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Evaluating the growth basal area method as a tool for estimating site productivity in uneven-aged ponderosa pine stands

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EVALUATING THE GROWTH BASAL AREA METHOD AS A TOOL FOR ESTIMATING SITE PRODUCTIVITY IN UNEVEN-AGED PONDEROSA PINE STANDS

by

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Director: Carl Fiedler

The move toward ecosystem management requires foresters to manage for a diversity of forest structures, including uneven-aged stands. There are numerous knowledge gaps in the science of uneven-aged management. This has become evident in the area of estimating potential site productivity. There are many methods of appraising "site quality," but all fall short in uneven-aged conditions. Foresters need a method of estimating site quality in uneven-aged stands that is both dependable and practical. This study evaluated the Growth Basal Area method and variations thereof for estimating site productivity in uneven-aged stands. The GBA method has been used successfully in even-aged stands, and may have potential for application in uneven-aged stands. Numerous amendments and extensions of the GBA concept were explored including basal area and sapwood area as density measures, and fixed- and variable-radius plot estimates of competition around the subject tree. Hall's GBA approach was applied and amendments explored in eight uneven-aged ponderosa pine stands across Montana. The results suggest that Hall's method may not apply well in uneven-aged stands. There is a lack of evidence to support the strong relationship Hall found between GBA tree growth and surrounding density estimates. Amendments to Hall's method indicate that variable-radius plots may be more effective than fixed-radius plots for estimating the density of competition around GBA trees. Results also indicated that sapwood area density measures may be no more helpful than basal area measures, within Hall's approach. The variable of GBA tree sapwood area provided the greatest correlation with GBA tree basal area increment, and is recommended for consideration in future models. This study suggests that until uneven-aged stand dynamics are better quantified, Hall's approach has marginal utility in uneven-aged ponderosa pine stands.

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Table of Contents

List of Tables

List of Figures

List of Appendices

Introduction

Increased interest in uneven-aged silviculture, due to public pressures and the influence of ecosystem management, has exposed numerous knowledge gaps in the base of silvicultural information. The lack of a method to estimate site quality in uneven-aged stands is one such knowledge gap. Forest site quality has been defined as the productive capacity of forest land derived from tree measurements that express all the biological and environmental influences on tree growth (Schonau 1988). Accurate estimation of site quality is not only important for successful regeneration and maintenance of stand structure in uneven-aged stands, but also serves as a reference point for any forest management activities (Guldin 1995).

There are many methods of estimating site productivity. There is site index, which is the height of dominant trees at a certain base age. Site index has long been used as an indirect estimate of site quality in even-aged stands. However, application of site index in uneven-aged stands violates some of the underlying assumptions of the method (e.g. site trees should show no history of suppression, and site trees should be within 10 years of the same age) (Barrett 1978). Soil-site index is another approach, but poor soil series maps can lead to inaccurate estimates of site productivity (Carmean 1975). Habitat types, which use characteristics of understory vegetation as an indicator of site quality, have been utilized in forest management, but are hard to translate into stocking concepts (Pfister et al 1977). Finally, there are physiographic site classification methods which integrate climate, relief, soil profile, ground water, and communities of plants into one model (Carmean 1975). This can prove impractical for the average forest manager.

One possible alternative for gauging site potential in uneven-aged stands would be to determine the current radial growth increment of a "site" tree, and compare it to the level of competition being exerted upon it. At higher site qualities, this radial growth would increase in relation to a constant density surrounding the tree (assuming no change in tree size). One such method was developed in even-aged stands that examines the rate of radial growth in comparison to the competition surrounding the subject tree (Hall 1987). This method, called Growth Basal Area (GBA), might be applicable in uneven-aged stands. The GBA method could be amended both in terms of density measures (e.g. basal area and sapwood area), the sampling methods used to estimate density (e.g. variable- and fixed-radius plots), and the estimates of individual tree growth.

The objective of this study is to evaluate the GBA method as a tool for estimating site quality in uneven-aged stands. In addition, the plot sampling scheme of the GBA method will be changed to incorporate other sampling approaches. The heterogeneity of the uneven-aged structure suggests a combination of fixed- and variable-plot sampling methods, and recent work using sapwood area as a density measure suggests its use in uneven-aged stands (O'Hara and Valappil 1995, Stage and Rennie 1994). The specific objectives are as follows: 1) test the standard GBA approach as a method of estimating site quality in uneven-aged stands, 2) evaluate sapwood area and basal area as alternative measures of density derived from both fixed- and variable-radius plots within the framework of the GBA approach, and 3) compare site quality ratings as suggested by site index and soil series information to estimates developed in this study.

Since little work has been done on the subject of site quality in uneven-aged stands, an investigation of the GBA method could have great utility. This project can contribute to the knowledge base in uneven-aged silviculture by evaluating variations of the GBA method in the most promising directions, thereby narrowing the focus of future work.

Literature Review

Site Quality Assessment

Forest site quality has been defined as the productive capacity of forest land and is derived from tree measurements that express all the biological and environmental influences on tree growth (Schonau 1988). Site quality is most often used in reference to growth of dominant trees, since dominants have the most dollar value and are most directly influenced by the site. Foresters often measure tree growth and assume that it closely approximates the site's quality (McLeod and Running 1987). Forest site quality has therefore become synonymous with the ability of forest land to grow trees, where site quality estimation corresponds to the land's capability to grow various plants (Carmean 1975). Forest site quality is a nebulous concept to foresters, yet knowledge of this term is fundamental to sound forest practices everywhere (Gessel 1988).

Need for Site Quality Assessment

Site classification is used by foresters to identify productivity and provide a frame of reference for silvicultural diagnosis and prescriptions (Jones 1969). Site classification plays an even more crucial role in the management of uneven-aged ponderosa pine stands. At a broad level, management of any uneven-aged condition requires the proper level of vigorous growing stock, which is in turn based on site classification estimates (Cochran 1992). Successful application of any uneven-aged management scheme requires a commitment to regeneration, which is difficult in unhealthy, low vigor stands (Becker 1995). For uneven-aged methods of regeneration to be employed, an idea of poor and good sites needs to be known, so that appropriate reserve density levels can be prescribed

(Guldin 1995; Fiedler, Becker, and Haglund 1988). Knowledge of site, therefore is necessary in order to develop appropriate management prescriptions. Successful management of ponderosa pine for timber production depends on satisfactory knowledge of tree growth under various stand and site conditions (Schmid et al 1991). Uneven-aged management of ponderosa pine works hand in hand with disturbance, a situation where site quality rating will play a vital role in future management decisions (Powers and Oliver 1978).

Methods of Site Quality Assessment

There are many methods of estimating site quality. Growth of trees on a site is subject to many factors such as light intensity, light quality, soil moisture, life span of trees, available water, and soil fertility (Kozlowski 1971). Site classification is related to scales. At a broad scale, climate plays an important role in rating site quality, at increasingly narrower scales, vegetation and soil are more important (Gessel 1988). A holistic approach to site classification is a broad scale technique. A model of the environment is developed classifying the environment as a whole (Jones 1969). There is the physiographic site classification method which considers the total site, integrating climate, relief, geological materials, soil profile, ground water, communities of plants, and humans into a complex model (Carmean 1975). At small scales, vegetation reflects the sum of all environmental elements that are important to plants (Gessel 1988). The productive capacity of a site can be estimated from either tree growth or site attributes, such as understory vegetation (Jones 1969, Pfister et al 1977, Gessel 1988). Site quality can be estimated from height data. For example, the growth intercept method uses periodic height growth in young trees as an index of site quality, rather than overall height at a given age (Carmean 1975). Site quality can also be estimated from vegetational characteristics only, such as with habitat types

(Jones 1969, Pfister et al 1977).

For even-aged stands beyond the sapling stage, the site index method of site quality estimation is widely used. Site index provides an estimate of site quality based on height and age measurements from free growing, uninjured, dominant or codominant trees. These measurements are used with a family of height-age curves to estimate total height of trees at an index age (Carmean 1975). The basic assumption in site index is that height growth is mostly free from the effects of density, in addition to being closely associated with volume growth in normally stocked stands (Carmean 1975, Jones 1969). The height of the dominant or tallest portion of the stand is the one measure of growth most independent of stand factors and therefore most reliable for site evaluation (Barrett 1978, Monserud 1984). Required characteristics of site index trees include: even-aged within ten years, no disease symptoms, no fine ring groups that would indicate suppression, internodal lengths consistent on taller trees, and no remnant understory that would indicate early competition (Barrett 1978). The site index method should only be used when current age and total height are known (Farr 1984).

A common shortcoming of site index curves is that they assume the same height growth patterns for all site indexes (Barrett 1983). Two Douglas-fir stands in Washington were used to evaluate this lack of detail in site index curves. Each of the stands had similar heights at index age 100, but differed in height at age 20 by 2:1 (Jones 1969). Site index curves often follow a harmonic growth pattern where growth curves are assumed the same for all site qualities (Carmean 1975). However, recent utilization of stem analysis techniques to develop polymorphic growth curves have eliminated some errors associated with site index (Monserud 1984). Another flaw with site index is its basic assumption that height growth is not affected by density, even though it has been shown with Douglas-fir and ponderosa pine that dense stocking can cause stagnation and slowed height growth (Jones 1969). Ponderosa pine is so affected by stocking that in some areas two sets of site index curves have been developed for two levels of stocking (Jones 1969, Barrett 1978, Powers and Oliver 1978). In addition to stagnation, many other factors can cause variability in site index estimates. If only dominant trees are sampled, then overestimation of site quality can occur when using site index curves developed from dominant and codominant trees. Initial height growth can be suppressed by shrubs or animals, and genetics can cause unexplained variation (Carmean 1975). Although not free from faults, site index likely remains the most utilized measure of site quality in forest stands.

Site Quality Assessment in Uneven-aged Stands

There are few developed methods of site quality estimation in uneven-aged stands. Site index has been used in uneven-aged stands to some extent. Unfortunately, many of the previously discussed requirements for the application of site index methods are violated by the very nature and structure of uneven-aged stands (Monserud 1984). Site index was meant for use in even-aged stands. In uneven-aged stands, age has a nebulous meaning (Moser and Hall 1969). Almost every tree in an uneven-aged stand has experienced competition from above or below which would cause almost all trees in an uneven-aged stand to be rejected as site index trees (Powers et al 1978). What is needed in uneven-aged stands is site estimation procedures not solely dependent on height growth of "site" trees. Adjustments for suppression effects need to be taken into account in uneven-aged stands, especially where potential stocking is limited (Phares 1978). Specifically, a site classification method needs to be developed that incorporates the characteristics of uneven-aged stands instead of adjusting for them.

Alternatives for Site Quality Estimation in Uneven-aged Stands

Certain stand attributes hold promise as measures of site quality in uneven-aged stands. Stand basal area has been shown to be closely tied to soils and topographic conditions. Estimates of stand basal area sometimes have paralleled site productivity estimates, occasionally better than site index (Fralish 1994). One study of a 50-year-old even-aged hardwood stand found that biomass was more strongly related to basal area than site index (Wiant et al 1984). Even as early as 1944, using stand basal area with site index was found to greatly improve site quality estimations (Gevorkiantz and Scholz 1944). In uneven-aged conditions where disturbance is common, stand basal area can reach pre-disturbance levels quickly, whereas height will never reach a maximum (Fralish 1994). In stands with uneven-aged structures, basal area data may be more useful than site index information (Bates, Robert, and Blinn 1992).

The most direct measure of site quality is the quantity of wood grown on an area of land within a given period (Schmoldt, Martin, and Bockheim 1985). Periodic growth in total stem volume has been shown to be strongly related to growing stock level at all times in a stand's history (Barrett 1983). Correlations have been found between volume increment and site index, for stands of the same age (McLeod and Running 1987). The application of radial increments of individual tree growth to rating site potential productivity appear highly promising, even more so in uneven-aged stands (Hall 1983). Not only can growth increments gauge potential productivity possibly better than site index, it works in terms that future timber management will deal with, such as volume growth per year (Murphy and Farrar 1985).

Leaf area index is a measure of foliage area representing all of the upper surface of leaves projected downward to a unit area of ground beneath the canopy (Waring and Schlesinger 1985). Strong linear and positive relationships have been established between productivity and leaf area index (Vose and Allen 1988). A combination of recent total volume growth and leaf area can produce indices known as growth efficiency. Growth efficiency simply is the stemwood production per unit of leaf area. It can be estimated by calculating the ratio of annual growth to potential radiation absorption (Kaufmann and Ryan 1986). In uneven-aged stands, total volume, leaf area, and periodic growth could potentially be combined into a measure of site quality.

The Growth Basal Area Method

Hall (1983) developed a method called Growth Basal Area (GBA), which uses radial increment and competition to determine stockability. Growth Basal Area is defined by Hall as, "a field method for determining site quality limitations on stockability." In a more technical sense, GBA is the basal area at which dominant trees will grow one inch in diameter per decade. The basic concept of GBA is that stand growth will reflect site potential for stockability. Diameter growth of one inch per decade was selected as the growth rate index to evaluate stockability and to create a prediction curve, not as a maximum or minimum thinning guide. The assumptions of GBA are: diameter growth indexes competition, change in GBA over time is related to stand age, and rate of diameter growth is assumed to index intertree competition (if diameter growth rate is declining). Hall's (1983) GBA concept was based on observations of ring width pattern in even-aged forests. The initial rapid growth of young trees, followed by slowing diameter increment, and lack of mortality, suggested that the rate of diameter growth decreased with increasing stand density as estimated by basal area. Subsequently, Hall (1983) explored using basal area as a variable to index stockability of a site with rate of diameter growth as a constant to compare sites. A system was created to convert current diameter growth to the index rate of one inch/decade with a concurrent adjustment in current basal area that would result in one inch per decade. A site with 150 square feet GBA means dominant trees will grow one inch per decade when stand basal area is 150 square feet. In contrast, a site with a rating of GBA 300 has twice the stockability because dominants will grow one inch per decade at 300 square feet of basal area. Site index and GBA address the problem of rating site quality in different ways. Site index and GBA are based on different aspects of tree growth, and therefore appear to be somewhat independent of each other.

As the GBA method is currently defined, it can be applied to uneven-aged stands. However, alterations to various GBA components can be proposed. For example, the importance of radial growth increment in the GBA approach is questionable in uneven-aged stands. Radial growth increment is in part dependent upon the diameter of the tree, stand age, and crown size (Wykoff, Crookston, and Stage 1982) -- all of which are highly variable in uneven-aged stands. Use of basal area growth increment of the GBA tree instead of radial increment as the dependent variable adjusts for tree size. In addition, the GBA method uses a variable-radius plot sampling approach to determine stand basal area. The heterogeneity of uneven-aged stands makes sampling of stand basal area a more complicated task, where one variable-radius plot estimate of basal area competition around each GBA tree may not suffice (Hall 1987b). In addition to the sampling scheme, alternatives to basal area as a density measure could also be evaluated. Recent research indicates that sapwood area may be a more refined density measure than basal area in uneven-aged stands (O'Hara and Valappil 1995b).

Sapwood Area in Uneven-Aged Stands

Sapwood area is one alteration to the GBA method which could be highly promising. In recent years, sapwood area has been shown to be a valuable measure of density in silvicultural applications. Its success is in part due to its strong correlation with leaf area.

The relationship is expressed in the pipe stem model, reflecting a linear relationship between foliage biomass and sapwood cross sectional area (Makela et al 1995, Waring et al 1982). This relationship has been found to be particularily strong within individual stands (Makela 1995). The sapwood/heartwood proportion in stems can be seen as a balance between two functions: mechanical support of the crown and water supply to foliage (Sellin 1994). During a tree's life span, sapwood will usually increase (in non-suppressed conditions) till it levels out at a certain age, although some studies have suggested that sapwood is more related to diameter than age (Sellin 1994). It follows that there is more sapwood in dominant trees than in suppressed trees, due to the crown position and class (Sellin 1994). For uneven-aged stands, the leaf area/sapwood area relationship follows a similar pattern for all social classes of trees: suppressed, intermediate, and codominant (Robichaud and Methven 1992). Makela (et al. 1995) found that site index did not influence the relationship between sapwood area and leaf area in even-aged stands, while another study (Coyea and Margolis, 1992) reported that site index did affect this relationship.

Leaf area is key to ecological studies of both individual trees and forest stands (Coyea and Margolis 1992). Because of its close relationship to leaf area, sapwood area has found utility in developing stocking guidelines for uneven-aged forests (O'Hara and Valappil 1995). What makes sapwood so attractive is its relative ease of measurement, when compared to leaf area. Leaf area can be well predicted from sapwood measurements taken directly below the crown, with accuracy decreasing slightly as samples are taken further down the bole (Makela et al 1995). Although sapwood area is a relatively new density measure for silviculturists, it has considerable potential for use in site quality evaluation, especially in uneven-aged stands.

Sampling for GBA in Uneven-Aged Stands

The heterogeneity of uneven-aged stand structures complicates the task of sampling stand data. Although there is little information concerning sampling designs to gauge competition on an individual tree in uneven-aged stands, there is some literature pertaining to the broader topic of uneven-aged sampling designs. Stand structure is an important consideration when designing sampling schemes in uneven-aged stands (Murphy and Farrar 1981). For example, the size and/or number of plots need to be related to the variability encountered in the stand (Murphy and Farrar 1981).

Since the GBA method was developed for application in even-aged stands, the associated sampling scheme is one commonly used in even-aged stands (variable-radius plot estimation of basal area density). An accurate estimate of the density around each GBA tree needs to be acquired for application of the GBA method. Point sampling (variable-radius plots) is an unequal probability selection process where larger trees have a higher probability of selection i.e., probability proportional to size (Shiver and Borders 1996). In the workup of the data, bias is removed, since there are fewer large trees per acre and more smaller trees (Shiver and Borders 1996). When growth is important, the relationship of basal area increment to basal area of individual trees makes variable-radius designs more efficient (Stage and Rennie 1994). Variable-radius plot sampling offers greater flexibility for achieving better biological representation of stand conditions and increased statistical efficiency, important attributes in the uneven-aged condition (Stage and Rennie 1994).

With fixed-radius plots in uneven-aged stands, the question is how large to make them to accurately represent structure yet maximize efficiency (Murphy and Farrar 1981). With fixed-radius plots, basal area growth has been shown to be consistent with changes that occurred in tree frequency by diameter class (Thomas and Parresol 1989). When using fixed-radius plot sampling, all trees have the same area of influence as opposed to variable-plot sampling (Stage and Rennie 1994). There appears to be more statistical efficiency by combining fixed-radius plots for sampling small DBH's, and variable-radius plots for larger DBH classes (Stage and Rennie 1994). Thus, there are some options available for modifying the GBA sampling approach to efficiently and accurately accommodate the structure of uneven-aged stands.

Methods

Selection of Sampling Sites

The initial selection of study sites involved finding well stocked, relatively undisturbed, uneven-aged ponderosa pine stands across the state of Montana. Three such sites were located in eastern Montana, and five in western Montana (Appendix 1). Stands selected for sampling met the following criteria: uneven-aged structure, nearly pure ponderosa pine species composition, low levels of mortality, lack of management activities, and absence of severe natural disturbances. As much as possible, sites were selected to represent a reasonable range of site qualities, from low to moderately high

Field Procedures

At each site, field procedures involved the installation of GBA plots and amendments, which consisted mainly of variable- and fixed-radius plot sampling of basal area and sapwood area (Appendix 2).

GBA Tree Selection: The first task at each location was the selection of appropriate GBA trees. Four or five trees were selected at each location that met the following criteria: full crown, upper canopy position, absence of insect/disease damage, modest to heavy level of surrounding competition, and absence of mortality in tree's vicinity.

GBA Tree Measurement: Each GBA tree was cored to its pith at breast height for subsequent age and growth increment determination. In addition, diameter at breast height (DBH) was taken to the nearest tenth of an inch, and height measured to the nearest foot.

Variable-Radius Plots: With each GBA tree serving as plot center, a 10-BAF variable-radius plot was established (Appendix 2). A 10-BAF prism was chosen because 6 to 12 "in" trees were recommended by the GBA method. The prism wedge was held close to the trunk of each GBA tree and swept clockwise for "in" tree determination. All borderline trees were measured for diameter and distance from plot center to determine their status as "in" or "out" trees. Only trees greater than 5.0 inches in DBH were sampled as potential "in" trees. All "in" trees were recorded by species, cored at DBH to determine width of sapwood, and measured for diameter. The sapwood/heartwood boundary on each core was marked with a pen. All cores were then inserted into straws for further analysis in the laboratory.

Fixed-Radius Plots: A circular fixed plot was installed around each GBA tree, once again using the GBA tree as plot center. The plot was 1/30-acre in size (21.5-foot radius), and was used to sample all trees greater than 0.6 inches in diameter. The procedure applied to all variable plot "in" trees was also applied to "in" trees in the fixed plots. However, increment cores were only taken from trees greater than 2.0 inches in diameter in each fixed plot.

Site Index: Two site index trees were selected at each location (in addition, the GBA trees could also be used as site index trees if little suppression occurred in their past). Site index trees were selected on the basis of vigorous open growth in the uneven-aged stand. The objective was to avoid trees that had been suppressed in the past. Site trees were selected by observing the structure around the tree of interest, along with the growth of the tree itself. Site trees were measured to the nearest 0.1 inch for diameter, to the nearest foot for height, and cored to the pith for age. In addition to tree measures as indicators of site quality, soil series was also determined at each location using soil survey maps. Habitat types were determined from subsequent discussion with area land managers.

Laboratory Procedures

Laboratory analysis focused on the increment cores collected in the field. The sapwood radius of each core was measured to the nearest millimeter under a UV light. The UV light reaffirmed the sapwood boundary marked in the field. Increment cores from GBA trees were also measured for five- and ten-year radial growth increment. A "Mideo Systems" ring reader was used to measure radial growth increment to the nearest 0.01 inch. The age at breast height of site index and GBA trees was determined from increment cores using a "Lintech" ring reader.

Data Summary and Analysis Methods

Summary procedures involved calculating the basal area increment of each GBA tree and the corresponding variable- and fixed-radius plot estimates of sapwood area and basal area surrounding each GBA tree.

Basal Area Increment Calculation: The radius at breast height inside bark was calculated to 0.01 inch, using field measured DBH and a double bark thickness equation (Faurot 1977). Next, the DBH radius had the measured radial increment subtracted from it, resulting in the creation of two radii. The two radii were used to calculate the area in square inches of two separate circles, with basal area increment equalling the difference between the two. The resulting value was the cross sectional area in square inches of five- or ten-year growth at breast height for GBA trees (Appendix 3).

Sapwood Area Calculation: The sapwood area was calculated in the same manner as basal area increment. The diameter inside bark was calculated to the nearest millimeter, then had the sapwood radius in millimeters subtracted from it. These two radii were used to calculate the area in square centimeters of two circles. One of these circles was the cross sectional area of the tree, inside bark. The other circle was the cross-sectional area of the heartwood. The difference in cross-sectional area of the two circles provided an estimate of sapwood area, in square centimeters.

Site Index Calculation: Site index was calculated using tree age (breast height), total height data, and the appropriate equation for ponderosa pine (Milner 1992).

GBA Calculation: Past 10-year radial increment, measured to the nearest 0.01 inch, was converted to 20ths of an inch. This radial growth measurement for each GBA tree, along with the average stand basal area at each location, was used to calculate a GBA measure (Hall's 1983 method). The GBA measure was in turn converted to a base-age 100 value.

Basal Area and Sapwood Area Summary: For each plot, basal area and sapwood area for all individual trees were expanded and summed, resulting in a basal area and sapwood area per acre value. For the variable-radius plot, individual tree sapwood area values were also summed but not expanded to a per acre value. Both basal area and sapwood area per acre were also calculated for the 21.5 foot fixed-radius plot.

Data Analysis: The primary objective of data analysis was to evaluate the GBA approach as a method for estimating site in uneven-aged stands, with secondary objectives pertaining to the evaluation of GBA amendments for this purpose. The first step was to acquire a general understanding of where sites ranked relative to site quality. Then sites were stratified as to high, medium, or low site quality. Next, Hall's (1983) method was used in a strict sense. GBA results were then evaluated on the basis of their reasonability and comparison to other "site" measures.

After Hall's GBA method was evaluated, regression analysis was begun. There were two dependent variables in this study: 5- and 10-year basal area increment. There were seven independent variables in this study: non-expanded variable-radius sapwood area, expanded variable-radius sapwood area, variable-radius basal area, fixed-radius sapwood area, fixed-radius basal area, DBH, and GBA tree basal area. The objective of the regression analysis was to determine whether significant amounts of variation in basal area increments of the GBA trees could be explained by alternative measures of competition. If effects of competition on individual tree growth can be quantified, then a significant amount of the variation that is left should be attributable to site quality (barring large contributions from other factors such as microsites or genetics).

Plots of the relationship between each dependent variable and independent variable were examined for distribution characteristics. Next, simple linear regression was performed using the stratified samples of high, medium, and low quality sites. Sites were stratified on the basis of physical location, site index values, and sapwood area values. The three site quality classes were then used to code variables for dummy regression. Under assumptions of the GBA approach, the y-intercept of the growth/density relationships should vary with site quality, but the slopes should remain the same. After regressions were executed for all combinations of dependent and independent variables, comparison of the models began. Regression diagnostics such as R-squareds, p-values, coefficients, and standard errors were used to compare all amendments of the GBA approach. Results of data analysis using simple linear regression and dummy regression can provide insights for future efforts to model site quality relationships in uneven-aged stands.

Sampling Site Descriptions

1. Tullock Creek: This site was located in eastern Montana near the town of Custer. It had a northerly aspect, and a slope between 15 and 18 percent. Soils were classified as Travessila Tullock fine sandy loam series (USDA SCS 1967). The stand was nearly pure ponderosa pine, with some juniper in the understory. It possessed a diverse uneven-aged structure, with a fair amount of regeneration. The habitat type of this site was *Pinus ponderosa/Festuca idahoensis* (Pfister et al. 1977). This stand showed little evidence of human activity, and was likely only entered to high grade a few logs for ranching purposes, if at all (Wheeler 1997).

2. Y-Bar Coulee: This site was located in eastern Montana, east of the city of Roundup. It had a southerly aspect and a slope of 15 to 17 percent. Soils were classified as a Flasher loamy series (USDA SCS 1939). The stand was nearly pure ponderosa pine. This site had limited regeneration but a good uneven-aged structure (broad distribution of size classes). The site was classified as a *Pinus ponderosa/Agropyron spicatum* habitat type (Pfister et al. 1977). Stand history was little related to human activity, with only a few trees removed years ago for ranching purposes, if at all (Wheeler 1997)

3. Silver Bullet: This site was located in eastern Montana, near the city of Roundup along the Mussellshell River. It had a predominantly northerly aspect and a slope of between 10 and 12 percent. Soils were classified as a Flasher loamy series (USDA SCS 1939). The stand was nearly pure ponderosa pine, with a very broad distribution of diameter classes. A disturbance some decades ago damaged numerous larger trees. Since this damage had occurred long ago (evidenced by a crook at about two-thirds total height), it was considered to have little effect. The site was classified as a *Pinus ponderosa/Festuca idahoensis* habitat type (Pfister et al. 1977). The history of this stand was very similar to the other two eastern Montana sites, with the exception that a few small diameter trees were removed about 40 years ago, most likely for corral poles (Wheeler 1997).

4. Potter Ranch: This site was located in western Montana on a ranch near Lubrecht Experimental Forest and the Blackfoot River. The site was nearly level, with a very slight eastern aspect. Soils at this site were classified as Winkler gravelly loam, cool (USDA SCS 1995). The species composition of this stand was predominantly ponderosa pine, with a few Douglas-fir in smaller diameter classes. The habitat type of this site was *Pseudotsuga menziesii/Vaccinium caespitosum* (Pfister et al. 1977). This site was selectively cut when the valley was settled, around 1900. Since 1915, the area has been entered only rarely for the salvage of individual trees (Goetz 1997).

5. Lick Creek: Lick Creek is located above Lake Como in the Bitterroot Mountains of western Montana, near the town of Darby. The site has a southerly aspect with slopes between 25 and 30 percent. Soils were classified as a woodside very stony sandy loam steep (USDA SCS 1959). The stand was nearly pure ponderosa pine, with just a few Douglas-fir in the smaller diameter classes. The habitat type was *Pseudotsuga menziesii/Calamagrostis rubescens, Pinus ponderosa phase* (Pfister et al. 1977). The stand had regeneration in canopy openings with high structural diversity resulting from its balanced, uneven-aged condition. The area was selectively logged between 1906 and 1910. How many trees were left after this event is not known, although many of the larger trees on the site predate that logging event. Scattered activities have occurred in the area since that time, with the last in 1962 (Menakis 1994).

6. Nine Mile: This site was located in western Montana, near Interstate 90 at the USFS Ninemile Ranger Station exit. It was nearly level, with a very slight southerly aspect. Soils were classified as Winkler very gravelly sandy loam series (USDA SCS 1995). The species composition was nearly pure ponderosa pine. This stand had regeneration in openings, and a modest diversity of diameter classes in its uneven-aged condition. The habitat type of this site is *Pinus ponderosa/Agropyron spicatum* (Pfister et al. 1977). The area was extensively logged around 1900 during European/American settlement of the valley and construction of the railroad along the Clark Fork River

(Slaughter 1997).

7. Superior: This stand was located in western Montana, near the Interstate 90 rest area 7 miles east of Superior. Soils at this site were classified as Krause Association gently sloping (USDA SCS 1979). The site was nearly level, with a slight easterly aspect. Species composition of this stand was nearly pure ponderosa pine, with a few scattered Douglas-fir. The distribution of diameter classes was very patchy, with lack of regeneration in the openings between patches. The habitat type of this site was *Pseudotsuga menziesii/Agropyron spicatum* (Pfister et al. 1977). The history of this site is related to high-grade logging, which occurred along the Clark Fork at the turn of the century. There has been no major disturbance to the site since (Martin 1997).

8. Tarkio: This site was located in western Montana near the Tarkio exit of Interstate 90. The stand was about 0.2 miles from the Clark Fork. Soils were classified as Krause gravelly loam (USDA SCS 1979). The site had a gentle slope (0 to 4 percent) with a south aspect. Species composition was nearly pure ponderosa pine, with patchy distribution and heavy regeneration in all openings. The habitat type of this site was classified as a *Pseudotsuga menziesii/Calamagrostis rubescens, Arctostaphylos uva-ursi phase* (Pfister et al. 1977). Stand history is similar to the other two sites along the Clark Fork (Slaughter 1997).

Results and Discussion

Quantification of Site Quality

For the purpose of data analysis, a broad estimate of the site quality of all locations had to be ascertained. Since there was no way of knowing the exact site quality of the separate locations, numerous measures of site quality estimation were explored. For each location, site index data were examined (Table 1). Site index, as discussed previously, could be considered a questionable measure of site quality in uneven-aged stands. Cores extracted from "site" trees nearly always revealed past suppression (Appendix 4). Even cores taken from vigorous trees that were growing in openings showed periods of suppression in their ring patterns. Despite this problem, site index still could be correlated with relative site quality observed in the field. Location seven, which appeared to have the highest site quality, also had the highest site index (Table 1). Until an adequate replacement is found, site index could be the means of choice for site quality ranking in uneven-aged stands.

The site index measures were compared with other reasonable measures of site quality: sapwood area density, basal area density, growth efficiency, and soil series (Table 2). Sapwood area and basal area densities appeared to be in agreement with the site index results (Table 2). It was thought that sapwood area density would best reflect site quality, since sapwood area is closely correlated to leaf area on a site. The soil series rankings were not consistent with the rankings based on other measures of site quality. Location four had the highest site quality according to the soil series information. Locations five and seven were considered medium quality through interpretation of the soil series results.

Locations five and seven were estimated to have the highest site quality, while locations one and two were rated lowest. The rest of the locations were estimated to be medium site quality. Table 2 was used in data analysis when some form of site quality ranking was

Table 1. Site index estimates, by location.

Location Number	Site Index (Base Age Fifty)
1 Tullock Creek	32
2 Y-Bar Coulee	35.6
3 Silver Bullet	32.5
4 Potter Ranch	54
5 Lick Creek	52
6 Nine Mile	43.5
7 Superior	56
8 Tarkio	52.2

Table 2. Location numbers ranked by various site quality measures, with the highest position in the table being the highest site quality level.

Site Index	Sapwood Area (Variable-Radius)	Sapwood Area (Fixed-Radius)	Basal Area (Fixed-Radius)	Basal Area (Variable-Radius)	Growth Efficiency	Soil Series
7	7	7	3	6	3	4
4	5	3	7	7	8	6
8	8	6	6	3	2	7
5	6	8	8	5	7	8
6	4	2	1	8	1	5
2	3	1	2	4	5	3
3	2	5	5	1	6	2
1	1	4	4	2	4	1

needed. Because site quality assessment is inexact, the rating of each location is approximate only. Site quality estimates were not used in an absolute sense in data analysis, but instead were used for ranking whenever stratification was needed

Growth Basal Area Method

A primary objective of this study was to evaluate the utility of the GBA method in uneven-aged stands. Hall's (1983) approach was used in a very strict sense to determine the actual GBA number for each location. The results of the GBA method are in agreement with the high-site locations (i.e. five and seven) (Table 3). The GBA method, however, ranked two western Montana sites as having the same site quality as the eastern Montana sites. A number of GBA components could contribute to the inconsistent performance of this method in uneven-aged stands. Ten-year radial growth may not accurately gauge recent growth of the GBA tree. Variable-radius plot estimates of basal area may not accurately reflect the competition environment in an uneven-aged stand. Consequently, use of the GBA method to derive site quality estimates in uneven-aged ponderosa pine stands appears questionable, at least in Montana.

Components of the GBA method were closely examined to identify potential problems. The use of 10-year radial growth to index the growth of GBA trees may have differentially influenced the GBA estimates. Hall (1983) attributes sequentially smaller radial increments of the GBA tree over the 10-year period of evaluation to the effects of competition. However, cross sectional area of the GBA tree must be taken into account. Uniform basal area increment on an ever-larger tree explains some slowing in radial growth of the GBA tree. The GBA trees in this study were not the same size, and in fact varied considerably in diameter. Theoretically, Hall's (1983) approach can only work if all GBA trees have the same DBH. Departures from this assumption may result in considerable variation in GBA

Figure 3. Ten-year basal area increment versus variable-radius plot estimates of sapwood area, by location.

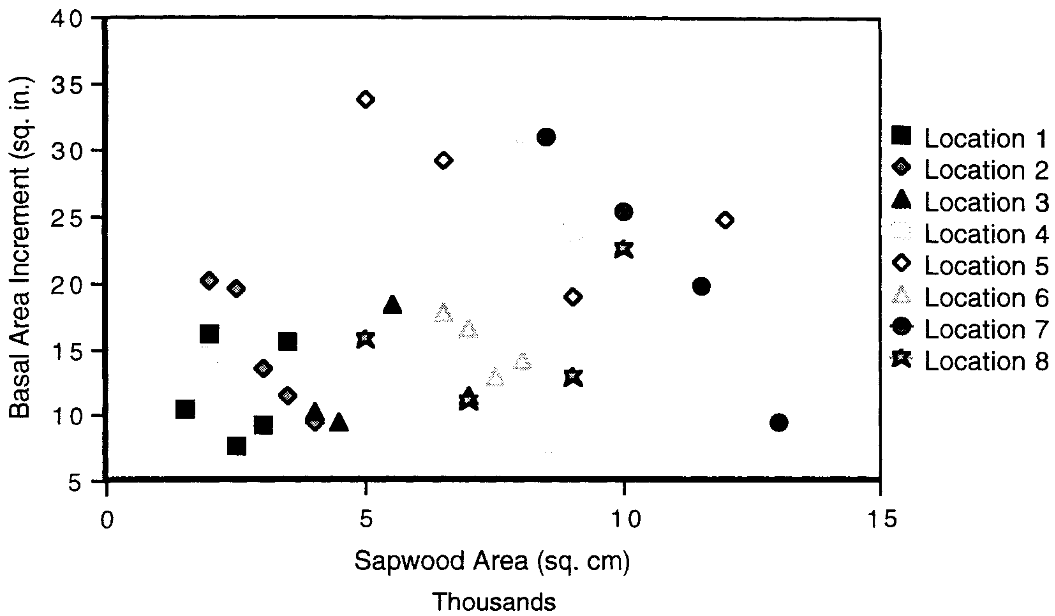
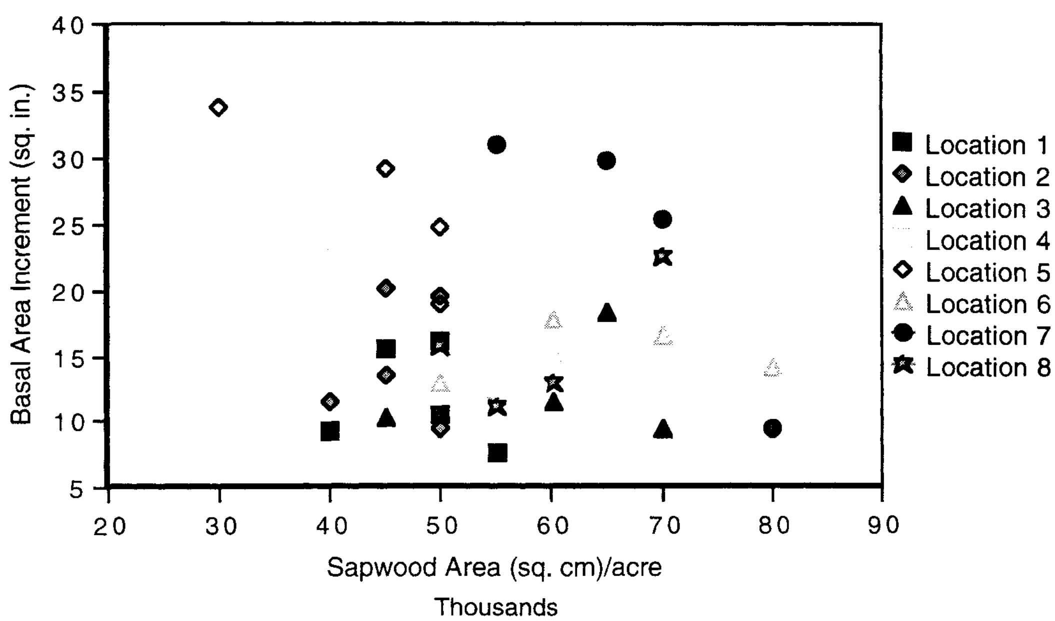


Figure 4. Ten-year basal area increment versus expanded variable-radius plot estimates of sapwood area, by location.



values.

Another key assumption of the GBA approach is the relationship between GBA tree growth increment and surrounding density measures. Due to the previously discussed shortcomings of radial increment as a dependent variable, basal area growth increment was used in all subsequent analyses. Basal area growth increment of GBA trees and variable-radius plot estimates of basal area competition are shown in Table 4. Visual examination of plots of these data indicates that this relationship is not strong (Figures 1 and 2). The GBA method is based on two assumptions: 1) rate of radial growth of a GBA tree decreases with increasing stand density, 2) GBA trees on different sites will demonstrate the same radial growth response to increasing density, but at different levels of basal area competition. Basal area increment of GBA trees should decrease with increasing basal area densities (competition). This relationship should exist for all sites, but at different levels, due to different site qualities. However, results of comparing 10-year basal area increment of GBA trees to variable-radius plot estimates of basal area competition suggests that this relationship may not be well defined in uneven-aged stands.

Regression was employed to examine the relationship between GBA tree growth and the basal area competition surrounding it. Pooling data from all sites (locations) violated the principle of site quality stratification, as evidenced by a low R-squared (Table 5). Alternatively, evaluating this relationship by individual location resulted in too few data points, R-squareds that varied from 0.006 to 0.78, and nonsignificant p-values (Table 5). By grouping locations into high, medium, and low site-quality rankings (pooling plots and increasing the degrees of freedom) the p-values decreased and the R-squareds stabilized. These results suggest that examining relationships by location should be avoided unless the number of GBA sample trees and associated plots approaches 20. Therefore, all subsequent data analysis used site quality groupings.

Analysis of the relationship between GBA tree basal area increment and variable-plot

Table 4. Five- and ten-year basal area increments of GBA trees, and associated variable-radius plot estimates of basal area competition around each tree.

GBA Tree #	5 Year BAI (sq.in.)	10 Year BAI (sq.in.)	Variable BA (sq.ft/acre)	GBA Tree #	5 Year BAI (sq.in.)	10 Year BAI (sq. in.)	Variable BA (sq.ft/acre)
1	9.624	16.194	100	18	6.928	14.477	110
2	5.874	9.331	70	19	17.100	29.159	100
3	5.042	10.586	90	20	12.540	24.766	100
4	5.042	7.673	90	21	15.940	33.813	90
5	5.798	15.587	80	22	11.470	18.977	100
6	5.625	13.512	70	23	7.313	16.534	140
7	8.998	20.086	70	24	10.100	17.635	120
8	9.244	19.564	60	25	5.577	12.871	110
9	6.204	11.578	70	26	7.482	14.023	140
10	5.384	9.431	80	27	12.420	25.387	110
11	6.187	10.231	80	28	16.890	29.778	110
12	5.987	9.423	110	29	17.060	31.093	90
13	7.019	11.545	110	30	4.847	9.587	130
14	11.210	18.212	130	31	6.291	12.845	110
15	2.712	6.762	80	32	6.341	11.153	90
16	12.320	23.799	70	33	8.186	15.676	80
17	15.280	31.104	79	34	11.250	22.629	110

Table 5. Results of the regression of ten-year basal area increment on basal area competition, by location and site quality groupings.

BAI10 vs VarBA	Probability>F	R-Squared	VarBA Coefficient	Standard Error	Total DF
All Locations	0.8949	0.0006	-0.00829	0.06226	33
Location 1	0.5910	0.1071	0.109482	0.18254	4
Location 2	0.1452	0.5609	-0.50663	0.25881	4
Location 3	0.2695	0.5336	0.141834	0.09375	3
Location 4	0.4952	0.2548	-0.28379	0.34315	3
Location 5	0.2481	0.5654	-0.95123	0.58969	3
Location 6	0.7528	0.0611	0.036233	0.10042	3
Location 7	0.1121	0.7883	-0.53763	0.19699	3
Location 8	0.6247	0.1409	0.126589	0.22104	3
High Quality Locations	0.0175	0.6377	-0.47948	0.14754	7
Med. Quality Locations	0.5016	0.0329	-0.48427	0.07019	15
Low Quality Locations	0.3413	0.1134	-0.11963	0.11825	9

*Relationship --> BAI10 = bo + b1(Variable) --> BAI10/Variable

estimates of competition used site quality groupings to stratify the samples (Table 2). When using these groupings, the 10-year increment/basal area density relationship had an R-squared of 0.0329 for medium site qualities (p-value=0.5016) (Table 5). The relationship (even when using 5-year BAI) had similar results for low and high site quality groupings. It appears Hall's (1983) method of using 10-year increment and variable-radius plot estimates of basal area in a stockability equation may not apply in uneven-aged stands.

After analyzing the strength of the relationship between GBA tree increment and basal area competition, the nature of this relationship was examined. The slope of the relationship between the growth of a GBA tree and its surrounding density should be the same no matter what site quality. In addition, the y-intercepts for this relationship should vary with site. A high site quality location should have a higher y-intercept resulting from higher basal area increments at a given density level. Using regression, with site quality groupings coded by dummy variables, the y-intercept was significantly different between high and medium/low sites (Table 6). There was insufficient evidence to detect a significant difference between the y-intercept of the medium and low site classes (Table 6). Using the same dummy variable coding, differences in slopes between site quality groupings were tested by adding two product terms (the independent variable in question times both of the dummy variables). Again, there was insufficient evidence to show a significant difference in slopes at different levels of site quality (Table 6). The relationship between basal area increment and variable-radius plot estimates of basal area appears to behave as Hall's (1983) approach suggests. The y-intercepts of the site quality groupings are different, but their slopes are not.

Hall's (1983) approach, in a broader sense, may still hold promise for application in uneven-aged stands. The specific variables of the GBA method may need to be replaced with variables that are more appropriate for the uneven-aged condition. Much of the effort of this study was focused on alternative variables and sampling approaches that fit within a broader concept of the GBA method.

Table 6. Results of the regression (with slope and intercept dummy variables) of ten-year basal area increment on basal area competition.

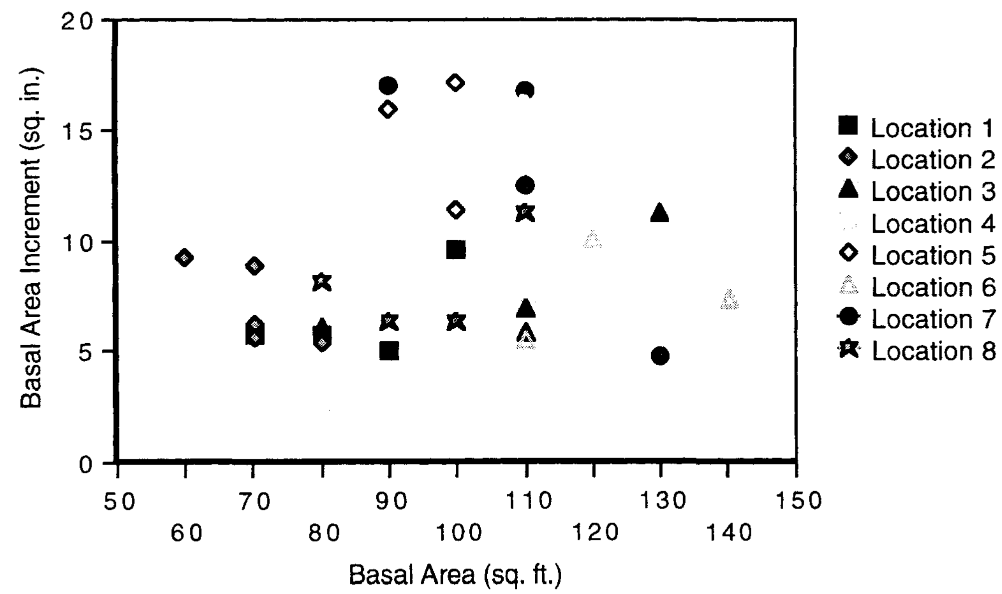
Regression Analysis	Probability >F	R-Squared	Parameter Estimate	Standard Error	Prob. > ITI	Degrees of Freedom
Intercept Dummy Part 1 *	0.0005	0.4438	Bo=21.642 B1=4.9409 B2=14.703	Bo=4.8715 B1=2.8091 B2=3.1744	Bo=0.0001 B1=0.0888 B2=0.0001	33
Slope** Dummy VARBA	0.0003	0.5457	B4=0.0712 B5=-0.3598	B4=0.1623 B5=0.2197	B4=0.6643 B5=0.1128	33

* Intercept Dummy Equation--> BAI10=Bo+B1(dum1)+B2(dum2)+B3(VarBA)

Part 1--> Low Site=Bo   Medium Site=Bo+B1   High Site=Bo+B2

** Slope Dummy Equation--> BAI10=Bo+B1(dum1)+B2(dum2)+B3(VarBA)+ B4(dum1*VarBA)+B5(dum2*VarBA)

Figure 2. Five-year basal area increment versus variable-radius plot estimates of basal area, by location.



Sapwood Analysis

In order to evaluate alterations to Hall's GBA variables, sapwood area was examined as a surrogate for basal area as a measure of competition around the GBA tree. Current literature indicates that sapwood area may provide valuable information on the competitive interactions between components of an uneven-aged stand. If sapwood area indirectly reflects the vigor and size of individual tree crowns in an uneven-aged stand, it would likely be a useful measure of density around individual trees. Consequently, the relationship between GBA tree growth increment and competing sapwood area was evaluated.

The density of sapwood competition around each GBA tree was sampled using three kinds of plots: variable-radius, expanded variable-radius, and fixed area (Table 7). The difference between the expanded and non-expanded variable-radius plot estimates of sapwood area is that the non-expanded estimates is simply the sum of sapwood areas of "in" trees, while the expanded estimates of density are on a per acre basis. Examination of the plots of 10-year basal area growth increments versus the three estimates of sapwood competition indicate no strong relationship (Figures 3, 4, and 5). Regression analysis performed between the GBA tree increment and these three estimates of sapwood density had mixed results. GBA tree increment showed no relationship with fixed-radius plot estimates of sapwood area at any site quality (Table 8). However, basal area increment of GBA trees was modestly correlated with the expanded and non-expanded variable-radius plot estimates of sapwood area at high site qualities (Table 8). These two models, however, performed poorly with medium site qualities and inconsistently with low site qualities (Table 8). It may be that a modest relationship between growth increment and sapwood area obtains only on high sites. More likely, it is a spurious relationship resulting from a small sample size. It also could be attributed to the assignment of sampling

Table 3. Growth Basal Area estimates, by location, using Hall's (1983) method.

Location Number	Avg. Radial 10 yr. Growth (20ths in.)	Avg. Stand Basal Area (sq. ft./acre)	GBA (base age 100)
1	7.2	86.0	65.8
2	8.6	70.0	55.0
3	7.5	107.5	84.1
4	6.5	82.5	64.0
5	10.2	97.5	104.8
6	7.7	127.5	109.1
7	10.0	110.0	103.6
8	8.5	97.5	75.8

Figure 1. Ten-year basal area increment versus variable-radius plot estimates of basal area, by location.

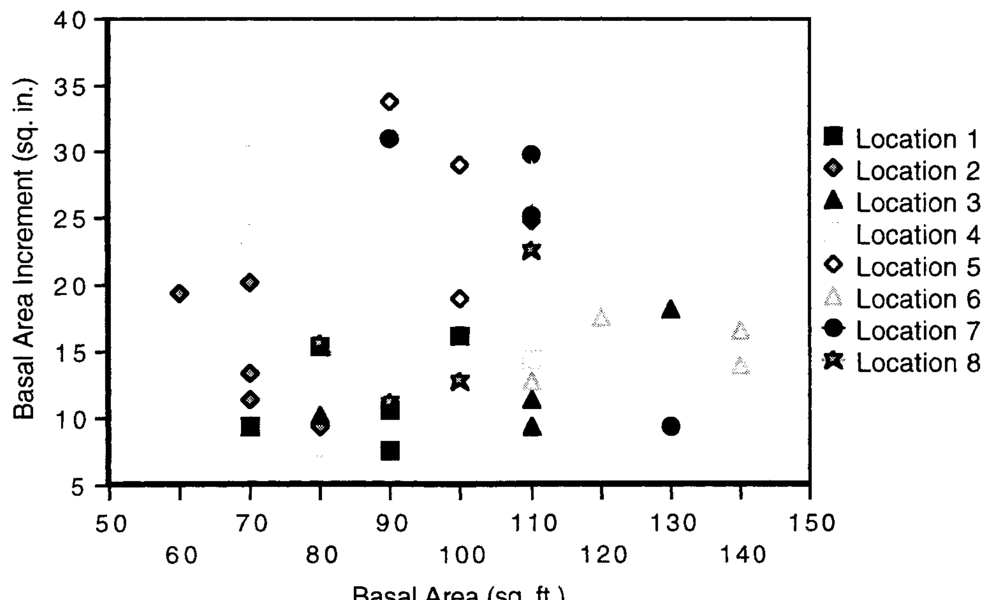


Figure 5. Ten-year basal area increment versus fixed-radius plot estimates of sapwood area, by location.

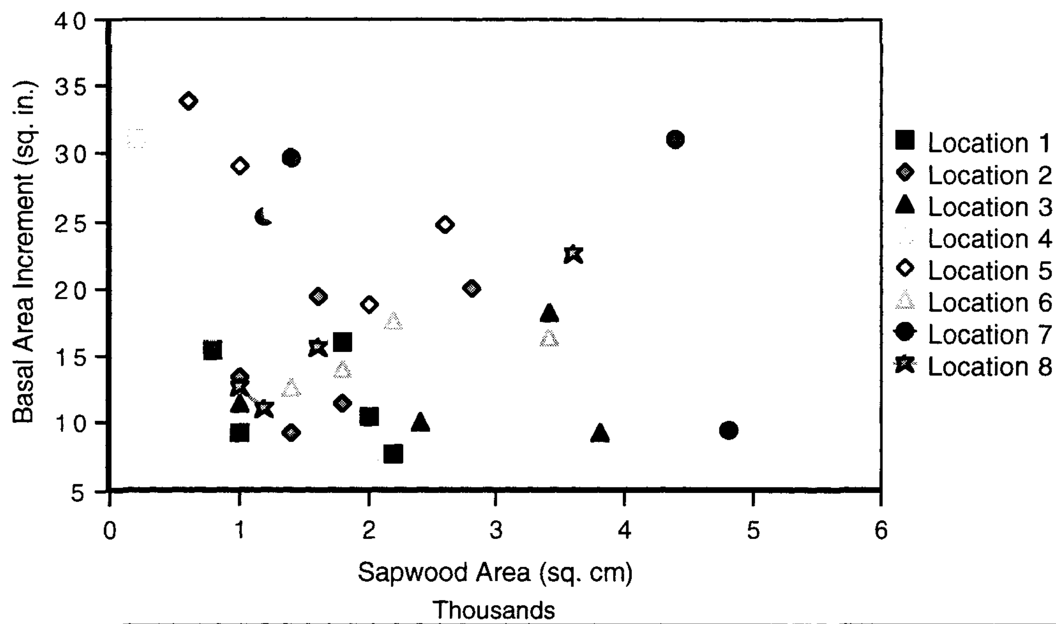


Figure 6. Ten-year basal area increment versus fixed-radius plot estimates of basal area, by location.

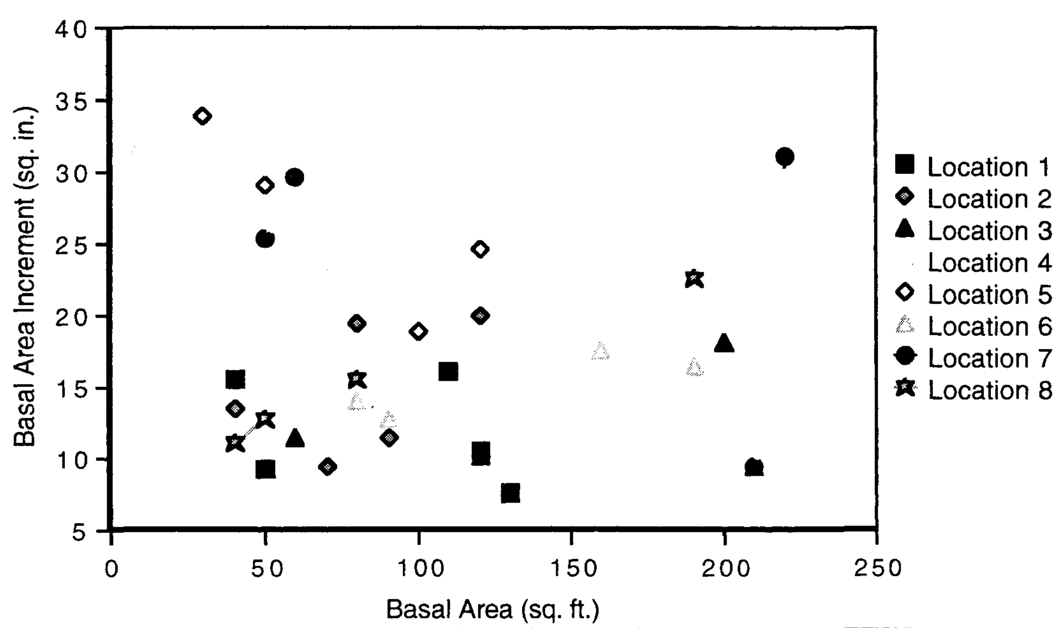


Table 7. Estimates of sapwood area competition around GBA trees based on three plot sampling methods.

GBA Tree #	Variable -Plot Sap.Ar. (sq.cm)	Expand. Variable Sap.Ar. (sq.cm) (1 acre)	Fixed-Plot Sap. Area (sq.cm) (1/33 acre)	GBA Tree #	Variable -Plot Sap.Ar. (sq.cm)	Expand. Variable -Plot Sap.Ar. (sq.cm) (1 acre)	Fixed-Plot Sap. Area (sq.cm) (1/33 acre)
1	1959.9	48709	1771.9	18	2079.4	58893	1909.6
2	2974.8	40525	986.8	19	6359.1	46778	1086.6
3	1986.2	49626	1926.2	20	12118.0	49429	2530.9
4	2237.3	50996	2201.3	21	5195.6	31354	614.8
5	2901.6	48070	839.6	22	9069.1	52401	1962.6
6	3187.5	44020	957.2	23	7167.6	71874	3413.8
7	2535.3	46994	2762.0	24	6484.7	59575	2221.3
8	2785.0	35912	1531.8	25	7583.3	49717	1449.8
9	2436.0	40091	1740.5	26	8023.7	82743	1772.5
10	3595.2	51028	1432.2	27	9870.0	68723	1130.9
11	4111.7	45040	2442.3	28	11630.0	67701	1290.2
12	4289.4	70820	3866.5	29	8281.5	54772	4541.7
13	7128.8	60743	1004.9	30	13321.0	80923	4807.0
14	5681.3	64953	3393.9	31	8747.9	58683	907.4
15	8420.0	41296	1953.0	32	6873.8	57113	974.3
16	8938.9	39520	1118.7	33	5072.3	49180	1671.3
17	8178.6	37035	222.3	34	9826.8	67263	3667.7

Table 8. Results of regression of ten-year basal area increment on alternative estimates of sapwood area, by site quality grouping.

Relationship	Site Quality Groupings	Prob. >F	R2	Coefficient	Standard Error	Total DF
BAI10 vs Variable-Plot Sapwood Area	High Quality	0.065	0.45	-0.00186	0.00082	7
	Medium Quality	0.186	0.12	0.00103	0.00074	15
	Low Quality	0.821	0.00	-0.00067	0.00291	9
BAI10 vs Expanded Variable-Plot Sapwood Area	High Quality	0.073	0.45	-0.00035	0.00015	7
	Medium Quality	0.942	0.00	-0.000007	0.00010	15
	Low Quality	0.337	0.11	-0.00028	0.00027	9
BAI10 vs Fixed-Plot Sapwood Area	High Quality	0.162	0.29	-0.00264	0.00166	7
	Medium Quality	0.520	0.03	-0.00097	0.00147	15
	Low Quality	0.586	0.03	0.00142	0.00251	9

*Relationship --> BAI10 = bo + b1(Variable) --> BAI10/Variable

locations to site quality classes; some of the medium sites may be more appropriately assigned to the low or high site quality groupings. The correlation between GBA tree basal area increment and variable-plot estimates of sapwood area density was slightly weaker than the relationship between GBA tree basal area increment and similar estimates of basal area competition.

Regression, with site quality classes coded as dummy variables, was conducted on GBA tree basal area increment data and the associated sapwood area estimates. Basal area increment regressed on sapwood area estimates derived from fixed-radius plots did not display the slope and y-intercept behavior as indicated by Hall's (1983) method (Table 9). Regressions using the two variable-radius plot estimates of sapwood area provided weak statistical evidence supporting assumptions of the GBA method. The y-intercept was significantly different between high and medium/low sites for the two variable-radius plot estimates of sapwood area (Table 9). However, there was insufficient evidence to show a significant difference in slopes at different levels of site quality for any of the three approaches to estimating sapwood area competition (Table 6).

The relationship between a dominant tree's growth in an uneven-aged stand and its surrounding sapwood area behaves as Hall's (1983) model suggests, but a strong relationship was not found. A potential problem exists with the non-expanded variable-plot estimates of sapwood area. Results of regression with this variable may be spurious. Because this variable was not translated to a per-acre basis, and its derivation violates the assumptions of variable-radius plot sampling, it should be held suspect.

In summary, a strong relationship was not found between GBA tree growth increments and estimates of sapwood area competition in uneven-aged stands. The reason for this may be due as much to the sampling scheme as to the variable itself. The variable-radius plot sampling approaches to estimating sapwood area appear to hold more promise than the fixed-radius plot. This question of sampling approach will be addressed in the next section.

Table 9. Results of regression of ten-year basal area increment on alternative estimates of sapwood area (with slope and intercept dummy variables).

Regression Analysis	Probability >F	R-Squared	Parameter Estimate	Standard Error	Prob. > ITI	Degrees of Freedom
Intercept* Dummy FIXSAP	0.0007	0.4306	Bo=15.845 B1=2.7975 B2=12.940	Bo=2.4384 B1=2.4401 B2=2.9016	Bo=0.0001 B1=0.2607 B2=0.0001	33
Slope** Dummy FIXSAP	0.0028	0.4607	B4=-0.0023 B5=-0.0040	B4=0.0036 B5=0.0036	B4=0.5138 B5=0.2708	33
Intercept* Dummy EVARSAP	0.0002	0.4787	Bo=22.770 B1=4.574 B2=14.205	Bo=4.3367 B1=2.5152 B2=2.8754	Bo=0.0001 B1=0.0789 B2=0.0001	33
Slope** Dummy EVARSAP	0.0009	0.5077	B4=0.0001 B5=-0.0001	B4=0.0003 B5=0.0003	B4=0.6513 B5=0.8911	33
Intercept* Dummy VARSAP	0.0019	0.3877	Bo=14.216 B1=3.5443 B2=14.180	Bo=2.4623 B1=3.4037 B2=4.8172	Bo=0.0001 B1=0.3606 B2=0.0062	33
Slope** Dummy VARSAP	0.0006	0.5217	B4=0.0017 B5=-0.0011	B4=0.0036 B5=0.0036	B4=0.6429 B5=0.7475	33

* Intercept Dummy Equation--> BAI10=Bo+B1(dum1)+B2(dum2)+B3(variable being examined)

Part 1--> Low Site=Bo   Medium Site=Bo+B1   High Site=Bo+B2

** Slope Dummy Equation--> BAI10=Bo+B1(dum1)+B2(dum2)+B3(variable being examined)

B5(dum1*variable being examined)+B6(dum2*variable being examined)

Evaluation of Sampling Techniques

Both variable- and fixed-radius plot sampling methods were employed to estimate basal area and sapwood area density. The relationship of basal area increment to variable-plot estimates of basal area and variable- and fixed-radius plot estimates of sapwood area have already been examined in this investigation. The relationship between basal area increment of GBA trees and fixed-radius plot estimates of basal area need to be explored before any comparisons between sampling techniques can be made.

No trend was discernible when 10-year basal area increment was plotted against fixed-radius plot estimates of basal area. (Figure 6) (Table 10). The regressions of 10-year basal area increment on fixed-radius plot estimates of basal area had poorer results than those using variable-radius plot estimates of basal area, with R-squared's near zero for medium and low sites (Table 11). Regressions of this relationship, with site classes coded as dummy variables, had associated slope values that provided modest support of Hall's (1983) GBA concepts (Table 12). However, the y-intercepts among site classes were less well differentiated than with corresponding models using alternative density estimates.

The basal area increment of GBA trees had a stronger relationship with variable-radius plot estimates of basal area and sapwood area than with fixed-radius plot estimates of density. For the high site quality group, R-squareds for models using variable- and fixed-radius plot estimates of basal area were 0.63 and 0.29 respectively (p-values 0.01 and 0.18 respectively) (Tables 5 and 11). The R-squareds for regressions using variable- and fixed-radius plot estimates of sapwood area were 0.45 and 0.29 respectively (p-values 0.06 and 0.16 respectively) (Table 8). In addition to having higher R-squareds and greater significance, models using variable-radius plot estimates of density were more consistent with Hall's (1983) y-intercept and slope behavior constructs (Tables 6, 9, and 12).

Table 10. Fixed-radius plot estimates of basal area associated with each GBA tree.

Plot #	Fixed BA (sq.ft.) (1 acre)	Plot #	Fixed BA (sq.ft.)(1 acre)	Plot #	Fixed BA (sq.ft.)(1 acre)
1	107.7	13	55.5	25	87.9
2	51.5	14	197.3	26	77.9
3	112.0	15	94.8	27	53.3
4	124.3	16	67.1	28	61.1
5	40.2	17	13.4	29	222.4
6	41.7	18	115.9	30	222.2
7	123.4	19	54.9	31	53.2
8	77.3	20	119.5	32	48.0
9	88.7	21	26.5	33	81.3
10	67.2	22	102.9	34	190.1
11	117.7	23	191.8		
12	206.3	24	163.2		

Table 11. Results of regression of ten-year basal area increment on fixed-radius plot estimates of basal area, by site quality grouping.

BAI10 vs FIXBA	Probability>F	R-Squared	FIXBA Coefficient	Standard Error	Total DF
High Quality Locations	0.1766	0.2908	-0.05421	0.03540	7
Med. Quality Locations	0.6871	0.0119	-0.01094	0.02661	15
Low Quality Locations	0.8835	0.0029	0.00713	0.04716	9

*Relationship --> BAI10 = bo + b1(Variable) --> BAI10/Variable

Table 12. Results of regression (with slope and intercept dummy variables) of ten-year basal area increment on fixed-radius plot estimates of basal area.

Regression Analysis	Probability >F	R-Squared	Parameter Estimate	Standard Error	Prob. > ITI	Degrees of Freedom
Intercept* Dummy FIXBA	0.0009	0.4187	Bo=15.508 B1=2.8934 B2=12.598	Bo=2.4558 B1=2.4869 B2=2.9037	Bo=0.0001 B1=0.2538 B2=0.0001	33
Slope** Dummy FIXBA	0.0037	0.4484	B5=-0.0180 B6=-0.0613	B5=0.0672 B6=0.0691	B5=-0.269 B6=-0.888	33

* Intercept Dummy Equation--> BAI10=Bo+B1(dum1)+B2(dum2)+B3(variable being examined)

Part 1--> Low Site=Bo Medium Site=Bo+B1 High Site=Bo+B2

** Slope Dummy Equation--> BAI10=Bo+B1(dum1)+B2(dum2)+B3(variable being examined)

B5(dum1*variable being examined)+B6(dum2*variable being examined)

Although basal area increments had minimal correlation with measures of density, there was an obvious difference between variable- and fixed-radius plot estimates of density and their ability to explain growth of the GBA tree. Variable-radius plot sampling of basal area and sapwood area provide better estimates of density, and therefore may better explain variation in basal area increment of GBA trees, than fixed-radius sampling designs (unless larger area fixed-radius plot designs are considered).

Alternative Dependent Variables

Alternatives to the dependent variable, basal area increment of the GBA tree, were also investigated. The purpose of this investigation was to find significant correlation between some measure of growth and corresponding density measures. It was hypothesized that if the dependent variable could somehow take into account tree cross sectional area or crown size, such as with individual tree basal area or growth efficiency, then perhaps a stronger relationship could be achieved with the various measures of density. Growth efficiency variables were created by dividing the dependent variable of basal area increment by the sapwood area of the GBA tree itself (Table 13). As expected, growth efficiency variables varied greatly from tree to tree due to the various degrees of competition encountered and the variation in tree sizes. Another dependent variable -- referred to as the basal area ratio (barat) -- was also created. The barat variable was the 10-year basal area increment divided by the basal area of the GBA tree itself. As evident in table 13, this variable did not vary as much as the growth efficiency variable, most likely because sapwood area of an individual tree would be more sensitive to relatively recent competition than basal area .

Each of the alternative dependent variables (growth efficiency and barat) were regressed on the five alternative estimates of the independent variable (density). The goal was to see if the independent variables could explain more variation in these alternatives to basal area growth of the GBA tree (Table 14). None of these models explained a significant amount

Table 13. Growth efficiencies (BAI10/GBA sapwood area) and BARAT (BAI10/GBA basal area) for each GBA tree.

GBA Tree #	Growth Effic. in^2/cm^2	BARAT in^2/ft^2	GBA Tree #	Growth Effic. in^2/cm^2	BARAT in^2/ft^2	GBA Tree #	Growth Effic. in^2/cm^2	BARAT in^2/ft^2
1	0.0227	0.00076	13	0.0147	0.00042	25	0.0060	0.00025
2	0.0103	0.00025	14	0.0187	0.00060	26	0.0147	0.00054
3	0.0098	0.00039	15	0.0017	0.00006	27	0.0119	0.00042
4	0.0103	0.00028	16	0.0078	0.00029	28	0.0172	0.00049
5	0.0115	0.00055	17	0.0010	0.00043	29	0.0155	0.00056
6	0.0125	0.00063	18	0.0043	0.00013	30	0.0078	0.00029
7	0.0137	0.00058	19	0.0128	0.00034	31	0.0101	0.00030
8	0.0098	0.00038	20	0.0092	0.00032	32	0.0208	0.00076
9	0.0166	0.00054	21	0.0118	0.00049	33	0.0154	0.00059
10	0.0138	0.00043	22	0.0146	0.00046	34	0.0097	0.00039
11	0.0179	0.00053	23	0.0071	0.00025			
12	0.0124	0.00031	24	0.0151	0.00051			

of variation in the alternative dependent variables. Instead, the GBA sapwood area and the GBA basal area variables should be treated as independent variables, since they may explain additional variation in GBA basal area increments.

Growth Basal Area Tree DBH and Sapwood Area

Tree size (diameter) and sapwood area could also help explain variation in basal area growth of the GBA tree. A large diameter tree, even if it had little radial growth, could accrue considerable basal area increment, while a small diameter tree with a large radial increment may accrue a relatively small amount of basal area. The sapwood area of a GBA tree might explain growth increment variation of the tree itself, since sapwood area has been shown to be closely correlated with leaf area (Waring et al 1982). A tree with a large DBH, or even more so a large sapwood area, should have a substantial amount of basal area growth over 10-years. A plot of basal area growth versus DBH of the GBA trees indicates that there was a positive relationship (Figure 7) (Table 15). Regression of GBA tree basal area increments on GBA tree DBH and sapwood area (by site quality classes) had favorable results. The model with DBH as the only independent variable had an R-squared of 0.56 for the high site quality class, although R-squared's for the medium and low site quality classes were somewhat lower (p-value= 0.03) (Table 16). The model with GBA sapwood area as the independent variable had even more favorable results, with R-squareds of 0.62, 0.21, and 0.36 for high, medium, and low sites, respectively (p-value= 0.01, 0.07, and 0.06 respectively) (Table 16). It appears that GBA sapwood area would be a useful variable to include in modeling efforts to explain growth variations in GBA trees.

Table 14. Results of regression of growth efficiency (GREFF) and BARAT on alternative estimates of density (high quality sites).

Relationship	Probability>F	R-Squared	Var. Coeff.	Std. Error	Total DF
Greff/Varsap	0.4532	0.0968	-0.000001	0.000001	7
Greff/EVarsap	0.7568	0.0172	-0.000002	0.000001	7
Greff/VarBA	0.2789	0.1910	-0.000106	0.000088	7
Greff/FixBA	0.5704	0.0566	-0.000001	0.000016	7
Greff/Fixsap	0.5003	0.0789	-0.000001	0.000001	7
Barat/Varsap	0.2515	0.2116	-0.000528	0.000416	7
Barat/EVarsap	0.4731	0.0889	-0.000006	0.000082	7
Barat/VarBA	0.1068	0.3746	-0.152841	0.080627	7
Barat/FixBA	0.7958	0.0121	-0.004671	0.017261	7
Barat/FixSap	0.7345	0.0206	-0.000290	0.000816	7

*Relationship --> BAI10 = bo + b1(Variable) --> BAI10/Variable

Table 15. Diameter at breast height and sapwood area for each GBA tree.

GBA Tree #	DBH (inches)	Sapwd. Area (sq. cm)	GBA Tree #	DBH (inches)	Sapwd. Area (sq. cm)	GBA Tree #	DBH (inches)	Sapwd. Area (sq. cm)
1	10.8	422.6	13	12.2	476.5	25	16.8	928.8
2	14.2	572.9	14	12.9	600.9	26	11.9	508.5
3	12.2	512.2	15	24.4	1598.7	27	18.1	1035.4
4	12.2	491.6	16	21.3	1586.5	28	18.2	981.0
5	12.4	502.8	17	19.9	1530.3	29	17.4	1102.2
6	10.8	448.5	18	25.0	1617.5	30	13.5	622.3
7	13.7	657.3	19	21.5	1333.8	31	15.2	625.1
8	16.8	933.8	20	20.7	1366.8	32	9.0	305.1
9	10.8	372.9	21	19.4	1348.6	33	12.0	532.9
10	10.9	391.3	22	15.0	785.5	34	17.8	1167.1
11	10.3	346.2	23	18.9	1030.8			
12	12.8	481.7	24	13.7	670.5			

Figure 7. Ten-year basal area increment versus diameter at breast height, all locations.

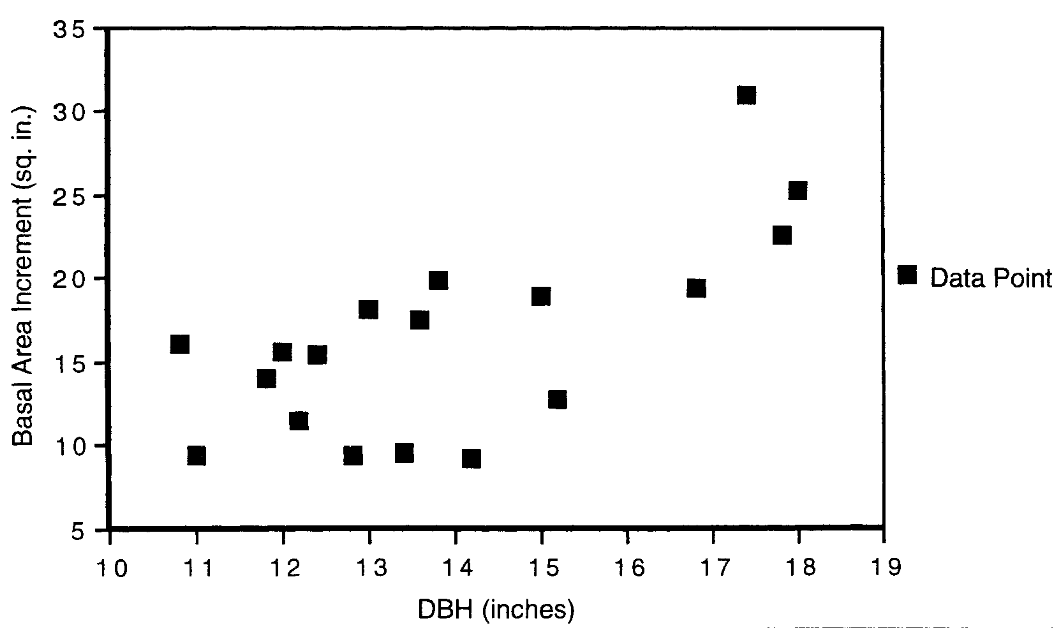


Table 16. Regression of ten-year basal area increment on GBA tree DBH and sapwood area, by site quality grouping.

Relationship	Site Quality Groupings	Prob. >F	R2	Varsap Coefficient	Standard Error	Total DF
BAI10 vs DBH	High Quality	0.03	0.56	2.17163	0.78029	7
	Medium Quality	0.30	0.07	0.34629	0.32227	15
	Low Quality	0.19	0.20	1.00692	0.70699	9
BAI10 vs GBA Sapwood Area	High Quality	0.01	0.62	0.02249	0.00715	7
	Medium Quality	0.07	0.21	0.00585	0.32222	15
	Low Quality	0.06	0.36	0.01589	0.00746	9

*Relationship --> BAI10 = bo + b1(Variable) --> BAI10/Variable

Dependent and Independent Variables

A number of dependent and independent variables merit consideration in future efforts to model growth/density relationships as a means of estimating site quality in uneven-aged stands. For the dependent variable of GBA tree growth, 10-year basal area increment appears preferable to 5-year increment. Ten-year basal area increment was in most cases slightly better correlated with surrounding density measures than 5-year BAI. This may be due to 5-year basal area increment incorporating a shorter history of the GBA tree's response to surrounding competition. It was initially hypothesized that five-year basal area growth may simply be 10-year basal area growth divided by two. All 10-year basal area growth estimates were divided by two and paired up with corresponding five-year estimates. A difference-of-means test was conducted between the two measures of basal area increment. The means for five- and 10- year increment were 8.979 and 8.601, respectively. The standard deviations for five- and 10-year BAI were 4.011 and 3.799, respectively. The t-test failed to reject the null hypothesis that there is no difference in basal area increment means (p-value 0.69). Although regressions using the five- and 10-year BAI as alternative dependent variables produced different R-squareds, the paired t-test failed to provide strong evidence of a difference between the two.

The growth increment of GBA trees did not show significant correlation with sapwood area density measures. Conceptually, sapwood area as a density measure still holds promise for application in site quality estimation, but may not have been sampled or modeled appropriately. The variable-radius plot sampling method did prove more valuable in this project than did fixed-radius plots, and it is proposed to further evaluate variable-radius plot sampling as a means of estimating density in uneven-aged stands. The use of either GBA tree sapwood area or DBH is recommended as an independent variable in Hall's (1983) approach. These variables greatly aided in explaining the variation in growth of the GBA tree -- variation that was not due to site variables.

Conclusion

Several methods of estimating site quality in uneven-aged stands were explored in this study. Results differed among traditional methods, such as site index and soil series. Site index and sapwood area density came closest to expected and reasonable estimates of site quality. Estimating site quality in uneven-aged stands is a difficult task, no matter what method is used. Hall's (1983) application of the GBA concept in even-aged stands does have shortcomings, and did not work well in uneven-aged stands in this study. Evaluation of his fundamental idea of radial growth in relation to stand basal area density, indicated that Hall's method may be adaptable to the uneven-aged condition. However, most of the amendments and alterations of Hall's GBA approach provide little insight into the growth-competition relationships in uneven-aged ponderosa pine stands. Results indicate that variable-radius plot estimates of density may be more useful than fixed-radius plot estimates in explaining variation in upper stratum tree growth. Results also indicate that for the sampling methods evaluated, sapwood area provides little advantage over basal area as a density measure. In this study, the growth of an upper stratum tree in an uneven-aged ponderosa pine stand showed little relationship to the density of surrounding members of the same stratum, and only a weak relationship to estimated densities of the subordinate strata. The two independent variables not directly related to density -- GBA tree sapwood area and GBA tree DBH -- showed a strong relationship with basal area growth of the GBA tree, and merit consideration in future work with GBA models.

Although the overall significance of models evaluated in this study rarely reached an appreciable level, results suggest that some extension of Hall's (1983) GBA approach might have utility in uneven-aged conditions. If a preliminary model for estimating relative site quality were proposed based on the results of this project, it would be 10-year basal area increment of a GBA tree dependent on the GBA tree's sapwood area, and on variable-radius plot estimation of either sapwood area or basal area surrounding the GBA tree. However, until further work regarding uneven-aged stand dynamics and competition is undertaken, the standard GBA approach appears to have marginal utility in uneven-aged ponderosa pine stands.

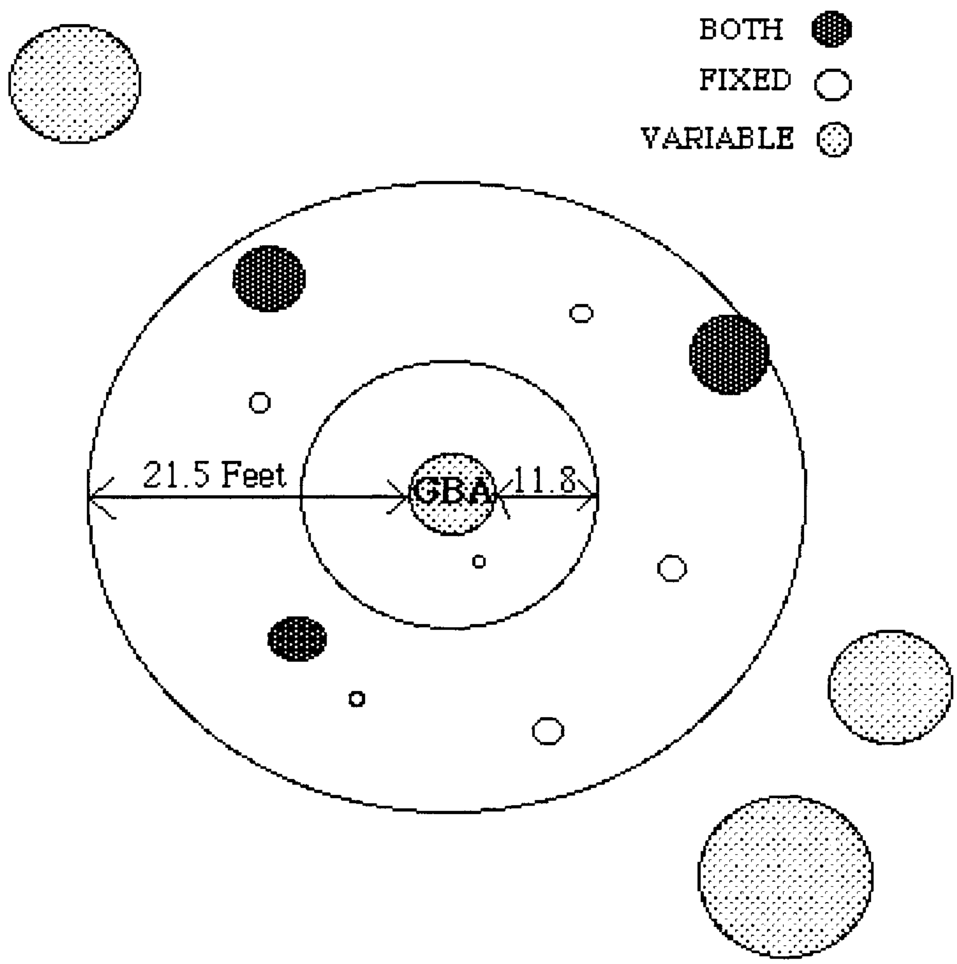
Appendix 1

Location of Plots

Location #	Location Name	Physical Location	Plot #'s at Location
1	Tullock Creek	Eastern MT, Near Custer	1, 2, 3, 4, 5
2	Y-Bar Coolee	Eastern MT, Near Roundup	6, 7, 8, 9, 10
3	Silver Bullet	Eastern MT, Near Roundup	11, 12, 13, 14
4	Potter Ranch	Western MT, Near Lubrecht	15, 16, 17, 18
5	Lick Creek	Western MT, Near Hamilton	19, 20, 21, 22
6	Ninemile	Western MT, Near Ninemile	23, 24, 25, 26
7	Superior	Western MT, Near Superior	27, 28, 29, 30
8	Tarkio	Western MT, East of Superior	31, 32, 33, 34

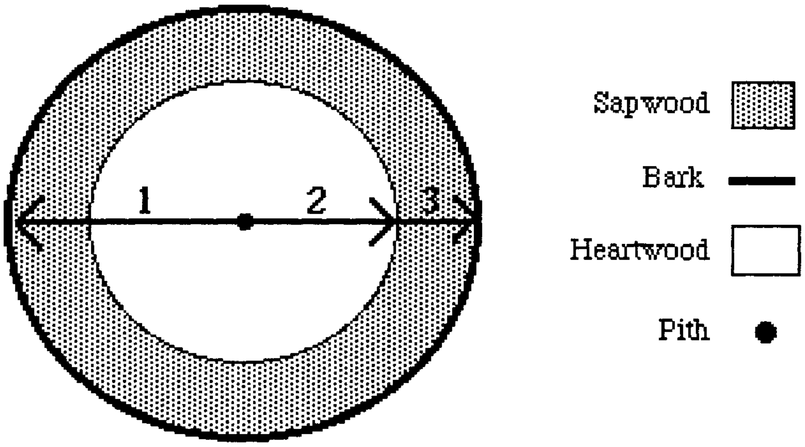
Appendix 2

Plots Surrounding GBA Tree



Appendix 3

Calculation of Sapwood Area and Basal Area Increment



Radius Inside Bark:

Diameter Inside Bark= Diameter Outside Bark- Double Bark Thickness (Faurot 1977)

Radius Inside Bark= Diameter Inside Bark /2 (1 on Diagram)

Sapwood Area :

(Radius Inside Bark ^{2} x Pi) - [(Radius Inside Bark - Sapwood Core Measure)^2 x Pi]

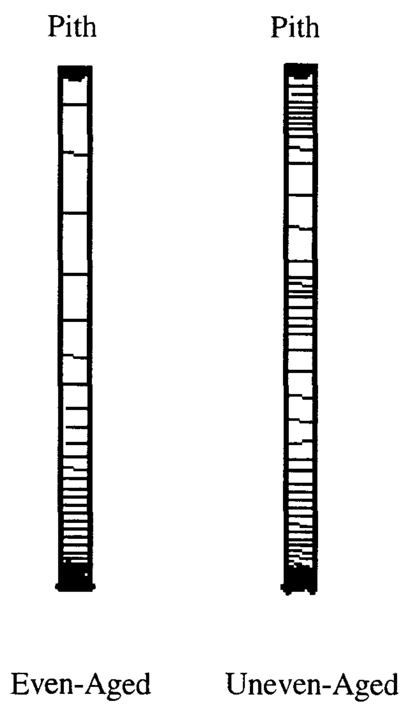
Following Diagram= (1^2 x Pi) - [$(1 - 3)^2$ x Pi]

Basal Area Increment:

(Radius Inside Bark ^{2} x Pi) - [Radius Inside Bark - Radial Growth Increment)^2 x Pi]

Appendix 4.

Site Index Cores



Appendix 5

Explanation of Abbreviations

Abbreviation	Explanation
BAI	Basal Area Increment
VARSAP	Variable-Radius Plot Estimates of Sapwood Area - Non-expanded
EVARSAP	Variable-Radius Plot Estimate (BAF 10) of Sapwood Area - Expanded
BA	Basal Area
DBH	Diameter at Breast Height
GBA	Growth Basal Area (refers to Fred Hall's 1983 Method)
FIXBA	Fixed-Radius Plot Estimate of Basal Area
VARBA	Variable-Radius Plot Estimate (BAF 10) of Basal Area
FIXSAP	Fixed-Radius Plot Estimate of Sapwood Area
GBASAP	Sapwood Area of the Growth Basal Area Tree
LOCAT	Study Site Location
BARAT	Basal Area Ratio, Basal Area Growth/Total Basal Area of Tree
GREFF	Growth Efficiency

Literature Cited

Barrett, J. W. 1978. Height growth and site index curves for managed even-aged stands of ponderosa pine in the Pacific Northwest. USDA Res. Paper. PNW-232. 14pp.

Barrett, J. W. 1983. Growth of ponderosa pine thinned to different stocking levels in central Oregon. USDA Res. Paper. PNW-311. 9pp.

Bates, P.C., P.C. Robert, and C.R. Blinn. 1992. Overlaying soil and timber inventories to assess aspen productivity in northern Minnesota. Soil Soc. Am. J. 56: 295-301.

Becker, R. 1995. Operational considerations of implementing uneven-aged management Pages 67 to 81 *in* Uneven-aged management: opportunities, constraints, and methodologies. Kevin O'Hara ed. MFCES Misc. Pub. No. 56.

Carmean, W. H. 1975. Forest site quality evaluation in the United States. Adv. Agron. 27: 207-269.

Cochran, P.H. 1992. Stocking levels and underlying assumptions for uneven-aged ponderosa pine stands. USDA Res. Note. PNW-RN-509. 10pp.

Coyea, M.R., and H.A. Margolis. 1992. Factors affecting the relationship between sapwood area and leaf area of balsam fir. Can. J. For. Res. 22: 1684-1693.

Farr, W.A. 1984. Site index and height growth curves for unmanaged even-aged stands of western hemlock and sitka spruce in southeast Alaska. USDA Res. Paper. PNW-326. 26pp.

Faurot, J.L. 1977. Estimating merchantable volume and stem residue volume in four Northwest timber species: ponderosa pine, lodgepole pine, western larch, Douglas-fir. USDA Res. Paper. INT-196. 55pp.

Fiedler, C., R. Becker, and S. Haglund. 1988. Preliminary guidelines for uneven-aged silvicultural prescriptions in ponderosa pine. Pages 235 to 241 *in* Ponderosa pine: the species and its management. D. M. Baumgartner and J. E. Lotan, ed. Symposium Proc. Sept 29 - Oct. 1, 1987.

Fralish, J.S. 1994. The effect of site environment on forest productivity in the Illinois Shawnee Hills. Ecol. Appl. 4: 134-143.

Gessel, S.P. 1988. Forest site evaluation and long-term productivity. Univ. Wash. Press. Seattle. 196 pp.

Gevorkiantz, S.R., and H.F. Scholz. 1944. Determining site quality in understocked oak forests. J. For. 42: 808-817.

Goetz, H. 1997. Personal Communication.

Guldin, J. M. 1995. Role of uneven-aged silviculture in the context of ecosystem management. Pages 1 to 26 *in* Uneven-aged management: opportunities, constraints, and methodologies. Kevin O'Hara ed. MFCES Misc. Pub. No. 56.

Hall, F. C. 1987. Growth basal area handbook. USDA Pacific Northwest Region. R6-Ecol-181b-1984. 84pp.

Hall, F.C. 1987b. Stocking considerations in uneven-aged management. *in* Growth basal area handbook. USDA Pacific Northwest Region. R6-Ecol-181b-1984. 84 pp.

Hall, F.C. 1983. Growth basal area: a field method for appraising forest site potential for stockability. Can. J. For. Res. 13: 70-77.

Jones, J.R. 1969. Review and comparison of site evaluation methods. USDA Res. Paper. RM-51. 27pp.

Kaufmann, M. R., and M. G. Ryan. 1986. Physiographic, stand, and environmental effects on individual tree growth and growth efficiency in subalpine forests. Tree Phys. 2: 47-59.

Kozlowski, T.T. 1971. Physiological ecology- A series of monographs, texts, and treatises, Vol. II- Cambial growth, root growth, and reproductive growth. 511 pp.

Makela, A., K. Virtanen, and E. Nikinmaa. 1995. The effects of ring width, stem position, and stand density on the relationship between foliage biomass and sapwood area in Scots pine (Pinus sylvestris). Can. J. For. Res. 25: 970-977.

Martin, T. 1997. Personal Communication.

McLeod, S. D., and S.W. Running. 1987. Comparing site quality indices and productivity in ponderosa pine stands of western Montana. Can. J. For. Res. 18: 346-352.

Milner, K. S. 1992. Site index and height growth curves for ponderosa pine, western larch, lodgepole pine, and Douglas-fir in western Montana. W. J. of Appl. For. 7: 9-14.

Menakis, J. P. 1994. A summary of ponderosa pine management activities in the Lick Creek drainage of the Bitterroot National Forest. M.S. Thesis, Univ. of Montana. 81 pp.

Monserud, R.A. 1984. Problems with site index: an opinionated review. Pages 161-180 *in* Forest land classification: experiences, problems, perspectives: Symposium proceedings. Ed. J. Bockheim, Univ. of Wis., Madison.

Moser, J.W., and O.T. Hall. 1969. Deriving growth and yield functions for uneven-aged forest stands. For. Sci. 15: 183-188.

Murphy, P.A., and R.M. Farrar. 1981. Stand structure variability and research plot size in uneven-aged stands of loblolly-shortleaf pine. USDA Res. Paper. SO-171. 3pp.

Murphy, P.A., and R.M. Farrar. 1985. Growth and yield of uneven-aged shortleaf pine stands in the interior highlands. USDA Res. Paper. SO-218. 11pp.

O'Hara, K. L. and N.I. Valappil. 1995. Sapwood - leaf area prediction equations for multi-aged ponderosa pine stands in western Montana and central Oregon. Can. J. For. Res. 25: 1553-1557.

O'Hara, K.L. and N.I. Valappil. 1995b. Age class division of growing space to regulate stocking in uneven-aged stands. Pages 123 to 143 *in* Uneven-aged management: opportunities, constraints, and methodologies. K. O'Hara ed. MFCES Misc. Pub. No. 56.

Pfister, R. D., B. L. Kovalchik, S. F. Arno, and R. C. Presby. 1977. Forest habitat types of Montana. USDA Gen. Tech. Report. INT-34. 174pp.

Phares, R.E. 1978. Research gaps and research needs for western forest regions. Pages 31 to 43 *in* Uneven-aged silviculture and management in U.S., Feb. 1978 Workshop.

Powers, R.F., and W.W. Oliver. 1978. Site classification of ponderosa pine stands under stocking control in California. USDA Res. Paper. PSW-128. 9pp.

Robichaud, E., and I.R. Methven. 1992. The applicability of the pipe model theory for the prediction of foliage biomass in trees from natural, untreated black spruce stands. Can. J. For. Res. 22: 1118-1123.

Schmid, J.M., S.A. Mata, and C.B. Edminster. 1991. Periodic annual increment in basal area and diameter growth in partial cut stands of ponderosa pine. USDA Res. Note. RM-509. 3pp.

Schmoldt, D. L., G. L. Martin, and J. G. Bockheim. 1985. Yield-based measures of northern hardwood site quality and their correlation with soil-site factors. For. Sci. 31: 209-219.

Schonau, A.P.G. 1988. Problems in using vegetation or soil classification in determining forest site quality. Pages 3 to 12 *in* Forest site evaluation and long-term productivity. Ed. D. Cole. Univ. Wash. Press. 196 pp.

Sellin, A. 1994. Sapwood-heartwood proportion related to tree diameter, age, and growth rate in Picea abies. Can. J. For. Res. 24: 1022-1028.

Shiver, B.D., and B.E. Borders. 1996. Sampling techniques for forest resource inventory. John Wiley and Sons. 356 pp.

Slaughter, S. 1997. Personal Communication.

Soil Survey - Bitterroot Valley Area, Montana. 1959. USDA, Soil Con. Ser., Mt. St. Ag. Exp. St. Series 1951, No. 4. 150 pp.

Soil Survey - Missoula County Area, Montana, Part 1. 1995. USDA, Nat. Res. Con. Ser., Forest Service. 301 pp.

Soil Survey - Musselshell County, Montana. 1939. Mt. Ag. Exp. St., Bozeman, Mt. Bulletin No. 374. 50 pp.

Soil Survey - St. Regis, Ninemile Area, Montana. 1979. Lolo Nat'l Forest, USDA, Northern Region. 35 pp.

Soil Survey - Treasure County, Montana. 1967. USDA, Soil Con. Ser., Mt. Ag. Exp. St. Series 1957, No. 22. 172 pp.

Stage, A. R. and J.C. Rennie. 1994. Fixed-radius plots or variable-radius plots?: designing effective inventory. J. For. 92: 12 (20-24).

Thomas, C.E., and B.R. Parresol. 1989. Comparing basal area growth rates in repeated inventories: Simpson's paradox in forestry. For. Sci. 35: 1029-1039.

Vose, J.M., and H. L. Allen. 1988. Leaf area, stemwood growth, and nutrition relationships in loblolly pine. For. Sci. 34: 547-563.

Waring, R. H., and W. H. Schlesinger. 1985. Forest ecosystems: concepts and management. Academic Press. New York. 340 pp.

Waring, R.H., P. E. Schroeder, and R. Oren. 1982. Application of the pipe model theory to predict canopy leaf area. Can. J. For. Res. 12: 556-560.

Wheeler, Bob. 1997. Personal Communication.

Wiant, H.V., R.K. Knight, and J.E. Baumgrass. 1984. Relation of biomass to basal area and site index on an Appalachian watershed. USDA Res. Note. NE-315. 4pp.

Wykoff, W.R., N.L. Crookston, A.R. Stage. 1982. Users guide to the stand Prognosis model. USDA Gen. Tech. Report INT-133. 112pp.