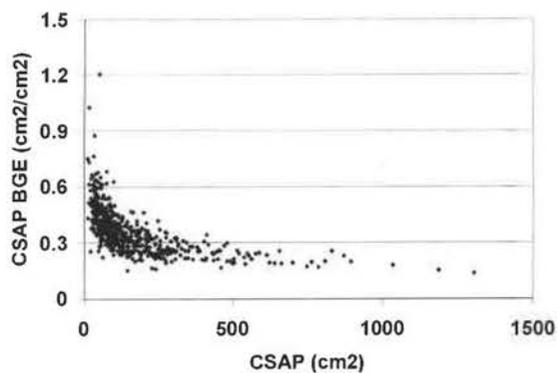
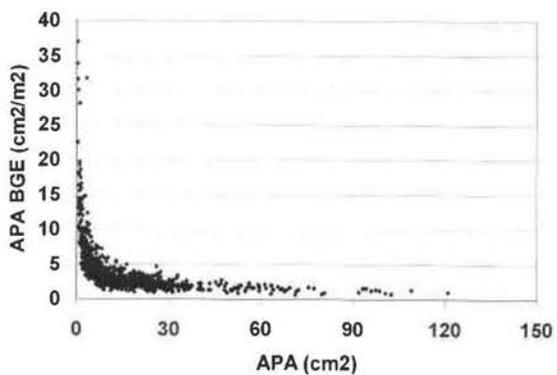
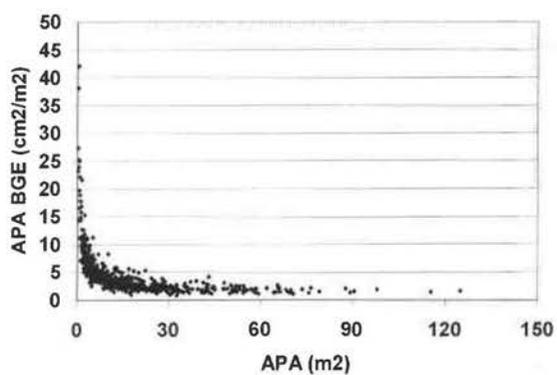
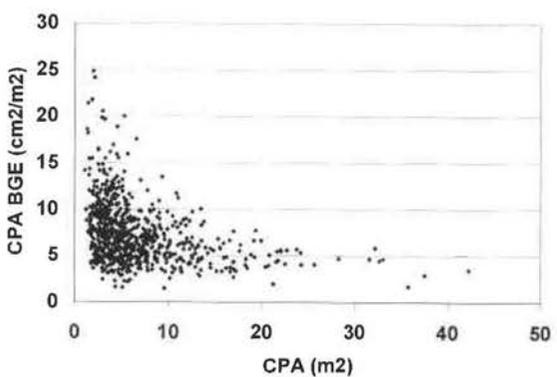
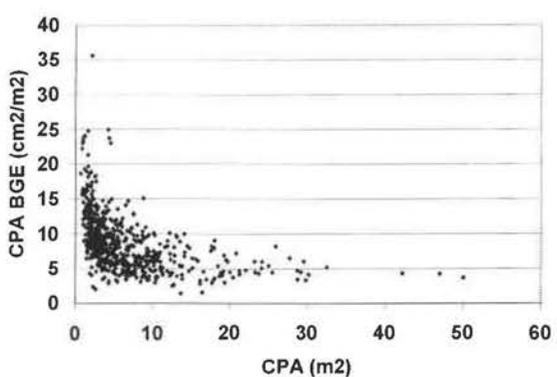
Implied growth efficiency, estimated by dividing estimated growth by spatial occupancy, was calculated for each tree based on the distance-dependent model. In doing so, the model was refit using the appropriate spatial occupancy index, thereby correcting the calculated GE by the other model covariates. Both basal area growth efficiency (BGE) and volume growth efficiency (VGE) were thus estimated on the basis of crown-base sapwood area, area potentially available, and crown projection area.

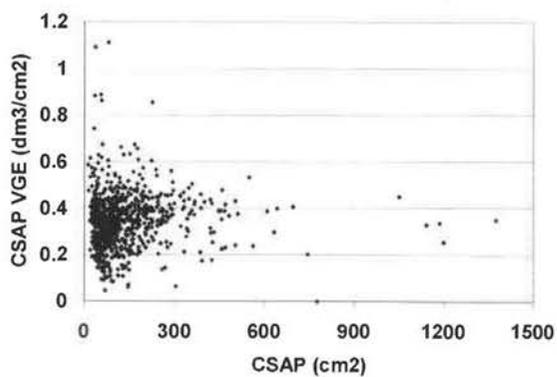
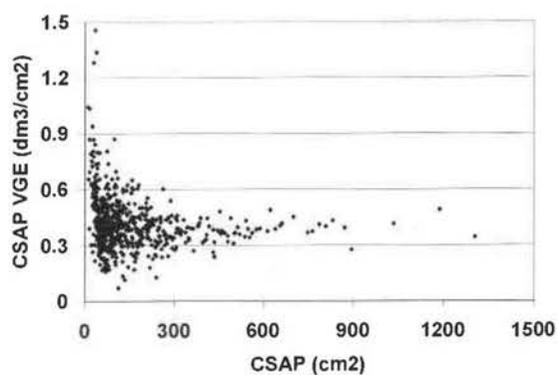
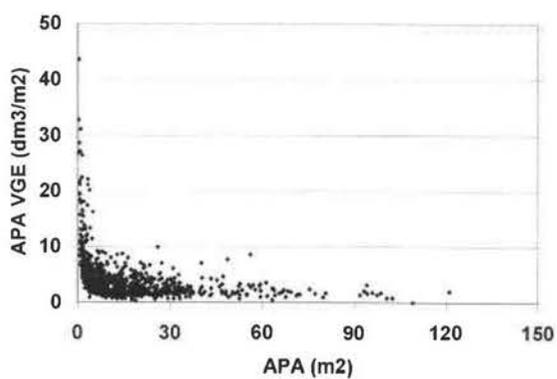
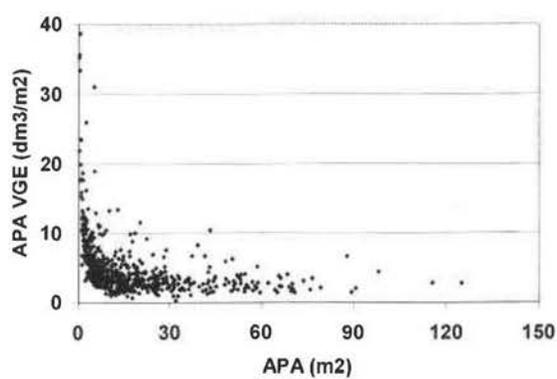
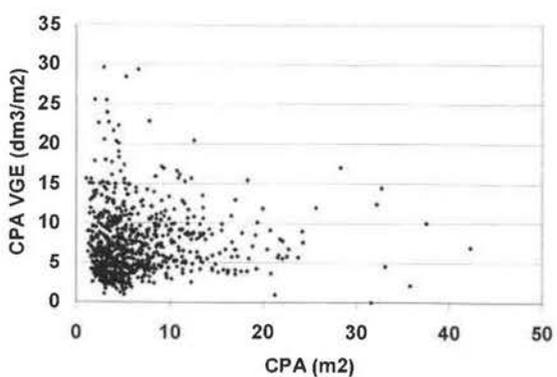
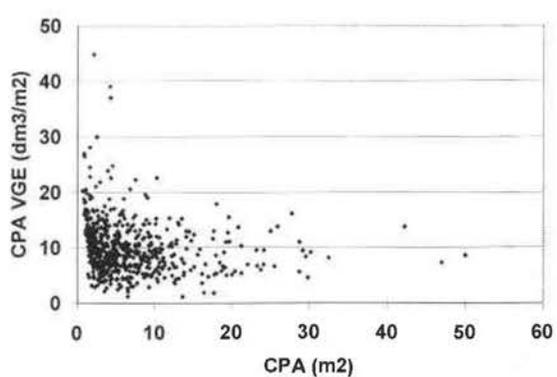
Plots of growth efficiency versus their respective spatial occupancy indices (figs. 2.20-2.31) indicate several general trends. The pattern in GE differs somewhat between BGE and VGE. This is particularly pronounced for CSAP, where BGE shows a continued drop with increasing CSAP for both species (figs. 2.20, 2.21). In contrast, VGE of both species (figs. 2.26, 2.27) maintains moderate values with increasing CSAP; that is, trees with CSAPs greater than 300 cm² are growing faster than many of the smaller trees. For ponderosa in particular, VGE_{CSAP} shows a general increase with increasing CSAP—the high CSAP trees are among the most efficiently growing trees. Presumably, leaf area GE would show the same patterns.

Patterns in BGE and VGE are less pronounced for crown projection area (CPA). The decreases in BGE_{CPA} with increasing CPA (figs. 2.24, 2.25) is not strictly followed for VGE_{CPA}, where some higher CPA trees maintain moderately efficient growth. (figs. 2.30, 2.31). The pattern in BGE (figs. 2.22, 2.23) and VGE (figs. 2.28, 2.29) is similar for area potentially available (APA). For this index, efficiency decreases quickly with increasing APA, slowing only once APA values increase above 10 m².

Comparison of model types

Distance-independent and distance-dependent models differ in the variables they utilize, in their scope of inference, and in the amount and cost of necessary data. The value of adding spatially explicit variables to distance-independent data can best be addressed by their additive effect on the distance-independent models. The three spatially explicit variables—area potentially available, point relative height, and basal area of small trees—were added to the variables in the distance-independent model. Extra sums-of-squares F-tests tested the gains made by the collection of spatially explicit

Figure 2. 20 Ponderosa, BGE_{CSAP} Figure 2. 21 Lodgepole, BGE_{CSAP} Figure 2. 22 Ponderosa, BGE_{APA} Figure 2. 23 Lodgepole, BGE_{APA} Figure 2. 24 Ponderosa, BGE_{CPA} Figure 2.25 Lodgepole, BGE_{CPA}

Figure 2. 26 Ponderosa, VGE_{CSAP} Figure 2. 27 Lodgepole, VGE_{CSAP} Figure 2. 28 Ponderosa, VGE_{APA} Figure 2. 29 Lodgepole, VGE_{APA} Figure 2. 30 Ponderosa, VGE_{CPA} Figure 2. 31 Lodgepole, VGE_{CPA}

variables.

For both lodgepole and ponderosa pine, addition of distance-dependent variables significantly improved the predictive power of distance-independent variables (table 2.7).

Table 2.7 Results of adding spatially explicit variables to the distance-independent basal area growth model

Full Model	Lodgepole pine			Ponderosa pine		
	MSE	R ²	p-value*	MSE	R ²	p-value*
1) Distance independent (DI)	0.1167	0.6623	NA	0.1298	0.7892	NA
2a) DI + lnAPA	0.1046	0.6976	1) <0.0001	0.1108	0.8201	1) <0.0001
2b) DI + H(⊙)	0.1152	0.6672	1) 0.0027	0.1273	0.7932	1) 0.0001
2c) DI + ST	0.1147	0.6685	1) 0.0007	0.1292	0.7901	1) 0.0637
3a) DI + lnAPA + H(⊙)	0.1037	0.7007	1) <0.0001 2a) 0.0121 2b) <0.0001	0.1086	0.8239	1) <0.0001 2a) <0.0001 2b) <0.0001
3b) DI + lnAPA + ST	0.1026	0.7038	1) <0.0001 2a) 0.0003 2c) <0.0001	0.1103	0.8211	1) <0.0001 2a) 0.0355 2c) <0.0001
4) DI + lnAPA + H(⊙) + ST	0.1020	0.7061	1) <0.0001 2a) 0.0002 2b) <0.0001 2c) <0.0001 3a) 0.0008 3b) 0.0306	0.1083	0.8246	1) <0.0001 2a) <0.0001 2b) 0.0003 2c) <0.0001 3a) 0.0969 3b) 0.0001

from extra-sums-of-squares F-test between specified model (full model) and numbered model (reduced model)

In each case, addition of a distance-dependent variable increased the subsequent R² and decreased the MSE. The only examples in which additions proved non-significant (at the $\alpha = 0.05$ level) were for small tree basal area added to the distance-independent ponderosa pine model, and this same variable added to the ponderosa pine model [3b], containing the distance-independent variables and lnAPA and H(⊙). However, in both cases, these additions were significant at the $\alpha = 0.10$ level. Nevertheless, it must be acknowledged that statistical significance doesn't necessarily translate into operational practicality. Although these variables significantly improve the predictive power of the

model, the labor-intensive data collection necessary for their inclusion probably precludes their use in most applications. As may be expected, the majority of the gain in predictive power is gained through APA as opposed to $H(\ominus)$ and ST.

Discussion

Interpretation of Distance-independent Models

Initial diameter and crown ratio are the two most commonly used variables in standard distance-independent basal area growth models. Ease of measurement, explanatory power, and mechanistic reasonability are principle reasons for their inclusion. Within a stand, dbh can be regarded as a surrogate for past growth and relative position in the stand, particularly in even-aged stands. Inclusion of crown ratio, an easily measured surrogate for photosynthetic area when combined with an absolute measure such as DBH, typically provides a significant amount of predictive power.

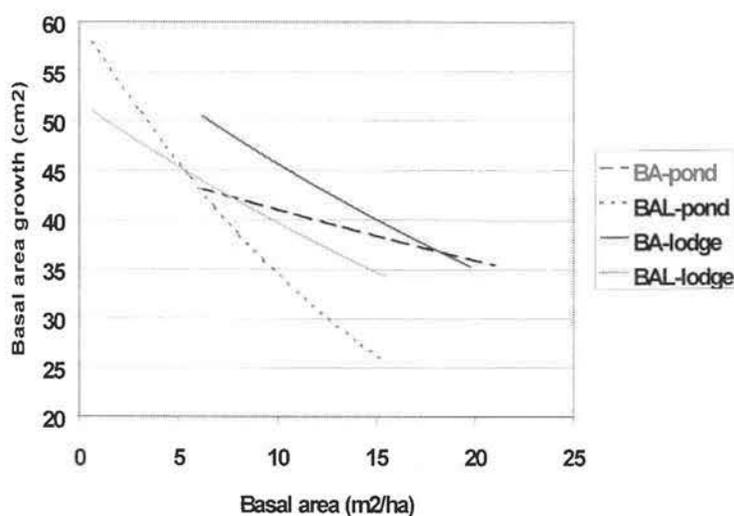


Figure 2.32 BAG at different levels of BA, BAL

overtopping trees and subordinate trees in negatively impacting a subject tree's growth.

A comparison between the two species indicates that the effects of basal area and BAL, while qualitatively similar, do differ quantitatively (Fig. 2.32). For lodgepole pine, their effect is essentially the same; that is, the decline in growth per unit increase in basal area is similar in regard to both BA and BAL. In contrast, for ponderosa, BAL has a much greater effect on tree growth than BA (steeper slope for BAL). It is also significant

The decline in five year basal area growth (per tree) with increasing stand basal area and increasing basal area in larger trees (BAL) is expected among trees in both even-aged and uneven-aged stands. BAL was found to have a stronger effect than BA, although BAL and BA together suggest the importance of both

to note that ponderosa pine growth declines more rapidly per unit increase in BAL than does lodgepole pine, but less rapidly per unit increase in BA than lodgepole pine.

The reasons for these differences are partly explained by the relative position of these two species within plots. Much of the lodgepole is growing in single-cohort patches. Lodgepole is thus more likely to be competing with other trees of a similar height. While a greater BAL in an even-aged stand is indicative of a poorer competitive position (described by BAL), height differentiation between neighboring trees is relatively slight (Roberts et al. 1993). Also, on the plot level much of the increase in BAL for lodgepole pine is contributed by ponderosa pine that are relatively free from the lodgepole pine patches; hence, the increase in plot-level BAL has a lesser effect. In contrast, the ponderosa pine showed greater height stratification and a less patchy spatial distribution. Because there is a strong positive relationship between height and diameter on these plots, greater diameters are usually associated with greater heights. The greater height stratification of ponderosa pine leads to a steeper light gradient between large and small trees. The greater tree-level LAI (CSAP) of ponderosa (relative to lodgepole) will further enhance this effect (table 2.x).

The site variable indicates that trees at the Timbers site are not growing as well as at the Blackrock site. This site effect may involve a large number of factors that are external to the focus of this study: inherent site quality differences; past logging history; past stand structure; current stand structure, and others.

Interpretation of Distance-dependent Models

Five year basal area growth (per tree) increases with increasing diameter, crown ratio, APA, and relative height, and decreases with increasing BAL and small tree basal area. Total plot basal area (BA) drops out of the distance-dependent model when APA, $H(\Theta)$, and ST are introduced. Just as with the distance-independent model, growth at the Blackrock site is better than that at the Timbers site.

This distance-dependent model explained approximately 4% more of the variability in basal area growth than the distance-independent model; that is, the coefficient of multiple determination increased from 79% to 83% for ponderosa pine and from 66% to 71% for lodgepole pine. In short these stands are sufficiently heterogeneous

that significant gains in predictive power can be gained by considering local stand structure. Ground space occupancy, measured as the area potentially available, estimates the unoccupied ground area theoretically exploitable by each tree. All other variables being equal, greater available ground area beyond a tree's crown projection is associated with greater basal area growth. APA thus may act at least partly as a surrogate for belowground resource reservoir from which the subject tree's roots can draw water and nutrients.

The greater basal area growth with increasing height of the subject tree relative to its neighbors ($H(\Theta)$) is consistent with the concept of dominance and is supported by previous studies (Maguire et al. 1998, O'Hara 1996, Roberts et al. 1993). The more favorable light environment experienced by a relatively taller tree probably enhances its growth.

Although the other model variables address the stand conditions for trees of 10 cm dbh and greater, the influential presence of still smaller trees is indicated by the small tree variable. The negative effect of small tree basal area (ST) (<10 cm dbh) confirms the inhibitory effect of small trees within three crown radii of the subject tree, although this variable had a relatively large p-value for ponderosa pine ($p=0.095$).

Growth Effect of Small Understory Trees

Use of a variable representing the density of trees less than 10 cm dbh in the distance-dependent model allows for separation of the competitive effect that these trees have on the subject trees.

Both models confirm the second hypothesis: that small tree basal area within three crown radii of a subject tree is both statistically significant and quantifiably negative. While the models indicate that these small trees have a negative effect on 5-yr basal area growth, determination of the economic loss from this effect, and the potential benefits of remedial action, require that the inhibition be translated into volume growth loss. Assuming that silvicultural treatments were applied at the beginning of the 1993-1998 growth period and that the measured height increments are not affected by stand density reduction, volume growth can be estimated by combining the observed height growth with predicted basal area growth. Five-yr basal area growth for different levels of

understory trees was calculated using the distance-dependent model. The resulting heights and diameters were then used in previously constructed volume equations for lodgepole and ponderosa pine (Cochran 1985).

The graphs indicate that understory trees exhibit a similarly negative effect on 5-yr volume loss for lodgepole and ponderosa pines of similar diameters (figures 2.33 and 2.34). Using an approximation of 5 board feet (Scribner) per cubic foot, one cubic decimeter is equivalent to about 0.18 board feet. Applying the 1999 prices for delivered ponderosa and lodgepole logs of approximately \$400 per thousand (<http://www.odf.state.or.us/TMBRMGT/LOGPPAGE.HTML>), a ponderosa of 35 cm with 0.5 m² of small tree basal area around the subject tree (corresponding to 25-5 cm dbh trees or 100-2.5 cm dbh trees) would experience a growth loss of 2 board feet, or about \$0.80 over 5 years. However, because the zone of the influence around a particular tree has significant overlap with the zones of other trees, pre-commercial removal of these trees would positively affect other nearby trees, thereby causing a greater positive growth effect than could be calculated for a single tree. Ten small trees randomly selected from the TH1 plot were found to be within an average of 10.3 zones.

Understory removal was simulated in two of the plots to determine the per hectare effect. Trees smaller than 10 cm dbh were removed, and 5-yr volume growth was re-estimated. In making these calculations, the same conversion rates were used as above, and all trees greater than 20 cm dbh were assumed to be merchantable. With small tree removal, plots TH1 and BH2, containing 552 and 813 small trees respectively, increased their volume growth by 317 and 319 dm³ in five years, thus increasing in value by approximately \$23 each, or \$58 per ha. Although unmerchantable, an additional 96 and 355 dm³ for the two plots, respectively, were gained in trees smaller than 20 cm dbh.

The increased growth is unlikely to produce positive net income from understory reduction or removal. The benefits to be gained from pre-commercial removal of small competing trees would depend a great deal on management objectives for a particular stand. These include current and target diameter distribution, current basal area, spatial distribution and stem counts of understory trees, current fire risk, availability of thermal or hiding cover for wildlife, and the anticipated date for future harvest entries. Calculation of the economic feasibility of an understory reduction would also require

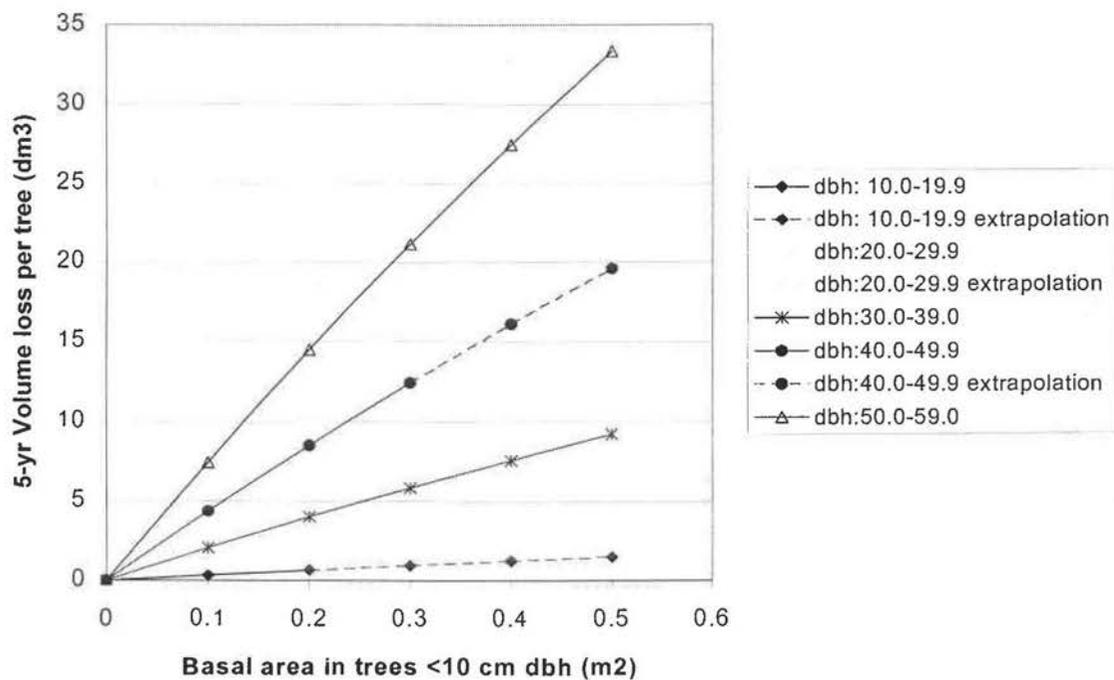


Figure 2. 33 Five year volume loss per tree (ponderosa pine) for different levels of understory trees

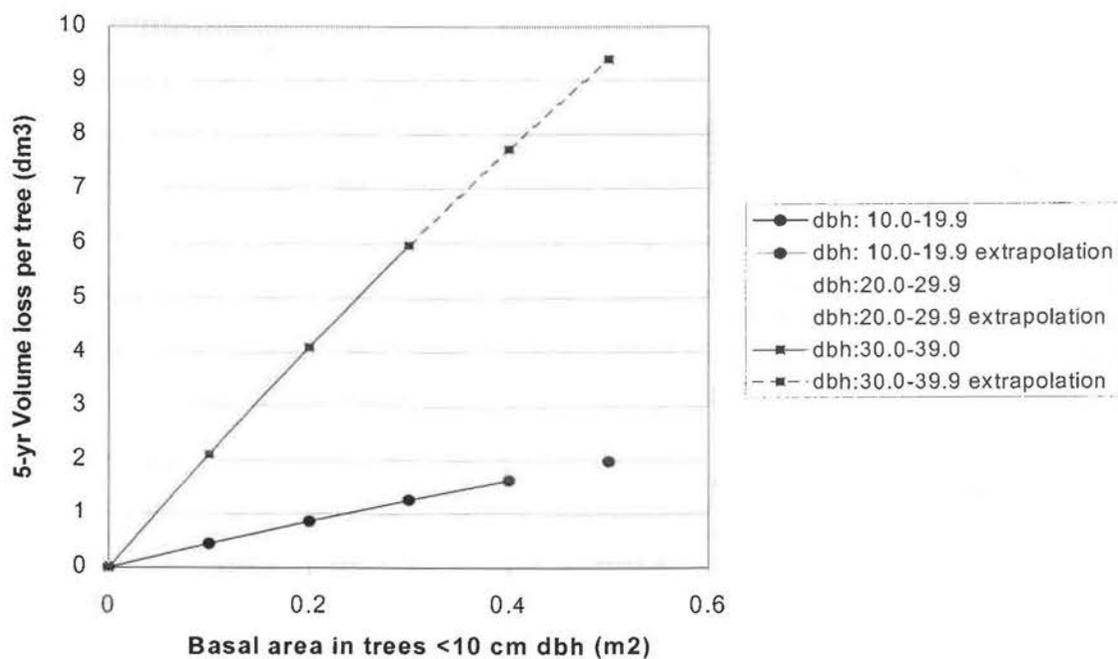


Figure 2. 34 Five year volume loss per tree (lodgepole pine) for different levels of understory trees

consideration of labor costs, stumpage value, and an acceptable rate of return. There exist many reasons for undertaking a PCT of the understory cohort, not all of them requiring a positive economic return. However, a PCT for the sake of enhancement of overstory growth would be most advisable where high counts of submerchantable understory trees are growing within stands whose overstory is predominantly sawtimber. Removing understory trees obviously becomes more attractive and profitable if the trees for removal have reached marketable size.

Growth Efficiency

A rough determination of whether tree rankings were consistent among GEs computed on the basis of alternative occupancy measures was made using Spearman's coefficient of rank correlation. Occupancy indices were compared for both VGE and BGE. Low p-values from this test ($p < 0.05$) would suggest a tree's GE ranking depends on the occupancy index used to define that GE (table 2.8). Ranking does depend strongly on the measure of site occupancy selected. The tree attributes and local stand structure that produce a given GE would by inference also depend on the selected occupancy measure, highlighting the importance of conditioning conclusions about GE on its definition.

Table 2.8 p-values from rank correlation test

	Lodgepole	Ponderosa
VOL		
csap-apa	<0.0001	<0.0001
csap-cpa	<0.0001	<0.0001
apa-cpa	0.0003	<0.0001
BAG		
csap-apa	<0.0001	0.0010
csap-cpa	<0.0001	<0.0001
apa-cpa	<0.0001	0.0006

Measurement of 5-yr basal area growth, and height growth and indices of site occupancy (crown base sapwood cross-sectional area (CSAP), area potentially available (APA), and horizontal crown projection (CPA)) made it possible to calculate both the basal area growth efficiency (BGE) and volume growth efficiency (VGE) of each tree under alternative measures of site occupancy.

Because CSAP, APA and CPA are correlated with numerous other tree and stand variables, isolating their effect on GE required that predicted growth be corrected by the model covariates representing these other variables. Because the value of these

covariates depends on the level of the occupancy index, growth (and GE) was predicted for different levels (subsets) within the observed range of the occupancy index, with the other covariates held at the mean value of all sampled trees within the subset being analyzed. By doing this, growth and GE predictions are properly corrected for other model covariates—each of the following graphs predicted growth and GE for 10-20 different levels of each occupancy index. Furthermore, these corrections explain why the graphs don't exhibit smooth curves—rather than showing a predictive surface described by each equation, they reflect the variability within this dataset.

The relationship between efficiency and the occupancy is revealed when efficiencies are plotted against their respective occupancy indices (fig. 2.35-2.40). In the case of basal area growth efficiency, each exhibits a drop in efficiency with an increase in the value of the index. This is not unexpected, given the diminishing basal area growth

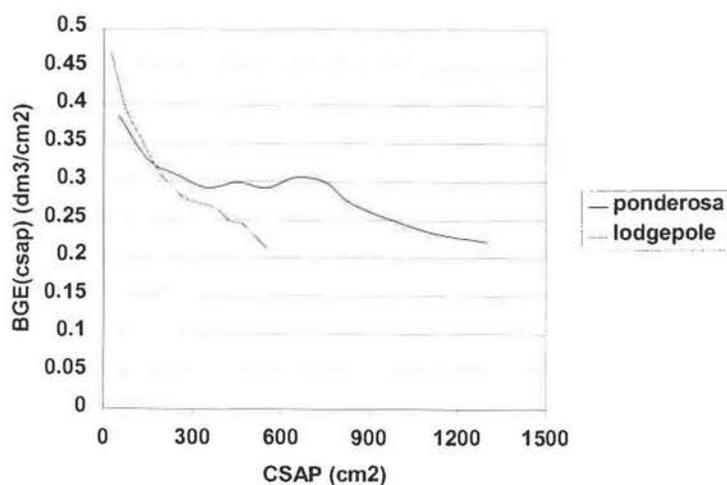


Figure 2. 35 BGE_{csap} for lodgepole and ponderosa, estimated from equation [2.2] and fixing predictors at the mean level associated with each level of CSAP

that takes place as trees increase in size, particularly in closed stands. BGE_{csap} exhibits the greatest differences between species (fig. 2.35). While lodgepole efficiency declines steadily with increasing CSAP, ponderosa BGE_{csap} declines at low levels of CSAP, yet plateaus between 300 and 750 cm² of CSAP per tree. This plateau may result from the interaction between the good light environment of trees of this size and increasing respiration and/or hydraulic limitation (O'Hara 1996, Roberts et al. 1993, Yoder et al. 1994). Above about 750 cm², efficiency declines again, due perhaps to the forementioned costs associated with large tree size. This may be due to the reduced photosynthesis (Yoder et al. 1994) and/or higher maintenance respiration of large trees.

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The difference between species apparent for CSAP is not apparent for APA. The decline in BGE is particularly apparent for APA, where efficiency drops precipitously to an APA of about 10-20 m² for both species (fig.2.36). At values of APA above that value efficiency follows a slower decline. Whereas differences in BGE_{csap} between species can

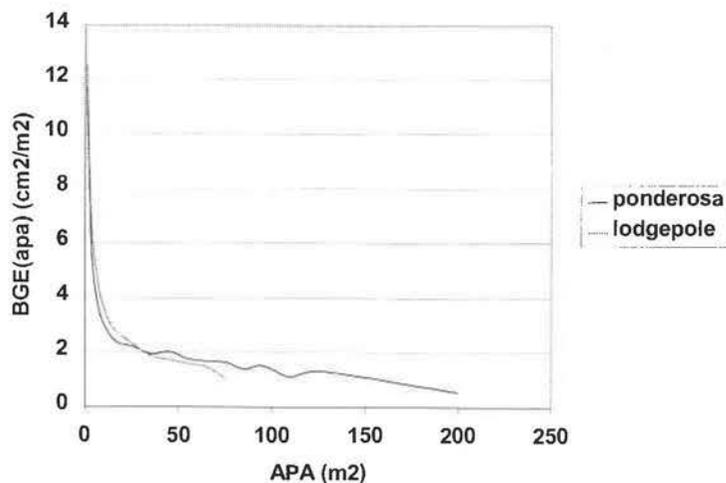


Figure 2. 36 BGE_{apa} for lodgepole and ponderosa, estimated from equation [2.2] and fixing predictors at the mean level associated with each level of APA

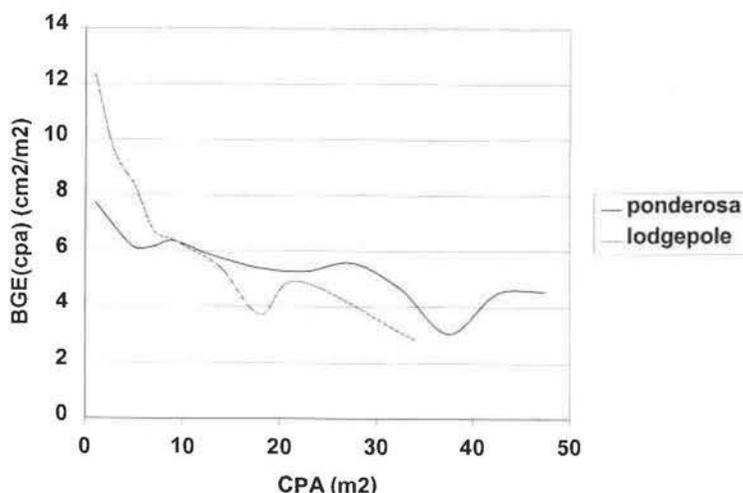


Figure 2. 37 BGE_{cpa} for lodgepole and ponderosa, estimated from equation [2.2] and fixing predictors at the mean level associated with each level of CPA

be associated with species and stand structural differences, the similarity in BGE_{apa} for both species probably results from APA being significantly more independent of those same type of species and structural differences.

The plot of BGE_{cpa} , like that of the other indices, shows a decline with increasing occupancy index (fig. 2.37). Like CSAP, this decline is less for ponderosa than it is for lodgepole, even showing a plateau of similar efficiency values for trees with CPAs between 15 and 30 m². This plateau probably corresponds to the same trees whose BGE_{csap} exhibited a plateau—generally, there

is a close positive correlation between CPA and CSAP. The patterns in BGE_{cpa} for both species reflect the same stand structural controls which influenced the BGE_{csap} curves.

The trends in BGE are further illustrated by the plots of VGE versus their respective indices. The plot of VGE_{csap} versus CSAP (fig. 2.38) is different for the two species, most likely a result of differences in the stand structure exhibited by each species

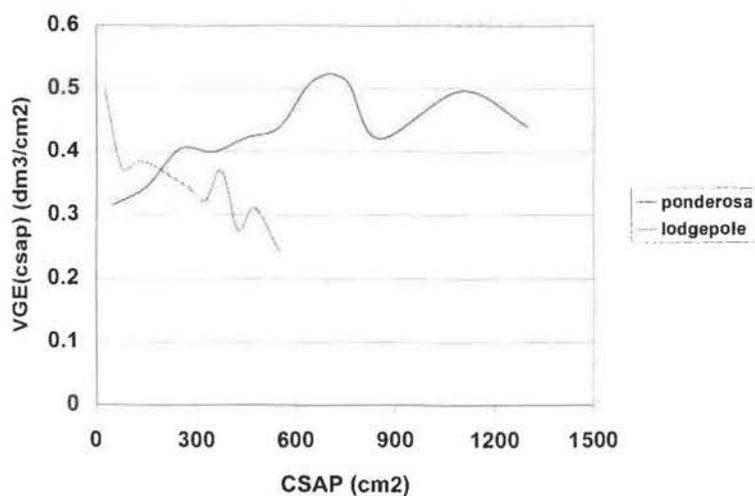


Figure 2. 38 VGE_{csap} for lodgepole and ponderosa, estimated from equation [2.2] and fixing predictors at the mean level associated with each level of CSAP

within the study plots.

The pattern of ponderosa pine, while indicating a great deal of variability, shows a generally increasing VGE_{csap} with increasing CSAP.

Importantly, these trees of high leaf area are the largest trees of the dataset.

This result, the variability included, is similar to that found by O'Hara (1996) in

ponderosa pine, whereby the oldest cohorts in multi-age stands exhibited the greatest VGE. Previous studies have suggested that the increased VGE of the largest trees in a multi-cohort stand is a result of an improved light environment (O'Hara 1996). This idea may be appropriately applied to these plots, as the ponderosa generally exhibited complex vertical canopy stratification, and is supported by the positive correlation of the relative height variable with basal area growth within the model. However, it appears that at the highest leaf areas, VGE_{csap} begins to decline. Trees of this size are quite old and have very large crowns. Previously mentioned research addressing the diminished growth rates of large trees may explain this diminished efficiency (Yoder et al. 1994).

In contrast, VGE_{csap} in lodgepole pine does not exhibit this pattern. Again, structural differences may account for this; much of the lodgepole within these study plots were in single cohorts patches. Studies analyzing VGE_{csap} in lodgepole pine and subalpine fir have suggested that GE in lodgepole pine decreases with increasing leaf

area because lodgepole generally grows in single cohort stands with relatively little vertical stratification. Although an increased leaf area suggests a tree of dominant canopy position, its position and light environment does not offset significantly factors

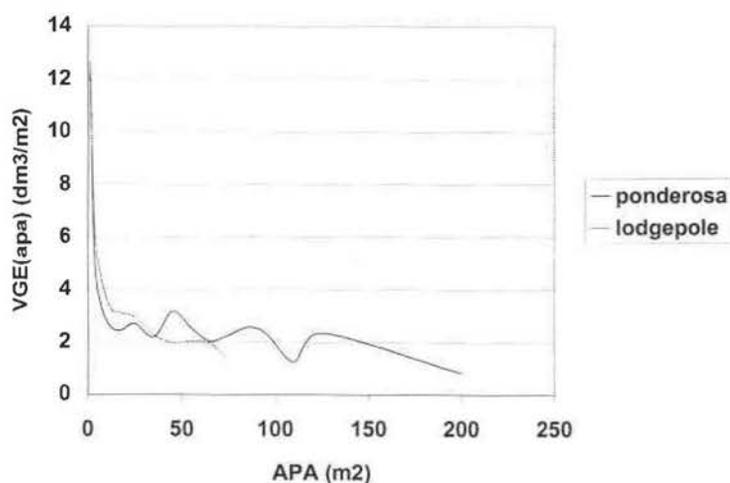


Figure 2. 39 VGE_{apa} for lodgepole and ponderosa, estimated from equation [2.2] and fixing predictors at the mean level associated with each level of APA

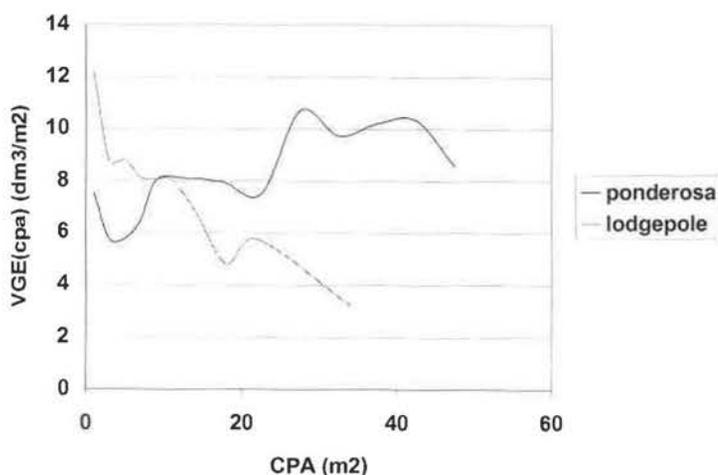


Figure 2. 40 VGE_{cpa} for lodgepole and ponderosa, estimated from equation [2.2] and fixing predictors at the mean level associated with each level of CPA

that lead to a decline in GE of larger trees (Roberts et al. 1993).

The greatest similarity between BGE and VGE is found for APA (fig. 2.39). As ponderosa and lodgepole have greater amounts of “unoccupied” ground area

around a tree, growth increases (as indicated by the models), but at a marginally decreasing rate per unit APA increase. The decrease in efficiency quickly slows at values of APA above 10 m² for both species. With APA, there is much less correlation between individual tree or stand structural characteristics. As a result, though variation exists in the VGE_{apa} decline for both species, the characteristics which give rise to these differences are the result of individuals within the

APA subclasses used to compute means of other predictors, and are probably not correlated with different levels of APA itself.

The plot of VGE_{cpa} appears similar to VGE_{csap} (fig. 2.40). As with BGE, this is no doubt a result of the correlation between large crown projection areas, large trees, and high CSAP. Just as large ponderosa pines (as defined by CSAP) show increasing VGE, ponderosa pines with high CPA also show increased VGE with greater size. For a given CPA, high VGE_{cpa} may be expected in trees that have especially long and full crowns (higher leaf area per unit CPA) (Kuuluvainen 1988). Development and maintenance of this kind of crown requires that light be available to the lower canopy.

It has been suggested that, in providing a better environment for photosynthesis, a

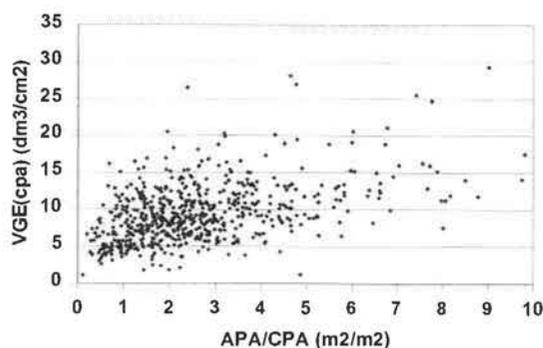


Figure 2.41 VGE_{cpa} with increasing degree of disengagement, lodgepole

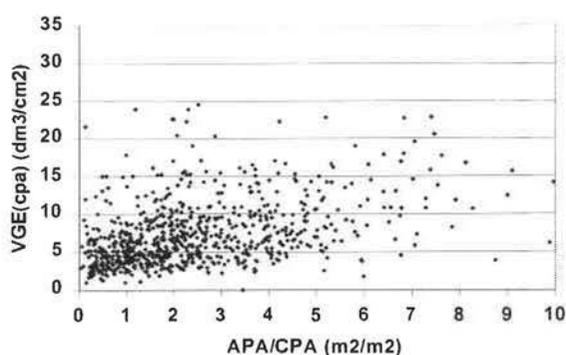


Figure 2.42 VGE_{cpa} with increasing degree of disengagement, ponderosa

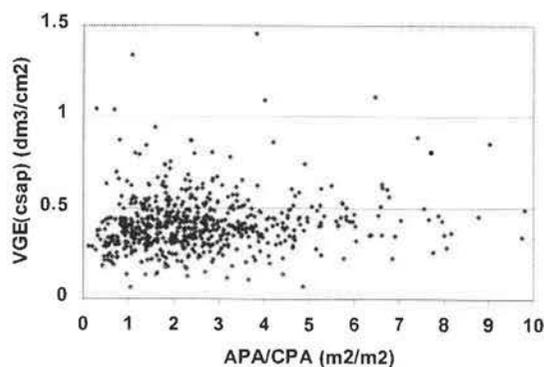


Figure 2. 43 VGE_{csap} with increasing degree of disengagement, lodgepole

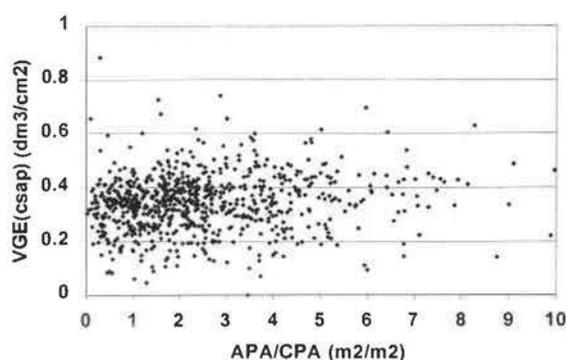


Figure 2. 44 VGE_{csap} with increasing degree of disengagement, ponderosa

large degree of disengagement is advantageous from the standpoint of ground area efficiency (Assman 1970). The correlation between VGE_{cpa} and APA/CPA (degree of

disengagement) would suggest this is valid, though the variability in the relationship indicates other significant factors exist (figures 2.41 and 2.42).

However, when measuring efficiency on the basis of CSAP (or leaf area), this relationship is weaker, (figures 2.43-2.44). This would support the theory that needles in the lower crown are not important for VGE_{csap} , consistent with previous studies (Smith and Long 1989).

For the even-aged lodgepole pine, natural stand development results in crown crowding, abrasion, and, eventually, short crowned, low VGE_{csap} trees (Long and Smith 1992). This crown form, previously shown to be associated with low VGE_{cpa} in other species (Kuuluvainen 1988), explains the decreasing VGE_{cpa} of lodgepole pine.

Differences between BGE and VGE for a particular index are especially obvious for ponderosa pines when efficiency is defined by CSAP or CPA. For these occupancy indices, there is a strong direct correlation between size (height, diameter) and the index. This is, in these relatively unspaced plots, less true for APA. As a result, trees with high CSAP or CPA are large trees whose volume growth takes place along a tall bole. Volume growth for these trees is therefore commensurately greater for a given basal area increment than it is for shorter trees.

One note of caution should be added: because these measurements were made on stands which have undergone repeated entries, the trees within the dataset may represent the dregs, and may thus not fully represent the growth potential on these sites. Though less true of relatively even-aged patches of the shorter-lived lodgepole pine, growth and growth efficiency of the mostly uneven-aged ponderosa pine may only be indicative of the lower end of the potential range, thereby suggesting that care be taken in applying these results.

Silvicultural Implications

The high GE of trees whose spatial occupancy is minimal indicates that stand growth is theoretically maximized by decreasing the leaf area or ground area per tree, thereby increasing the number of stems on a site. Although total wood production is of ultimate interest where timber production is emphasized, only under a pulpwood objective and under absence of potential insect or disease pests, would individual tree

growth be fully subordinated to stand growth. In general, this strategy is inappropriate under a variety of ecosystem constraints and management objectives. However, natural stand dynamics would cause trees to differentiate in most cases, leading to differentiation in GE as well. As addressed by Roberts (1993), individuals in even-aged subalpine fir stands differentiate strongly, to a large extent because its shade tolerance allows suppressed individuals below the main canopy to persist. Hence, at the low end of the range of leaf area, an increase in this leaf area is associated with a significant improvement in their light environment and in GE. However, because differentiation in lodgepole pine stands is relatively weak, an increase in leaf area does not cause the light environment or GE to significantly improve. Vertically stratified, uneven-aged ponderosa pine stands resemble strongly differentiating subalpine fir, but the results from the subalpine fir may be further enhanced by the even greater vertical stratification found in the multi-cohort ponderosa pine.

In the case of dry, central Oregon pine forests, because log size and some types of insect and disease resistance are negatively correlated with high stem densities, sacrifice of some total stand growth is made for the sake of ensuring development of individual tree vigor and potentially merchantable sizes. Simply put, fiber production is best maximized by minimizing spacing while still ensuring that other objectives are met.

The quicker production of larger individual trees with wider spacing may be a priority. Because trees grow relatively slowly in south central Oregon, economic considerations may deem it necessary to sacrifice some of the total stand volume production for quicker individual sawlog production and hence greater value production. The resulting wider spacing would also better meet specifications for pest resistance—vigorous trees are believed to better respond to attacking insects or diseases than are their smaller crowned counterparts (Mitchell et al. 1983, Larsson et al. 1983).

Area potentially available, a surrogate for root spread, belowground resource pool, and degree of crown crowding, is an appealing measure of spatial occupancy due to its direct relevance to tree spacing as a common specification in silvicultural treatments. However, whereas CSAP and CPA values actually correspond to distinct and measurable spatial occupancy values, APA can't be so easily defined. Root overlap from both trees and brush make it impossible to suggest that only a single tree occupies a

given area. Instead, APA is only a very rough estimator of relative or proportional growing space occupied by an individual tree. As a result, trees of high or low APA values, with their subsequent low or high growth efficiencies are of dubious use alone in interpreting the effect of spacing. In such cases, APA values are likely a poor relative measure of a tree's root spread or belowground resource pool.

The ponderosa pine plot of APA GE versus APA, which includes the effect of leaf area, indicates that efficiency of trees occupying 10 m^2 to 30 m^2 is relatively similar. The large amount of variability for different levels of occupancy suggests that after index value is accounted for, individual tree characteristics play a large role in determining efficiency. For example, a larger APA may be accompanied by a larger crown with a better light environment, with growth thereby increased sufficiently to produce a similar efficiency. Those trees most efficiently using the larger APAs will be those whose growth, and thus crowns are sized appropriately for their APA. The relatively equivalent efficiency potential from APAs of 10 m^2 to 30 m^2 suggests that, in theory, very little growth may be lost in giving trees more space, and will concentrate growth on larger, more utilizable stems.

For lodgepole pine, the plots of APA GE versus APA shows a steady loss of growth efficiency with increased APA. While a decrease in spacing would thus provide significantly higher growth efficiency, management of the even-aged patches of lodgepole is constrained by bark beetle concerns. Thinned stands of relatively low stocking have been found to best resist significant mountain pine beetle mortality (Mitchell et al. 1983, Larsson et al. 1983). Although recommendations have suggested limiting stocking to an upper management zone not exceeding an SDI of 170 for minimized beetle susceptibility (Cochran et al. 1994), patches of even-aged lodgepole such as these, where mixed or isolated by mixed cohort ponderosa and lodgepole pine, may be safe when stocked slightly higher than this.

The evidence that large ponderosa exhibit the most efficient volume growth is promising from a timber management perspective. Structuring a stand to maximize efficiency for the trees of the largest size class is desirable as they occupy more space, produce more valuable wood, and are the economically better investment. In continuing efficient growth, they preserve future options—leaving large trees for some future cutting

cycle becomes a viable financial option. However, this relationship must be balanced against obtaining and maintaining vigorous regeneration given the apparent sensitivity of ponderosa pine growth to relative social position in the stand. In general, suppressed ponderosa pine does slowly respond to release if not too severely suppressed. One previous thinning study found diameter and height growth responded quickly among 40-70 year old ponderosa saplings (averaging 5 cm in diameter) following overstory removal and spacing (Barrett 1965). Where overstories were retained, similar saplings responded, but did so more slowly (Barrett 1969).

Light environment has been put forward as one of the most important determiners of growth and growth efficiency in an uneven-aged stand (O'Hara 1996, Maguire 1998). For this study, the demonstrated ability of small trees to continue acceptable growth rates is no doubt due to the relatively low LAI for ponderosa and lodgepole pine on these sites. The ability of small trees to continue efficient growth is advantageous. While the models have demonstrated that neighboring trees, however large, diminish the growth of a subject tree, even in a subordinate position small trees are efficiently using space, regardless of how it is defined. Certainly overstory density needs to be controlled so that young ingrowth maintains a straight stem form with enough crown to ensure post-harvest release. Nevertheless, given the high efficiency of small trees, the dedication of leaf area to a few small trees of young cohorts is a good investment. Conversely, the negative effect of subordinate trees both on trees within the same cohort and on their larger neighbors means that the counts of these younger cohorts, regardless of size, need to be kept from getting excessively high.

The negative effect that small trees and other understory vegetation has on the growth of older trees indicates that their removal could increase their growth, and, all else being equal, their growth efficiency. The decision to remove any or all of this material will depend on the size and density of the understory (and the efficiency with which it can be removed), and the resulting value increase of the overstory.

Chapter Three: Patterns in Growth Efficiencies Based on Alternative Definitions of Site Occupancy in Heterogeneous Stands of Ponderosa and Lodgepole Pine of Central Oregon

Introduction

In studies of forest growth, growth efficiency (GE) has typically been defined on the basis of growth per unit leaf area (Waring et al. 1981, Long and Smith 1989, Long and Smith 1990, Roberts et al. 1993, O'Hara 1996, Maguire et al. 1998). GE has been analyzed primarily in relation to increasing leaf area; that is, no covariates are included to correct for the influence of other variables, particularly those included in more generally applicable growth models. These covariates are not only correlated with leaf area, but they also may be correlated with other occupancy indices on which GE could validly be based. Hence, in the absence of additional covariates, the effect of increasing leaf area is not isolated. Similarly, interpretation of general GE is incomplete without some insight into the behavior of alternate GEs, for example, growth per unit crown projection area (Assman 1970, O'Hara 1988) or growth per unit area potentially available (Nance et al. 1988).

In addition to the comparative behavior of individual GEs, the combined effects of alternative measures of occupancy on GE have not been considered, except very generally (e.g. degree of disengagement (Assman 1970)). For a given leaf area, the amount of a tree's occupied ground area, be it crown projection area (CPA) or area potentially available (APA), may have a large additional influence on its photosynthetic capacity, as it reflects the tree's ability to capture both above and belowground resources. Inclusion of ground area within a growth model estimating GE based on leaf area may explain additional variation in GE of individual trees (Assman 1970), especially in relatively dry interior pine forests where ground area may generally represent water available to individual trees (Waring 1983).

Leaf area is correlated with tree size, particularly with height, and hence, indicates both the tree's ability to capture light and the relative illumination of its leaves. Previous studies have related increases in GE with increasing relative height in the stand (Roberts et al. 1993, O'Hara 1996, Maguire et al. 1998). However, the large variation in relative

height (based on the stand maximum) within an uneven-aged stand, coupled with extreme variation in stand structure, may render relative height a less than ideal surrogate for light availability. A distance-dependent *localized* relative height would be a potentially more useful covariate.

Growth efficiency is also influenced by crown architecture. Increased maintenance respiration (Ryan and Waring 1992) and diminished hydraulic conductance (Yoder et al. 1994) of crowns with long branches and high branch biomass have been implicated in declining GE. For a given leaf area, these effects may be represented by CPA. Other variables representing crown architecture have also been examined, including foliar density (Kuuluvainen 1988), branch mass: crown mass ratio (Roberts and Long 1992), and the whorl-density per unit crown length as an index of past suppression (Maguire et al. 1998).

In short, alternative definitions of growth efficiency have been applied to compare growth of different stand components. Some of these can be interpreted as growth per unit site occupancy, with site occupancy measured in three possible ways: 1) leaf area, here represented as crown base sapwood area (CSAP), 2) crown projection area (CPA), and 3) ground area potentially available (APA).

The objectives of this study were to test the following hypotheses:

- 1) The relative growth efficiency of different stand components will vary depending on the specific definition of growing space occupancy by which GE is defined (GE_{CSAP} vs. GE_{CPA} vs. GE_{APA}).
- 2) Analysis of growth responses to all three measures of site occupancy simultaneously lends insight in to the effect of stand structure on GE:
 - a) For a given leaf area, GE_{CSAP} increases with increasing APA and increasing CPA.
 - b) For a given CPA, GE_{CPA} increases with increasing APA and CSAP
 - c) For a given APA, GE_{APA} increases with increasing CSAP and CPA.

Methods

Study Sites

Data were collected in the summer of 1998. Nine square, 0.4-ha plots were established within Crown Pacific's central Oregon tree farm, centered approximately at Gilchrist, Oregon (43°28' N, 121°42' W). These nine plots, split evenly between two sites, are in the *Pinus ponderosa/Purshia tridentata* plant association (Franklin and Dyrness 1973).

The two sites represented two different stand types. The first, termed the Timbers site, consisted primarily of multi-aged ponderosa pine (Pipo) (87% of basal area is Pipo). The second site, called Blackrock, also contains primarily ponderosa pine (55% of basal area is Pipo), but a significant component of lodgepole pine (Pico) also is present. Much of the lodgepole pine occurs in single-cohort patches. Nevertheless, the presence of many large, old ponderosa pine stumps testifies to previous stand conditions and previous disturbance types. Evidence of more recent disturbance includes numerous skid trails, often free of regeneration, which in many places partition the plots into small patches of trees. The understory of both sites is dominated by bitterbrush (*Purshia tridentata*).

This portion of central Oregon, like much of the interior west, is characterized by cold winters, warm and dry summers, and limited precipitation falling mostly as snow during the winter months. The dry summers are further characterized by periodic drought. Over the last 30 years, the mean January minimum was -8°C and the mean July maximum was 27°C. Total annual precipitation during this time averaged 54 cm, with approximately 70% of this falling as snow (<http://www.ocs.orst.edu/>).

The target population for the growth analysis consisted of multi-cohort ponderosa/lodgepole pine stands. Square, 0.4 ha plots were subjectively sampled to meet the following requirements:

- Variability in local stand density, vertical stratification, diameter range, and presence of small trees and regeneration.
- No large treeless areas or large areas of high stem densities prohibitive to mapping.
- No management activity for the past five to ten years.

- Common aspect and no obvious differences in soil type, plant association, or landform.

Although, like trees, brush acts as a drain on belowground resources, its impact was not addressed by this study. Its distribution throughout the study plots was approximately uniform, and was assumed to draw on belowground resources in a spatially uniform manner. Furthermore, whereas Crown Pacific sometimes removes small trees (by mechanical crushing or manual PCT), they do not carry out mechanical or chemical site prep or release treatments specifically targeting brush. As a result, the question of what effect brush presence on overstory trees was not addressed in this study, but may have an influence on maximum growth rates attainable on these sites.

Individual plots ranged in basal area and trees per hectare from 7.3 to 24.3 m² and 306 to 2684, respectively (Table 3.1). Basal area by species and diameter distribution by plot reveal the irregular uneven-aged structure of the subject plots (figures 2.1-2.10 in chapter 2).

Table 3. 1 Attributes of the nine 0.4 ha study plots from the pumice region of central Oregon

Plot	All trees	Ponderosa Pine									Lodgepole Pine								
	# of trees	Number of trees		5-yr basal area growth/tree (cm ²)		DBH (cm)		Height (m)		Basal Area (m ²) All trees	Number of trees		5-yr basal area growth/tree (cm ²)		DBH (cm)		Height (m)		Basal Area (m ²) All trees
		>10 cm dbh	< 10 cm dbh	mean	range	mean	range	mean	range		>10 cm dbh	< 10 cm dbh	mean	range	mean	range	mean	range	
BL 2	195	69	22	73.6	11.9-186.5	29.4	11.9-67.0	13.7	5.9-23.3	5.43	63	41	52.5	16.0-111.3	19.7	10.1-34.8	11.7	6.8-18.1	2.30
BL 3	188	40	11	83.7	13.0-278.6	24.6	10.2-73.5	11.9	4.5-28.5	2.40	48	89	59.2	15.5-149.4	18.1	5.2-37.4	13.1	4.8-20.0	1.76
BM	454	65	19	46.8	5.4-150.2	25.4	10.3-47.1	12.2	5.4-26.6	3.05	118	252	46.2	6.6-166.1	19.5	10.2-42.7	13.9	6.3-21.3	6.67
BH 1	687	49	20	56.8	7.3-200.2	25.4	10.3-60.2	13.1	5.4-26.6	3.07	140	478	40.9	11.5-101.2	18.5	10-32.5	13.5	6.1-19.0	4.73
BH 2	1086	81	43	53.5	7.4-194.0	24.6	10.1-50.5	12.7	4.4-22.7	4.44	192	770	25.2	7.2-82.7	14.4	10.0-33.0	11.1	5.1-20.5	5.37
T L1	124	57	45	56.6	14.5-180.6	18.0	5.9-50.2	7.8	2.6-21.5	2.45	16	6	65.1	23.2-171.1	18.3	10.2-35.2	8.5	4.9-14.3	0.52
T M	412	96	313	39.3	9.2-213.1	17.0	10.0-60.7	8.1	3.7-28.7	3.30	2	1	32.8	16.8-48.8	16.0	11.2-20.8	9.5	7.6-11.3	0.04
T H1	753	148	475	24.6	5.7-91.9	18.0	10.1-61.9	10.6	4.3-30.8	5.43	53	77	42.6	10.8-134.5	17.7	10.2-30.4	10.9	5.0-22.9	1.63
T H2	478	190	242	34.0	6.8-193.0	18.5	10.0-39.7	8.1	4.2-21.2	6.43	10	36	41.1	23.2-74.5	18.1	10.3-35.7	8.2	4.9-14.2	0.37

Sampling Design and Field Measurements

Following establishment of plot corners, all trees > 1.37 m in height were numbered and mapped by recording distance and azimuth to an appropriate plot corner using a Criterion 400. On most plots tree density was such that some trees needed to be referenced to interior points that, in turn, were referenced to a plot corner. All tagged trees were measured for dbh to the nearest 0.1 cm. For each plot tree greater than 10 cm dbh, the following additional attributes were measured:

Ht: Height from ground to tree tip, representing height at the end of the 1998 growing season (nearest 0.1 m).

Ht₅: Height from ground to the fifth whorl from the tip of the tree, representing total height at the end of the 1993 growing season (nearest 0.1 m).

HCB: Height to live crown base (nearest 0.1 m), defined as the lowest whorl in which approximately 75% of the branches were still alive.

CW: Geometric mean of two crown widths, representing the greatest width in the north-south and east-west direction.

ΔR : Radial increment for the past five years (nearest 0.5 mm). Each tree over 10 cm dbh was randomly assigned a number, 1-4, indicating the initial location for coring (1-south side, 2-southwest, 3-west, 4-northwest). Each tree was cored twice—the second core was made at a location 180° from the first. Where scars were located in the part of the tree to be cored, the coring location was advanced to the next quadrant (1-4) until a suitable location was found.

BT (Bark thickness): Distance to pith was measured (nearest 1 mm) on cores from approximately 60 trees of each species, covering a range of diameters. Double bark thickness was assumed equal to the difference between dbh (as measured by d-tape) and twice the radius inside bark as measured on the cores. A bark thickness equation was then constructed for application to the rest of the subject trees: $DIB = b_1 DOB^{b_2}$

SAP: Breast height sapwood radii were measured from each of the increment cores (nearest 1 mm). Sapwood cross-sectional area (SAP) was computed as:

$$SAP = \pi(R^2 - (R - SR)^2)$$

where $R = DIB/2$

SR = Geometric mean of two sapwood radii

$DIB = b_1 DOB^{b_2}$

DIB = diameter inside bark at 1.37 m

DOB = diameter outside bark at 1.37 m

Several variables were computed to indicate site occupancy of competition position of each tree with dbh > 10 cm:

APA: Area Potentially Available was calculated as constrained, tree-weighted polygons for each tree (Nance et al. 1988).

H(Θ): Point relative height was calculated by determining the height of the subject tree as

a fraction of neighboring trees. Neighboring trees were defined as those trees whose height penetrated an inverted cone produced by a 360° sweep made with a fixed angle Θ from the tip of the subject tree (figure 3.1). The subject tree's point relative height was based on the height of the tallest tree entering this inverted cone. Two angles were tested: 30 and 45 degrees.

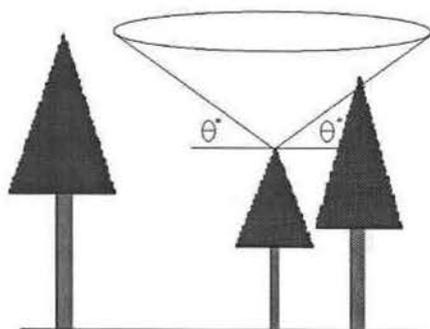


Figure 3. 1 Point relative height

ST: Total basal area of small trees with diameter less than 10 cm, was calculated within zones surrounding subject trees. These circular zones had radii equal to multiples of the crown width of each tree, where the multiples were 1.5, 2, 2.5, 3 and 3.5 times the crown width of the subject tree.

CSAP: Crown base sapwood cross sectional area was estimated from the sapwood cross sectional area at breast height assuming that the relative sapwood taper for ponderosa and lodgepole pine was similar to relative sapwood taper in coastal Douglas-fir (Maguire and Batista 1995). The crown base sapwood area should theoretically better represent actual leaf area, particularly among stands and plots of widely differing stand densities and,

hence, differing heights to crown base (Waring et al. 1982). Empirical studies have confirmed this expectation (Dean and Long 1986).

Trees which had any type of defect were noted. Observed defects included broken tops, scars, leaners (with large amounts of compression wood), misshapen stems, and trees exhibiting signs of disease.

Backdating

Numerous tree and stand-level variables were computed for regression analysis of growth and growth efficiency (table 3.2).

Backdating of variables was necessary in order to base the past five year growth on initial growth period conditions. During the course of field measurements, 1993 height was measured directly at the fifth whorl below the tree tip. The 1993 diameters were determined using the five-year diameter increments, and applying the calculated bark thickness equation. Where possible, all subsequent individual tree and stand variables were calculated using these backdated values. Sapwood cross-sectional area, crown width measurements, and crown ratios were assumed to have remained unchanged over the growth period.

Small tree (dbh < 10 cm) basal area growth rates over the previous five years were computed by assuming small trees had relative basal area growth equivalent to the average for large trees on the same plot. Because understory trees often exhibit less growth than their overstory counterparts, this assumption may underestimate the small tree basal area at the start of the five year growth period. If so, the parameter value of the small tree basal area variable may be overestimated.

Table 3. 2 Table of Variables used for Model Construction

Variable	Abbr.	Units	Notes
<i>Dependent variable</i>			
Basal Area Growth	BAG	cm ²	
<i>Independent variables</i>			
Diameter	D	cm	
Volume	V	m ³	From equation in Cochran (1985)
Sapwood Volume*	SV	m ³	From equation in Maguire and Batista (1995)
Point Relative Height	H(30,45)	m/m	Height relative to tallest nearest neighbor. Values in parentheses indicate defining angle in degrees.
Plot Relative Height	RH	m/m	Height relative to tallest plot tree
Plot Average Height	HAVG	m/m	Height relative to plot average
Breast Height Sapwood XS Area*	SAP	cm ²	
Crown Base Sapwood XS Area*	CSAP	cm ²	Calculated using equation in Maguire and Bastista (1995)
Crown Length/CSAP*	CL/CSAP	m/cm ²	
Area Potentially Available	APA	m ²	Calculated using program detailed in Nance et al. (1988)
Horizontal Crown Proj. Area*	CPA	cm ²	
Basal area of small trees	ST	m ²	Defined by subject tree crown width
Timbers	T	indicator	Site indicator variable = 1 if Timbers = 0 if Blackrock

*Variable was assumed to be constant over the last five years

Statistical Analysis

The model constructed for this analysis was mechanistic in nature in that it sought to distinguish the effects of the three measures of occupancy (CSAP, CPA and APA) as well as other spatially explicit or functionally related variables. The analysis was performed separately for the two species to accommodate expected differences in growth behavior. Both logarithmically transformed and untransformed forms of the independent variables were explored using scatterplots. Variables were logarithmically transformed where this was deemed appropriate.

Initial screening for the appropriate variables was based on variance inflation factors (VIF), Mallow's C_p statistic, coefficients of multiple determination (R^2), compatibility with existing growth models, biological understanding, ease of variable interpretation, and consistency in model forms between species.

Model checking was performed by examining residuals for homogeneous variance and normality, and outliers were screened with Cook's Distance and standardized residuals. Identified outliers were checked to ensure proper variable values, and the possible influence of tree defects. Where unusual data values were found through this check, some field remeasurement was required for confirmation.

Variables were selected not necessarily to maximize correlation but rather to address those components of the system which together act to enhance or diminish tree growth (table 3.2). Because it was considered desirable to include both spatial occupancy variables and small tree competition variables, the selection procedure always included one variable representing spatial occupancy. These latter variables included horizontal crown projection area (CPA), area potentially available (APA), breast height sapwood cross-sectional area (SAP), and crown base sapwood cross-sectional area (CSAP). Each of these was included with the other potential variables, and an all-subsets procedure helped identify the best models.

Of the spatial occupancy variables, the first two describe ground coverage (CPA and APA), and the second two (SAP and CSAP) are estimators of photosynthetic surface. From this first round of model selection, it was found that models with APA consistently

outperformed those with CPA, and that those with CSAP consistently outperformed those with SAP. Because the combination of terms for photosynthetic surface and ground coverage seemed both biologically reasonable and offered the potential to depict slightly different aspects of site occupancy, CSAP and APA were both retained in the model.

For detailed analysis of growth efficiency by the three primary indices of site occupancy (CSAP, CPA APA), alternative growth models were also fit with the other two possible combinations of these variables (CSAP and CPA, and CPA and APA), as well as with all three occupancy variables.

Implied volume growth efficiency (VGE) of each tree was calculated from estimated growth and alternative indices of site occupancy: crown base sapwood cross-sectional area (CSAP), area potentially available (APA), and horizontal crown projection (CPA). Basal area growth was estimated from equation [3.1], height growth was measured directly, and volume growth was defined as the difference in tree volume between 1993 and 1998 as predicted from Cochran's equations (1985). Proper calculation of VGE required that the equation contain the occupancy index upon which GE was defined. Because the mechanistic model contains two site occupancy variables, $VGE_{csap/apa}$ and $VGE_{apa/csap}$ were inferred from equation [3.1], $VGE_{csap/cpa}$ and $VGE_{cpa/csap}$ were inferred from equation [3.2], and $VGE_{cpa/apa}$ and $VGE_{apa/cpa}$ were inferred from equation [3.3].

Implied VGE for each of the three occupancy indices was examined across the respective range of each occupancy index. Values of other model variables were set to their mean value within segments of the index range. In using two separate equations, growth, and thus growth efficiency was corrected for the separate effect of the other occupancy covariate (figs. 3.13-3.15).

Results

Although basal area growth models has been represented in non-linear form due to non-normality of residuals on the log-transformed scale (for example, Ritchie and Hann 1985), normality plots indicated superiority of the log transformed model in this regard. In fact, Furnival's index (Furnival 1961) also suggested that the logarithmic form

of the model was marginally better. The best model for both ponderosa and lodgepole pine was therefore identified as:

Equation 3. 1

$\text{Ln}(\text{BAG}) =$

$$\gamma_0 + \gamma_1 \text{Ln}(\text{CSAP}) + \gamma_2 \text{Ln}(\text{APA}) + \gamma_3 \text{Ln}(\text{CL}/\text{CSAP}) + \gamma_4 \text{Ln}(\text{H45}) + \gamma_5 (\text{ST}) + \gamma_6 (\text{T}) + \epsilon$$

This model explained 87.2% and 81.9% of the variation in the logarithm of ponderosa pine and lodgepole pine basal area growth, respectively and yielded RMSEs of 0.280 and 0.251, respectively. Parameter estimates indicated positive effects of CSAP, APA, and H(⊙), but negative effects of CL/CSAP and small tree basal area (tables 3.3 and 3.4). Residual plots indicated close conformity to constant variance and normal distribution of residuals.

Table 3. 3 Parameter estimates for ponderosa pine, mechanistic model

Variable	Parameter estimate	Standard error
γ_0	0.374311	0.080338
γ_1	0.393487	0.044473
γ_2	0.090502	0.016319
γ_3	-0.43344	0.06172
γ_4	0.112668	0.053533
γ_5	-1.64407	0.240258
γ_6	-0.09477	0.034739

Table 3. 4 Parameter estimates for lodgepole pine, mechanistic model

Variable	Parameter estimate	Standard error
γ_0	-0.16289	0.081589
γ_1	0.335911	0.032984
γ_2	0.099363	0.013139
γ_3	-0.59104	0.047468
γ_4	0.286493	0.046453
γ_5	-0.59863	0.205271
γ_6	-0.15163	0.022744

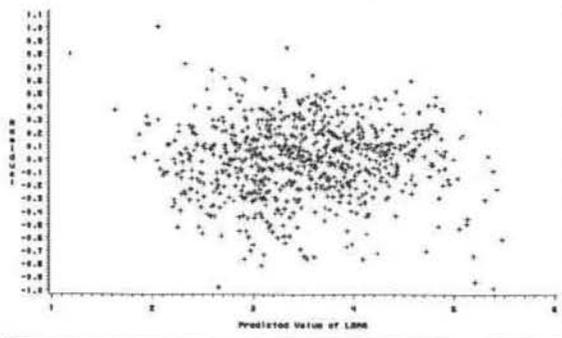


Figure 3.2 Residual plot for the distance-dependent ponderosa pine model

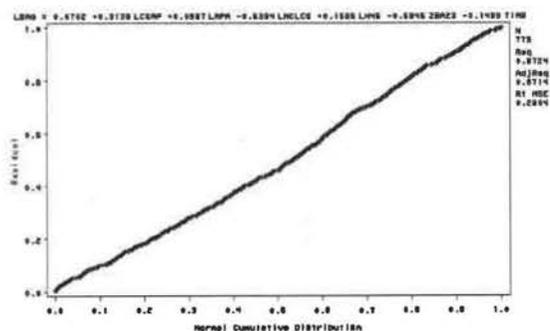


Figure 3.3 Normal probability plot for the distance-dependent ponderosa pine model

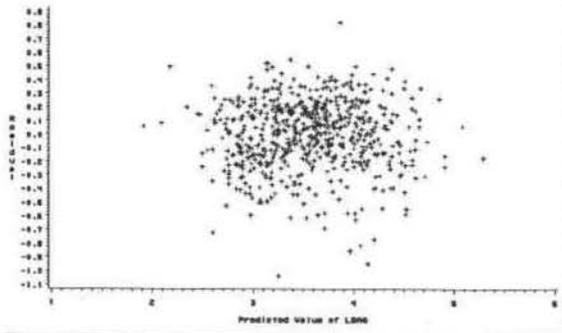


Figure 3.4 Residual plot for the distance-dependent lodgepole pine model

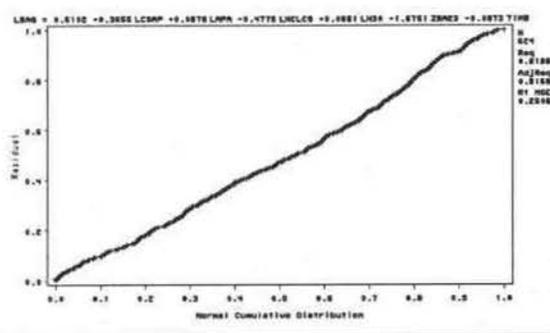


Figure 3.5 Normal probability plot for the distance-dependent lodgepole pine model

Refitting this model form with the other two combinations of occupancy variables yielded the following two equations.

Equation 3. 2

$$\text{Ln(BAG)} = \gamma_0 + \gamma_1 \text{Ln(CSAP)} + \gamma_2 \text{Ln(CPA)} + \gamma_3 \text{Ln(CL/CSAP)} + \gamma_4 \text{Ln(H45)} + \gamma_5 \text{(ST)} + \gamma_6 \text{(T)} + \epsilon$$

Equation 3. 3

$$\text{Ln(BAG)} = \gamma_0 + \gamma_1 \text{Ln(CPA)} + \gamma_2 \text{Ln(APA)} + \gamma_3 \text{Ln(CL/CSAP)} + \gamma_4 \text{Ln(H45)} + \gamma_5 \text{(ST)} + \gamma_6 \text{(T)} + \epsilon$$

Although some predictive power was lost in moving from equation [3.1] to either [3.2] or [3.3] (table 3.5), the relative effects of variables were stable (tables 3.6-3.9). In particular, increase in any occupancy variable resulted in an increase in basal area growth.

Equation 3. 4

$$\text{Ln(BAG)} = \gamma_0 + \gamma_1 \text{Ln(CSAP)} + \gamma_2 \text{Ln(APA)} + \gamma_3 \text{Ln(CPA)} + \gamma_4 \text{Ln(CL/CSAP)} + \gamma_5 \text{Ln(H45)} + \gamma_6 \text{(ST)} + \gamma_7 \text{(T)} + \epsilon$$

When all three occupancy variables were incorporated into the model (equation 3.4), predictive power increased marginally for ponderosa pine, and not at all for lodgepole pine (table 3.5). With the three variable model, CPA is a less useful predictor variable, proving to be somewhat significant for ponderosa pine, and statistically insignificant for lodgepole pine (tables 3.10-3.11). For ponderosa pine, increases in each occupancy variable results in an increase in BAG.

Table 3. 5 Results from fitting mechanistic model form with other spatial indices

<i>Occupancy indices</i>	Ponderosa pine		Lodgepole pine	
	<i>RMSE</i>	R^2	<i>RMSE</i>	R^2
CSAP/APA	0.281	0.872	0.251	0.818
CSAP/CPA	0.288	0.865	0.257	0.810
APA/CPA	0.293	0.861	0.265	0.797
CSAP/APA/CPA	0.280	0.873	0.251	0.818

Table 3. 6 Parameter estimates for lodgepole pine, refit with CSAP and CPA

Variable	Parameter estimate	Standard error
γ_0	0.271241	0.09461
γ_1	0.419214	0.049488
γ_2	0.051541	0.02743
γ_3	-0.46354	0.063097
γ_4	0.176406	0.053325
γ_5	-1.75839	0.251997
γ_6	-0.10977	0.035961

Table 3. 7 Parameter estimates for ponderosa pine, refit with CSAP and CPA

Variable	Parameter estimate	Standard error
γ_0	-0.31456	0.083473
γ_1	0.315751	0.037021
γ_2	0.109367	0.028385
γ_3	-0.68806	0.046482
γ_4	0.320062	0.047394
γ_5	-0.9319	0.217727
γ_6	-0.16472	0.023283

Table 3. 8 Parameter estimates for lodgepole pine, refit with CPA and APA

Variable	Parameter estimate	Standard error
γ_0	0.839785	0.085765

Table 3.8 (continued)

γ_1	0.135025	0.025444
γ_2	0.109623	0.017817
γ_3	-0.8115	0.037839
γ_4	0.205227	0.045652
γ_5	-1.90247	0.260677
γ_6	-0.19912	0.035427

Table 3.9 Parameter estimates for ponderosa pine, refit with CPA and APA

Variable	Parameter estimate	Standard error
γ_0	0.218003	0.083018
γ_1	0.161977	0.026998
γ_2	0.098557	0.014026
γ_3	-0.86402	0.035821
γ_4	0.486681	0.041243
γ_5	-0.57563	0.221879
γ_6	-0.21349	0.022438

Table 3.10 Parameter estimates for lodgepole pine, fit with CSAP, APA, and CPA

Variable	Parameter estimate	Standard error
γ_0	0.408897	0.096294
γ_1	0.380051	0.049032
γ_2	0.087966	0.016783
γ_3	0.018007	0.027612
γ_4	-0.43702	0.061992
γ_5	0.109763	0.053743
γ_6	-1.68168	0.247192
γ_7	-0.09871	0.035276

Table 3.11 Parameter estimates for ponderosa pine, fit with CSAP, APA, and CPA

Variable	Parameter estimate	Standard error
γ_0	-0.08862	0.087505
γ_1	0.302097	0.036013
γ_2	0.092323	0.013453

Table 3.11 (continued)

γ_3	0.065269	0.028309
γ_4	-0.59041	0.047336
γ_5	0.283341	0.046343
γ_6	-0.73742	0.213364
γ_7	-0.15256	0.022684

Discussion

Interpretation of Mechanistic model

While sapwood cross-sectional area at breast height has been shown to be highly correlated with leaf area at a given site (Grier and Waring 1974), taper within the sapwood between breast height and crown base suggests that sapwood cross-sectional area at crown base should be a more reliable estimator of leaf area across stands (Waring et al. 1982). In fact, crown base sapwood cross-sectional area (CSAP) gave a much lower prediction variance than did breast height sapwood cross-sectional area for these lodgepole and ponderosa pine trees. The relationship between leaf area and sapwood cross-sectional area was not quantified for these sites, but the values should indicate similar relative leaf area among trees (O'Hara and Valappil 1995). The increased photosynthetic potential associated with larger leaf area (sapwood area), is reflected in greater basal area growth.

Although leaf area has been used as a measure of spatial occupancy of a site, a measure of ground occupancy has the appeal of accounting for greater resource availability, and thus improved photosynthetic potential (Assman 1970), in open or repeatedly entered stands. Ground occupancy also relates directly to spacing, which is often the guideline for implementing silvicultural prescriptions. For open-canopied stands, APA can be calculated as either a weighted or constrained APA. The former gives more weight to larger trees, and the latter limits the radius of a tree's occupancy polygon where no other competing trees would otherwise interfere (Nance et al. 1988). While it is too simplistic to suggest that each tree's APA corresponds to its root spread, the APA is likely correlated with the proportional amount of soil resources accorded to

each tree (assuming that all competitors, including brush, is accounted for).

Of two trees that are similar with respect to other model variables, the tree with more ground space available to it will exhibit greater basal area growth, presumably reflecting the greater availability of belowground and aboveground resources. The presumed functional connection between APA and belowground resource availability is strengthened by including a leaf area surrogate in the model; specifically, when leaf area is apparently equivalent between two trees, greater adjacent ground area will confer some advantages for growth.

The ratio of crown length to crown base sapwood area provides a surrogate for foliar density. The negative effect of this variable indicates basal area growth is slower for trees that have their leaf area distributed on a longer crown, that is, trees with sparser or lower density crowns. This result is similar to that found by Smith and Long (1989).

Relative tree height has previously been related to growth and is assumed to indicate the light environment of a tree (Roberts et al. 1993, O'Hara 1996, Maguire et al. 1998). The height of a tree relative to its neighbors will determine the degree to which its crown is shaded and, therefore, its potential photosynthesis, all else being equal. In stands carrying low levels of leaf area, a tree may be overtopped and thereby suppressed by another, without this suppression being of a lethal level. In such a scenario, lessened growth may also be expected.

Point relative height, vs. absolute height, is advantageous in these heterogeneous stands since it reflects local structure rather than mean plot structure. Alternative relative height measures based on the whole plot average or maximum height would make it impossible to distinguish between two trees with identical relative heights but very different local light environments. The tallest of the neighboring trees defined by an inverted cone therefore served as the basis for calculating point relative height of the subject tree.

The development of dense understories of seedlings and saplings is a common phenomenon in the interior west. While the presence of such material has been shown to exert a competitive effect on larger neighbors (Barrett 1963, Barrett 1970, Oren et. al. 1987, Riegel et. al. 1992, Hanson 1997), qualitative results are little help where timber is

being managed under tight economic constraints. In this case, quantification of the effect is necessary to determine whether the benefits make up for the cost of removal. One objective of this study was to test and quantify the effect of small trees on overtopping trees. The effect of these trees was represented in the model by basal area of small trees ($\text{dbh} \leq 10 \text{ cm dbh}$) within a crown-width multiple of the subject tree. Because the understory trees are competitors for belowground resources, basal area was assumed to be proportional to understory leaf area and transpirational potential. Also, some multiple of crown width is probably correlated with average distance of root spread. Crown width multiples of 1.5 to 3.5 were tested, sometimes with little difference in significance. The radii implemented and the zone subsequently calculated may be larger than the subject tree's average root spread and less than its greatest root spread. The ability for multiple radii to exhibit statistical significance suggests small tree basal area within a zone of a given size remains proportional between trees as zone size is changed. In general, a zone of influence 3 x the crown width was the most powerful predictor.

Comparison of Mechanistic model to other model types

Comparing the efficacy of the mechanistic model versus models which contain more standard growth and yield variables can be done by comparing coefficients of multiple determination and RMSEs among model types. These results indicate that the

Table 3. 12 Comparison of R^2 , RMSE among model types

	Ponderosa pine		Lodgepole pine	
	R^2	RMSE	R^2	RMSE
Distance- independent <i>(LnD, CR, BAL, BA)</i>	0.79	0.360	0.66	0.342
Distance- dependent <i>(LnD, CR, LnAPA, BAL, H(Θ), ST)</i>	0.83	0.329	0.71	0.320
Mechanistic	0.87	0.280	0.82	0.251

functionally related variables of the mechanistic model offer significantly greater predictive power than the traditional distance-independent and distance-dependent model variables (table 3.12). As was the case for both the distance-independent and distance-dependent models, more variation was explained in the case of ponderosa pine, though variance was lower for lodgepole pine. In fact, one variable of the mechanistic model, CSAP, alone explained 81.7% and 77.7% of the variation with RMSEs of 0.334 and 0.277 for ponderosa and lodgepole pine, respectively. In contrast, what might be considered the conventional surrogates for leaf area, dbh and crown ratio, explained 73.7% and 61.4% of the variation, with RMSEs of 0.365 and 0.402, for ponderosa and lodgepole pine, respectively.

The high correlation of CSAP with basal area growth helps explain the great predictive ability of the mechanistic model. In representing leaf area, CSAP is reflective of both tree size and competitive position, and hence, suggestive of a tree's ability to capture both above- and below-ground resources. Clearly, a tree can only produce as much photosynthate as its leaf area allows. But the ability to support leaf area is balanced by belowground allocation to coarse and fine roots (Kramer and Kozlowski 1997).

Although the mechanistic model does offer a significantly better prediction of basal area growth, its use as a growth and yield projection tool is limited. As a model for future growth predictions, it lacks utility due to intensive data collection requirements. However, in associating growth potential with structural components of trees or stands, it is a beneficial guide to understanding the biological implications of different silvicultural treatments.

An example of the utility of the mechanistic model was found in comparing VGE_{csap} calculated by the mechanistic and distance-dependent models (DD results in chapter two). This comparison indicates that, while estimates from the two models for lodgepole pine are within 5% of each other, ponderosa pine VGE_{csap} is consistently lower when BAG is estimated by the mechanistic model (fig. 3.6). These differences are greatest at the highest leaf areas. The better correlation of the mechanistic model, and the more biological reasonability of its variables might suggest the lower estimates from the mechanistic model are more accurate. The main difference in the two models is in their

representation of photosynthetic area. Whereas the distance dependent model uses crown ratio to represent photosynthetic area, the mechanistic model uses CSAP. Furthermore,

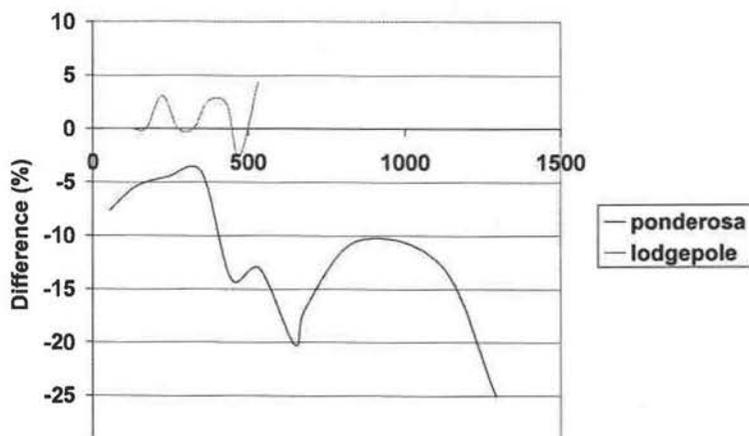


Figure 3.6 Difference in VGE_{csap} between mechanistic model (MM) and Distance-dependent model (DD) [Difference = MM - DD]

foliar densities differ between similarly-sized trees with equal crown ratios. Though this may significantly affect growth (as testified by the significance of the CL/CSAP variable in the mechanistic model), its effect is not captured when using crown ratio to describe photosynthetic area. In better accounting for between-tree crown structural variation, the ponderosa pine mechanistic model may thus more realistically predict growth, diminishing VGE_{csap} estimates for large trees. This bias between models was not found for VGE calculated with the other occupancy indices.

Little difference in VGE appears when a second covariate is added to the model, suggesting that the other occupancy index has a limited effect on the relationship between VGE and the occupancy variable on which VGE is based. However, this is likely a result of inclusion of the other covariates as well. When volume growth is plotted for various combinations of the two covariates (setting all other model variables to their means), the influence of the second covariate becomes obvious (figs. 3.7–3.12).

When growth is plotted for CSAP at different levels of APA (fig. 3.7) and CPA, the second variable increases growth, though this increase depends on the species. For example, an increase in CPA for a given CSAP (fig. 3.8), has a proportionally larger influence on volume growth of ponderosa pine (fig. 3.8). The powerful influence of CSAP is obvious from the large increase in growth per unit increase in CSAP (average slope of the curve in fig. 3.7 and fig. 3.8). This influence is also seen when CSAP

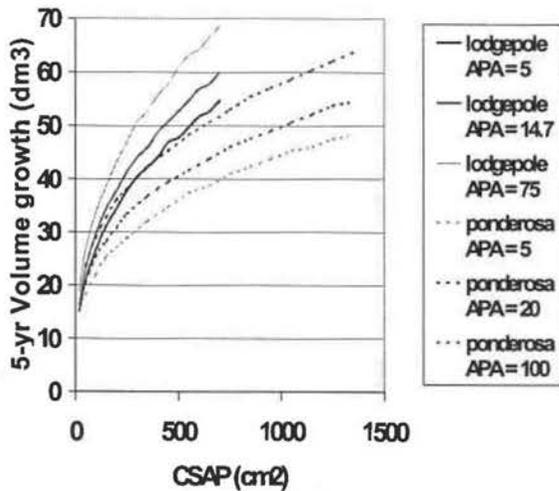


Figure 3.7 Volume growth (per tree) at different levels of CSAP and APA, from equation 3.1

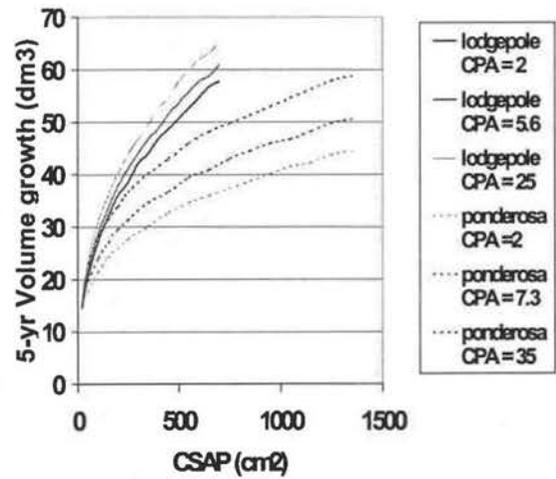


Figure 3.8 Volume growth (per tree) at different levels of CSAP and CPA, from equation 3.2

is increased at a given level of APA or CPA (figs. 3.9 and 3.11). Although APA and CPA curves are shaped similarly regardless of the second covariate, growth increases from adjusting the second covariate are much greater when the second covariate is CSAP (compare fig. 3.9 and 3.11 comes obvious (figs. 3.7–3.12).

The most important result from these figures is that at a given level of the index on which GE is based, (CSAP, APA, or CPA), an increase in the level of the second index is associated with increased growth, and thus in increased GE based on the

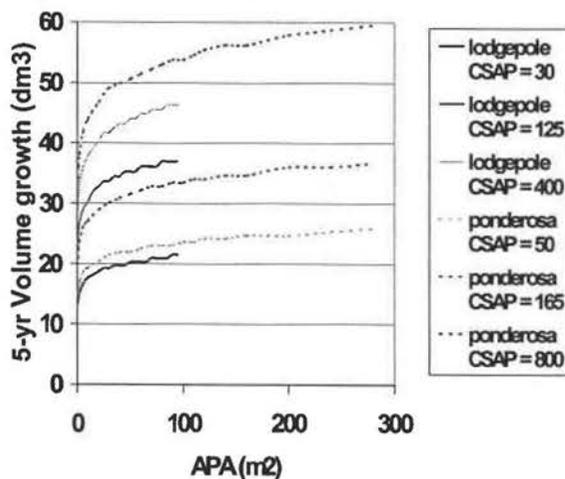


Figure 3.9 Volume growth (per tree) at different levels of APA and CSAP, from equation 3.1

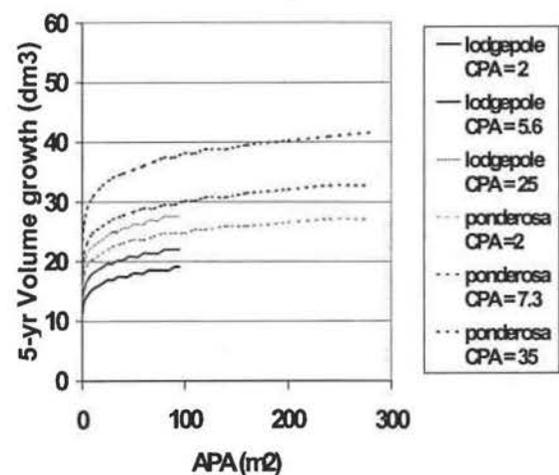


Figure 3.10 Volume growth (per tree) at different levels of APA and CPA, from equation 3.3

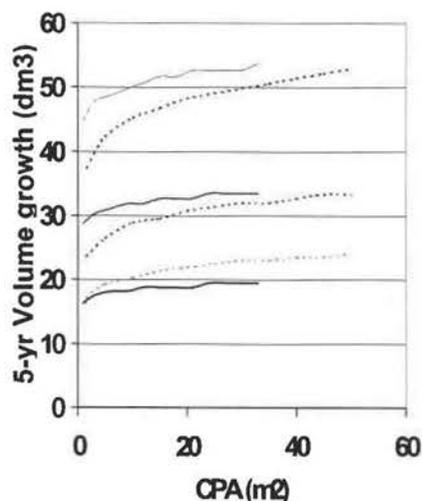


Figure 3. 11 Volume growth (per tree) at different levels of CPA and CSAP, from equation 3.2

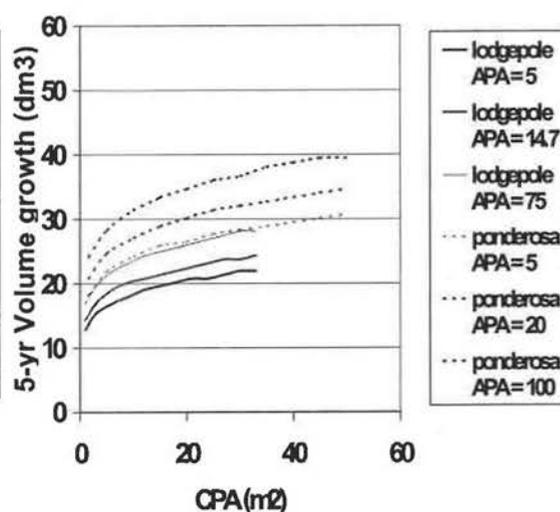


Figure 3. 12 Volume growth (per tree) at different levels of CPA and APA, from equation 3.3

first variable, all else being equal. This increase in growth and efficiency is greatest when CSAP is increased for a given level of APA and CPA, and is perhaps smallest when CPA is increased for a given level of CSAP. At a given level of CSAP, greater CPA might suggest a more dominant tree, but the limited growth increase may result from the forementioned costs associated with a longer crown or more branches that do not result in a substantially improved light environment for most of the foliage.

Because all the curves describing volume growth increase with increasing site occupancy index are concave downward, VGE based on each index is implied to be monotonic decreasing. However, correlations among the indices and other covariates in the models result in a different picture when the other covariates are set at their mean levels for segments of the index range (figs. 3.13 –3.15).

Because CSAP, APA and CPA are correlated with numerous other tree and stand variables, isolating the effect of each on GE required that predicted growth be corrected by the model covariates representing these other variables over the entire range of possible responses. Because the value of these covariates depends on the level of the occupancy index, growth (and GE) was predicted for different levels (subsets) within the observed range of the occupancy index, with the other covariates held at the mean value

of all sampled trees within the subset being analyzed. By doing this, growth and GE predictions are properly corrected for other model covariates—each of the following graphs predicted growth and GE for 10-20 different levels of each occupancy index. Furthermore, these corrections explain why the graphs don't exhibit smooth curves—rather than showing a predictive surface described by each equation, they reflect the variability within this dataset.

VGE_{csap} depends a great deal on CSAP and species (fig. 3.13). For ponderosa pine, VGE_{csap} shows an almost linear increase in trees with a CSAP < 200 cm^2 , the range covering about 80% of the sample trees. Above 300 cm^2 of CSAP, covering about 10%

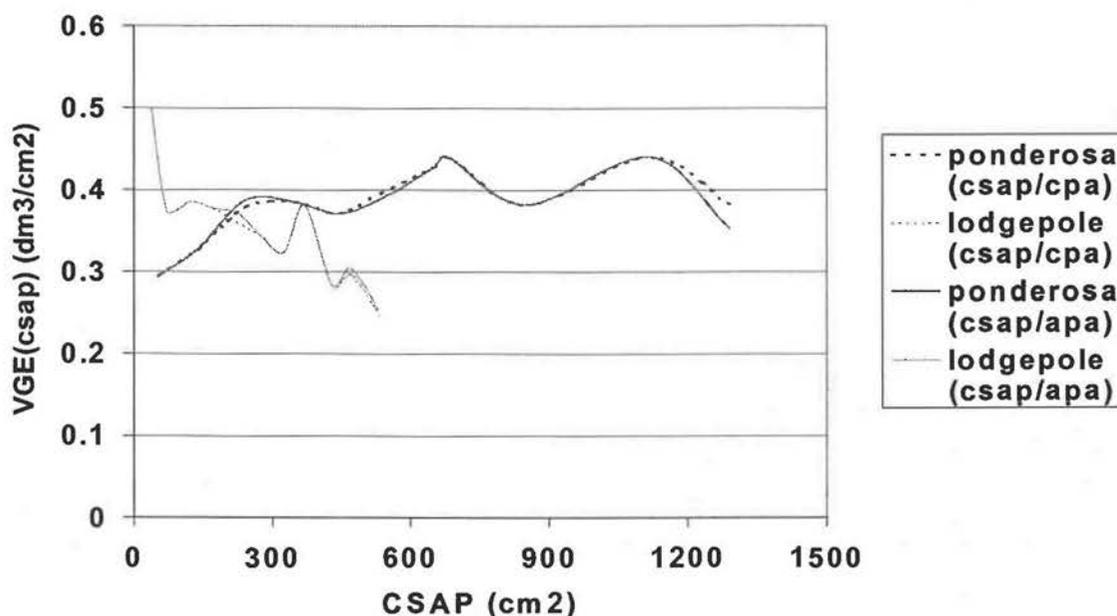


Figure 3. 13 VGE_{csap} for ponderosa pine and lodgepole pine—implied by models with either APA or CPA as additional occupancy variables.

of the sample trees, VGE varies, but appears to approximately plateau. Nevertheless, VGE_{csap} is highest in some of the largest trees, that is, those with the greatest leaf area. This result is ascribed to the better light environment associated with trees having larger leaf areas within multi-aged stands.

For lodgepole pine, VGE_{csap} drops as CSAP increases (fig 3.13). This result is consistent with the previous results in lodgepole pine documented by Roberts et al. (1993), and reflects the mostly even-aged structure of lodgepole pine patches on these

study plots. In addition, many of the lodgepole pines with very high CSAP were relatively open grown. Although the lower crown needles capture enough light to persist, the diminished hydraulic conductance of the lower branches, the high maintenance respiration costs associated with large crowns, and/or their relative depth in the entire stand canopy (Smith and Long 1989) explains their low efficiency.

Figure 3.13 also indicates that the relationship between VGE_{csap} and CSAP depends very little on whether APA or CPA is the second index of site occupancy. Part of this reflects the correlation between APA and CPA— particularly true in even-aged

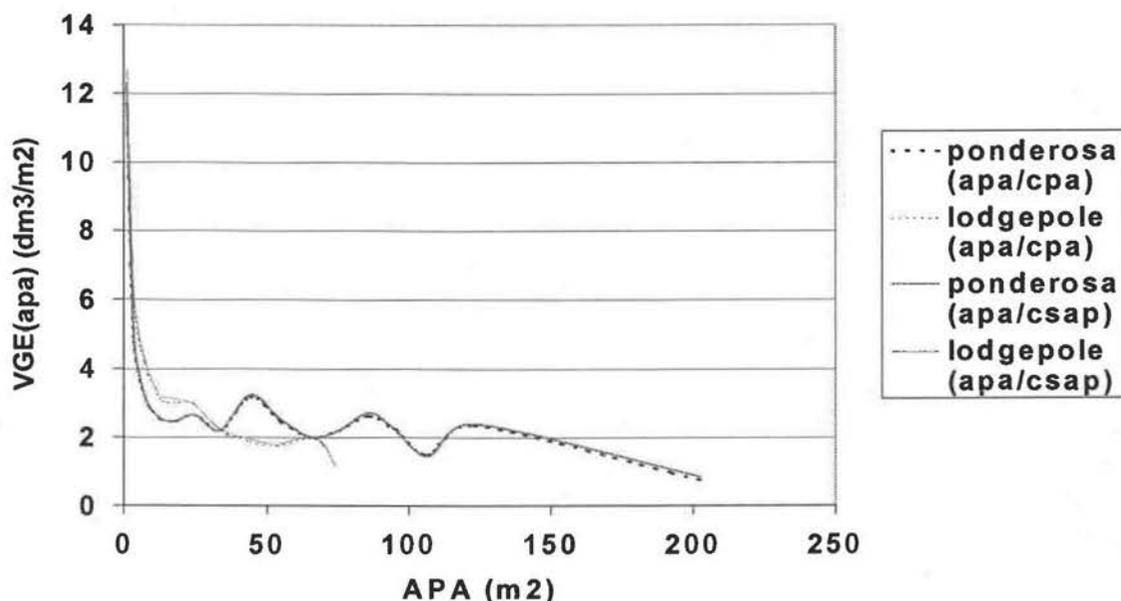


Figure 3. 14 VGE_{apa} for ponderosa pine and lodgepole pine—implied by models with either CPA or CSAP as additional occupancy variables.

stands where the limits of lateral crown growth are significantly influenced by the proximity of neighbors. However, the fact that neither lodgepole nor ponderosa pine show great differences in VGE_{csap} , regardless of which other occupancy variable is used is evidence that both models isolate the influence of CSAP alone (see figures 3.7 and 3.8).

The VGE_{apa} curves are similar for both species (fig. 3.14). The decline in VGE_{apa} with increasing APA occurs at a fast rate for $APA < 10-20 \text{ m}^2$. As APA continues to increase, the loss in VGE_{apa} continues more sharply for lodgepole than for ponderosa

pine. For ponderosa pine, although VGE_{apa} at $APA > 20 \text{ m}^2$ shows significant variability with APA class, further decreases remain minor for APAs $< 50 \text{ m}^2$. However, this stable VGE_{apa} with increasing APA would not be found for a given tree, all other characteristics being equal (see figs. 3.9, 3.10). Rather, it would continue to decrease if APA increased independently of the other covariates. The correlation between APA and tree size causes some increase in VGE_{apa} because larger, more efficiently growing trees are increasing the APA class average in some larger APA classes.

The relationship between VGE_{apa} and APA depends very little on whether CSAP or CPA is the other variable used to describe spatial occupancy, again indicating that both models isolate the effect of APA. When other covariates are set at their sample means, multi-collinearity in the data ensures that their values don't represent the actual covariate values for trees covering a range in occupancy values. This result underscores the need to isolate the effect of individual predictor variables for understanding the stand structural mechanisms controlling individual tree growth and growth efficiency.

When volume growth efficiency is calculated with crown projection area, general trends are similar to those for VGE_{csap} (fig 3.15). Ponderosa pine VGE_{cpa} generally

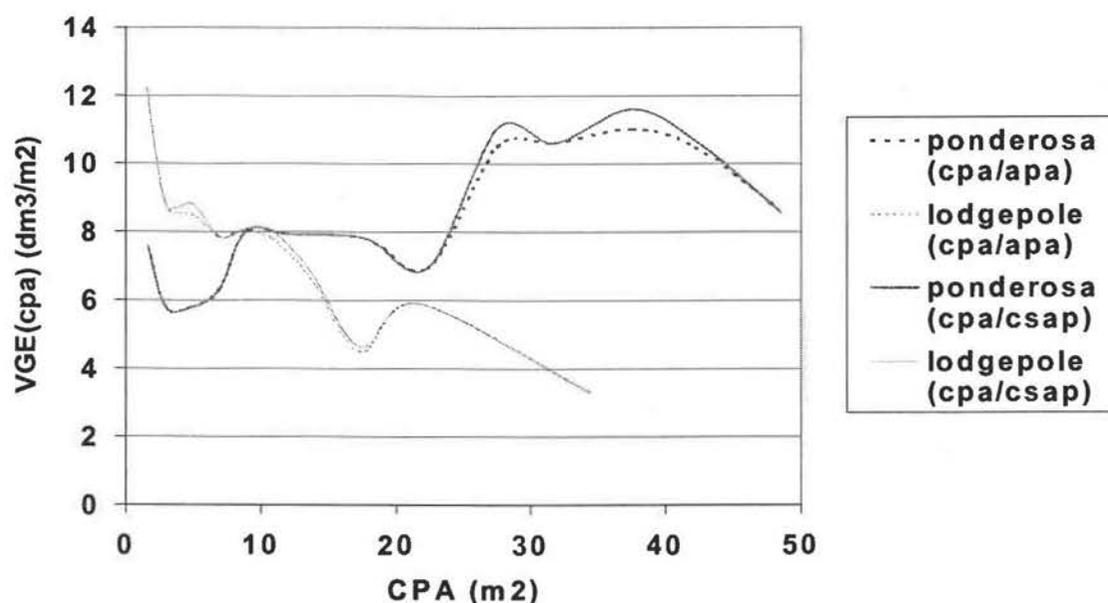


Figure 3. 15 VGE_{cpa} for ponderosa pine and lodgepole pine—implied by models with either APA or CSAP as additional occupancy variables.

increases with increasing CPA, and is maximized at high levels of CPA. The high CPA trees, just like the high CSAP trees, are large crowned individuals which, by virtue of the uneven-aged structure of these plots, dominate the stand. Though the large branches which give them high CPAs have been shown to have lower assimilation rates per needle area (Yoder et al. 1994), their superior competitive position for capturing light improves their VGE_{cpa} relative to those trees lower in the canopy. Within even-aged stands, the lowest levels of VGE_{cpa} have generally been found in the more suppressed trees (Kuuluvainen 1988, O'Hara 1988).

For lodgepole pine, there is a steady decrease in the VGE_{cpa} with increasing CPA. As is the case with CSAP, larger CPAs are associated with the larger crowned trees, which have already been shown to exhibit low VGE_{csap} . The reasons for their lower efficiency are probably similar—without an appreciably improved light environment, costs associated with larger CPA will cause VGE_{cpa} to decrease. The lower needle efficiency of the needles of the lower (and larger) branches of high CPA trees compensate for the greater ground area occupied. Similar to the results found in even-aged Norway spruce, the narrow crowned trees have the greatest levels of VGE_{cpa} (Kuuluvainen 1988). Although the forementioned open grown lodgepole pines might be expected to exhibit a greater CSAP:CPA ratio, thus having a greater VGE_{cpa} , these individuals did not appreciably raise the VGE_{cpa} of their class. Part of this may be a result of the type of trees that remain—many are of poor form, with forks or broken tops.

Although such trees of poor form are in the minority, it should be noted that these measurements were made on stands subjected to repeated entry. As a result, the trees within the dataset may not fully represent the growth potential on these sites. Though less true of relatively even-aged patches of the shorter-lived lodgepole pine, growth and growth efficiency of the mostly uneven-aged ponderosa pine may only be indicative of the lower end of the potential range, thereby suggesting that care be taken in applying these results.

Conclusions

The analysis of growth and growth efficiency under combined effects of different occupancy indices suggests that an analysis of growth efficiency based upon a single measure of occupancy may not fully or adequately describe the mechanisms controlling growth. The final models, with pairs of occupancy indices, proved to be statistically significant, indicating that the growth and implied GE of a tree having a particular occupancy will also depend upon the level of a second index. More specifically, it was shown that for a given level of any of the occupancy indices, both growth and GE based on that index increase as the second index increases.

The choice of variables for a model describing growth and GE is very important for understanding growth mechanisms controlled by stand structure. The predictive improvement of the mechanistic model over either a distance-independent model or a distance-dependent model (chapter 2) containing more standard growth and yield variables is substantial. By including a second occupancy index, it properly clarifies the factors controlling growth. However, correlations among occupancy indices and other covariates must be understood also to predict the effects of alternative stand structures on tree and stand growth.

The influence of size, species, and local environment on relative GE of different stand components is widely accepted. Clearly, the choice of site occupancy variables is equally important, with different measures leading to different results, answering different questions, and resulting in different conclusions.

Chapter Four: Simulated Growth Responses to Alternative Silvicultural Treatments and Residual Stand Structure in Heterogeneous Ponderosa Pine and Lodgepole Pine in Central Oregon

Introduction

Most silvicultural objectives include at least some provision for maintaining individual tree vigor, commonly measured by growth efficiency. Maintenance of tree vigor requires manipulating stand density to keep it below some maximum beyond which individual tree growth is not acceptable. At the same time, it is often desirable under various silvicultural objectives to maintain full site occupancy, typically defined by a minimum stand density. Under both even and uneven-aged management scenarios, specification of stand density is crucial, but there are a wider variety of options for specifying residual stand structure under uneven-aged management alternatives. Past approaches to regulation of uneven-aged stands have included BDq (Nyland 1996) and allocation of SDI (Cochran 1992), but many stands in reality consist of only 2-3 age classes; hence, it may not be practical or desirable to manage such stands in a strictly regulated uneven-aged manner. Regardless of the ultimate silvicultural goal, the implications of a given silvicultural treatment and resulting stand structure must be understood in terms of impacts on individual tree growth and vigor.

Copious natural regeneration, once controlled primarily by periodic ground fires, has reached high levels in central Oregon pine stands. Fire exclusion has created stands with very dense understories of lodgepole pine and ponderosa pine, which are expensive to eliminate. Hence, the spacing needed to maintain individual tree vigor comes at a cost. This cost has highlighted a major question about degree to which removal of small stems influences the vigor of residual overstory trees. Quantification of growth response to this type of silvicultural operation is therefore highly desirable.

The objective of this study was to estimate the growth dynamics resulting from various alternative residual structures in multi-cohort stands. The target population was a managed forest type in central Oregon that consists of one or more cohorts each of ponderosa pine and lodgepole pine. Control of stand density is crucial in this dry

environment, where marginal growing conditions and severe pest problems necessitate that high priority be attached to the maintenance of individual tree vigor.

Stand Structure and Growth

Size class distribution in a multi-age stand will have a large impact on how leaf area is distributed among trees in a stand. Leaf area, the source of photosynthetic production, is important both in its quantity and in its arrangement within and between trees. It is largely through this arrangement and consequent light interception that actual allocation of growing space among size classes determines future stand growth.

Recent research in uneven-aged stands has addressed the effect of structure on the growth and growth efficiency of trees (O'Hara 1996). Results have focused on identifying those stand and tree structural characteristics which influence growth efficiency defined as stem growth per unit leaf area. One study comparing two different species in even-aged stands, *Abies lasiocarpa* (subalpine fir) and *Pinus contorta* (lodgepole pine), found that they differed in the relation between efficiency and leaf area; furthermore, these differences were explained by canopy structure (Roberts et al. 1993). In the case of the vertically stratified and shade tolerant fir, efficiency increased to a maximum at moderate leaf areas, after which it decreased. This peaking behavior was attributed to the direct relationship between leaf area and relative height within the stand. Efficiency will increase as long as increased height improves the tree's canopy position, but above a certain point, increased leaf area is associated less with improved light conditions and more with offsetting costs that lead to a decline in growth efficiency. In contrast, lodgepole pine efficiency decreased across the full range in increasing leaf area, because an increased leaf area did not correlate with relative height in these relatively even canopies; hence, there was no improvement in light environment associated with increasing leaf area.

Previous studies looking at multi-age stands ponderosa pine stands have found that leaf area index (LAI) per cohort decreases with decreasing age of cohort (O'Hara 1996). These differences in leaf area, related to stand structure, translate into large differences in the distribution of growth among cohorts. While this study found that the

oldest cohorts, containing the most leaf area, were growing most efficiently (as defined by leaf area), this may be highly dependent on the characteristics of an individual tree.

For *Picea rubens* (red spruce) in uneven-aged stands, growth efficiency declined with increasing leaf area when efficiency calculations were based on a volume growth model with leaf area as the only independent variable (Maguire et al. 1998). This trend persisted when variables for relative tree height and degree of past suppression, were included.

In a study in even-aged Douglas-fir, the most efficient trees prior to thinning were tall trees with large sized crowns. Following thinning, the most efficient trees were tall with medium sized crowns (O'Hara 1988). Significantly, the large crowns prior to thinning were similar in size to the medium crowns following thinning. This, coupled with the size dependency of efficiency found among subalpine fir, suggests that although large ponderosa pines may be most efficient as an entire cohort, individual trees may not display this efficiency once their crown becomes too large. The long branches of large ponderosa pine crowns are believed to display diminished hydraulic conductance, resulting in diminished diurnal photosynthesis relative to needles from short branches (Yoder et al. 1994).

Structural influences on growth are not limited to the influence of dominant trees on lower trees. In low LAI pine stands, where light extinction within the crown is limited, there can be a large number of shrubs and understory trees. Their presence is particularly important in water limited environments, where their ability to hinder the growth of their larger neighbors has been documented. (Barrett, 1963, Barrett 1970, Oren et. al. 1987, Riegel et. al. 1992, Hanson 1997). This fact has brought suggestions that for uneven-aged ponderosa pine stands, strict submission to a traditional "reverse-j" diameter distribution is likely to retard stand growth by allocating too much growing space and soil resources to small size classes whose numbers are unnecessarily high for crop tree replacement (Cochran 1992).

Uneven-aged management of central Oregon pine involves periodic stand entries, employed for the sake of both volume extraction and stocking control. Numerous silvicultural treatments and systems have been used in central Oregon pine, each leaving different stand structures, thereby favoring different stand components and differentially

influencing the subsequent growth and growth efficiency of the stand and its constituent trees.

Application of these different silvicultural regimes may address both short and long term objectives, but have very different implications for stand structure and the schedule of economic return.

Selection harvest (overstory reduction)

Selection systems, specifically formulated for ponderosa pine, have been aimed at removing mature and valuable trees, while at the same time providing growing space for smaller cohorts, and lowering a stand's susceptibility to bark beetles (Brandstrom 1937). Such systems were particularly applicable within stands of old growth pine and following the introduction of tractor skidding and truck hauling.

Different types of selection systems have been advocated, including the maturity selection system (Munger 1941) and the improvement selection system (Pearson 1942). Both advocate light cutting at regularly spaced intervals. Though primary consideration is placed upon the removal of valuable, overmature trees unlikely to survive until future entries, advocates of both methods deny that either method constitutes high grading. In harvesting the large and old trees, growing space was to be allocated to those trees best able to respond with enhanced growth rates.

The improvement selection system also prioritizes the removal of large trees whose value is negative with regard to growth potential and its detrimental effect on the growth of younger cohorts. Because this practice is not followed in the mature selection system, the improvement selection, at some cost, better addresses the condition of the future stand.

Reverse-J

The residual size class distribution in a managed uneven-aged stand has been commonly described by the BDq approach to regulating stand structure. In this approach, the diameter distribution is characterized as a reverse J-shaped curve, defined by a residual basal area, a maximum diameter class, and a q-factor. The q-factor, (generally between 1 and 2 in an operational setting) is the ratio of trees per unit area in

one diameter class to the trees per unit area in the next larger diameter class (Smith 1997). The reverse J-shaped curve described by the q -value thus describes the relative numbers of trees in each diameter class.

Even with relatively small q -values, the smallest diameter class in a stand has a large number of trees—made up of eventual replacements for the larger diameter classes. This approach has been criticized in water limiting environments such as central Oregon. Cochran (1992) believed this approach delegated too many trees to smaller diameter classes. High numbers, though made up of small trees, constitute a large drain on site resources, and through it, competition on the larger diameter classes. Likewise, the intense inter-tree competition among small trees produces trees that enter into the minimum merchantable classes with poorer vigor than necessary. Rather than strict submission to a J-shaped curve, a better approach might be to have only as many trees as necessary to replace those in the next larger diameter classes.

Understory reduction

In an understory reduction, removals are concentrated among the smallest diameter classes. In an uneven-aged stand with removals concentrated among younger cohorts, this type of thinning results in a narrower range of age classes and the residual stand more closely resembles an even-aged stand in stature. This type of harvest may only be appropriate where a two-storied stand or an even-aged system is desirable. In meeting a particular residual density, concentration of removals among the smallest diameter classes means that more stems are removed, with the result being a stand with fewer, larger, and often more regularly spaced stems. Regular spacing within the stand can be expected to minimize crown asymmetry, improve stem form, and eliminate clumped patterns previously implicated as centers of endemic bark beetle activity (Olsen et al. 1996).

Among the disadvantages of thinning the understory cohort is the limited or negative economic return from an entry. Removal of small pulp-sized pieces or unmerchantable material is costly, and must be paid for either with the removal of a few valuable trees, or with the anticipated return from the improved growth of the residual stand. From the standpoint of volume production, this latter expectation is the primary

advantage of thinning the understory cohort. In concentrating growth upon larger trees whose dominance is established, production can be concentrated upon those stems which are more immediately utilizable.

Objectives

Calculation of stand growth responses to different silvicultural treatments, and distinguishing responses between diameter classes will help understand the responses to stand structural differences created by the silvicultural intervention. Growth and growth efficiency information, when coupled with the operational constraints of timber production in central Oregon, can facilitate design of silvicultural treatments and systems to meet specific silvicultural objectives.

The specific objectives of this analysis are:

- 1) To compare estimated basal area growth, volume growth, and growth efficiency of residual stands subjected to differing simulated silvicultural treatments.
- 2) To compare these same growth parameters among different components of the residual stand.
- 3) To draw some general conclusions about the growth potential of alternate residual structures.

Silvicultural treatments were simulated by removing various stand components from large study plots, and expected growth responses were estimated from growth equations developed from data collected on plots of widely varying stand structure.

Methods

Study Sites

Data were collected in the summer of 1998. Nine square, 0.4-ha plots were established within Crown Pacific's central Oregon tree farm, centered approximately at Gilchrist, Oregon (43°28' N, 121°42' W). These nine plots, split evenly between two sites, are in the *Pinus ponderosa/Purshia tridentata* plant association (Franklin and Dyrness 1973).

The two sites represented two different stand types. The first, termed the Timbers site, consisted primarily of multi-aged ponderosa pine (Pipo) (87% of basal area was

pipo). The second site, called Blackrock, also contained primarily ponderosa pine (55% of basal area was Pipo), but a significant component of lodgepole pine (Pico) also was present. Much of the lodgepole pine occurred in single, patchy cohorts. Nevertheless, the presence of many large, old ponderosa pine stumps testified to previous stand conditions and previous disturbance types. Evidence of more recent disturbance included numerous skid trails, often free of regeneration, which in many places partitioned the plots into small patches of trees. The understory of both sites was dominated by bitterbrush (*Purshia tridentata*).

This portion of central Oregon, like much of the interior west, is characterized by cold winters, warm and dry summers, and limited precipitation falling mostly as snow during the winter months. The dry summers are further characterized by periodic drought. Over the last 30 years, the mean January minimum was -8°C and the mean July maximum was 27°C . Total annual precipitation during this time averaged 54 cm, with approximately 70% of this falling as snow (<http://www.ocs.orst.edu/>).

These sites, chosen from among many candidates, were subjectively selected for their fitness in meeting the objectives of the model. The target population for construction of the model consisted of multi-age ponderosa/lodgepole pine stands. Square, 0.4 hectare plots were subjectively sampled to meet the following requirements:

- Variability in density, vertical stratification, diameter class distribution, and small regeneration attributable to logging or mortality rather than microsite differences.
- No large treeless areas or large areas of high stem densities prohibitive to mapping.
- No management activity for the past five to ten years.
- Common aspect and no obvious differences in soil type, plant association, or landform.

In order to look at how different types of residual structures would affect growth and growth efficiency of the residual stand, removal of a portion of the trees was simulated on each of three plots: Blackrock high-2 (BH2), Timbers high-1 (TH1), and Timbers high-2 (TH2). The choice of these three were based on stand density and spatial arrangement. Site occupancy on some of the plots was at a level for which silvicultural

treatment was deemed unnecessary (BL1, BL2, TL1, TM). In addition, previous entries on some heavily-stocked plots had left them somewhat regularly spaced (BM, BH1).

	BH2	TH1	TH2
Control	206.40	145.55	137.85
Reverse-J	136.30	96.64	97.10
Overstory reduc.	151.84	106.01	103.70
Understory reduc.	126.82	88.88	89.40

Table 4.1 Post-treatment SDI

Total basal areas on the three high density plots were reduced to a residual basal area arrived at by stand density index guidelines (Cochran 1994). Values were 11.6 m²/ha (50 ft²/ac) for the two Timbers plots and 16.3 m²/ha (70 ft²/ac) for the

Blackrock plot (post-treatment SDIs are shown in figure 4.1). Although these residual basal areas are low, choice of these levels was based on the uneven stem distribution within the stand, and the belief that the percentage reduction in these levels would enable clumps of high density to be thinned to an appropriate degree. From a plot map, trees were selected for removal so as to meet the residual density or diameter distributions under one of four silvicultural treatments described below. Trees were chosen based first on diameter and second on producing a regular residual spacing.

Silvicultural Treatments

Control

For this treatment, no stems were removed. The diameter distributions for the three plots were quite variable (Figs. 4.47, 4.51, 4.55).

Reverse J target structure

This selection treatment sought to apply a classic uneven-aged (J-shaped) diameter distribution upon the plots. Due to the starting plot distributions, the final diameter distribution could not conform strictly a negative exponential distribution that the B-D-q approach would produce. The theoretical distributions were originally produced with a q-factor of 1.3, but current distributions being what they were, strict

conformity to this was not possible (Figs. 4.48, 4.52, 4.56). Removal of trees was based on both the need to meet this J-distribution and spacing.

Overstory reduction

This method was chosen as a simple way to simulate a selection cut by diameter limit. For this treatment, the largest trees were removed until the target basal area was reached. In reaching this residual density, absolute dbh was not the ultimate criterion—smaller trees within an equivalent diameter class to a larger tree might be removed based on improved residual spacing, or to concentrate removals among poorer trees. Final diameter distributions were heavy to small trees (Figs. 4.49, 4.53, 4.57).

Understory reduction

This treatment was chosen to simulate stand improvement or thinning from below in the understory cohort, designed without thought to its commercial potential. In general, the smallest trees were removed until the residual basal area was reached. Like the overstory reduction, absolute dbh was not the ultimate criteria. Trees from the smallest diameter classes were removed with spacing in mind (Figs. 4.50, 4.54, 4.58).

Growth and growth efficiency

Basal area growth and growth efficiency for the first 5 years after treatment were predicted with basal area growth models (equation 4.1) based on residual stand structure (Chapter 2).

Equation 4. 1

$$\text{Ln}(\text{BAG}) = \beta_0 + \beta_1 \text{Ln}(\text{D}) + \beta_2(\text{CR}) + \beta_3 \text{Ln}(\text{APA}) + \beta_4(\text{BAL}) + \beta_5(\text{H45}) + \beta_6(\text{ST}) + \beta_7(\text{T}) + \epsilon$$

where:

BAG is basal area growth

D is diameter at breast height

CR is crown ratio

APA is constrained, diameter weighted polygons, corresponding to the area of occupancy of each tree.

BAL is basal area in trees whose diameter is greater than the subject tree.

H(Θ) is point relative height (with Θ = angle), was calculated by determining the height of the subject tree as a fraction of neighboring trees. Neighboring trees were defined as

those trees whose height penetrated an inverted cone produced by a 360° sweep made with a fixed angle Θ from the tip of the subject tree.

ST is total basal area of small trees whose current diameter is less than 10 cm, and within crown width based zones surrounding subject trees.

T is an indicator variable for site

Table 4. 2 Parameter estimates for ponderosa pine, lodgepole pine

Variable	Ponderosa pine		Lodgepole pine	
	Parameter estimate	Standard error	Parameter estimate	Standard error
β_0	1.099418	0.19447585	1.734346	0.24199558
β_1	0.485935	0.05212912	0.274063	0.07601025
β_2	1.762887	0.13539446	1.663325	0.10755936
β_3	0.171185	0.01468925	0.183244	0.02141236
β_4	- 0.133276	0.01141408	- 0.093950	0.01547749
β_5	0.208438	0.05317825	0.156119	0.07567528
β_6	- 0.421100	0.25166008	- 1.539712	0.31544625
β_7	- 0.290214	0.03038249	- 0.118937	0.04986244

Volume growth was calculated using Cochran's (1985) volume equations. In applying these volume equations, five-year height growth was assumed to be independent of stand density, and equal to that observed for the 1994-1998 growth period. Growth efficiency for each tree was then calculated by dividing the calculated growth by each of three alternative spatial occupancy indices—CSAP (crown base sapwood area as a surrogate for leaf area); CPA (crown projection area); and APA (area potentially available).

Analysis

In reporting and discussing these results, consideration was given to the application of the growth model to "treated" plots. The model was constructed based on plots which had not been entered for at least 10 years. The corresponding measurements thus would be indicative of trees already occupying available growing space, or, as in the case of low density, or previously spaced plots, still filling that growing space made available following the last entry.

The crown and root characteristics of the post-treatment trees reflect the structure of the manipulated stand. Given these physical characteristics, response to the newly available growing space would be expected to accelerate after some period of crown and

root expansion, and perhaps thinning shock. In other words, while some initial release of resources causes a direct increase in growth, a subsequent build-up of crown and roots from increased growing space causes a further indirect increase in growth.

The model-based response estimates made here are more reflective of the indirect effect—that is, those following a re-occupation of available growing space. Those trees best able to occupy newly available space are those most quickly able to respond (i.e. those which already have a large measure of site occupancy). A tree's CSAP, in representing leaf area, may best represent this occupancy in that it indicates both a tree's ability to intercept light, as well as the mass of fine and course roots available to support it. Within the model, this ability may be best represented by a combination of the BAL variable, ranking trees by their relative size, and the $H(\Theta)$ variable, representing each tree's new light interception ability. To some extent, the inclusion of spaced or lower density plots in estimating model parameters (chapter two) builds this response into the model predictions of post-treatment growth.

Changes in the occupancy indices, upon which growth efficiency values are based, will generally increase with treatment—those treatments which best space the plots could be expected to have the largest index increases. CSAP and CPA would be likely to change most as the crowns widen and build leaf area in response to stand density reduction. APA would change relatively little since it is largely a function of stem location, and only secondarily a function of the subject tree's size relative to neighbors. The net result of changes in occupancy indices is that immediate post-treatment GE_{apa} values will probably be overestimated—especially where large increases in an index results.

Because both CSAP and CPA were measured at the end of the five-year growth period, and could not be backdated, they are assumed not to have changed. This assumption is more appropriate for trees where growing space is fully occupied, and less so where it isn't. Trees which experience substantial growth would presumably have the largest changes in CSAP or CPA, and therefore have the most questionable GE values. However, because model estimates were based on stands that have not recently been thinned, and because the growth of trees responding fastest may thus be underestimated,

this, with an underestimated occupancy index may together give a more accurate value of GE.

The responses also don't assume any increased site occupation of understory vegetation. Although a five year growth reponse may not be enough time for brush response to negatively affect the growth rates of mature trees, many understory species can quickly occupy open growing space to the detriment of conifers. This potential concern should increase with the number of entries—brush, often colonizing available growing space more quickly than trees, provides intense competition to developing trees (Hansen 1997).

Results

Ponderosa pine

Growth

The graphs of ponderosa pine growth for plot BH2 indicates that both volume and basal area growth increase with increasing diameter class for each treatment (figs 4.1 and 4.2).

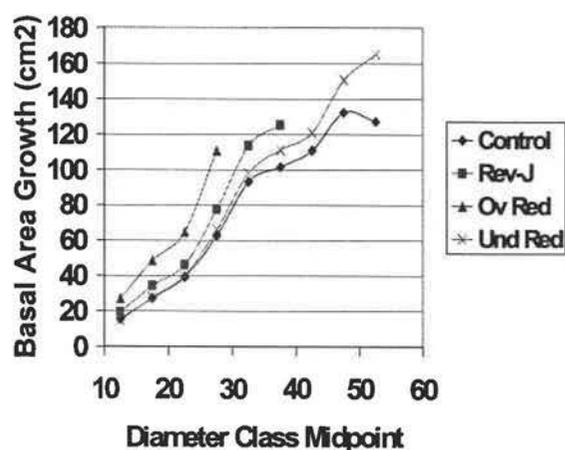


Figure 4.1 Ponderosa pine, mean estimated 5-yr basal area growth per dbh class, plot BH2

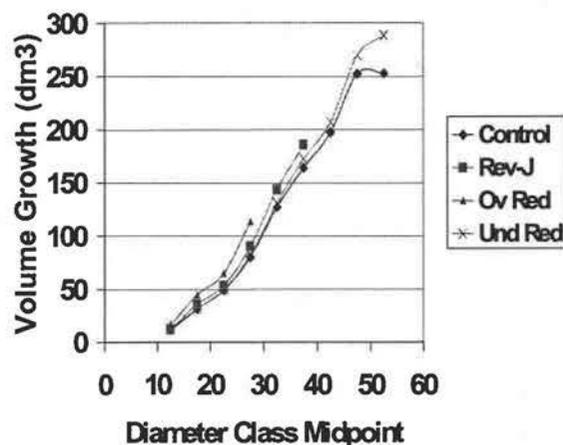


Figure 4.2 Ponderosa pine, mean estimated 5-yr volume growth per dbh class, plot BH2

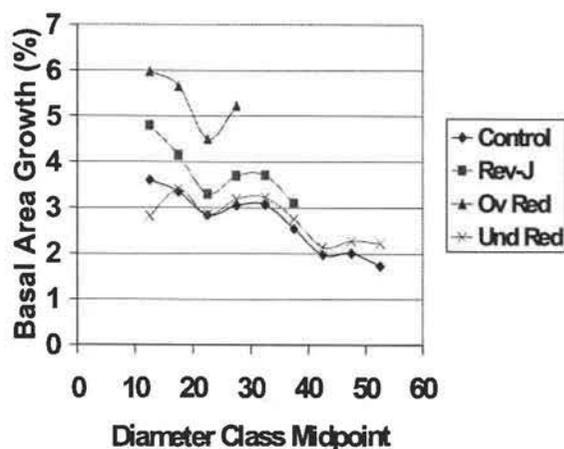


Figure 4.3 Ponderosa pine, mean estimated annual % basal area growth per dbh class, plot BH2

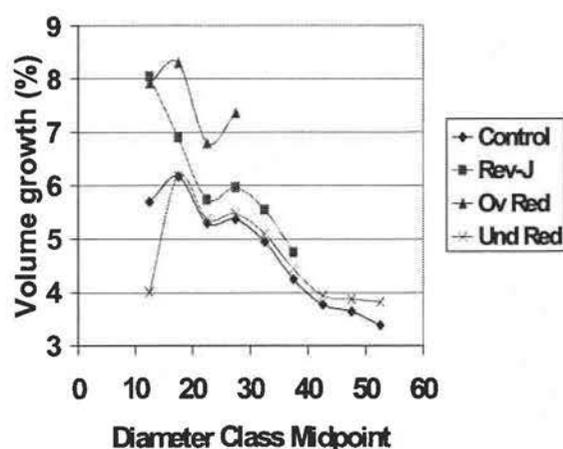


Figure 4.4 Ponderosa pine, mean estimated annual % volume growth per dbh class, plot BH2

Although the average growth per tree follows similar trends for each treatment, the overstory reduction and the reverse-J treatments are associated with the greatest individual tree growth for a given dbh class. According to the graph, the growth differences between the trees of the understory reduction and the control are minor except for the largest size classes.

The plots of volume and basal area growth by percent (figs. 4.3 and 4.4) indicates that the growth increase amounts to 2-2.5% and 0.5-1.0% annually for overstory reduction and reverse-J treatment trees 15-40 cm dbh, respectively, in the 15-40 cm dbh classes. The high variability in growth percent of the lowest diameter classes results from a few poor residuals (in the case of the understory reduction) and the effect of overstory removal and spacing (in the case of the reverse-J treatment).

The major difference between volume and basal area growth is that basal area growth tends to flatten off with trees of the largest diameter classes. However, the greater heights of these trees, and apparently continued height growth means that these trees continue to put on significant volume growth. The largest trees are still growing 20% in volume over five years without treatment. The understory reduction provides only a slight improvement over the control.

As with plot BH2, both volume and basal area growth on plot TH1 (figs. 4.5 and 4.6) generally increase with increasing diameter. Likewise, growth increases following treatment, and is maximized with the overstory reduction and reverse-J treatments. Whereas the difference between growth of the understory reduction and control treatments increased for increasing diameters on plot BH2, this difference was not predicted on plot TH1; for the largest size class (45-50 cm dbh), volume growth per tree is approximately similar for these two treatments.

For diameter classes of 30 cm dbh and below, the graph of percent volume growth (fig. 4.8) indicates both the overstory reduction and the reverse-J treatments had a 1.0-2.0% greater annual volume growth than the control. This difference diminishes with increasing diameter. The percentage volume growth of the largest diameter classes is approximately 3% over five years, about 1% lower than that on plot BH2. The result is at least partly attributable to the indicator variable included in the basal area growth model to adjust slower growth on the Timbers site. The lower volume and basal area

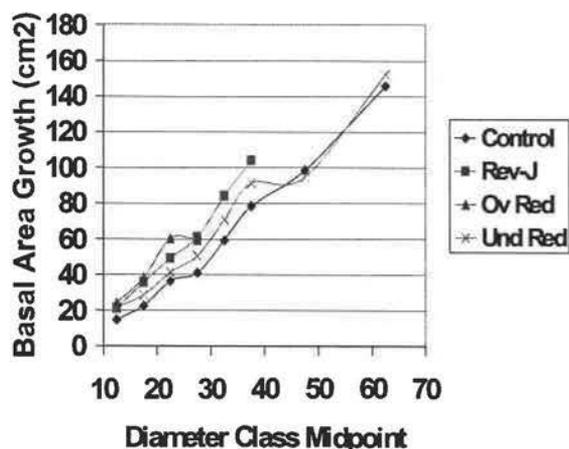


Figure 4. 5 Ponderosa pine 5-yr basal area growth, plot TH1

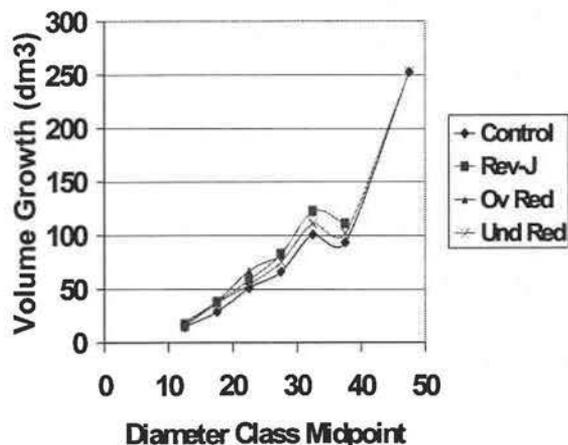


Figure 4.6 Ponderosa pine 5-yr volume growth, plot TH1

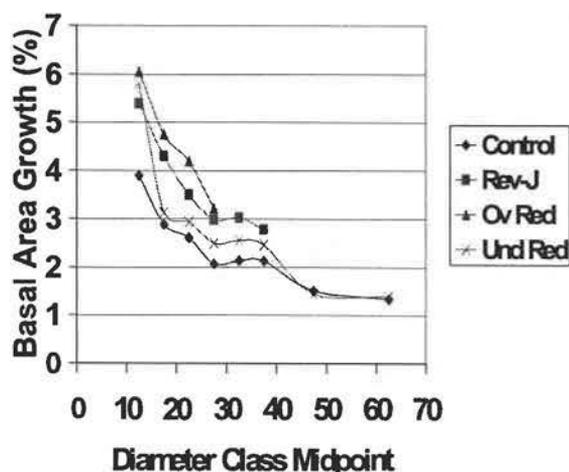


Figure 4. 7 Ponderosa pine, annual % basal area growth, plot TH1

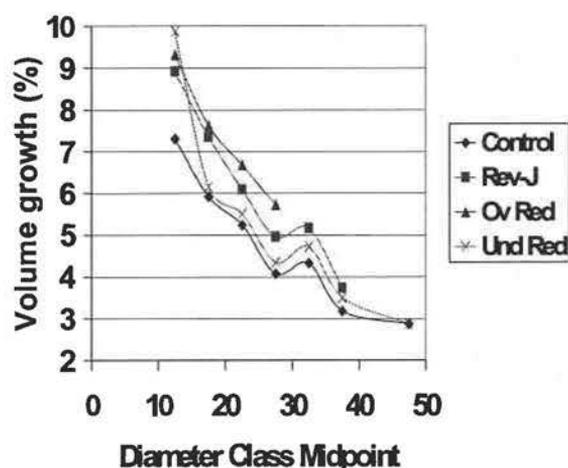


Figure 4. 8 Ponderosa pine, % annual volume growth, plot TH1

growth percentage of all diameter classes of plot TH1 (versus BH2) suggests that the smaller basal area retention on the timbers plots is important for maintenance of both growth and vigor.

Volume and basal area growth for plot TH2 (figs. 4.9 and 4.10) show similar patterns to the previous study plots. Absolute growth per tree increases steadily with increasing diameter class. Growth is maximized with the overstory reduction and the reverse-J treatments, though the treatment effect is much less pronounced on this plot than for either of BR2 or TH1.

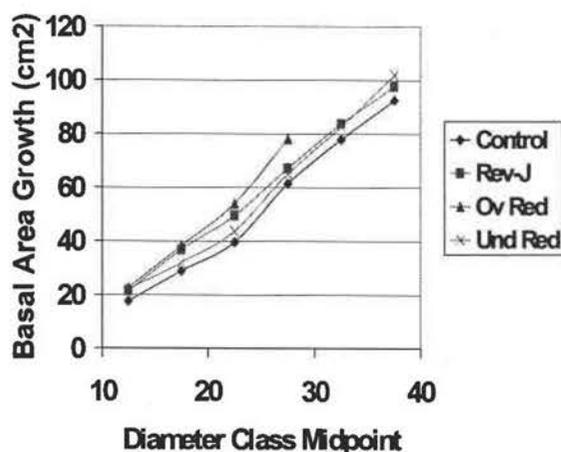


Figure 4.9 Ponderosa pine, 5-yr basal area growth, plot TH2

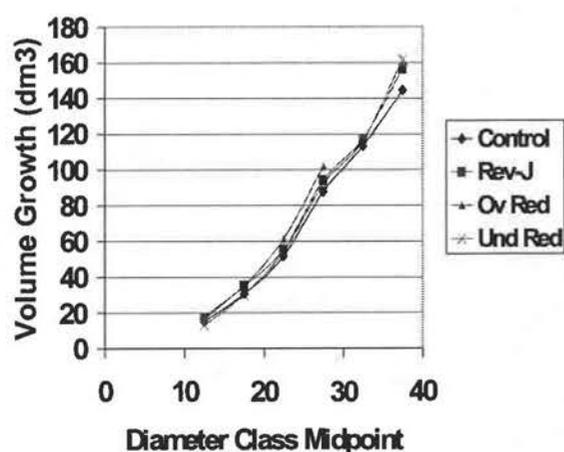


Figure 4.10 Ponderosa pine, 5-yr volume growth, plot TH2

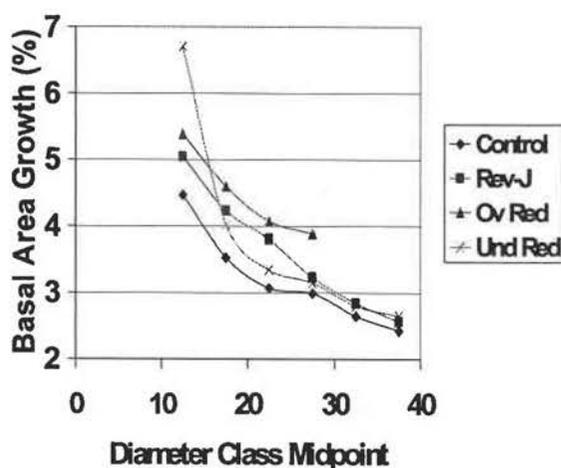


Figure 4.11 Ponderosa pine, annual % basal area growth, plot TH2

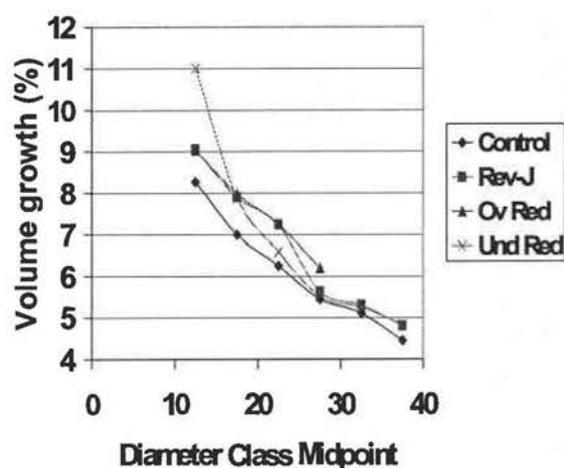


Figure 4.12 Ponderosa pine, annual % volume growth, plot TH2

One noticeable aspect of this plot is the high percentage growth of the small diameter classes of the understory reduction (figs 4.11 and 4.12). Similarly found on plot TH1, this pattern is the result of thinning and its associated release effect. Due to the desire for maintaining a well-spaced stand, the few small trees remaining following treatment were likely to have been well spaced to begin with, and thus had full crowns and good growth.

The percentage volume growth rates of the stems on this site are more similar to that found on BH2 than TH1. However, plot TH2 does not have any stems greater than 40 cm dbh, which on the other two sites grew most slowly on a percentage basis.

Growth Efficiency

The three types of growth efficiency detailed here are defined by area potentially available, crown-base sapwood cross-sectional area, and crown projection area. In making these comparisons, it is important to re-emphasize that crown-base sapwood area and crown projection area are assumed not to have changed between the beginning and end of the growth period.

Graphs of VGE_{apa} for ponderosa pine (figs. 4.13, 4.14, and 4.15) indicate that efficiencies vary greatly by plot. The most consistent similarity is that the trees of the control plot have the maximum growth efficiency. Because the expansion of space around trees has a quickly diminishing positive effect with increasing space, APA efficiency may be expected to drop with the removal of stems.

For ponderosa pine, the overstory reduction could generally be expected to have the smallest negative effect on efficiency, because basal area removal is concentrated on a small number of trees. Plot BH2 is an exception to this, however, because ponderosa

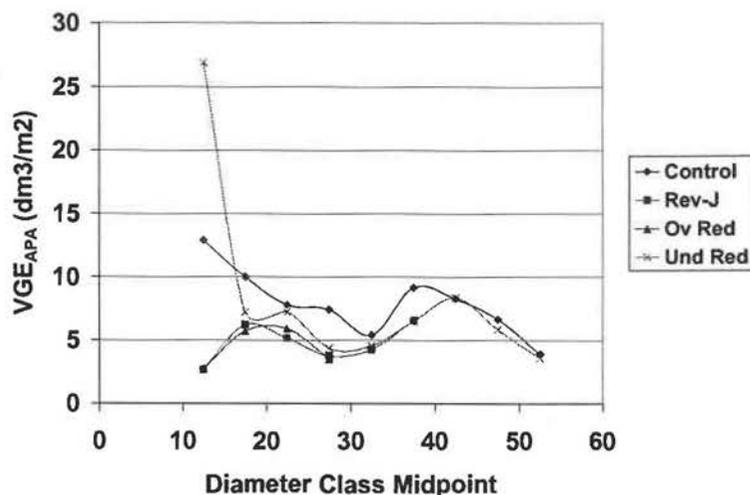


Figure 4.13 Ponderosa pine, estimated mean VGE_{APA} by dbh class, plot BH2

and lodgepole tend to grow in single species patches. Because the largest (and removed) trees are primarily ponderosa pine, their neighboring trees have a significantly increased space. While this will have a positive effect on growth of neighboring trees, efficiency will generally go down as a result of the positive growth effect not

making up for the gain in space.

True for the other plots also, the diameter classes where efficiency drops are those whose member trees are bordering large removals. On plots BH2 and TH2, (figs 4.13 and 4.15) these neighboring trees are primarily from small diameter classes.

The highly influential effect of a few trees can be seen in figure 4.14. Following each treatment, 10 trees remained in the 25-30 cm diameter class. With treatment,

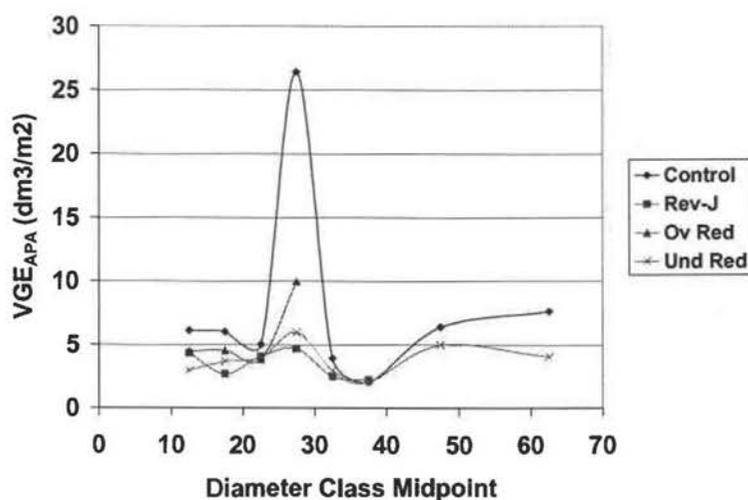


Figure 4.14 Ponderosa pine, estimated mean VGE_{APA} by dbh class, plot TH1

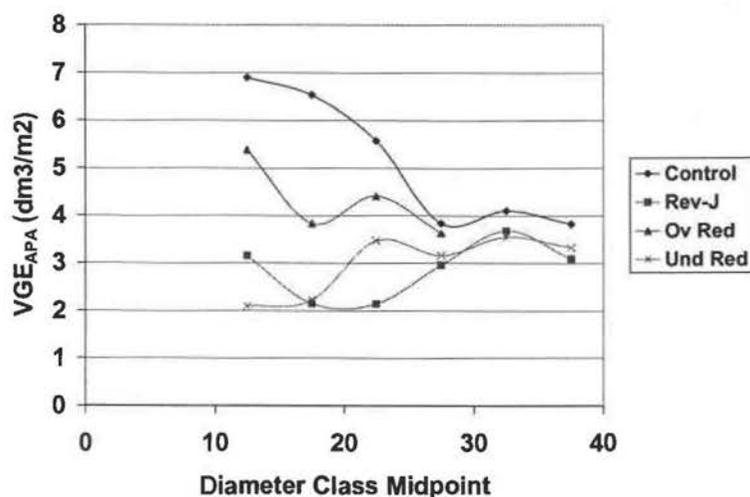


Figure 4.15 Ponderosa pine, estimated mean VGE_{APA} by dbh class, plot TH2

varying numbers of these trees' neighbors were removed, having a great effect on the combined growth efficiency of the class.

The least efficient of the treatments is usually either the understory reduction or the reverse-J treatment. Not incidentally, these treatments had the most stems removed and thus, are also the best spaced. Although individual tree growth increases, the residual trees cannot make as efficient use of the growing space in the short term until they reoccupy the vacated growing space.

Defining efficiency on the basis of crown base sapwood, an assumed surrogate for leaf area, has the forementioned disadvantage of not strictly representing the initial leaf area, but rather a final leaf area. If leaf area builds and CPA expands in response to the silvicultural treatments, then GE_{cpa} and GE_{csap} are underestimated for the growth period as a whole. APA will change only to the extent that relative size of adjacent trees changes. However, because the program which calculates

APA uses both current and estimated future diameter in the calculation, GE_{apa} is probably most reliable. One valuable conclusion to be drawn from these graphs is the trend in

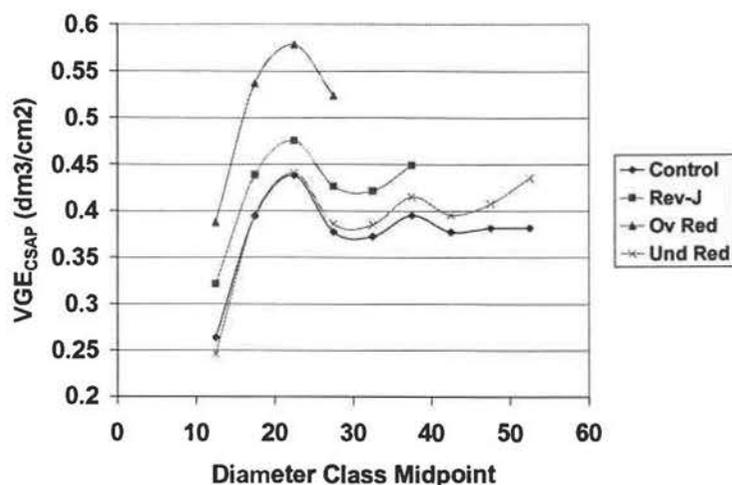


Figure 4.16 Ponderosa pine, estimated mean VGE_{CSAP} by dbh class, plot BH2

efficiency across diameter classes. For plot BH2 (fig. 4.16) and plot TH1 (fig. 4.17), efficiency is greatest for trees with diameter between approximately 20 and 30 cm. Efficiency for larger trees is approximately constant on plot BH2, but drops above 30 cm on plot

TH1.

In contrast to this pattern, VGE_{CSAP} on plot TH2 (fig 4.18) exhibits a more steady increase, reaching an approximate maximum at diameters of 20-30 cm and then leveling off. Many of the large trees on this plot were part of a tightly-spaced single cohort clump, and had crowns

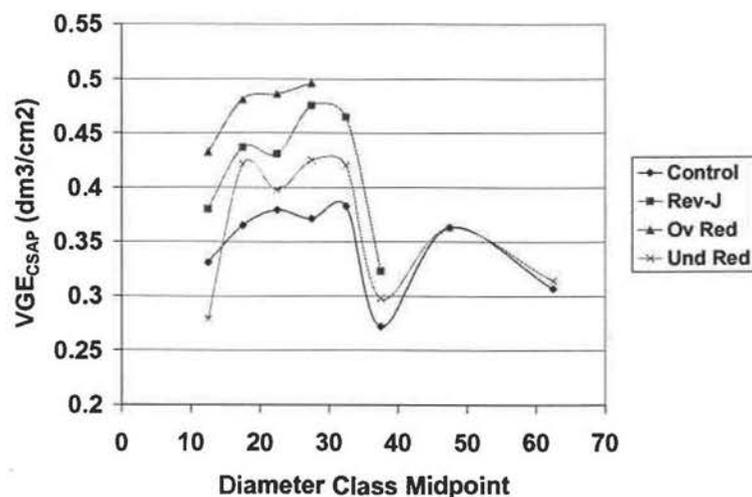


Figure 4.17 Ponderosa pine, estimated mean VGE_{CSAP} by dbh class, plot TH1

suggestive of this type of structure. The 35-40 cm trees on plot TH2 have crowns with 27% more leaf area than 30-35 cm dbh trees, yet 5% smaller crown widths and smaller crown ratios. In contrast, on plot TH1, the 35-40 cm trees have 15% more leaf area, 2% larger crown width and longer crown ratios than the

30-35 cm trees. These dimensional differences may explain some of the differences in efficiency. Longer branches have exhibited shorter diurnal photosynthesis as a result of

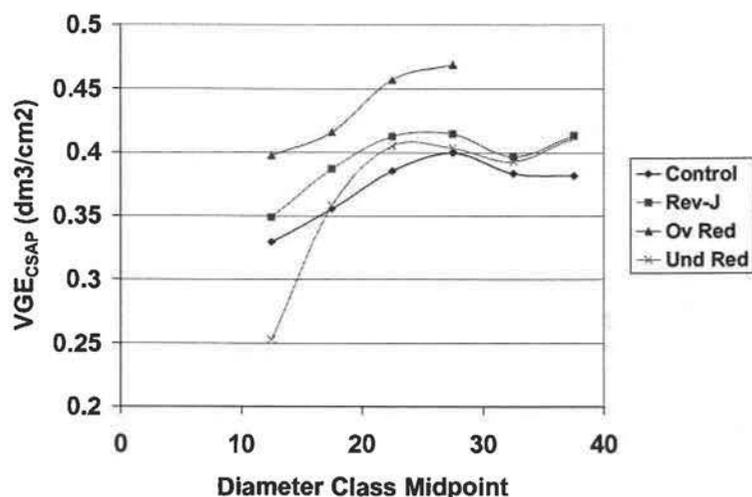


Figure 4.18 Ponderosa pine, estimated mean VGE_{CSAP} by dbh class, plot TH2

unknown change in CPA over time, as with VGE_{csap} . Thus, the relative efficiency of each treatment is similar to the results of each plot's volume growth.

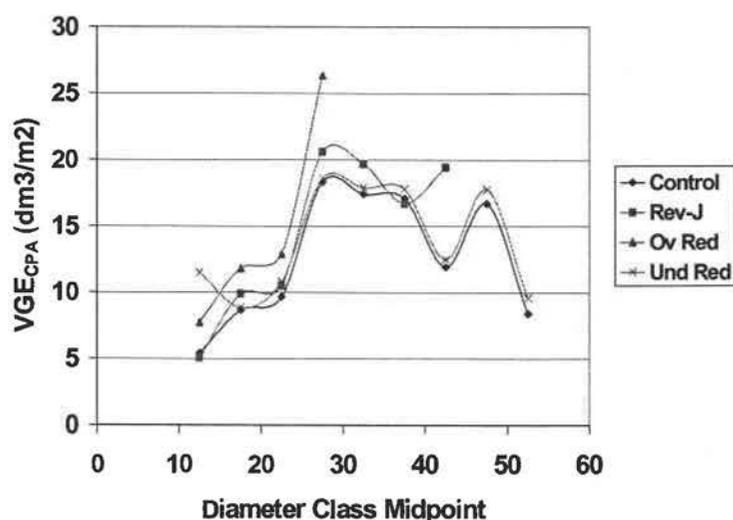


Figure 4. 19 Ponderosa pine, estimated mean VGE_{CPA} by dbh class, plot BH2

of 25-40 cm dbh, followed by a general decline. The efficiency of smaller diameter classes gradually increases until reaching this plateau. The lower efficiency of the smaller trees may result from light restricted environments. Though small trees may survive and continue lateral growth in a relatively shaded environment, their inability to tap above

water deficits (Yoder et al. 1994). In addition, the 35-40 cm dbh trees on plot TH2, being the largest of the trees on the plot, benefit from the enhanced light environment of the upper canopy.

When VGE is defined by crown projection area, efficiency projections are limited by the

Graphs of VGE_{cpa} for the three study plots (figs. 4.19, 4.20, and 4.21) indicate that with some variation, efficiency increases with diameter up to approximately 30 cm dbh, but beyond 30 cm, large plot to plot variation makes any general pattern indiscernible. For plot BH2, there is an approximate peak or plateau of equal efficiency for trees

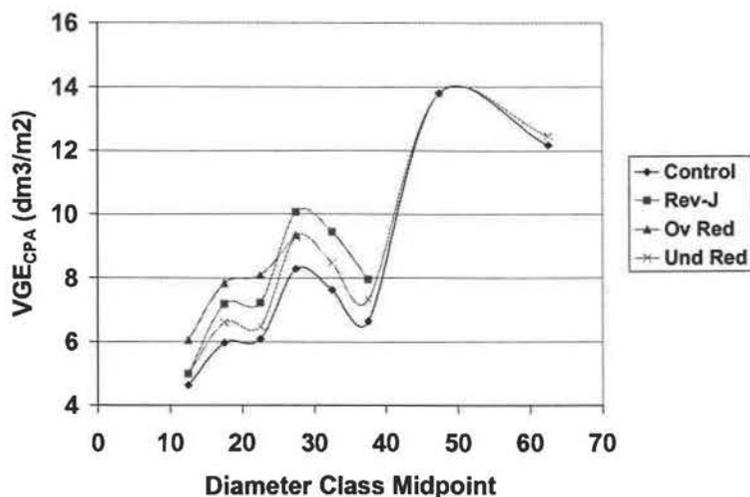


Figure 4.20 Ponderosa pine, estimated mean VGE_{CPA} by dbh class, plot TH1

and belowground resources necessary for maintaining leaf area, and thus growth, would be limited. The increase of VGE_{cpa} with size among small size classes is apparent for plots TH1 and TH2 as well. In contrast to plot BH2, neither of these plots reaches an efficiency plateau, with a general increase on plot TH1 and great variation on plot TH2. Both Timbers plots have similar VGE_{cpa} maximum efficiencies, but are both lower than on Blackrock plot.

The physical crown dissimilarities of trees within the two largest diameter classes of plot TH2 helps explain the difference in efficiency. The largest diameter class had greater leaf area, but narrower crowns than did the next largest class. This would support

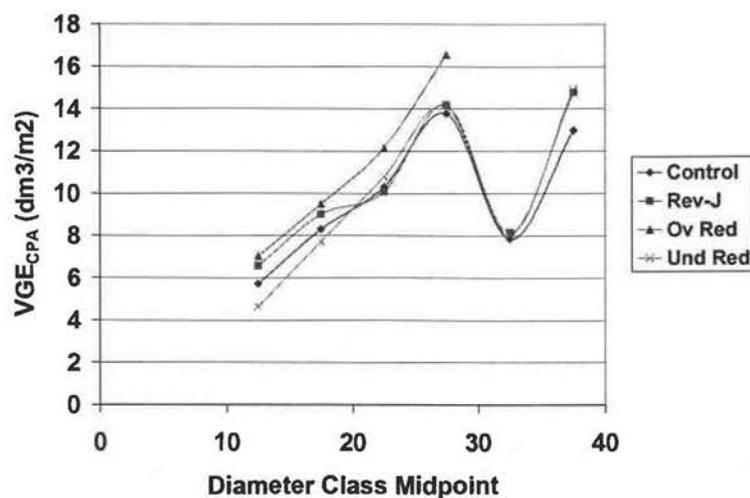


Figure 4.21 Ponderosa pine, estimated mean VGE_{CPA} by dbh class, plot TH2

the idea that the most CPA efficient trees have long, yet narrow crowns. This idea is demonstrated graphically by substituting CSAP/CPA for VGE_{cpa} (figure 4.22). The shape of the graph indicates that crown shape (approximated by csap/cpa) is a highly correlated surrogate for VGE_{cpa} . Likewise, it

demonstrates the strong association between CSAP and volume growth.

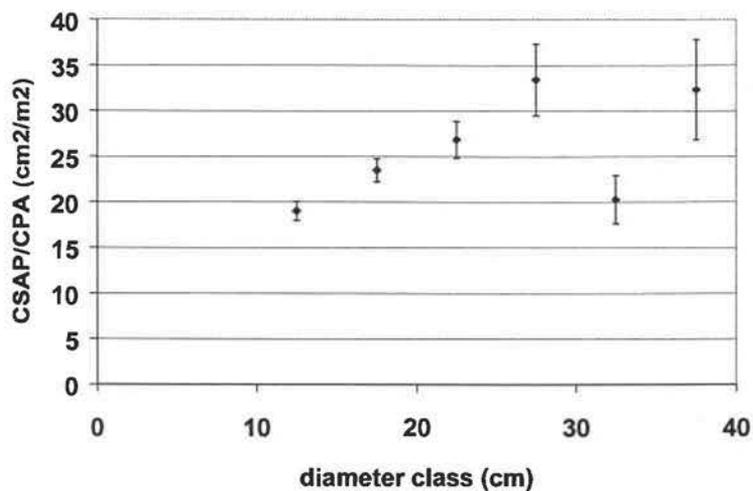


Figure 4.22 Ponderosa pine CSAP/CPA by diameter class, plot TH2

of their crown size and position in the canopy, remain efficient by this other measure.

In contrast, this ratio does not correlate directly with VGE_{csap} . Figure 4.18 indicates that VGE_{csap} of the 30-35 cm dbh class remains high though its CSAP/CPA ratio is comparable to the trees of the smallest diameter

class. This would suggest that the crowns of the 30-35 cm dbh class, by virtue

Lodgepole pine

Growth

The volume growth of lodgepole pine is somewhat similar to that of ponderosa pine in that, in general, volume growth increases with increasing diameter class. Plot

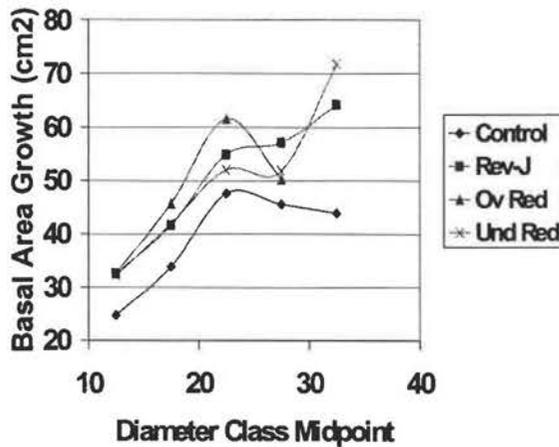


Figure 4.23 Lodgepole pine, 5-yr basal area growth, plot BH2

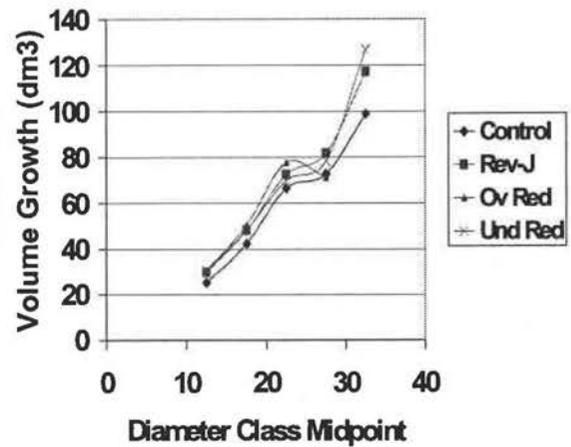


Figure 4.24 Lodgepole pine, annual % volume growth, plot BH2

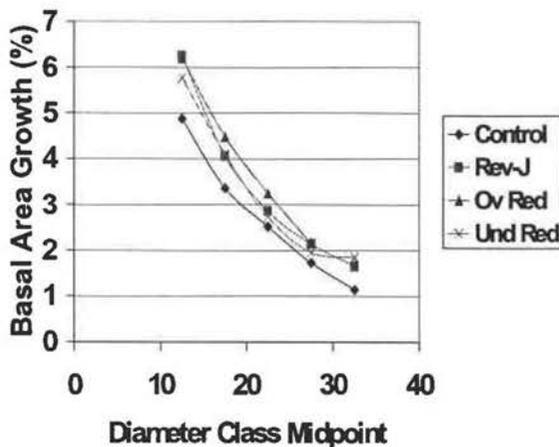


Figure 4.25 Lodgepole pine, 5-yr basal area growth, plot BH2

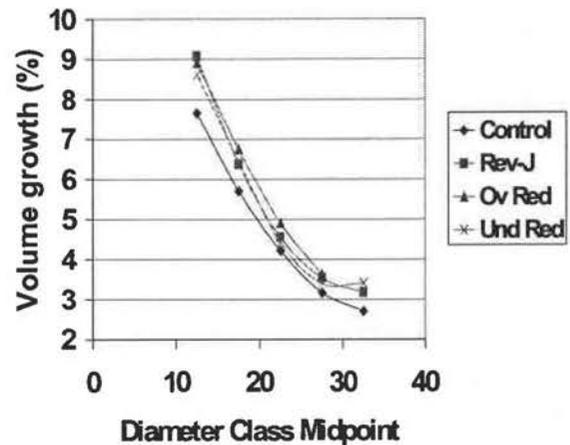


Figure 4.26 Lodgepole pine, annual % volume growth, plot BH2

BH2 volume growth (fig. 4.24) follows this trend. While the response of trees to the three treatments is in approximately the same order as was true for ponderosa pine, growth following the understory reduction is more positive than was previously seen in

ponderosa pine. The majority of lodgepole was in even-aged patches. The diameters within these cohorts were such that they were heavily thinned in the understory treatments, thereby increasing the APA, decreasing the number of competing small stems adjacent to numerous trees, thereby giving them a significant growth dividend. The basal area growth of lodgepole pines above 25 cm varies by treatment. Few trees existed within these classes, and the basal area growth results reflect the growth of individual residuals. The graphs of percentage volume growth (fig. 4.26) indicate that for trees greater than 20 cm dbh, the annual differences in growth between treatments is less than 0.5%.

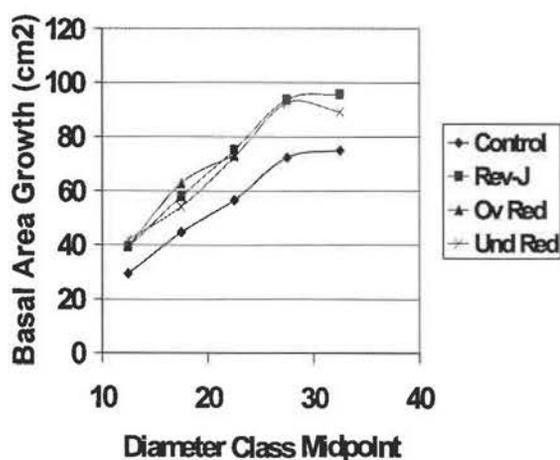


Figure 4.27 Lodgepole pine, 5-yr basal area growth, plot TH1

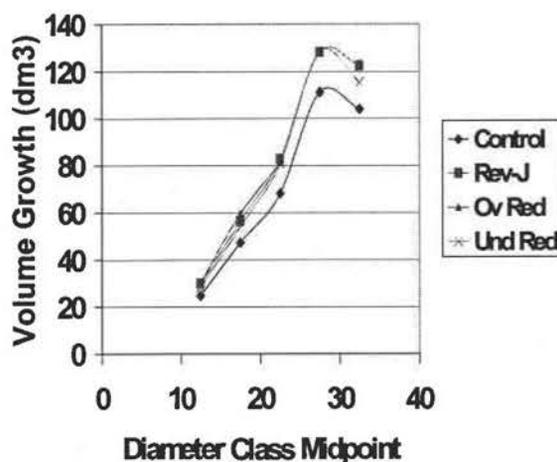


Figure 4.28 Lodgepole pine, 5-yr volume growth, plot TH1

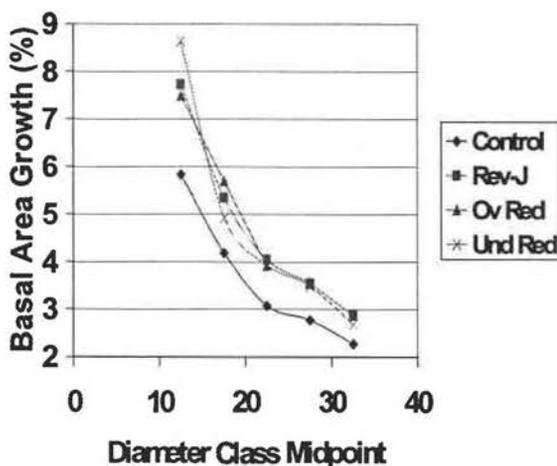


Figure 4.29 Lodgepole pine, annual % basal area growth, plot TH1

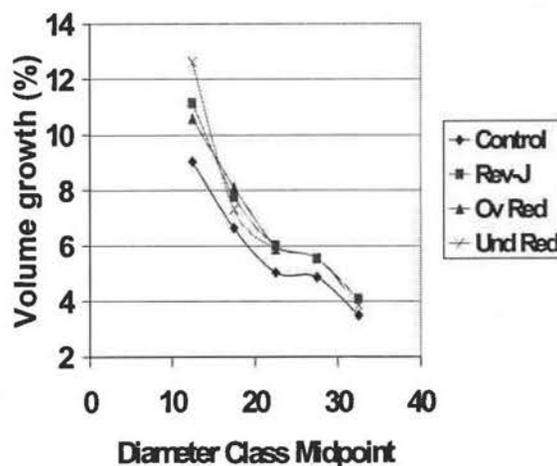


Figure 4.30 Lodgepole pine, annual % volume growth, plot TH1

The relative responses of the different treatments is less pronounced for plot TH1. While volume growth (fig. 4.28) increases with increasing diameter class, this is not true for the largest diameter class. Once again, the three treatments give approximately equal growth responses. Basal area growth (fig. 4.27) exhibits the same relative response.

The positive effect of the understory reduction for lodgepole on this plot is apparent despite the fact that structure of lodgepole on this plot is different than on plot BH2. On this plot, lodgepole is not in even-aged patches, but is more scattered. The growth equations (equation 4.1) used for this study indicate that the negative effect of small trees is greater for lodgepole, and that of BAL is smaller. It might be expected, therefore, that a understory reduction would be more advantageous for lodgepole pine. Lodgepole apparently experiences more competition from below than does ponderosa.

Growth Efficiency

The parameter value of the growth model's APA variable means that, all else being equal, an increase in APA will necessarily decrease APA efficiency. Therefore, those diameter classes showing large decreases in efficiency with treatment indicate

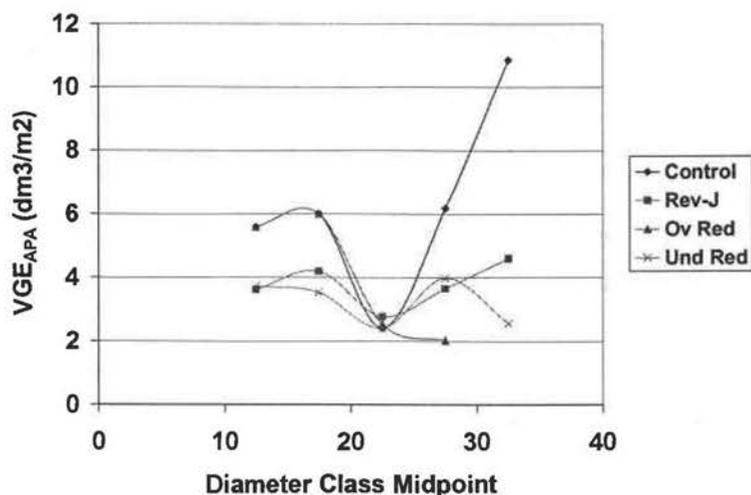


Figure 4.31 Lodgepole pine, estimated mean VGE_{APA} , by dbh class, plot BH2

classes whose trees have significantly more space. Figure 4.31 indicates that the understory reduction and reverse-J treatments have the lowest efficiency, consistent with their greater spacing, and greater growth. The graph also indicates that the stems which have benefitted from this spacing occur in every class but 20-25 cm class.

The lack of VGE_{apa} change for this size class suggests that spacing was not changed much for this size class. The great drop in efficiency for the largest size class resulted from a large drop in APA for a single tree.

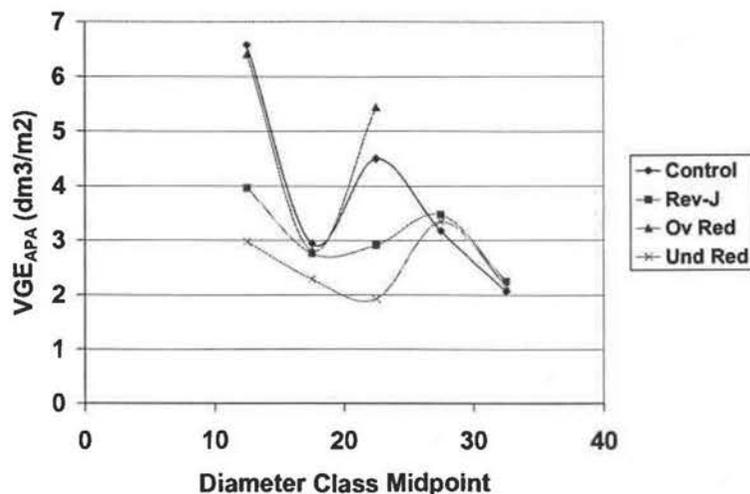


Figure 4.32 Lodgepole pine, estimated mean VGE_{APA} by dbh class, plot TH1

suggestive of their high pre-treatment density. The more equitable spacing among dbh classes in the reverse-J and understory reduction treatments creates a more even efficiency across diameter classes.

When efficiency is defined by leaf area, plots BH2 (fig. 4.33) and TH1 (fig. 4.34)

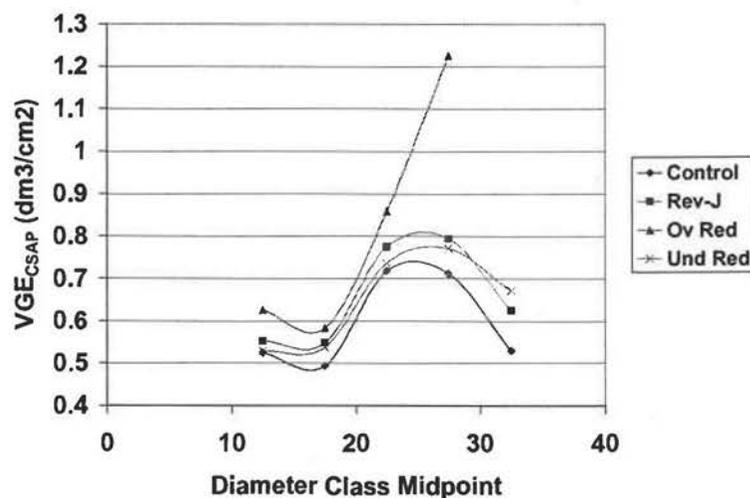


Figure 4.33 Lodgepole pine, estimated mean VGE_{CSAP} by dbh class, plot BH2

For plot TH1, as with plot BH2, the spacing provided by the reverse-J and understory reduction treatments is associated with a commensurate loss in efficiency (fig. 4.32). The re-spacing was imposed primarily on the 10-15 cm and 20-25 cm dbh classes, whose high VGE_{apa} in the control is

exhibit different efficiency patterns. In both cases, diameter classes exhibiting high VGE_{csap} are the result of one or two individuals of very high efficiency.

The trees in the 20-30 cm dbh class in plot BH2 with the highest VGE_{csap} have small crown ratios (approx. 25%) and have small amounts of leaf

area (about 25% of the class average). While trees of this description in an even-aged plot are more likely to be suppressed, these trees have

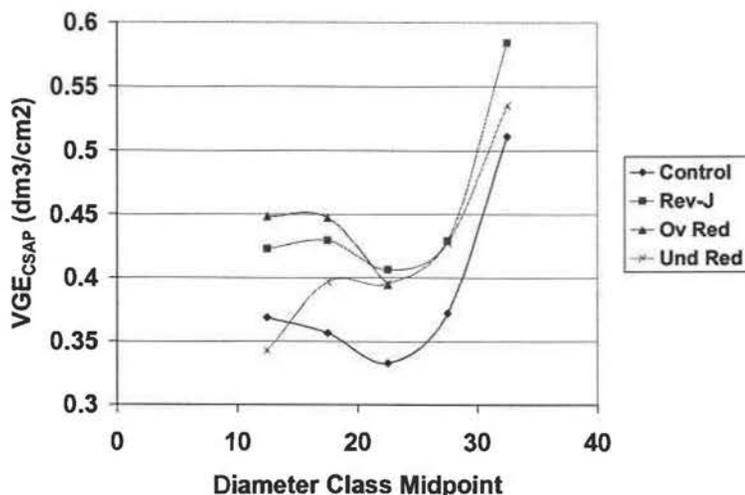


Figure 4.34 Lodgepole pine, estimated mean VGE_{CSAP} by dbh class, plot TH1

the two classes), CSAP volume efficiency would be 0.58 and 0.46 dm^3/cm^2 for the 25-30 cm and 20-25 cm dbh classes, respectively.

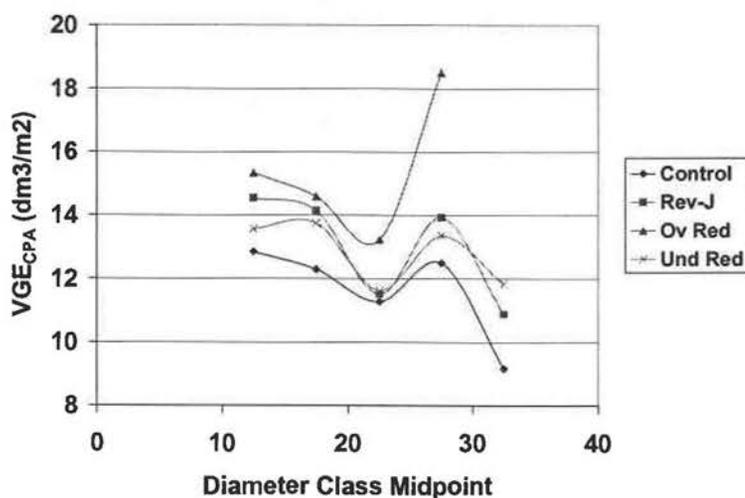


Figure 4.35 Lodgepole pine, estimated mean VGE_{CPA} , by dbh class, plot BH2

dm^3/cm^2 .

When volume growth efficiency is defined by CPA, those lodgepole pine which are growing in high density even-aged patches (plot BH2, 10-20 cm dbh) are highly

suppressed, these trees have been released following removal of larger neighbors. As a result, these small crowned trees are tall, and have good light exposure. In addition, these trees are not crowded, thereby enabling greater access to belowground resources. Without three individuals (of 15 total in

The high VGE_{CSAP} of the largest diameter class of plot TH1 (fig. 4.34) is also the result of one of three individuals in the class. The largest individual has less than 20% of the leaf area of the other two, and more than 4 times the efficiency. Without this individual, the class efficiency would be approximately 0.25

efficient (fig. 4.35). Whereas Douglas-fir trees will exhibit when growing in even-aged structures (O'Hara 1988), the lower shade tolerance of lodgepole pine means that shorter, suppressed lodgepoles are less likely to survive, resulting in a more uniform canopy depth, and less stratification. The higher efficiency of the 25-30 cm dbh class compared to the 20-25 cm dbh class is a result of their greater crowding; that is, they have smaller

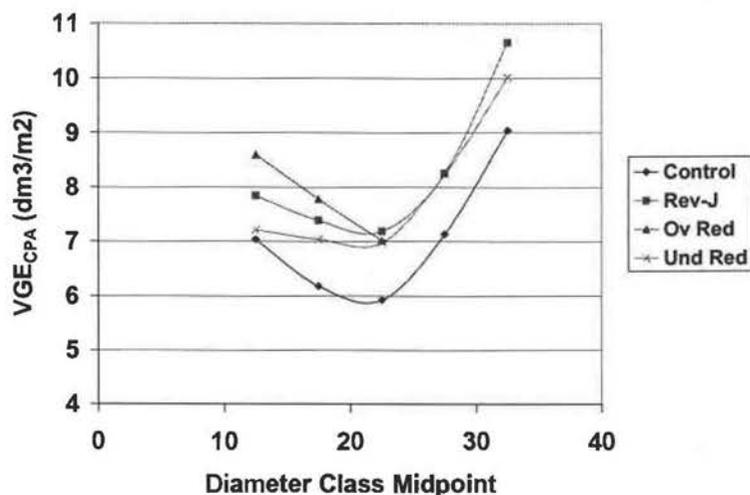


Figure 4.36 Lodgepole pine, estimated mean VGE_{CPA} , by dbh class, plot TH1

trees on this plot are those of the largest diameter class, made up of three trees. The two most efficient members of this class have long (85%) crown ratios, and relatively narrow crown widths.

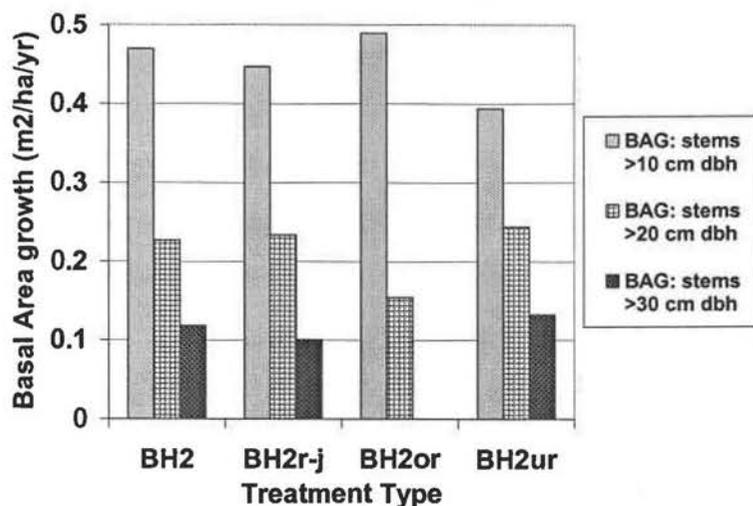


Figure 4.37 Estimated stand basal area growth by treatment and diameter, plot BH2

and narrower crowns, a characteristic previously found to be present in high efficiency trees.

The smallest classes of plot TH1 (fig. 4.36), growing within multi-cohort patches, do not exhibit the high CPA efficiency of the even-aged small classes from plot BH2. The most efficient

Stand growth

Previous allusion to the unavoidable trade-off between individual tree and stand growth resulting from a thinning necessitates a more quantitative description of the stand effects resulting from the treatments applied for this study. Plots of 5-yr growth

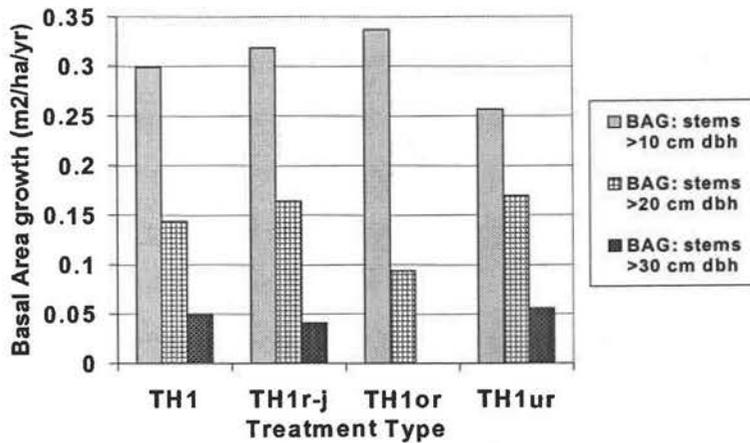


Figure 4. 38 Estimated stand basal area growth by treatment and diameter, plot TH1

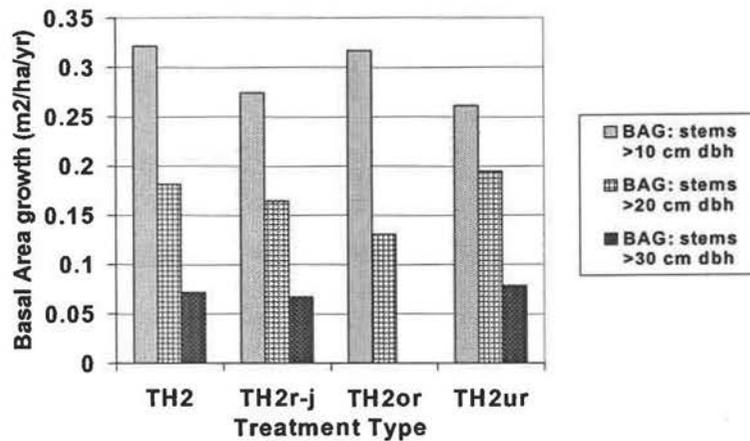


Figure 4. 39 Estimated stand basal area growth by treatment and diameter, plot TH2

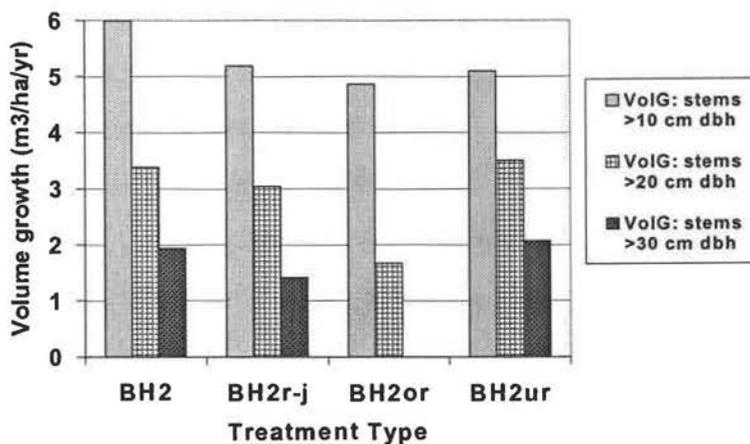


Figure 4. 40 Estimated stand volume growth by treatment and diameter, plot BH2

for each of the one acre plots are delineated by diameter, specifying growth among all stems, stems of dbh greater than 20 cm, and stems of dbh greater than 30 cm. Patterns of 5-yr basal area growth (figs 4.37, 4.38 and 4.39) are relatively consistent across study plots. On each plot, total basal area growth for all trees is maximized with an overstory reduction, with a reverse-J treatment offering the second highest growth. In each case, total basal area growth is least for the understory reduction.

When trees of larger merchantable size are considered, growth is maximized by an understory reduction followed by the reverse-J treatment. Without exception, the least growth within these larger merchantable classes, control included, is

exhibited by the overstory reduction. The small amount of growth for trees of dbh >20 cm and no growth for trees of dbh >30 cm with an overstory reduction results from the

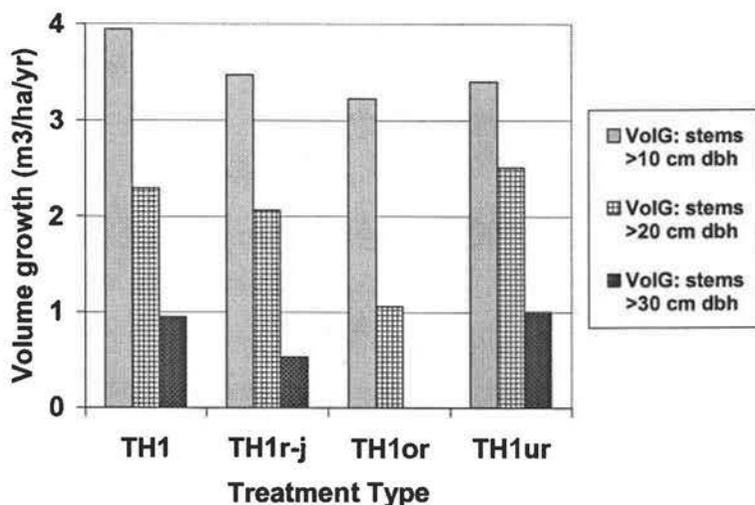


Figure 4. 41 Estimated stand volume growth by treatment and diameter, plot TH1

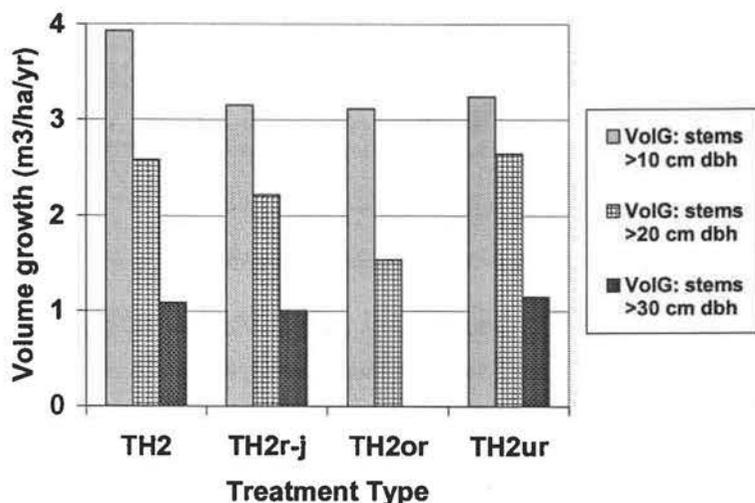


Figure 4.42 Estimated stand volume growth by treatment and diameter, plot TH2

removal of much of these larger size classes. For total stand volume growth (figs. 4.40, 4.41, 4.42), each plot exhibits a similar volume growth response. The control plot, for which site occupancy is greatest, has greater volume growth than any of the treated plots. The total stand volume growth of the overstory reduction treatment is lowest, even though the overstory reduction had the fewest number of stems removed. More pronounced is the minimal volume growth among the larger size classes following this treatment. Like basal area growth, the low volume growth in the large trees of the overstory reduction is a result of low stocking of large trees. Of the other two treatments, total stand volume growth was similar. Nevertheless, the larger size classes exhibited greater volume growth following an understory reduction—the result of few or no removals of these larger, merchantable classes.

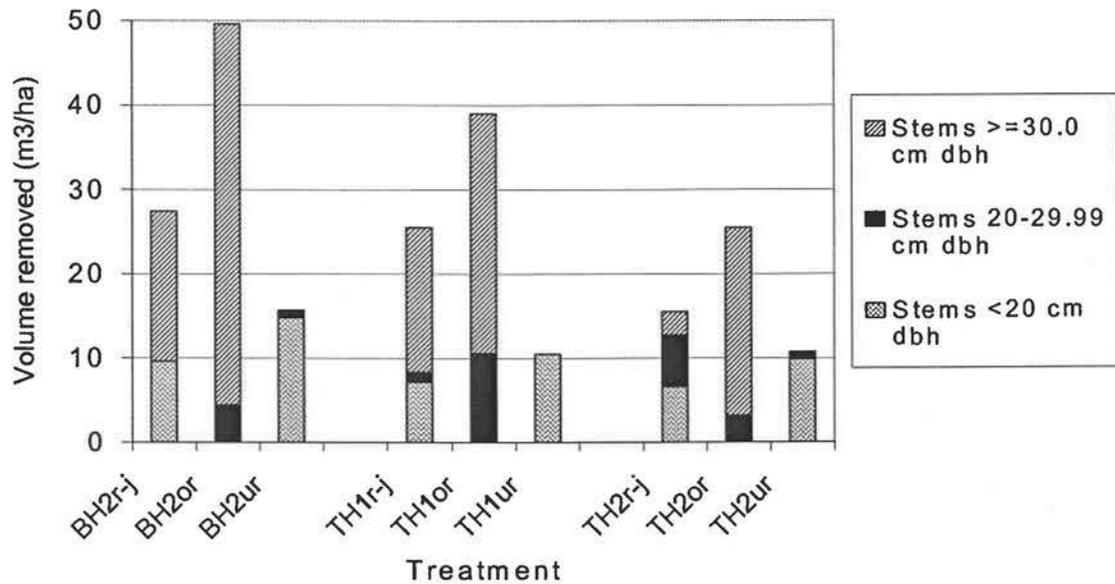


Figure 4.43 Volume removed by plot, treatment, and size class (r-j = reverse-J, or = overstory reduction, ur = understory reduction)

The initial volume removal, and how it is distributed among size classes for a particular treatment is an important design for specification for a harvest, and will largely determine economic viability of the operation. For a given plot, the same residual basal area was used for each treatment. However, because each treatment focused removals

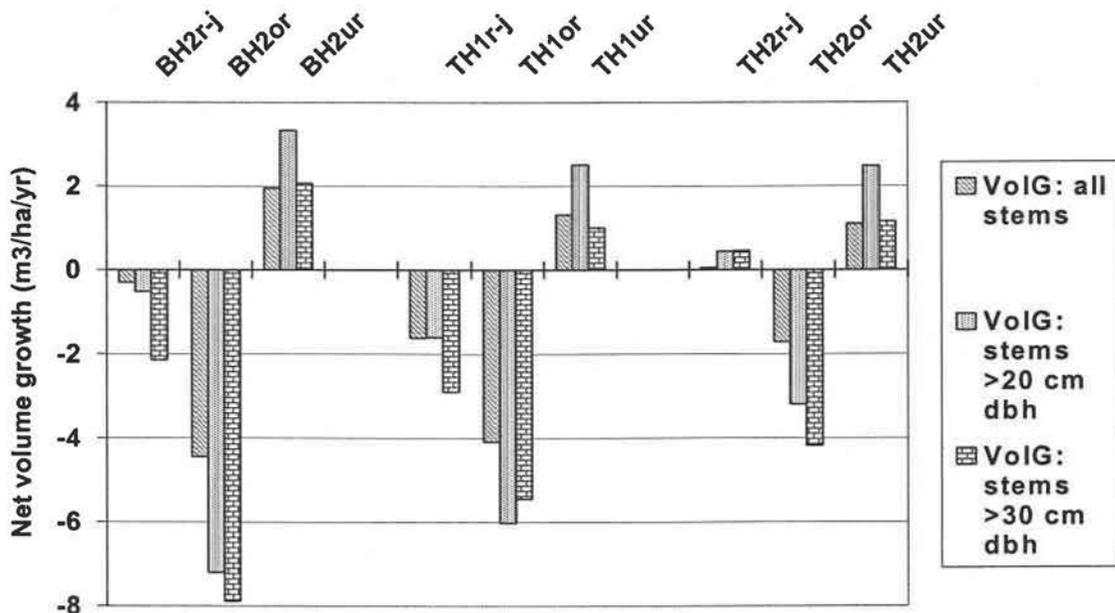


Figure 4.44 Estimated 5-year net volume growth by plot, treatment, and size

within specific size classes, volume removal with treatment varied a great deal. Figure 4.43 shows how volume removals were distributed among size classes for each plot and treatment. For each plot, volume removal was directly related to the volume:basal area ratio (VBAR) of the trees removed; that is, for a given basal area removed, harvest of larger trees resulted in greater volume due to their large VBAR. Accordingly, the overstory reduction, followed by the reverse-J treatment, maximized volume removal.

The summary of change in volume is shown in figure 4.44. The greater volume harvests of the overstory reductions, though spurring greater individual tree growth, produce a negative change in stand volume. The understory reduction treatments, in removing very little volume but significant basal area have exhibited a positive change after five years. The reverse-J treatment after five years has very nearly matched in growth what was removed during the harvest treatment. In fact, plot TH2, exhibiting a J-shaped pre-treatment diameter distribution, shows a net five year growth of approximately zero, suggesting similar volume removal could be achieved on a 5-10 year cutting cycle.

Discussion

The chosen group of explanatory variables contained within the growth model and their associated parameter estimates had a large effect on the results simulated in this study. In an analysis of growth models constructed for the full set of plots (chapters 2 and 3), leaf area per tree was found to be the most significant single variable. Therefore, growth estimation with such a model depends on the ability to estimate changes in the leaf area as well. In this study, the modeling data represented net growth from 1994-1998, and CSAP was measured at the end of the growth period as a surrogate for leaf area. The degree of change in leaf area would be expected to be proportional to intensity and timing of previous entry. The study plots were selected to avoid areas entered more recently than 10 years ago. Hence, it is likely that the most rapid time of leaf area change had passed and that relatively little change probably occurs over a five year growth period.

When efficiency is defined by APA, the increase in this index with a thinning will automatically cause efficiency to decrease without a proportional increase in growth

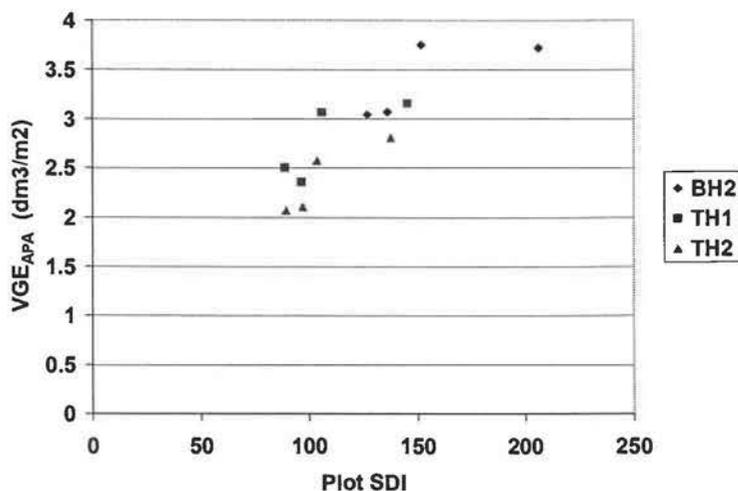


Figure 4. 45 VGE_{apa} by plot SDI

VGE_{apa} due to the inevitability of some unoccupied growing space or un-utilized resources.

When applied to the stand as a whole, the same result emerges. Generally speaking, a decrease in plot density is accompanied by a decrease in VGE_{apa} (fig. 4.45). As might be expected, the overstory removal, with the fewest trees removed, has a VGE_{apa} second to that of the control for each plot. This is particularly true where much of the residual material was less than 10 cm dbh. This size class, though affecting growth negatively, did not influence APA. On plot BH2, where this size class was particularly dense, the overstory removal has a greater VGE_{apa} than the control plot, though it's SDI is 25% lower.

An overstory reduction, as discussed earlier, will only lead to a greater APA for those trees neighboring the removed stems. The smaller number of removals necessary to meet a residual density with a overstory reduction thus limits the number of trees whose APA increases. In addition, the removal of large trees has a large effect on BAL, since values for each tree within the stand are adjusted by the combined basal areas of most removals. Because the removed trees are tall, many of the residuals within the stand will have a greater relative height after treatment. Estimates of future growth calculated with the distance-dependent model will thus be enhanced, and the static levels of APA for many of the trees will lead to an increased growth efficiency.

resulting from that extra growing space. Analysis of the distance-dependent model indicates that a doubling of APA would be associated with a 12.6% increase (95% CI: 10.3-14.9%) in the median BAG. As a result, according to the model, a post-treatment structure with fewer trees can't have an increased

However, both the mechanistic model and the regressions between BAG and single variables indicate that CSAP is the most influential single variable for estimation of BAG. While the residuals will increase their total leaf area following an overstory reduction, the distribution of new openings in relation to residuals is unlikely to enable many of these trees to develop significantly greater leaf area. Stems that are not adjacent to removed trees will experience a level of crowding similar to their pre-treatment status, and their ability to develop leaf area will be diminished due to local crown competition, as well as the finite area into which root volume may extend. As a result, growth may be overestimated in relation to those silvicultural treatments leaving better spaced residuals.

While residual trees following an overstory reduction are predicted to have a greater growth efficiency and absolute growth, much of this growth, will not accrue on large, high-value logs. An overstory reduction, that removes a few of the largest trees per acre may leave many patches of dense understory, and, hence, much of the residual stand remains in an unspaced, and almost "unmanaged" state.

Poor spacing can be associated with diminished crown size and form, thereby resulting in trees of low vigor and poor form and hence, in pest-susceptible trees of low commercial utility. Each of the high density plots contained dense clumps of ponderosa pine, commonly comprising 5-6 stems emerging from the ground within an area of 1-2 square meters. In every circumstance, smaller or suppressed stems within these patches exhibited a great deal of sweep and associated compression wood. While these trees sometimes showed acceptable growth rates, their form detracted from their potential to yield sawn lumber, while at the same time their presence inhibited the growth of the dominant tree of the patch.

An understory reduction, because of the large number of stems removed to meet the residual density, leads to a significant increase in APA for most trees. The resulting gain in growth at least initially will not be enough to offset the increased APA, thus leading to a loss in GE_{apa} . The variables within the distance-dependent model which would predict enhanced growth following an overstory reduction will not change substantially following an understory reduction—as a result, predicted growth increases only as a result of an enlarged APA, and fewer small trees.

The immediate decrease in VGE_{apa} following the understory reduction was clear in figures 4.13-4.15 and 4.31-4.32. However, although efficient utilization of space is an important consideration for any residual stand, it is not the only one. A second crucial consideration is the absolute growth rate of an individual tree. Because trees grow relatively slowly on these central Oregon sites, producing many slow growing trees per unit area may be less advantageous than producing fewer stems with faster growth, both for economic return and pest resistance.

Among the objectives of an understory reduction or reverse-J treatment is a re-spacing which gives each tree more room. Differences in APA following treatment differ by treatment type (fig. 4.46). A lower percentage of trees in the overstory treatment had large changes in APA. In contrast, the largest changes in APA were most common in the

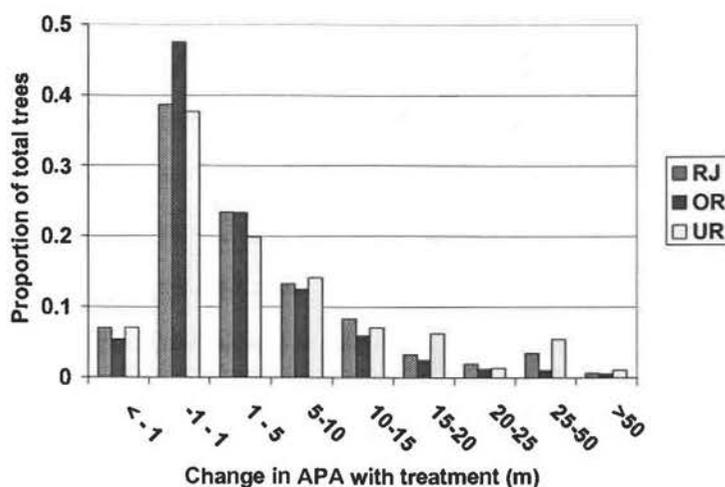


Figure 4.46 Change in APA by treatment type

(implied by the mechanistic model; chapter three).

Because the re-occupation of this newly available space takes time, the resulting growth response will at least partly reflect the rate of crown expansion. Five year growth estimates for the period immediate following thinning don't fully represent the potential to be gained from the thinning. The combination of thinning shock, and timelag involved in root and crown development will delay the response of residuals to newly available growth space. CSAP (and by correlation, leaf area) will only be developed as quickly as height and shoot growth allow. Where a great deal of space is opened, five years may not

understory reduction.

After these treatments, many trees not only increase their APA, but this increased space arrests or slows crown recession. The increase in individual-tree leaf area, distributed among the residual stems, will be significant, and will clearly lead to an increase in growth among the stems

be enough time for the tree to develop its full complement of leaf area. As a result, the growth dividends to be gained from those thinning treatments which re-space the understory cohorts or all cohorts simultaneously (understory reduction and reverse-J, respectively) are realized mainly in the long term. Unfortunately, the level of this expected response is not quantifiable due to the inability of the model to reflect these dynamic crown changes.

A silvicultural treatment in which trees are removed from all size classes or cohorts in an uneven-aged stand is a combination of numerous silvicultural treatments; the treatments labeled here as overstory and understory reduction, can be interpreted to include selection regeneration harvest, overstory removal, and thinning or improvement cutting. This treatment is represented by the reverse-J treatment, which combines the positive attributes of thinning in several age classes.

On the practical side, the distribution of removed volume by diameter class can be used to assess the economic viability of an entry. Clearly, the overstory reduction, in concentrating removal in large volume trees, would provide a profitable harvest. Just as obviously, the lack of sawtimber in the understory reduction makes the understory reduction precommercial. The reverse-J treatment is a compromise between the two. It is an economically viable operation in that, like the overstory reduction, large trees are removed. A further advantage is the increased growth and efficiency of residuals associated with the removal of larger trees.

Like the understory reduction, the reverse-J treatment re-spaced the trees. In doing so, clumped trees or trees of poor form and dubious future merchantability may be dealt with immediately. This respacing can also be expected to lead to increases in crown size (and leaf area) for the residuals, thereby enhancing the growth potential of most of the trees within the stand. Also, whereas the understory reduction may better set the stand up for conversion to an even-aged system, the reverse-J treatment seeks to ensure that all diameter classes are represented in the present and in the future. Because the reverse-J treatment would not be as immediately profitable as an overstory reduction, due to the fact that some non-merchantable material will be treated, the long term potential of the stand will increase by reducing the negative effect of small trees on the growth and form of residuals.

Silvicultural Implications/Recommendations

In using diameter selection as the thinning criteria, these treatments correspond to taking removals from the high end, low end, and full range of diameters. The three thinning treatments considered do not therefore fully address the array of options available for density management within an uneven-aged system. Nevertheless, they make it possible to compare the effects resulting from removal of these stand components, and illustrate the bounds on possible silvicultural treatments since they represent the extremes.

In analyzing and designing a silvicultural treatment or system, the objectives must be clearly established. Of ultimate concern in managing land for timber is to ensure a profitable yet sustainable operation. The sustained production of timber often necessitates that some concessions be made, for example, accepting lower present profit for the sake of ensuring quality growing stock, soil protection, and pest resistance. Any recommendations must therefore take these priorities into consideration.

Harvest Costs

The economic feasibility of a harvest depends a great deal both on the volume and grade of logs removed. Where harvests focus on small trees destined for pulp, the cost of extracting large numbers of small volume stems make this type of harvest marginally profitable at best. This is particularly true in uneven-aged stands where stems must be individually marked and care must be taken not to damage residual trees. The profitability of such a harvest depends on the present condition of the pulp market and the quality of the species to be removed. For example, lodgepole pine is a more valuable pulp species than ponderosa pine. A pulp harvest, with removals similar to those of an understory reduction, may be conducted as part of a stand improvement entry, rather than a commercial harvest.

Harvest of large trees, represented here by an overstory reduction, can ensure the economic viability of an entry by virtue of greater volume and value extraction. If coupled with removal of non-commercial material, the removal of a few large trees can cover the costs of removing smaller material, as would be true in the reverse-J treatment.

It must be acknowledged that what is immediately profitable, may in the long term give lower returns due to diminished growth rates, quality, and natural losses resulting from poor stand maintenance. However, an analysis of the long term economic implications of each of these treatments is beyond the scope of this study.

Stand damage

Residual damage is unavoidable during harvests, particularly for uneven-aged stands. Fortunately, the combination of resinous in pine and dry conditions which inhibit fungal spore release and speed wound drying, limit the occurrence of stem rot in stands damaged by logging. Nevertheless, the buildup of callous tissue, resin, and a potentially misshapen stem makes these stems commercially less desirable.

Each of the three treatments will probably cause similar damage to residual stems. (A more open stand will necessarily receive less damage from the felling of large trees than a crowded stand. However, trees damaged within a crowded stand may not be retained damage notwithstanding.)

Soil damage is another concern. Research in central Oregon has found these volcanic soils experience increased bulk density following tractor logging (Allbrook 1986, Davis 1992) and that increased compaction resulting from such logging methods has diminished height growth of planted ponderosa pine (Cochran and Brock 1985). Furthermore, pumice bridging within compacted soils may be a problem (Cochran 1971). Silvicultural systems which feature single tree selection or short cutting cycles, increase the number of entries on a given piece of ground within a given time, and thus encourage this type of damage.

Natural regeneration

Generally, harvest entries can't be scheduled to correspond with good seed crops. Although the presence of mature residuals in an uneven-aged stand is a way to ensure seed availability, the species, quantity, and quality of the next generation of trees will depend in part on the structure of the current stand, in absence of artificial regeneration.

Because the largest ponderosa pine trees produce a disproportionate share of seed (Barrett 1979), removal of these trees may significantly diminish the quantity and quality

of ingrowth. Removal of a large portion of the potential seed source is of particular concern where ponderosa and lodgepole pine grow in mixed stands. Because lodgepole pine is a prolific seeder and can produce seed annually beginning at the age of 5-10 (Lotan and Critchfield 1990), it has an impressive ability to establish. In contrast, ponderosa begins to bear seed at a later age, and produces significant seed crops only at 4 to 5 year intervals (Barrett 1979). Where these two species are mixed, without management procedures specifically geared toward ensuring ponderosa pine regeneration, lodgepole may eventually dominate the regeneration layer.

The overstory reduction treatment is problematic from a regeneration perspective in that at least some of the most productive seed producers are removed. The forementioned problem of tipping the balance in favor of lodgepole pine seed is probable in this situation, given that the largest trees on any of these sites are ponderosa pine. Furthermore, having a large amount of lodgepole pine capable of seed production is likely only to increase the costs of future pre-commercial thinning.

Though it has been shown to diminish the growth of trees from all size classes, one advantage of leaving a limited number of saplings present is that future growing stock, and thus future options are preserved. Such options are lost in the understory reduction, although the growth response to treatment which was given in the analysis would be little different if a few trees of the youngest cohort were left. The reverse-J treatment, in limiting the number of small trees, addresses the need for preserving future growing stock, while limiting the growth impact on current stock.

Pests

The harvest method and subsequent residual structure will have a major influence on potential pest activities.

The mountain pine beetle (MPB) *Dendroctonus ponderosae* is an aggressive scolytid known for its ability to kill both lodgepole and ponderosa pine. It is best known for its activity in overstocked, even-aged stands.

The silvicultural tool most commonly used to decrease a stand's susceptibility to the MPB is reducing stand density through thinning. Thinning is believed to decrease a stand's susceptibility to the beetle by a number of different mechanisms. These include

the improvement of tree vigor, and with it, defensive reaction (Mitchell et al. 1983, Larsson et al. 1983, Christiansen et al. 1987), a changed microclimate, and with it, beetle behavior (Amman et al. 1988, Schmid et al. 1991, Bartos and Amman 1989, Schmid et al. 1995), and the spacing of stands, thus removing weak focus trees or high density clumps (Eckberg et al. 1994, Olsen et al. 1996). Both the reverse-J and understory reduction treatments accomplish this goal.

The fact that research addressing the effects of the MPB has focused on even-aged stands suggests that a uneven-aged condition, by both limiting the density of beetle susceptible trees and leaving of the stand relatively open, probably keeps the beetle hazard low. However, where lodgepole is a major stand component it generally grows in even-aged patches. Limiting these patches in size and distribution across the landscape will limit the chances of them serving as a source of population build-up.

Two endemic root pathogens, *Armillaria* and *Heterobasidion Annosum* (Annosus) are endemic pathogens in central Oregon. The incidence and effect of each can be influenced by management activities. *Armillaria* can act as both a parasitic necrotroph, or as a decomposing saprophyte, spreading by root contact. As a saprophyte, it has been found to remain as a source of inoculum for up to 50 years in large stumps (Roth et al. 1980). In contrast, Annosus infects freshly exposed wood via airborne basidiospores. As with *Armillaria*, an established infection, can spread via root contact.

Although thinning is a common practice aimed at improving forest resistance to both insect and disease damage, this creates problems in regard to *Armillaria* and *Annosus*. The creation of well distributed stumps increases the likelihood of infection and spread—frequency of cutting has been cited as a critical factor promoting disease.

Because the regular creation of stumps increases the incidence and strength of this disease, all three treatments, and any single tree selection system may perpetuate these diseases on a site. Limiting the distribution of large stumps, while at the same time maintaining the vigor of neighboring trees is the best defense.

Black stain root disease (BSRD) (*Leptographium wageneri*), is a vascular wilt vectored by beetles. One variety, *var. ponderosum*, is specific to ponderosa and lodgepole pine.

Most research into this pathogen has addressed the variety, *pseudotsugae*, which attacks Douglas-fir. BSRD incidence in Douglas-fir is associated with stressed trees, and particularly where there has been soil disturbance, precommercial thinning, or areas with impeded drainage (Hansen et al 1985). Where BSRD is present, it is most commonly found along roads, occurring in small to large patches of trees. In pines, the stress resulting from high stand densities or root disease presence was found to be a factor in the incidence of BSRD (Hunt and Morrison 1986).

The flat topography and selection systems used in this region have led to a high road density, theoretically creating stressed trees, and thus conditions suitable for BSRD incidence. Although this pest has not been a great problem in pine, the association of this pest with roadsides is yet another reason to limit skidtrail density or other activities which cause soil compaction.

Dwarf mistletoe can be a damaging pest of both lodgepole and ponderosa pine and is present in some areas of the Crown Pacific ownership. Because of its means of dispersal, multi-storied, naturally regenerated stands present special problems. Unless specifically dealt with through containment or clearcutting, it can be expected that this pest will persist in these species-poor uneven-aged stands.

Growth efficiency

With the inherent constraints on timber production in central Oregon, it is important that trees are grown efficiently on those lands where timber growth and harvesting are acceptable objectives.

From this study, efficiency as defined by APA appears to have limited utility as a means to determine an optimum stand structure. The growth model indicates that efficiency drops as a tree's area of occupancy increases, but over time it will tend to increase as well. Determination of the proper spacing for a tree requires the establishment of minimally acceptable individual tree growth rates and a firm understanding of responding growth dynamics.

Growth assessment with GE_{csap} was problematic in this study due to the difficulty of backdating or projecting leaf area development. Nevertheless, VGE_{csap} of ponderosa pine has been shown to increase with CSAP (chapters 2 and 3), a result that is consistent

with previous research (O'Hara 1996). However, at high levels of CSAP, efficiency may decline. Structuring a stand to maximize efficiency for the trees of the largest size class is desirable as they occupy more space, produce more usable fiber, and are the economically better investment. In continuing efficient growth, leaving large trees for some future harvest ensures some financially viable options in the future.

Of the treatments applied in this study, the reverse-J structure appeared to offer the best compromise between individual tree and stand growth. In addition, it best addressed other concerns such as spacing, future density control, and regeneration. One of the motivations for this study was to broaden the assertion that high q-factor J-distributions, which retained many stems for the smallest size classes, would be unnecessarily inhibiting to the growth of replacement trees (Cochran 1992). This growth-inhibiting effect was quantitatively demonstrated in this study, and, coupled with the greater efficiency of large ponderosa, would suggest that larger trees should be favored in the distribution of stand growing space.

Maintaining only enough small trees required to replace those in the smallest merchantable classes argues for a very low q-factor, perhaps in the 1.1-1.2 range. In using a low q-factor, space and growth is not wasted for trees which will be removed when they have little or no value. This strategy is particularly relevant for pure ponderosa stands, where the small stems are of limited value even for chipping. The concerns of a small q-factor, namely that mortality will outpace growth, and thus diminish the counts of larger size classes in the future, are minimized if vigor is maintained for the residuals by maintaining proper densities (e.g. basal area or SDI).

Efficiency can be addressed by using other structures also. Ponderosa pine on plot TH2 shows a gradually increasing VGE_{csap} , reaching and maintaining a plateau for the largest size classes. It was stated earlier the largest trees of this plot tended to have smaller and narrower crowns and contained more leaf area than trees of the next smaller diameter class (their CPA efficiency was considerably greater also). The high VGE_{csap} of large trees, and the crown characteristics which give plot TH2 trees their high VGE_{csap} , would suggest that structures which limit lateral crown width would encourage efficiently growing trees.

Limiting crown development by controlling stand density can best be accomplished through crowding by neighboring trees in the same canopy strata. Patches of trees in a similar cohort, besides providing the structure necessary to bring about these crown characteristics, is an appropriate structure for ponderosa pine. Previous research into natural stand development patterns in ponderosa pine have confirmed the patchy nature of ponderosa pine (Morrow 1985, Arno et al. 1995). This type of structure may be simulated using group selection harvests, adjusting the size and extent of these groups out of financial, logistical, and other concerns. Besides mimicing natural stand development patterns, this system may address other timber management concerns, including harvest costs, stand damage, regeneration, and pests.

The generally flat terrain and dense road network within most central Oregon pine stands helps to limit the difficulty and costs associated with timber harvest. However, the wide distribution of trees targeted for removal with a single tree selection system makes harvest expensive due to the time commitment necessary for marking, locating, and extracting. By having removals more concentrated, this process is faster, and thus more efficient.

Stand damage is a second concern. Use of group selection as a harvest system limits damage to edges or to entries made prior to final harvest of groups. Because the final removal of large trees occurs simultaneously, damage to any residuals is more limited. Furthermore, soil compaction is restricted by limiting entries on a particular piece of ground.

The use of natural regeneration requires that sufficient seed is available, and that sites conducive to germination and establishment are present. Use of a group selection system with natural regeneration means that groups must be limited in size and well distributed. In addition, where appropriate, leave trees may be necessary where regeneration is insufficient. Previous work has suggested that shrubs or other debris, providing amelioration of direct sunlight and heat, improves establishment (Callaway et al. 1997). While a group selection harvest may damage shrubs appreciably, slash may provide enough favorable microsites for germination.

Of the potential pest problems previously mentioned, only one may be exacerbated by a group selection. The mountain pine beetle seemingly prefers a more

even-aged structure. However, in keeping a group low in density, small in area, distributed among groups of other age classes, and growing vigorously, this concern is reduced. In limiting harvesting to smaller, closely distributed areas, the large stumps and soil damage which are potentially most problematic from the standpoint of the forementioned root pathogens are less widely distributed and would have more limited root to root contact with other trees. Furthermore, whereas dwarf mistletoes can be expected to persist in a vertically stratified stand, group selection harvests can be used to contain its extent and ability to spread.

Lodgepole pine VGE_{csap} is not improved with greater leaf area. In fact, data from the plots indicates that large lodgepole pines, when they are capable of significant growth are significantly less efficient than smaller trees. Presently, on these sites, lodgepole pine grows within even-aged patches, or sparsely dispersed among ponderosa pine.

Management of lodgepole in even-aged groups matches its natural dynamics, and is advantageous for the same reasons given for ponderosa pine. Because lodgepole pine is a good chip species, and because of its susceptibility to western gall rust (*Endocronartium harknessii*), density management to produce sawtimber sized trees may or may not be of value. Where it is sparsely mixed with ponderosa pine, it may be appropriate to use lodgepole to fill in gaps in regeneration. However, as previously stated, its ability to produce copious regeneration may too quickly allow this species to dominate future stands.

Diameter Distributions: Blackrock H2

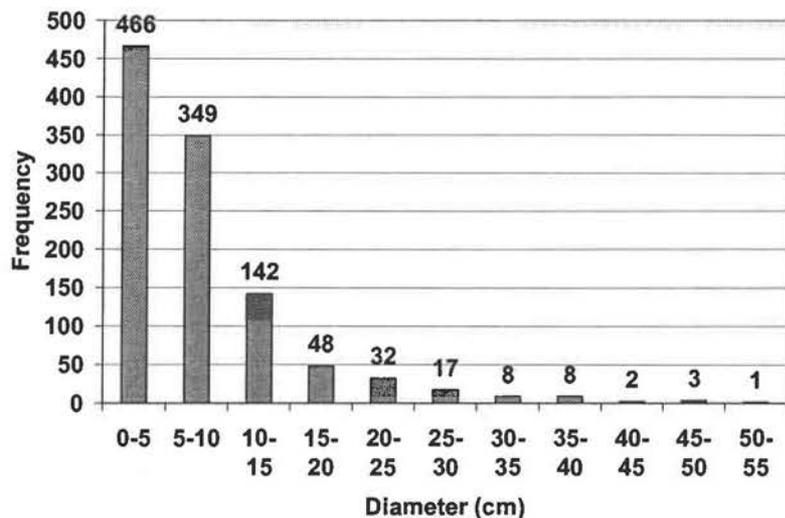


Figure 4.47 Diameter distribution, control

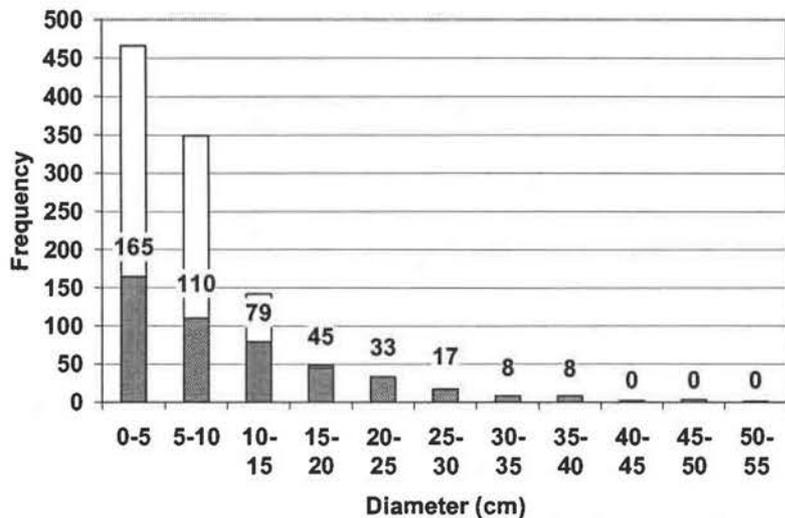


Figure 4.48 Diameter distribution, reverse-J

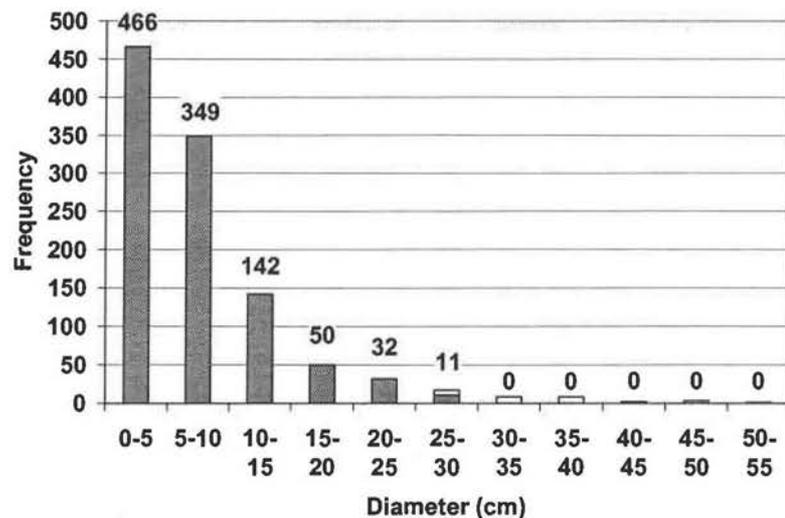


Figure 4.49 Diameter distribution, overstory reduction

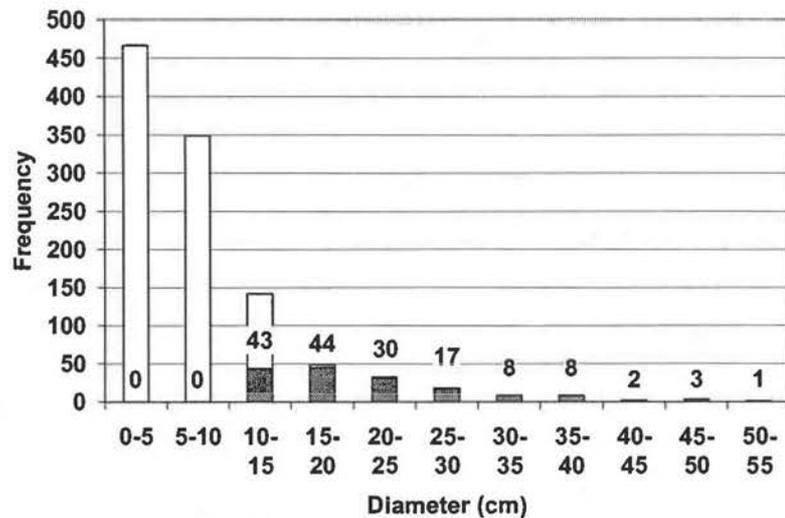


Figure 4.50 Diameter distribution, understory reduc.

Diameter Distributions: Timbers H1

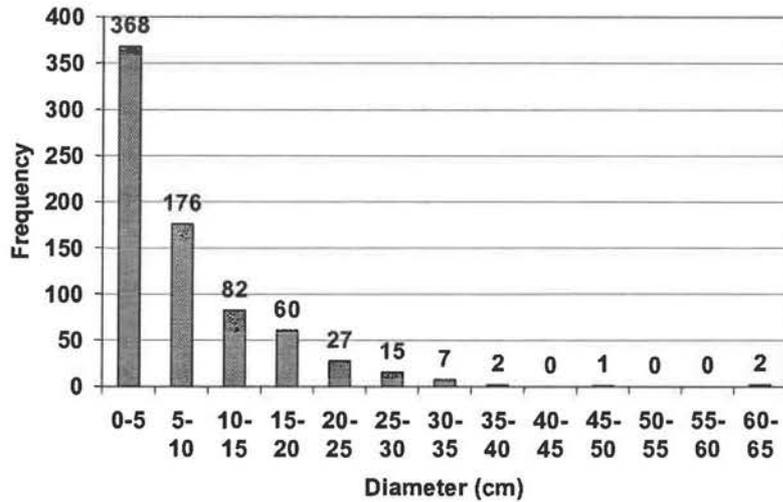


Figure 4. 51 Diameter distribution, control

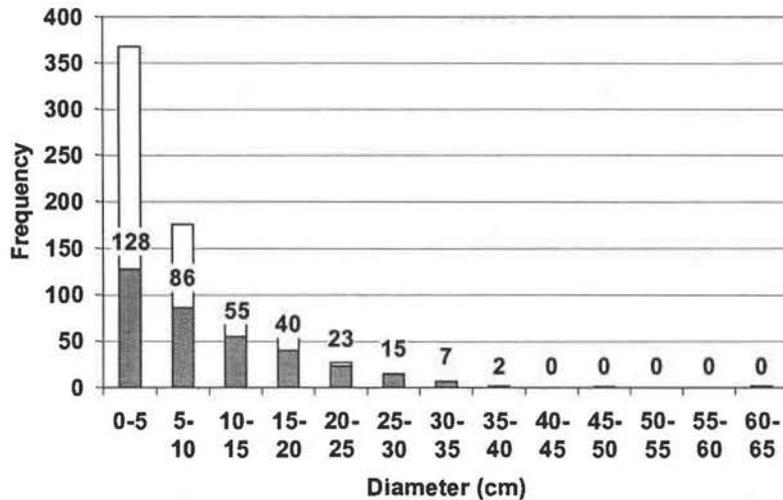


Figure 4. 52 Diameter distribution, reverse-J

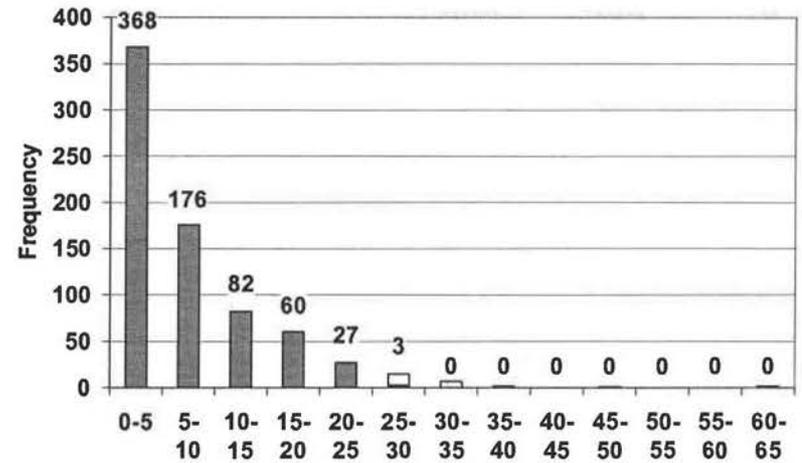


Figure 4. 53 Diameter distribution, overstory reduction

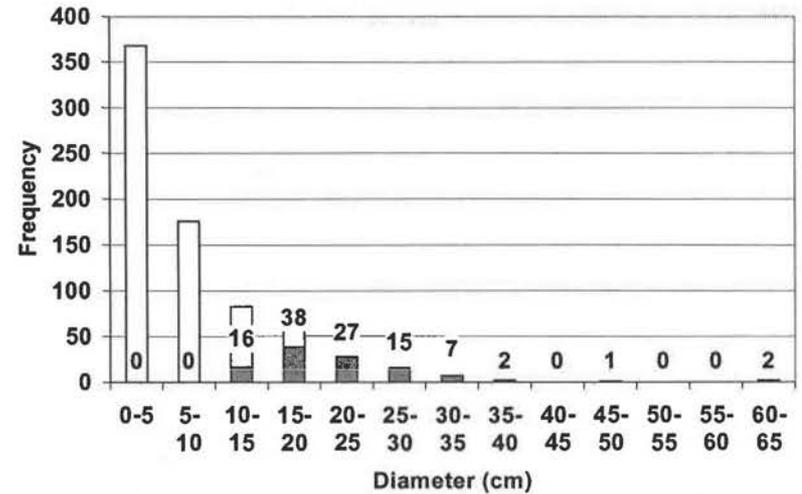


Figure 4. 54 Diameter distribution, understory reduc.

Diameter Distributions: Timbers H2

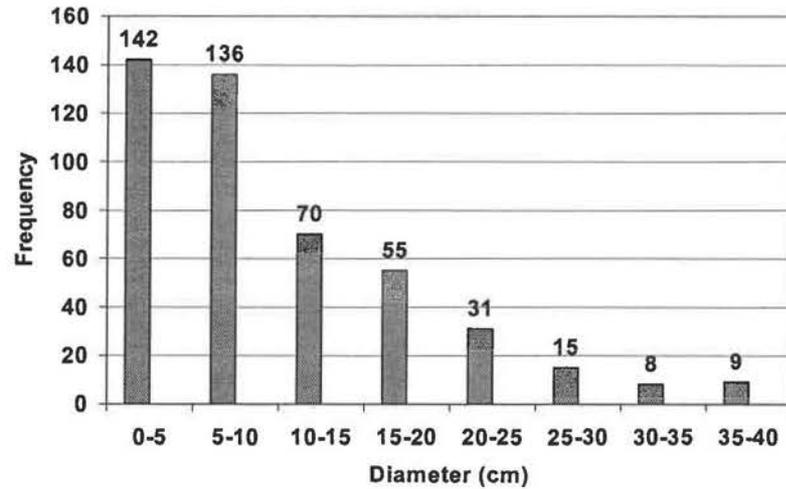


Figure 4. 55 Diameter distribution, control

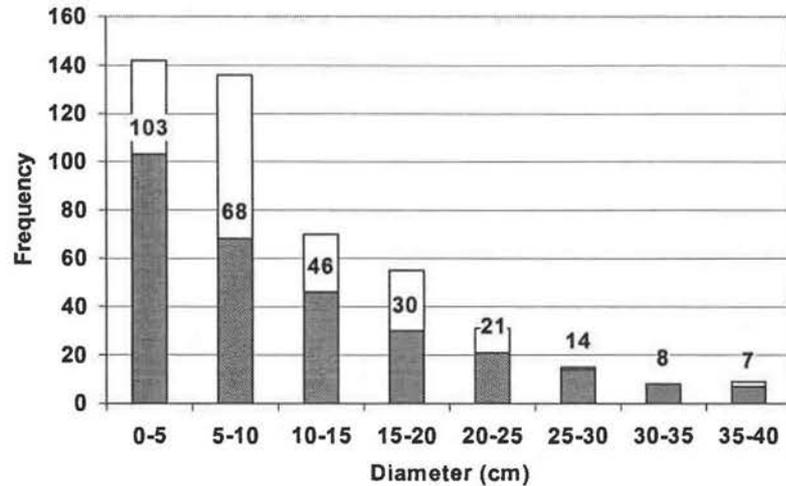


Figure 4. 56 Diameter distribution, reverse-J

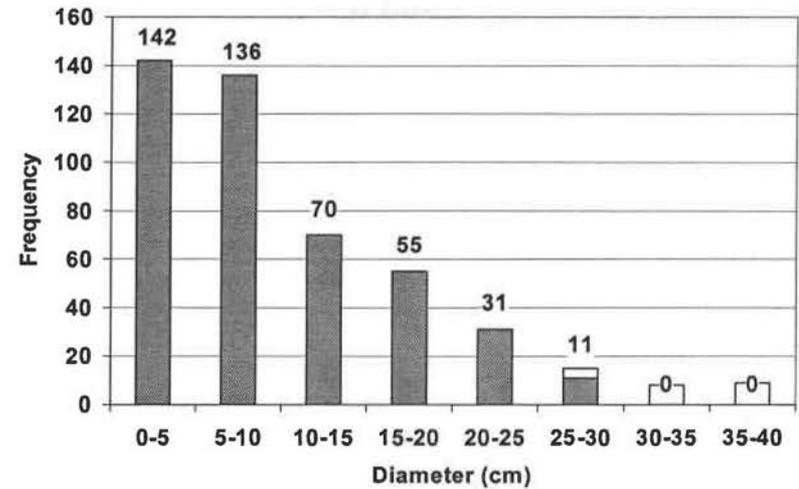


Figure 4. 57 Diameter distribution, overstory reduction

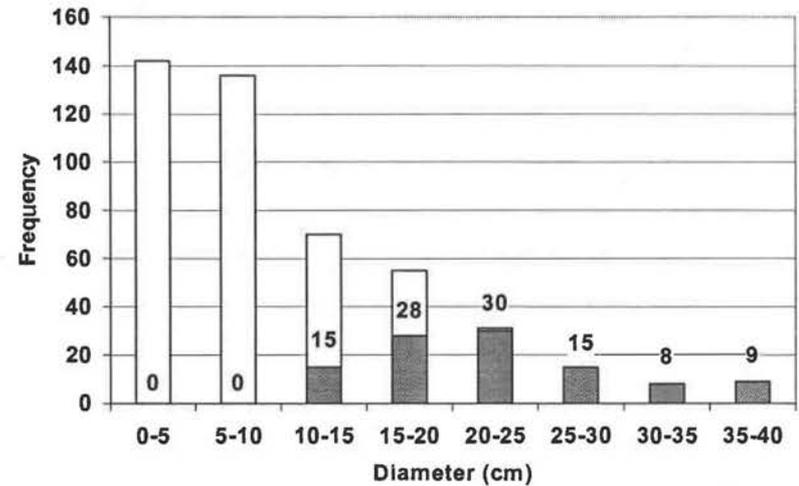


Figure 4. 58 Diameter distribution, understory reduc.

Chapter Five: Conclusion

Many pine forests in central Oregon are presently in a multi-age condition as a result of prevailing disturbance patterns. Forest managers have many reasons to work with, and maintain this structural heterogeneity.

Crown Pacific, the large central Oregon timber company upon whose land this study was carried out, manages its lands using uneven-aged silvicultural systems. With application of uneven-aged silvicultural systems, stands will undergo numerous entries. Therefore, it is in the interests of the managers to maintain healthy and productive growing stock, forsaking some present volume and value extraction for future dates.

In the marginal growing conditions of central Oregon, efficient and timely production of sawtimber and minimization of losses to pests require careful control of stand density. Understanding how growing space allocation among the different size and age classes within an uneven-aged stand affects the growth and growth efficiency of the trees within is a necessary prerequisite for those charged with extracting and sustaining value. This study has developed a quantitative connection between stand structural characteristics, the distribution of growing space, and individual tree and stand growth, growth efficiency, and vigor.

Analysis of the distance-independent (DI) and distance-dependent (DD) models constructed to answer questions of interest indicated that use of distance-dependent variables improves growth predictions versus those made with only distance-independent variables. However, this improvement, limited to 5 % for 5-year basal area growth, is not sufficient to warrant the labor-intensive collection procedures for growth and yield information.

Many interior pine stands are overstocked with small regeneration. By including a variable within the DD model for the basal area of these trees, small trees (<10 cm dbh) were found to have a quantifiably significant negative effect on the growth of larger trees. The merchantable volume growth gained as a result of removing these small trees (160 $\text{dm}^3/\text{ha}/\text{yr}$, or \$11.60/ha/yr from removal of 800 stems) was small enough to question the utility of doing so for improving overstory growth. However, because the density of regeneration on the study plots was relatively low (to simplify mapping), a PCT might

make sense where the size and density of small stems makes manual removal more efficient.

The growth efficiency of a given tree was found to depend a great deal upon the index of growing space by which that efficiency was defined. Likewise, patterns were different for each species. Basal area growth efficiency declined with increasing site occupancy regardless of tree species, or the index used to define occupancy (crown base sapwood area, CSAP; area potentially available, APA; crown projection area, CPA). While volume growth efficiency declined with increasing index levels for lodgepole pine, ponderosa pine VGE_{csap} and VGE_{cpa} were greatest for the trees with the greatest CSAP and CPA, respectively.

A single index of spatial occupancy was found to be an insufficient description of a tree's spatial occupancy from the standpoint of growth. Inclusion of multiple indices of spatial occupancy to growth models improved growth predictions significantly, though the implied growth efficiency values calculated from two-index models depended very little upon which two indices were used within the model.

When different types of harvests (overstory removal, understory removal, reverse-J) were simulated on these plots, the growth responses (predicted from the DD growth model) depended a great deal upon which size classes the removals came from. Growth response within a given size class was greatest when basal area removal across the plot was concentrated among the largest trees. Accordingly, growth response was greatest following the overstory removal, followed by the reverse-J and understory removal treatments. In contrast, stand growth response followed the opposite trend. Growth efficiency of residual trees was most dependent on the arrangement and characteristics of individual trees on each plot.

In managing timberlands using uneven-aged systems, both readily extractable volume and long term stand maintenance must be priorities. This study found that a harvest which removes basal area from among all diameter classes best balances production of immediate and profitable volume and long term regrowth. The high growth efficiency of large ponderosa pines, and particularly of those whose crown spread is minimized, implies that stands should be arranged to produce such trees. A group selection system would produce this type of structure, while simultaneously addressing

other management concerns (harvest costs, stand damage, natural regeneration, and pest losses) within an uneven-aged framework.

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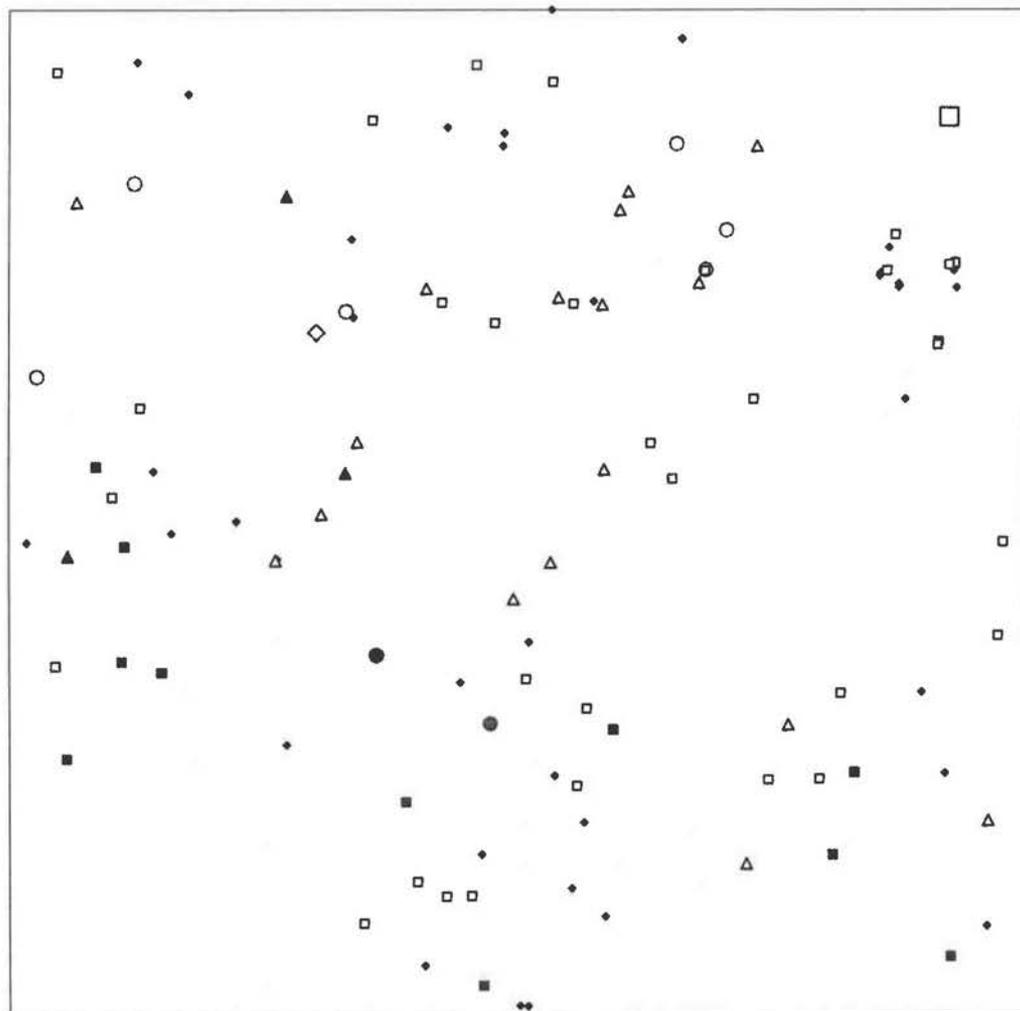
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Appendix



- <10 cm dbh
- Lodgepole: 10-20 cm dbh
- ▲ Lodgepole: 20-30 cm dbh
- Lodgepole: 30-40 cm dbh
- ◻ Ponderosa: 10-20 cm dbh
- △ Ponderosa: 20-30 cm dbh
- Ponderosa: 30-40 cm dbh
- ◇ Ponderosa: 40-50 cm dbh
- ◻ Ponderosa: >50 cm dbh

Figure A. 1 Stem map, plot Timbers low two (TL2)

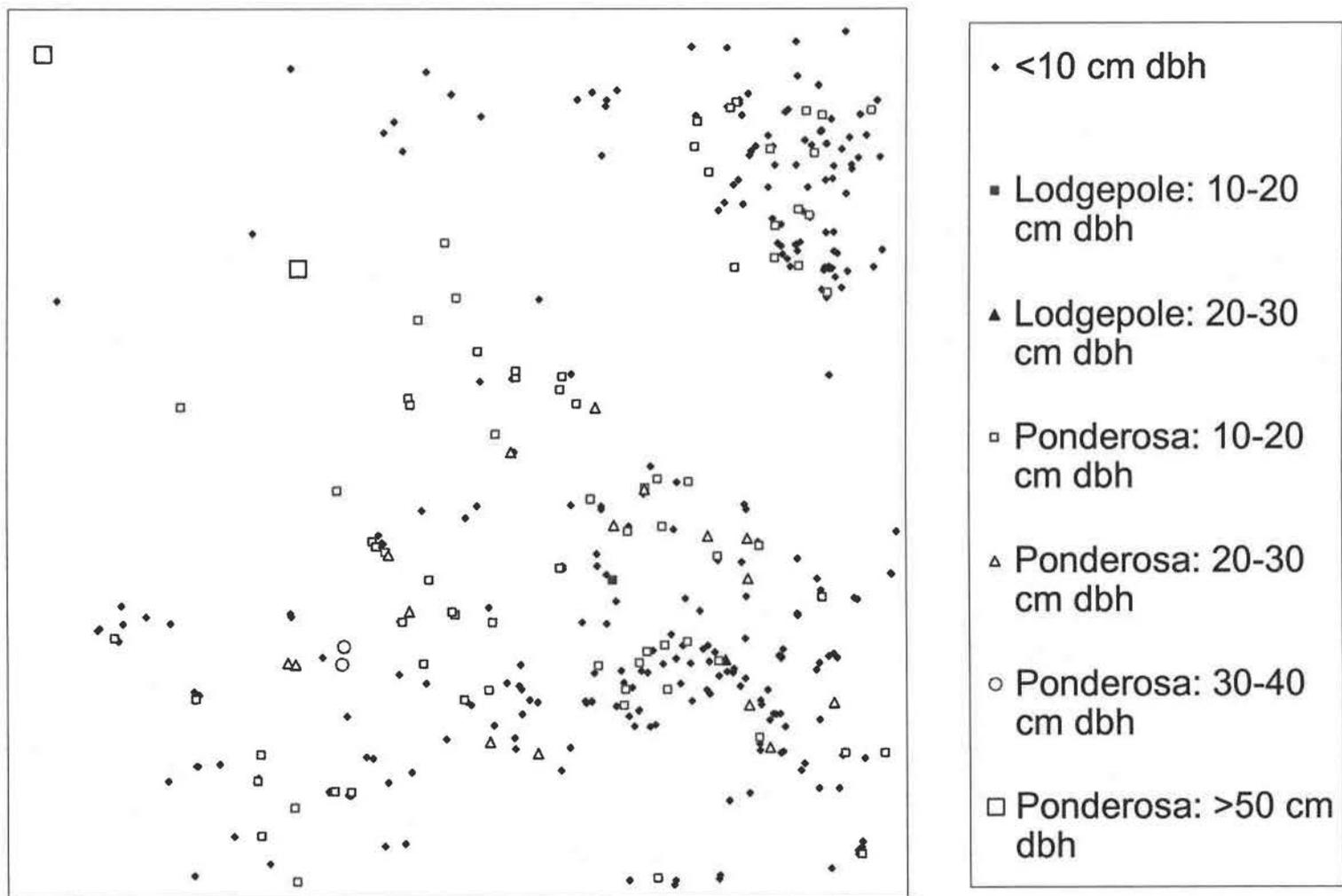
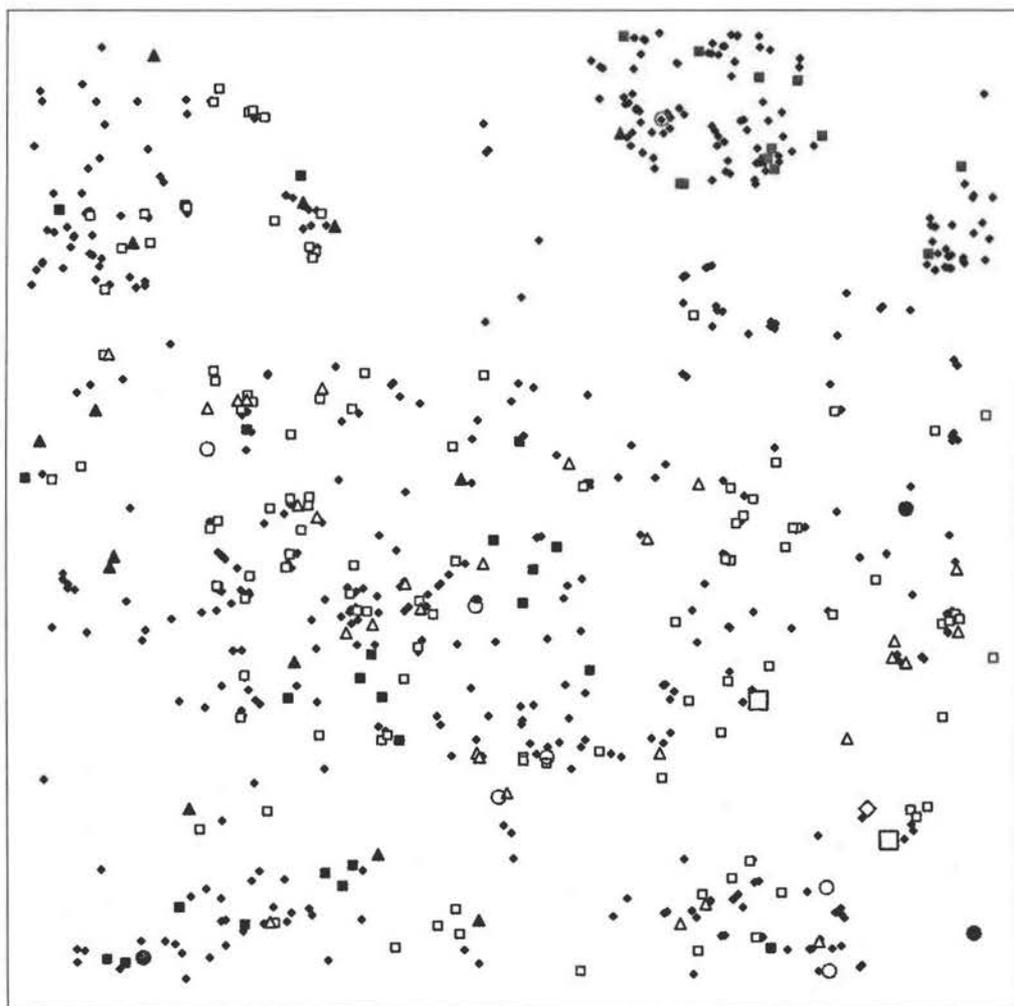
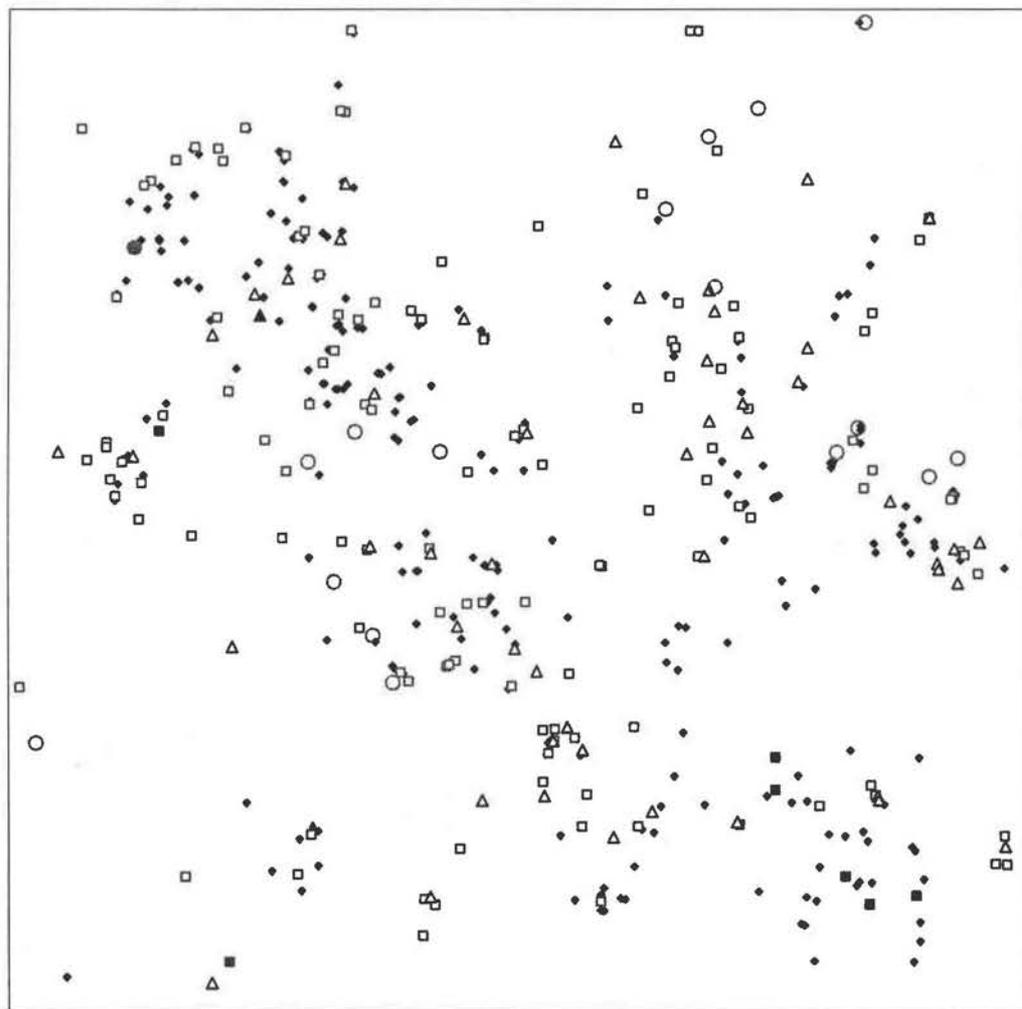


Figure A.2 Stem map, Timbers medium one (TM1)



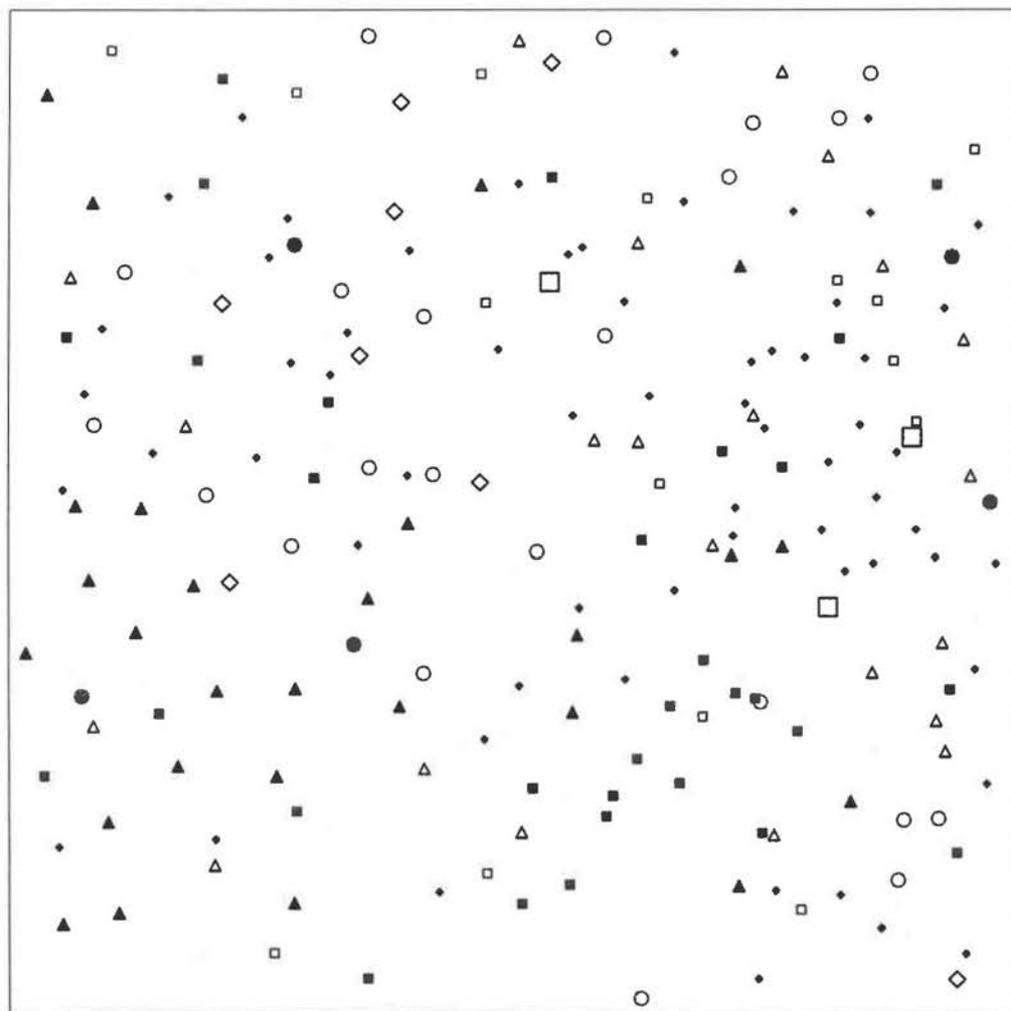
- <10 cm dbh
- Lodgepole: 10-20 cm dbh
- ▲ Lodgepole: 20-30 cm dbh
- Lodgepole: 30-40 cm dbh
- ◻ Ponderosa: 10-20 cm dbh
- △ Ponderosa: 20-30 cm dbh
- Ponderosa: 30-40 cm dbh
- ◇ Ponderosa: 40-50 cm dbh
- ◻ Ponderosa: >50 cm dbh

Figure A.3 Stem map, Timbers high one (TH1)



- <10 cm dbh
- Lodgepole: 10-20 cm dbh
- ▲ Lodgepole: 20-30 cm dbh
- Lodgepole: 30-40 cm dbh
- ◻ Ponderosa: 10-20 cm dbh
- △ Ponderosa: 20-30 cm dbh
- Ponderosa: 30-40 cm dbh

Figure A.4 Stem map, Timbers high two (TH2)



- <10 cm dbh
- Lodgepole: 10-20 cm dbh
- ▲ Lodgepole: 20-30 cm dbh
- Lodgepole: 30-40 cm dbh
- ◻ Ponderosa: 10-20 cm dbh
- △ Ponderosa: 20-30 cm dbh
- Ponderosa: 30-40 cm dbh
- ◇ Ponderosa: 40-50 cm dbh
- ◻ Ponderosa: >50 cm dbh

Figure A.5 Stem map, plot Blackrock low two (BL2)

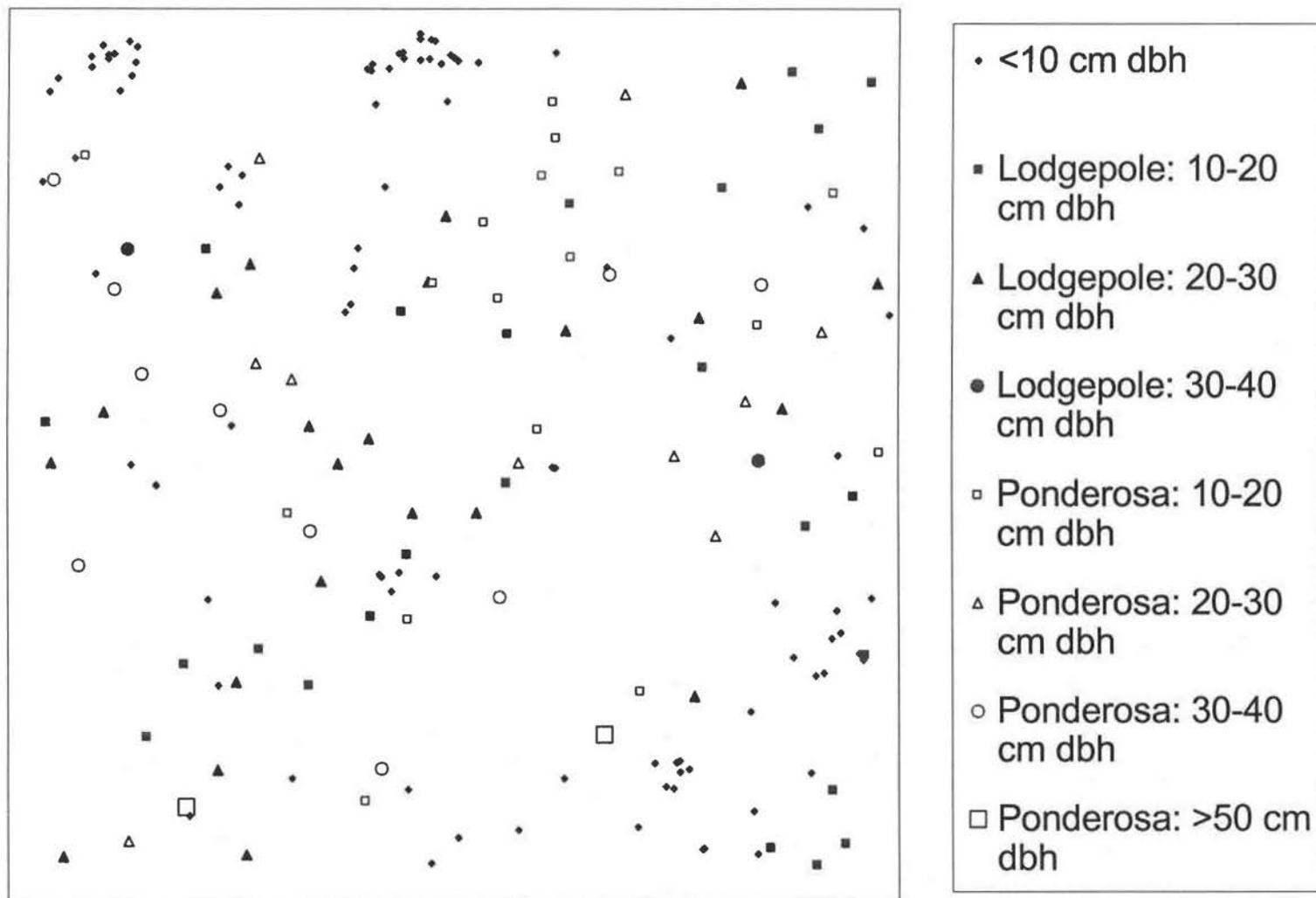
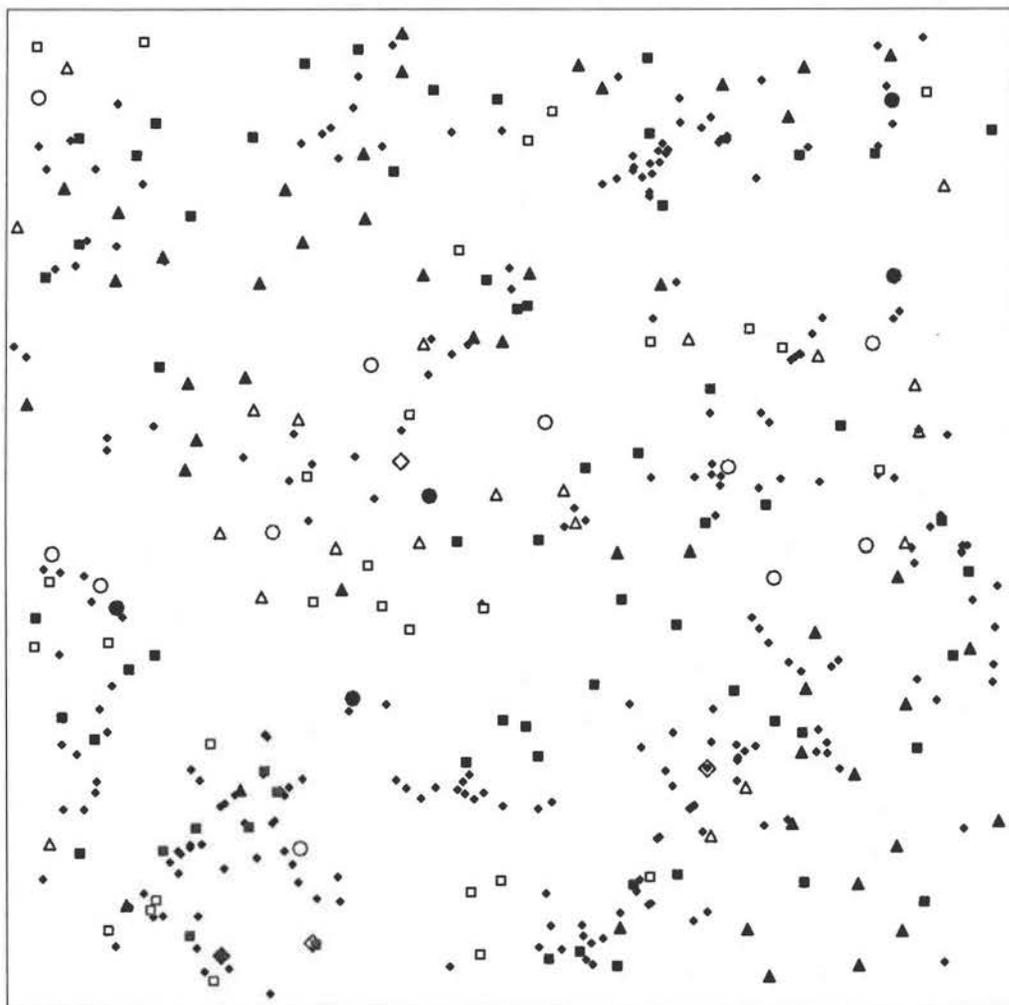
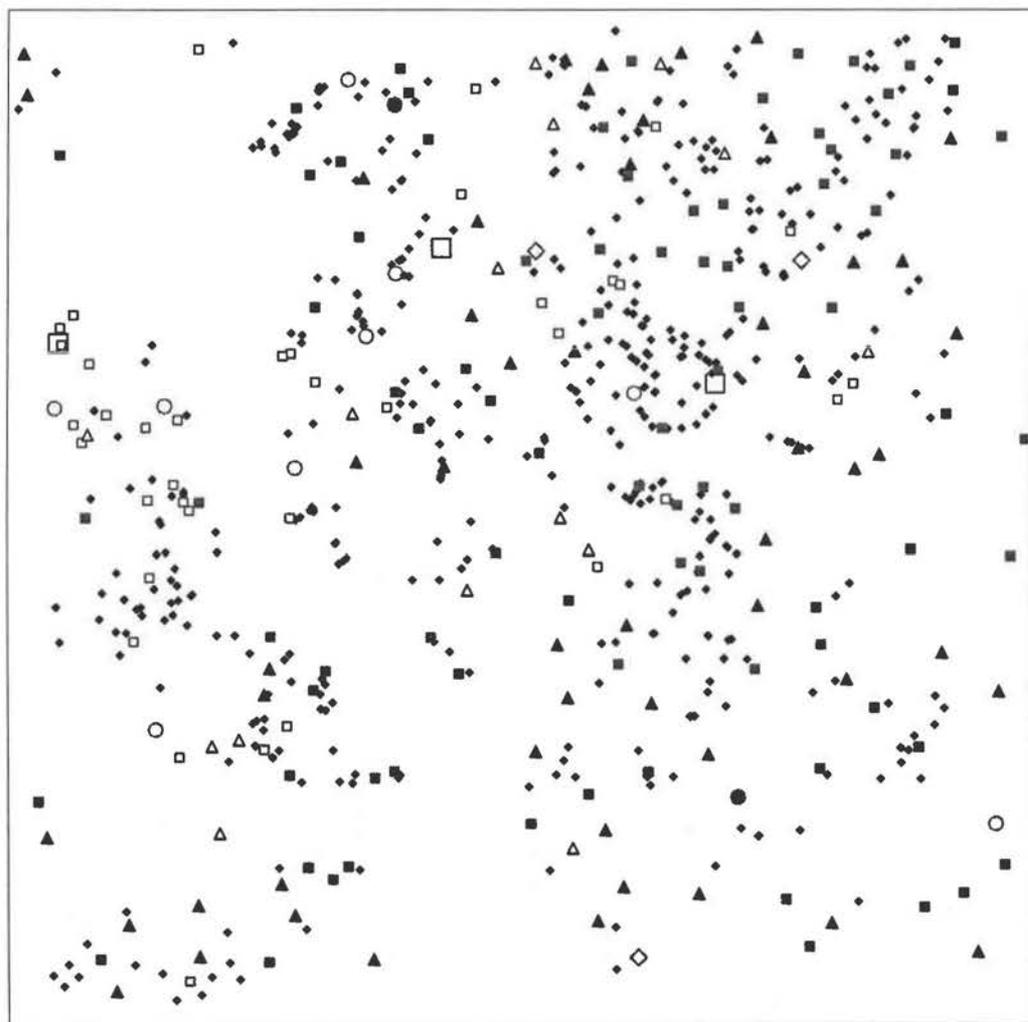


Figure A.6 Stem map, plot Blackrock low three (BL3)



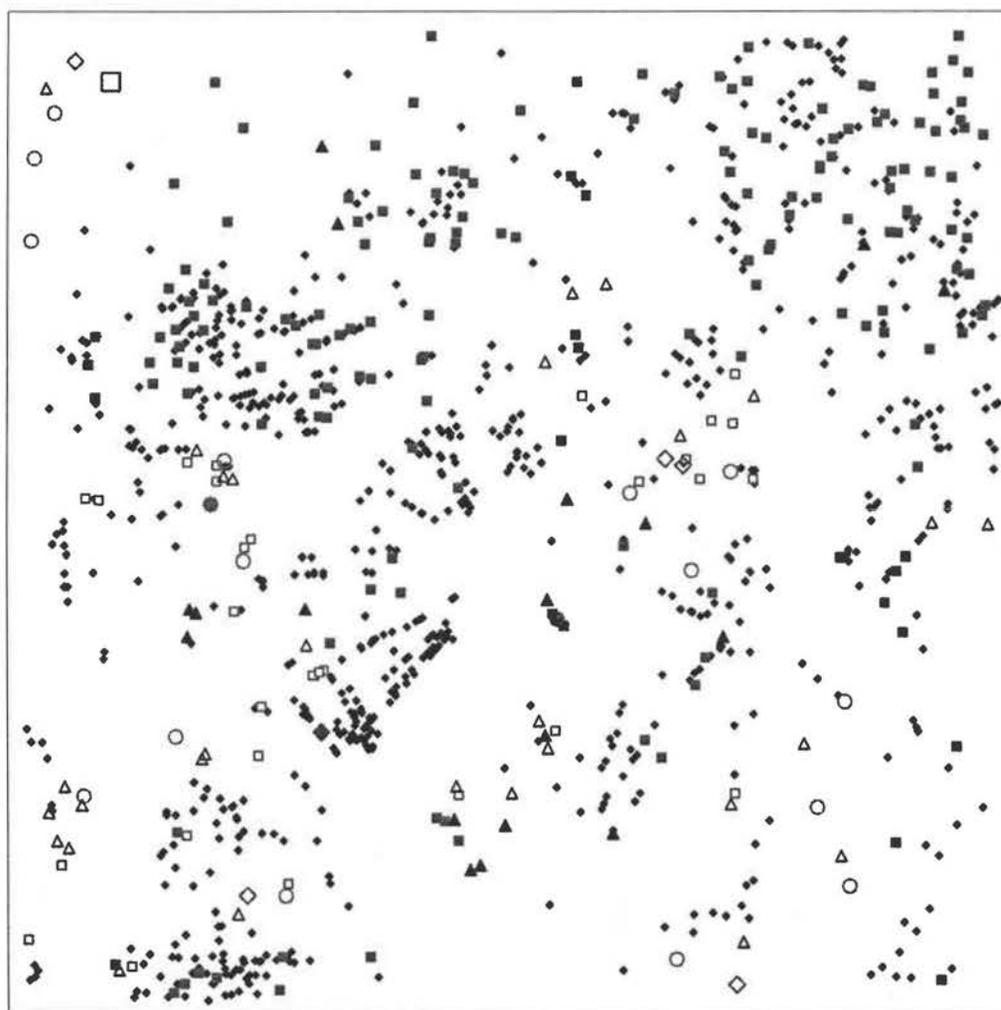
- <10 cm dbh
- Lodgepole: 10-20 cm dbh
- ▲ Lodgepole: 20-30 cm dbh
- Lodgepole: 30-40 cm dbh
- ◆ Lodgepole: 40-50 cm dbh
- ◻ Ponderosa: 10-20 cm dbh
- △ Ponderosa: 20-30 cm dbh
- Ponderosa: 30-40 cm dbh
- ◇ Ponderosa: 40-50 cm dbh

Figure A.7 Stem map, plot Blackrock medium (BM)



- <10 cm dbh
- Lodgepole: 10-20 cm dbh
- ▲ Lodgepole: 20-30 cm dbh
- Lodgepole: 30-40 cm dbh
- Ponderosa: 10-20 cm dbh
- △ Ponderosa: 20-30 cm dbh
- Ponderosa: 30-40 cm dbh
- ◇ Ponderosa: 40-50 cm dbh
- Ponderosa: >50 cm dbh

Figure A.8 Stem map, plot Blackrock high one (BH1)



- <10 cm dbh
- Lodgepole: 10-20 cm dbh
- ▲ Lodgepole: 20-30 cm dbh
- Lodgepole: 30-40 cm dbh
- ◆ Lodgepole: 40-50 cm dbh
- ◻ Ponderosa: 10-20 cm dbh
- △ Ponderosa: 20-30 cm dbh
- Ponderosa: 30-40 cm dbh
- ◇ Ponderosa: 40-50 cm dbh
- ◻ Ponderosa: >50 cm dbh

Figure A.9 Stem map, plot Blackrock high two (BH2)

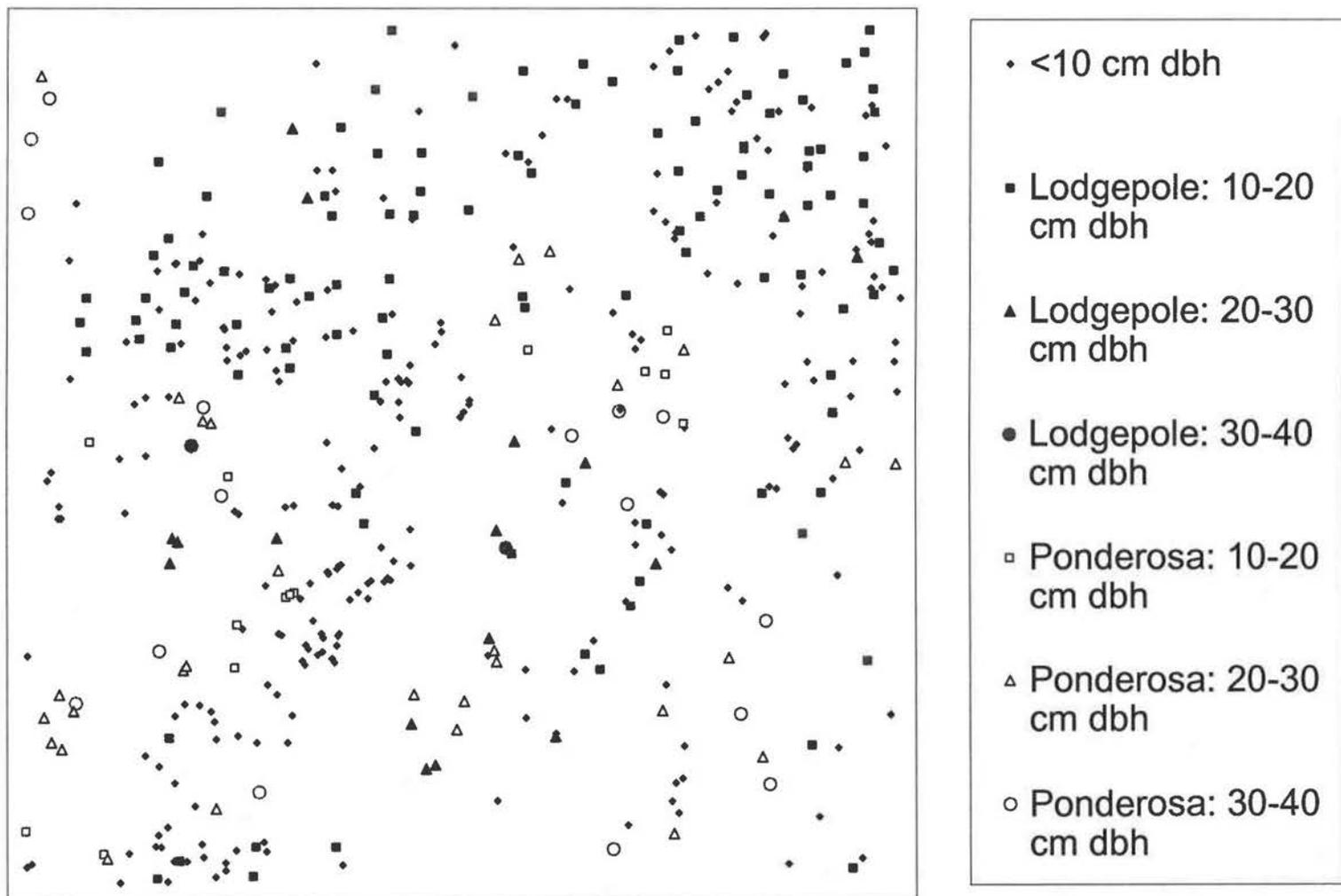


Figure A.10 Stem map, plt Blackrock high two, reverse-J target treatment

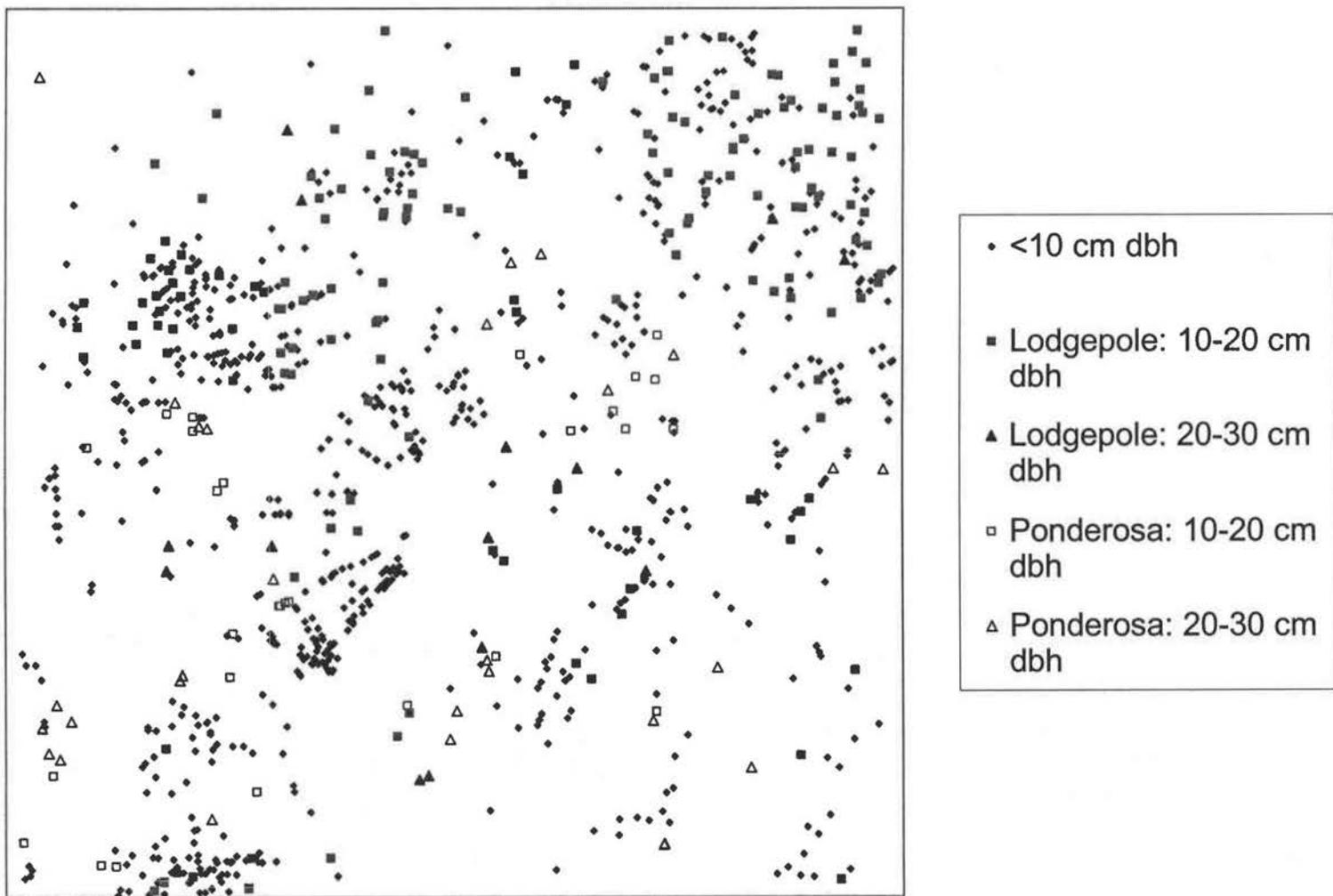


Figure A.11 Stem map, plot Blackrock high two, overstory reduction treatment

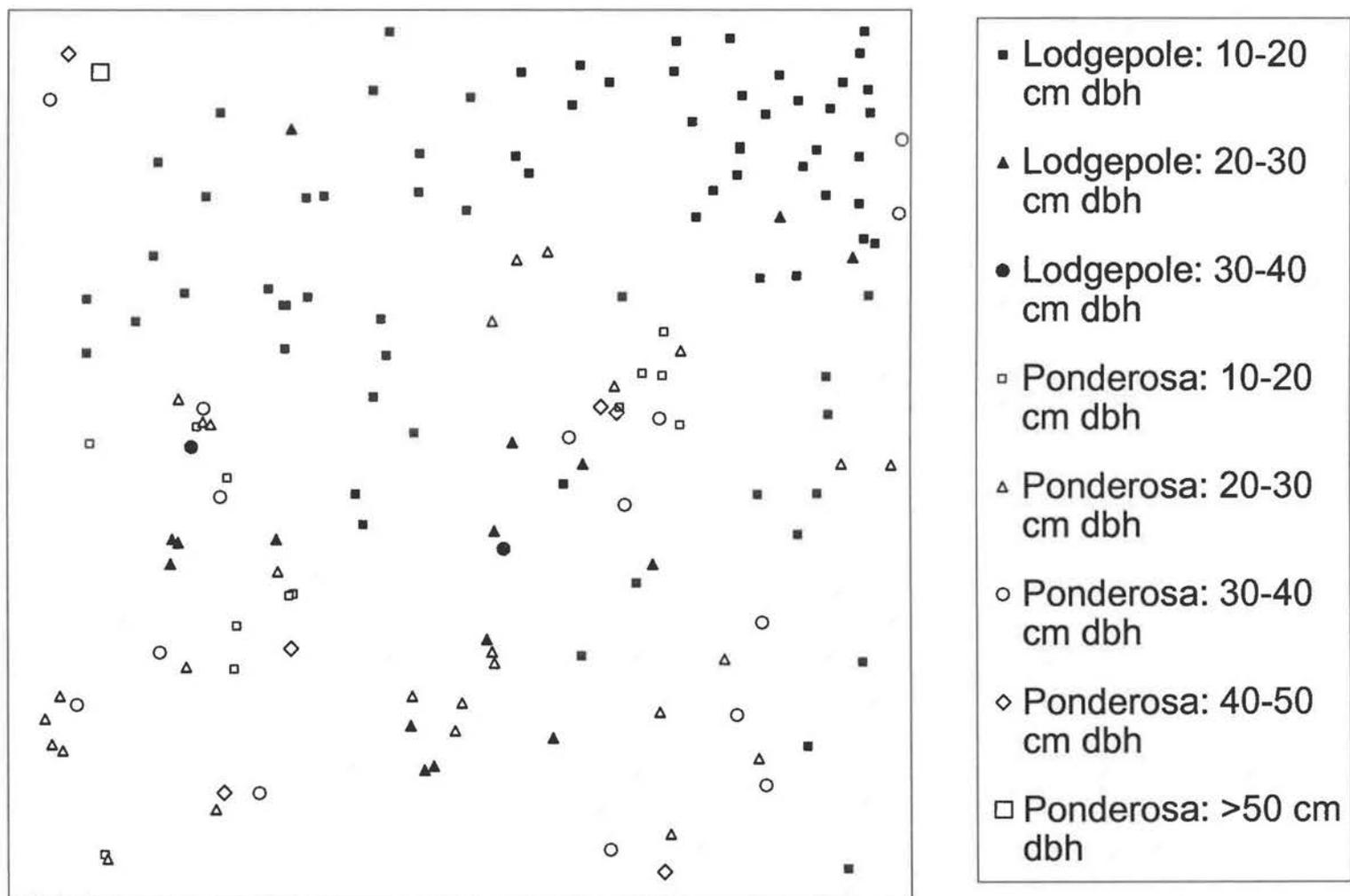
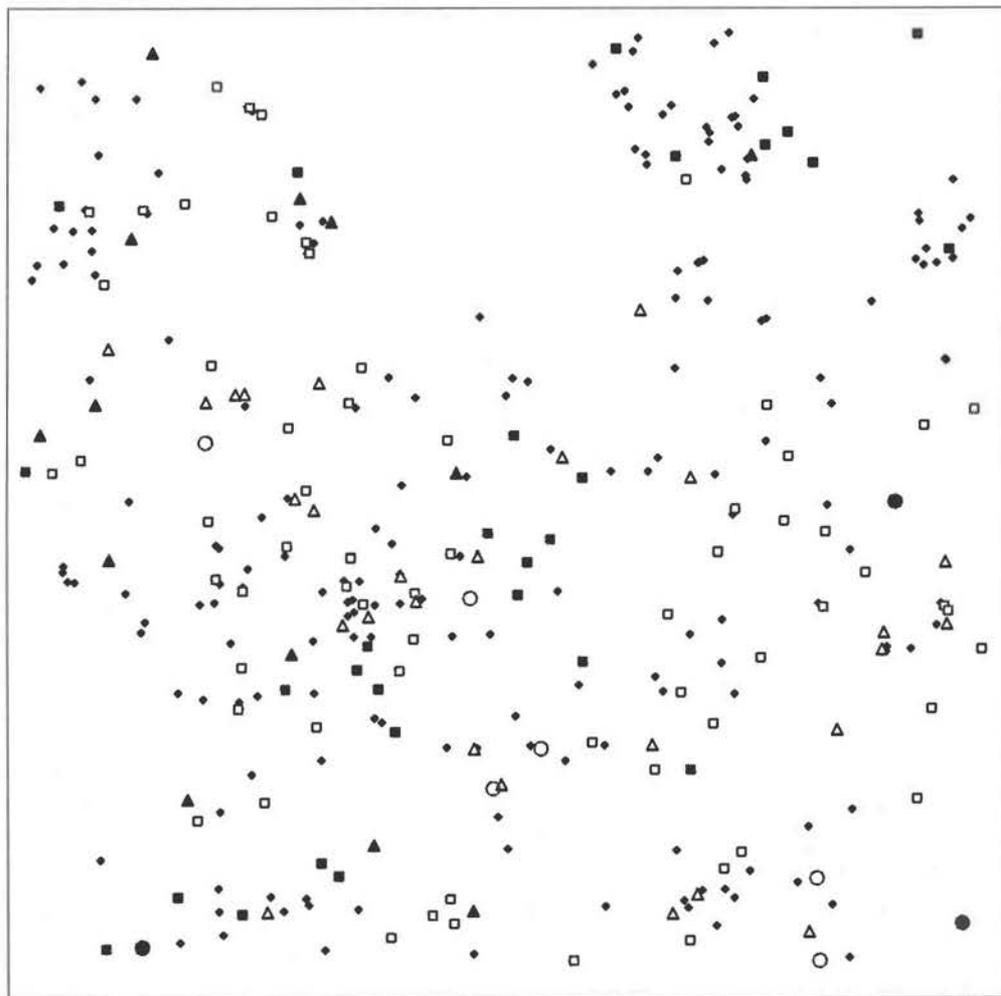
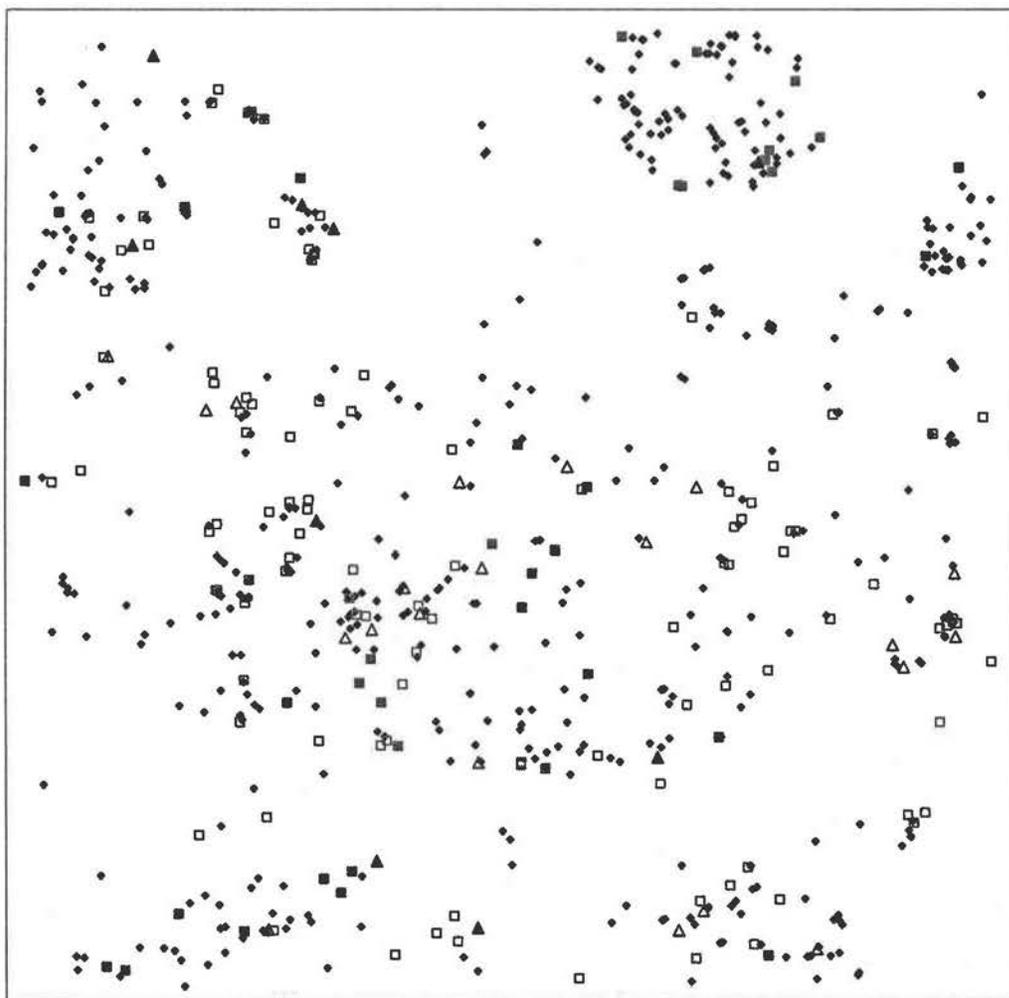


Figure A.12 Stem map, plot Blackrock high two, understory reduction treatment



- <10 cm dbh
- Lodgepole: 10-20 cm dbh
- ▲ Lodgepole: 20-30 cm dbh
- Lodgepole: 30-40 cm dbh
- ◻ Ponderosa: 10-20 cm dbh
- △ Ponderosa: 20-30 cm dbh
- Ponderosa: 30-40 cm dbh

Figure A.13 Stem map, plot Timbers high one, reverse-J target treatment



- <10 cm dbh
- Lodgepole: 10-20 cm dbh
- ▲ Lodgepole: 20-30 cm dbh
- ◻ Ponderosa: 10-20 cm dbh
- △ Ponderosa: 20-30 cm dbh

Figure A.14 Stem map, plot Timbers high one, overstory reduction treatment

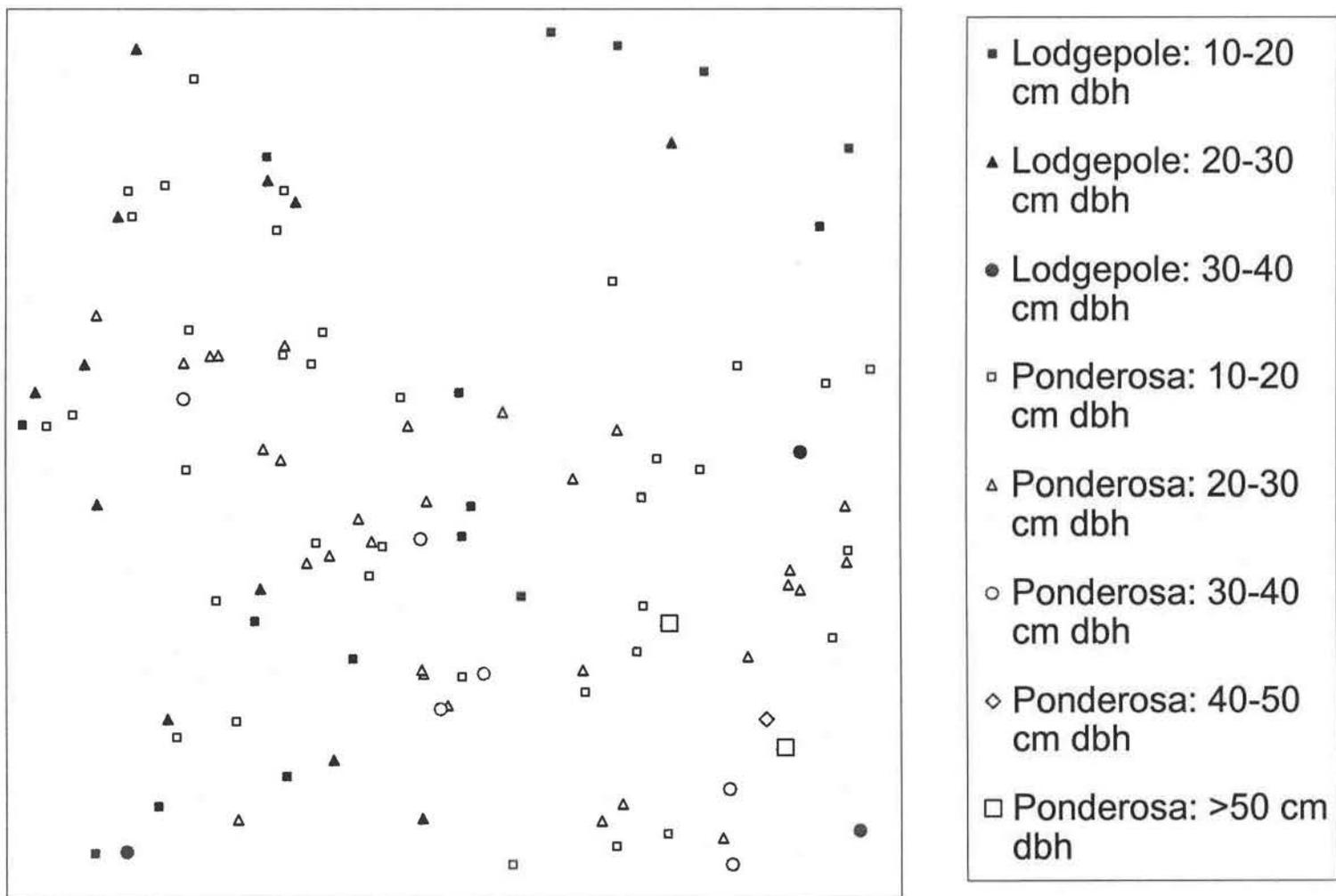
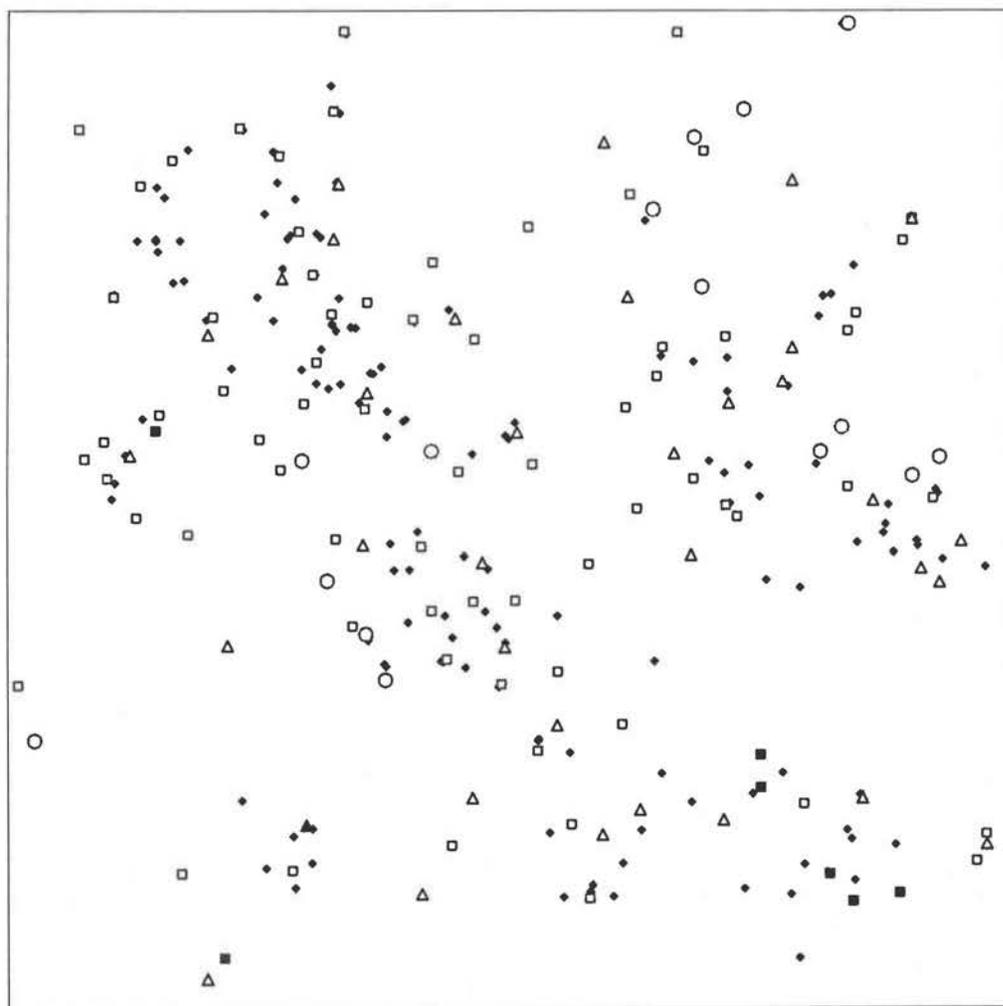


Figure A.15 Stem map, plot Timbers high one, understory reduction treatment



- <10 cm dbh
- Lodgepole: 10-20 cm dbh
- ▲ Lodgepole: 20-30 cm dbh
- ◻ Ponderosa: 10-20 cm dbh
- △ Ponderosa: 20-30 cm dbh
- Ponderosa: 30-40 cm dbh

Figure A.16 Stem map, plot Timbers high two, reverse-J target treatment

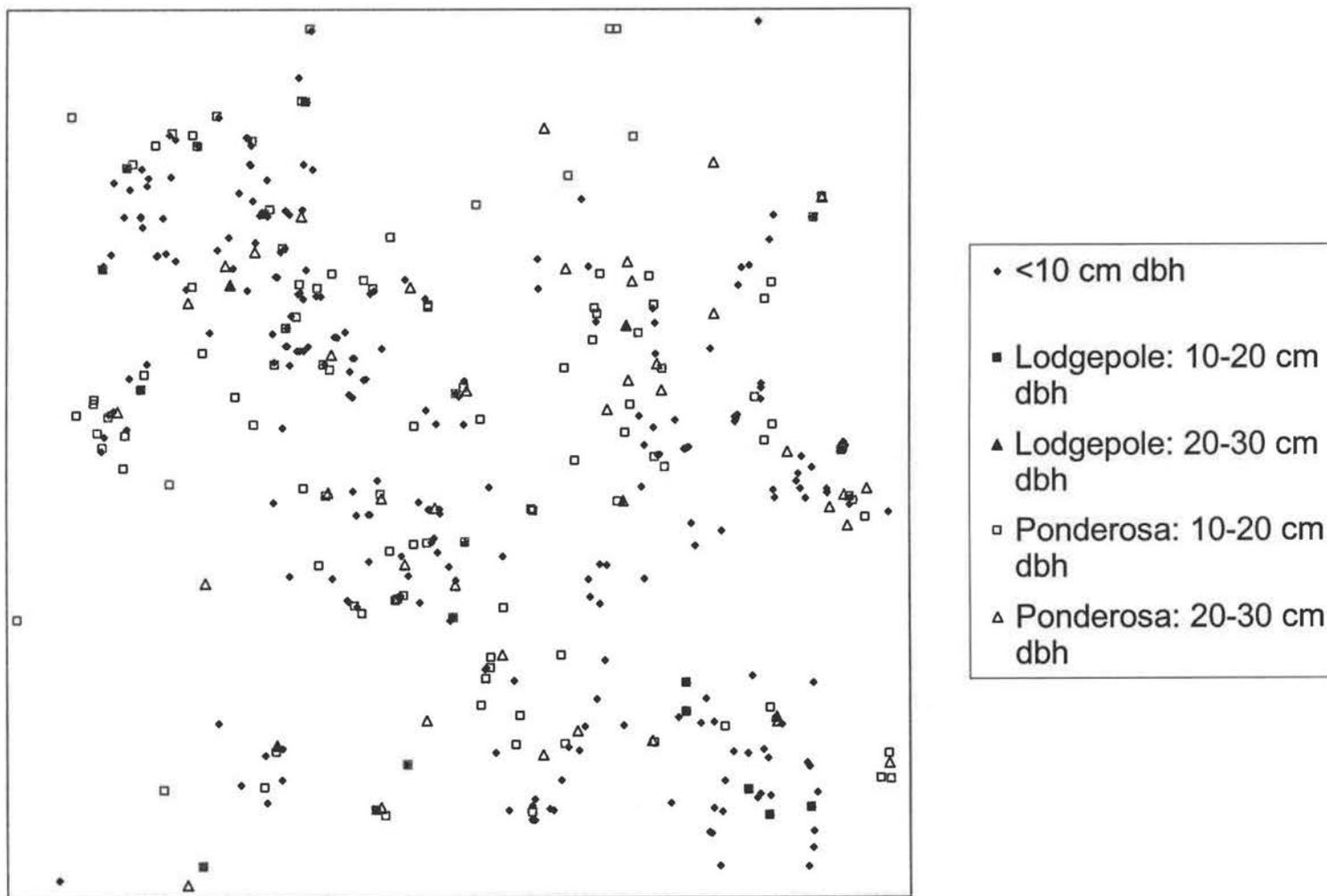


Figure A.17 Stem map, plot Timbers high two, overstory reduction treatment

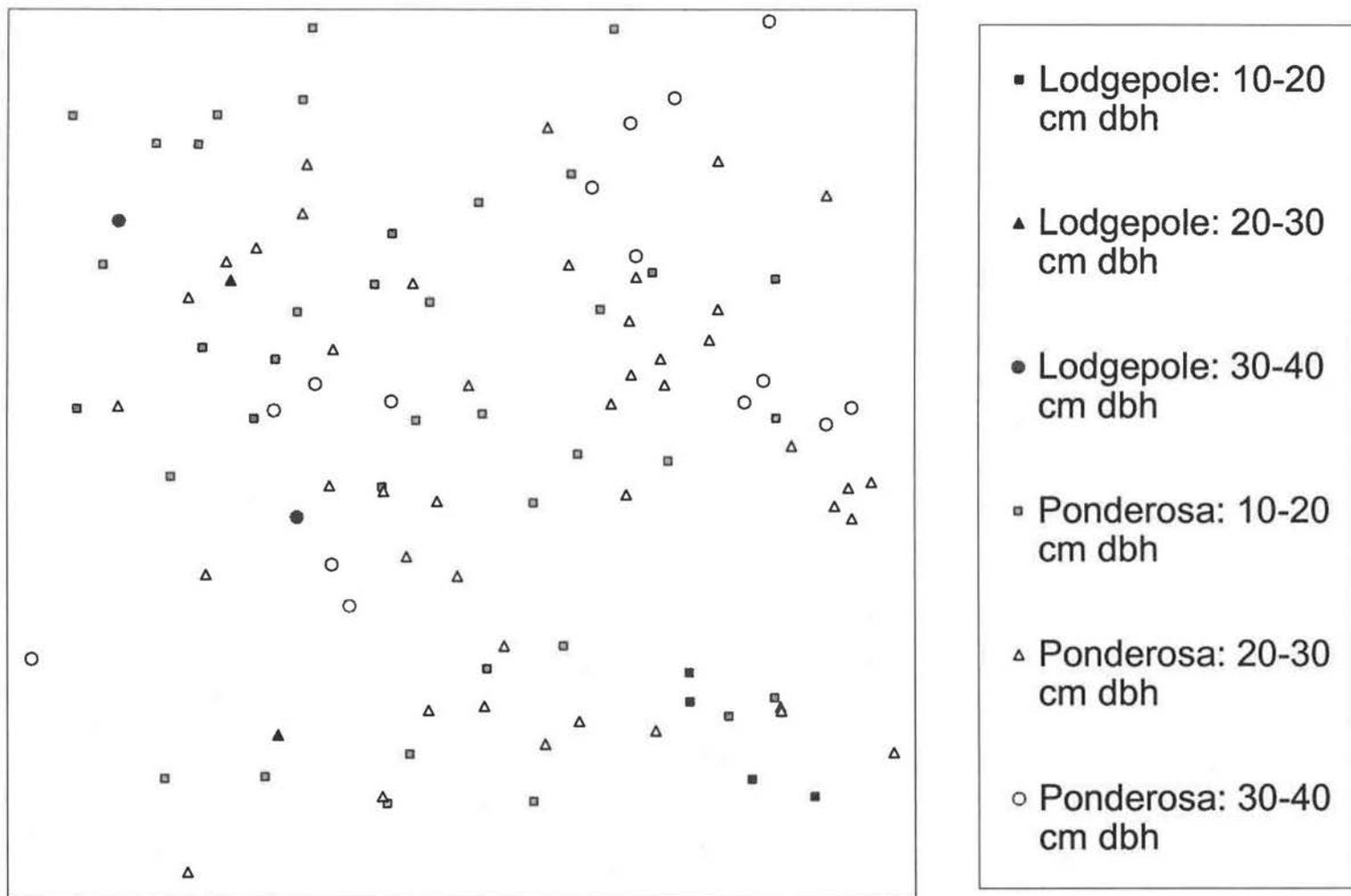


Figure A.18 Stem map, plot Timbers high two, understory reduction treatment