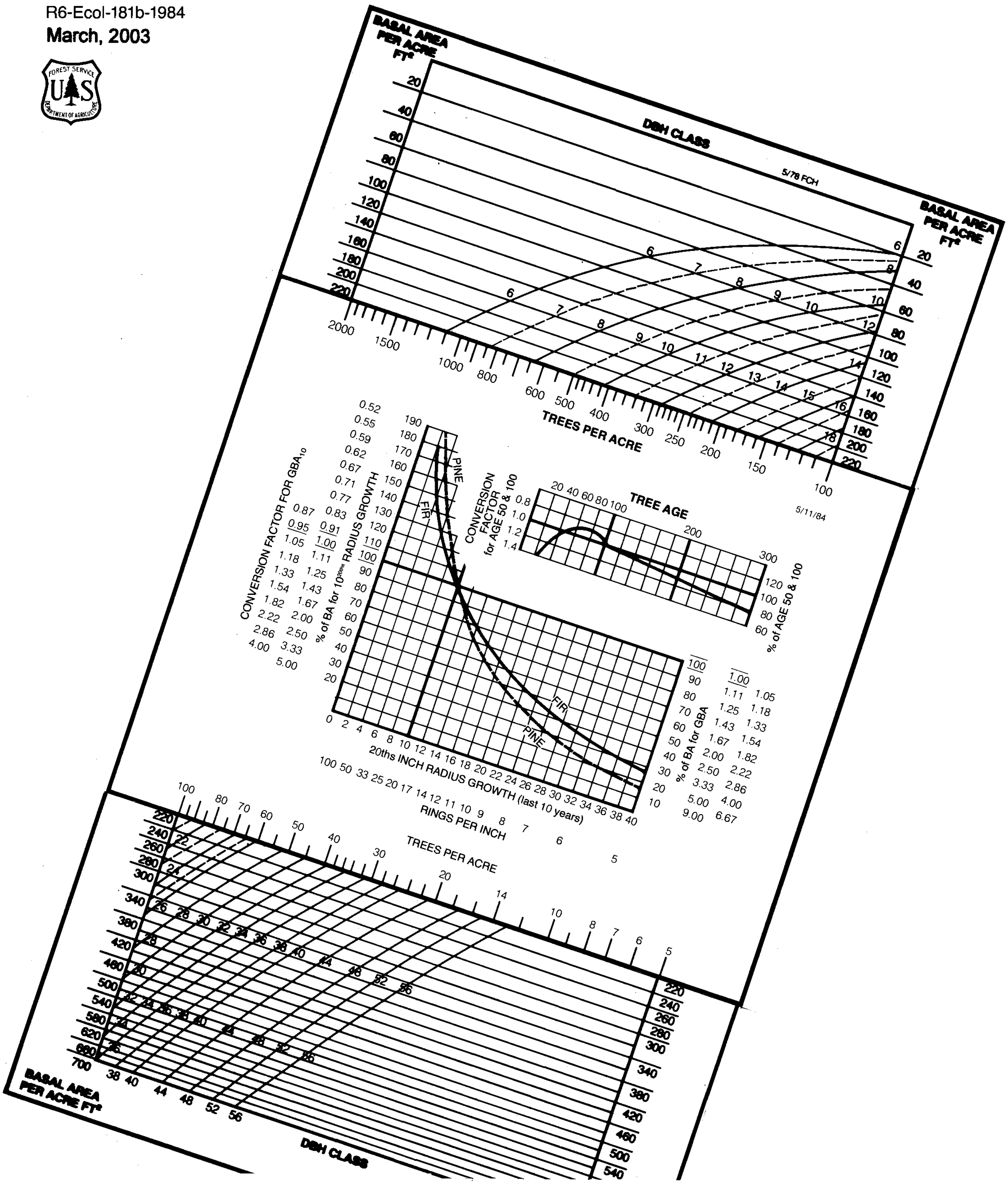
United States
Department of
Agriculture

Forest Service

**Pacific
Northwest
Region**

R6-Ecol-181b-1984
March, 2003

Growth Basal Area Handbook



Growth Basal Area Handbook

Frederick C. Hall
Plant Ecologist

Updated March 2003

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ABSTRACT

Growth basal area (GBA) is that basal area at which dominant trees grow at 1.0 inch in diameter per decade at age 100. Diameter growth rate of 1.0 inch per decade is a constant used to compare sites; basal area is a variable used to express stockability. GBA is a field method for estimating site potential for stockability using current stand growth. Parameters measured are basal area per acre and rate of diameter growth. Current basal area is adjusted by use of a GBA curve to that basal area which will result in 1.0 inch diameter growth per decade of dominant trees, the GBA of the site. Two GBA curves are provided. The GBA concepts employed, development of GBA, determination of GBA, use of GBA, and GBA in relation to stand growth are discussed. GBA is combined with site index to index different productivity levels within a site index class and to help identify those productivity levels in the field. Appendixes provide description of a GBA slide rule, additional data, and forms for determining GBA.

PREFACE

The primary purpose of this monograph is to document, as completely as possible, the background, development, and use of growth basal area (GBA). A second purpose is to provide the field forester with instructions on the use and interpretation of GBA. GBA is a site-specific measure of forestland stockability--i.e., it indicates how many trees a site is capable of supporting. Stocking is expressed in terms of basal area per acre, assuming 1.0 inch per decade diameter growth on dominant trees. In this way, sites can be compared on the basis of how much basal area they will support at a diameter growth level of 1.0 inch per decade. For example, a GBA of 120 means dominant trees will grow 1.0 inch per decade in diameter at 120 ft^2 basal area per acre. In a stand with twice the stockability (GBA 240), dominant trees would grow 1.0 inch per decade in diameter at 240 ft^2 of basal area per acre.

GBA can be used to help determine the appropriate number of trees to leave following precommercial thinning, to prescribe thinning to attain a desired rate of diameter growth, to estimate rate of diameter growth following a given level of thinning, and to establish planting goals for artificial reforestation. GBA indicates growth characteristics of various tree species on a site so that the fastest growing species can be selected for thinning and planting. When GBA is combined with site index (SI) it indicates both different productivity levels within an SI class and permits identification of these productivity levels in the field. GBA can be used with other information to establish priorities for treatment by ranking various tracts from highest to lowest, the highest GBA being the most productive.

GBA can be used to modify simulation models or normal yield tables by comparing GBA to the model basal area per acre and taking the percentage of GBA as a percentage of stand productivity. GBA can be part of mapping and inventory of forest sites used in land management planning and project planning.

Thus, GBA may be used by land managers in dealing with treatment of forest stands, inventory of forestland site potentials, and land management planning. This monograph is designed to familiarize professionally trained or technically experienced people with the background, concepts, use, and interpretation of GBA.

CONTENTS

CHAPTER 1

Introduction

Growth basal area (GBA) is a field method for determining forestland site potential for stockability. It is the basal area per acre (BA/A) at which dominant trees grow at the rate of 1.0 inch in diameter per decade (1.0 in/dec.) at age 100. Tree diameter growth is used as a measure of competition and BA/A as an index of stand density. GBA will be discussed in chapters dealing with its development, determination, use, and relationship to stand productivity.

Stand Density, Stocking, and Stockability

Several terms used throughout this handbook must be defined for clarity.

Stand density refers to a measure of tree stocking expressed in such units as basal area or trees per acre (Ford-Robertson 1971). It is also a measure of tree crowding or competition. Often the term "density" will be used in lieu of stand density.

Stocking is the proportion of a tract that is occupied by trees or the number of trees compared with the desired number, i.e., 60% stocked or 60% of normal (Ford-Robertson 1971).

Stockability is the capacity of a forest site to grow trees. It refers to the ecological ability of a site to support a certain maximum number of trees or a certain maximum stand density. For example, a poor site at 100% stocking may be capable of supporting 150 trees per acre averaging 10 inches diameter at breast height (dbh) for a stand density of 82 ft^2 BA/A. A good site at 100% stocking may be able to support 400 trees per acre averaging 10 inches dbh for a stand density of 218 ft^2 BA/A. The stand densities of 82 ft^2 and 218 ft^2 BA/A represent both maximum stocking and maximum intertree competition for the two **sites**. They should not be confused with maximum density for a **species**.

Maximum density is the greatest number of trees or the highest BA/A that a **species** can attain throughout its range of occurrence. The maximum is assigned a relative density of 1.0, which means that no sites have the capability of stand densities greater than 1.0. Drew and Flewelling (1979) evaluated Douglas-fir[1/] and found maximum densities of 330 to 380 ft^2 BA/A, depending on dbh. Long and McCarter (1985) applied the concept to lodgepole pine using stand density index and found a maximum BA/A of 350 ft^2. Only the best sites are capable of supporting maximum density.

GBA is a means by which other sites can be identified and compared with the maximum. For example, the 82 ft^2 site is a relative density of 0.2 and the 218 ft^2 site is 0.6 according to Long and McCarter. These two sites can never reach a relative density of 1.0 because of adverse environmental factors. Their densities are only 20% and 60% of maximum for the species.

Competition occurs whenever several organisms require the same things in the same environment. Intensity of competition depends on the amount by which demand exceeds supply. Often, competition is greatest between two individuals of the same species because their demands are identical and they compete for the same environmental factors. Since some essential environmental factors are limited, increasing the number of trees decreases the amount available to each. The result is decreasing tree vigor and growth, although the same stand growth per acre may be maintained. Maximum competition occurs when further growth requires a reduction in the number of surviving trees. Rate of diameter growth is one measure of tree vigor, growth, and competition.

Indexes of stand density were reviewed by Curtis (1970), including stand density index (SDI), number or spacing of trees in relation to height, tree area ratio (TAR), crown competition factor (CCF), and number of trees in relation to volume (relative density, or RD--the density management concept of Drew and Flewelling (1979)). He concluded that all were suitable expressions of relative stand density, but proposed using a power function of dbh to index density. Alemdag (1978) evaluated five density indexes as they relate to predicting tree diameter growth and proposed two new ones. All were based on crown area or overlap (similar to CCF) or distance relationships to tree dbh (such as TAR). In the Pacific Northwest, Smith and Bell (1983) developed a competitive stress index (CSI) for Douglas-fir based on the assumption that the growing space

[1/] Scientific names of species are shown in App. 1.

available to a tree is a function of the dbh, a concept similar to TAR and to Curtis' proposed power function of dbh. Other than possibly the ratio of crown to stem diameter, no system used direct measures of tree vigor as an expression of competition.

As an index of stand density, GBA is unique in using tree diameter growth as a measure of competition.

GBA History

The GBA concept evolved during an ecological study of pine and fir forests in the Blue Mountains of eastern Oregon (Hall 1971, 1973). Many old growth ponderosa pine stands were sampled where BA/A was 40% to 60% of normal stocking (Meyer 1938), crown cover was not closed, and current rate of diameter growth was only 0.5 in/dec. Similar low stand densities were found in stagnated sapling and pole stands 40 to 80 years old also growing 0.4 to 0.6 in/dec. with only 70% to 90% crown closure. These stands were still near their prime age for growth, yet none approached normal stocking as described by Meyer (1938).

The assumption was that these stands were fully stocked even though basal areas were well below normal and crown canopies were not closed. They were judged to be below normal because of adverse site factors. Crown closures less than 100%, often 40% to 60%, did not indicate understocking. The assumption of full stocking at low crown closures was supported by field observations of abundant tree roots in soil pits between trees and root studies documenting root spreads of 1.5 to 5.2 times the crown radius (Brent and Gibbons 1958, Curtis 1964, Reynolds 1970, Smith 1964). Precommercial thinning in these stagnated stands resulted in diameter growth rates changing from 0.6 to 3.6 in/dec. when 80% of the BA was removed (figure 1). Similar responses have been reported elsewhere in the Pacific Northwest (Barrett 1981, 1982; Lynch 1958; Oliver 1972).

The following observations, particularly in stagnated stands, led to development of GBA:

1. Most stands exhibited little mortality.

2. A consistent ring-width pattern occurred wherein rings were widest at the pith and gradually narrowed toward the cambium. Rapid initial diameter growth, such as 4.0 in/dec., gradually decreased to about 0.5 in/dec. in the outer 1/2 inch of diameter. This ring-width pattern, coupled with lack of mortality, suggested that rate of diameter growth decreased with increasing stand density.

3. Different sites consistently had 0.4 to 0.6 in/dec. diameter growth in the last 1/2 inch of diameter but had widely differing BA/A.

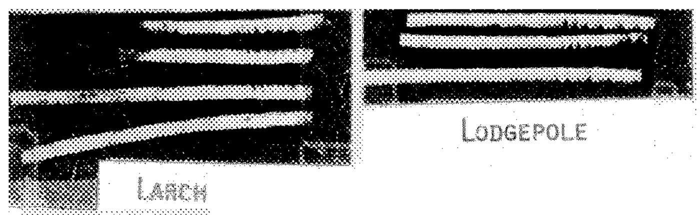


Figure 1. Diameter growth response of lodgepole and larch to precommercial thinning. The original stand of 3,000 TPA and 187 ft^2 BA/A was reduced to 280 trees and 35 ft^2. Diameter growth changed from 0.6 to 3.6 in/dec. of dominants. Diameter growth increased six times when basal area was reduced five times.

These observations suggested using BA/A as a variable to index stockability of a site with rate of diameter growth held constant to compare sites.

The "growth" of GBA is set at 1.0 in/dec. diameter growth and held constant. The "basal area" of GBA is a variable used to index different stand densities and thus stockabilities. For example, a site with a GBA of 150 ft^2 means dominant trees will grow at a rate of 1.0 in/dec. in diameter when stand BA is 150 ft^2/A. This is half the stockability of a site with 300 ft^2 GBA, where dominants will grow 1.0 in/dec. at 300 ft^2 BA/A.

GBA Concepts

Concepts important to understanding GBA include causes for change in diameter growth, age effects on GBA, site effects on GBA, and physiological differences between height and diameter growth.

Diameter growth. Several assumptions about diameter growth are central to the understanding and use of GBA. First, stand density is the major factor affecting rate of diameter growth in stands not seriously impacted by insects or disease. Most thinning studies have shown residual tree diameter growth increases following reduction in BA (figure 1) (Barrett 1981, 1982, 1985; Cole 1984; Dahms 1971b, 1973b; Harrington and Reukema 1983; Heninger 1981; Lynch 1958; Oliver 1972; Reukema 1979; Reukema and Pienaar 1973; Ronco et al. 1985; Seidel 1980, 1982, 1984; Tappeiner et al. 1982; Williamson 1976, 1982). This relationship has been shown to be predictable (Hall 1983, Hopkins 1986). Predictability is further supported by many of the thinning studies cited above. Graphs of density/diameter growth relationships are presented in Appendix 4.

Second, rate of diameter growth reflects competition. Slow diameter growth, such as 1.0 in/dec., indicates significantly greater competition than does 3.0 in/dec. Although this competition is usually considered to be between trees, shrubs and herbs can also reduce tree diameter growth (Barrett 1979, 1982, Gordon 1962, Van Sickle 1959). The assumption is that a decreasing rate of diameter growth is directly related to increasing competition. Further, a given rate of diameter growth indicates a somewhat universal degree of competition for most tree species. For example, a dominant pine and a dominant fir growing at 0.8 in/dec. are assumed to be under similar degrees of competition.

Third, rate of diameter growth reflects competition independent of crown closure. A stand at 30% crown closure whose dominants are growing 0.8 in/dec. is assumed to be under a similar degree of competition as a stand at 100% closure with dominants growing at the same rate. Competition is assumed to be independent of crown closure due to differences in site potential. Poorer sites cannot support as many trees as good sites. The influence of site factors on diameter growth has been demonstrated by fertilization studies (Agee and Biswell 1970, Barclay et al. 1982, Barrett 1979, Cochran 1979b, Harrington and Miller 1979, Wheetman et al. 1985).

The diameter growth rate of 1.0 in/dec. was selected as an index by which stands could be compared for stockability for several reasons:

(1) It is somewhat slower growth than that associated with 45% live crown ratio in ponderosa pine which appears to be necessary for prompt response following thinning (Barrett 1968).

(2) Height growth of ponderosa pine, western larch, Douglas-fir, lodgepole pine, and grand fir are reduced at stand densities resulting in 1.0 in/dec. diameter growth of dominants (see Chapter 4, "Management Implications of Stand Density").

(3) It is fast enough diameter growth to preclude suppression mortality according to data calculated from Avery et al. (1976), which showed 80% of ponderosa pine mortality occurring at dominant-tree diameter growth rates slower than 0.7 in/dec.

(4) Growth slower than 1.0 in/dec. seems to make pine susceptible to **Ips** and **Dentroctonus** beetles (Johnson 1967, Sartwell 1971).

(5) Spacing and thinning studies suggest that 1.0 in/dec. diameter growth does indicate highly significant intertree competition (Assmann 1970; Avery et al. 1976; Barrett 1981, 1982; Curtis and Reukema 1970; Dahms 1971a, 1971b 1973b; Lynch 1958; Oliver 1972; Seidel 1980, 1982).

The 1.0 in/dec. diameter growth rate was selected as a **reference** point for indexing stockability of sites. It is not a maximum or minimum diameter growth guide for thinning or other treatment anymore than SI age 100 is a management guide for ponderosa pine or Douglas-fir. Chapter 2 discusses stand density/diameter growth relationships in detail.

Age Effects. A second concept is that GBA changes with stand age. Many mensurational studies have documented change in rate of periodic annual increment with age (Assmann 1970; Barrett 1979; Cochran 1979a; Dahms 1966, 1983). Therefore, GBA should change with stand age. Hall (1983) studied this phenomenon and found that maximum GBA for a stand occurs approximately at culmination of periodic annual increment. This age/GBA relationship is discussed in Chapter 2.

Site effects. A third concept is that GBA is affected by site qualities (Hall 1971). Different site qualities are often reflected by significant differences in plant communities. Plant communities can be used to quickly stratify the landscape into different sites. Best estimates of GBA are attained by stratifying samples into reasonably similar sites. GBA as a site indicator is discussed in Chapter 5.

Tree physiology. The fourth concept of GBA is that diameter growth tends to be a different physiological function than height growth (Kozlowski 1971, Zimmermann and Brown 1971). Height growth starts earlier in the season, utilizes stored food reserves, and tends to terminate prior to severe environmental stress. Diameter growth starts later in the growing season, utilizes currently produced food, and tends to terminate with adverse growing conditions.

It is the sensitivity of diameter growth to growing conditions that permits rather delicate indexes of site stockability. Since height growth and diameter growth tend to be different physiological functions and tend to be influenced by different environmental factors (Hall 1971), GBA and SI are somewhat independent. An SI class may have more than one stockability potential and thus more than one productivity level within it (Assmann 1970; Bradley et al. 1966; Cole and Edminster 1985; Dahms 1966, 1973a; McKay 1985; MacLean and Bolsinger 1973; Franz 1967).

GBA is used to index different site potentials within a site index class and to identify these site potentials in the field (Chapter 5).

Development of GBA

This chapter deals with the development of GBA theory and stand density- diameter growth prediction curves referred to as GBA curves. The first two sections discuss site occupancy and the relationship of age to diameter growth. The following three sections deal with development of curves for predicting the relationship between stand density and diameter growth (GBA curves), validation of these curves, and estimation of age effects on GBA. The final section discusses GBA and basal area growth.

Site Occupancy

Root spread. A common concept of "full stocking" is crown closure. Apparently, crown spread and root spread were once considered equal. Therefore, it was assumed that crowns of a fully stocked stand had to be touching for full root system occupancy and therefore site occupancy. Smith (1964) pointed out that root spread of conifers exceeds crown spread by 1.2 to 3.0 times. Reynolds (1970) found that root spread of deciduous trees often exceeds crown spread by 2 to 4 times. Ponderosa pine root spread can range from 1.2 to 5.4 times the crown radius, Douglas-fir from 1.4 to 3.0, and lodgepole pine from 2.5 to 3.2 times the crown radius (Brent and Gibbons 1958, Curtis 1964, Reynolds 1970, Smith 1964). Eis (1970) discussed root grafting and how it often increases growth of residual trees after partial cutting. Root grafts occur when root systems extend beyond the crowns of trees and overlap those of adjacent trees.

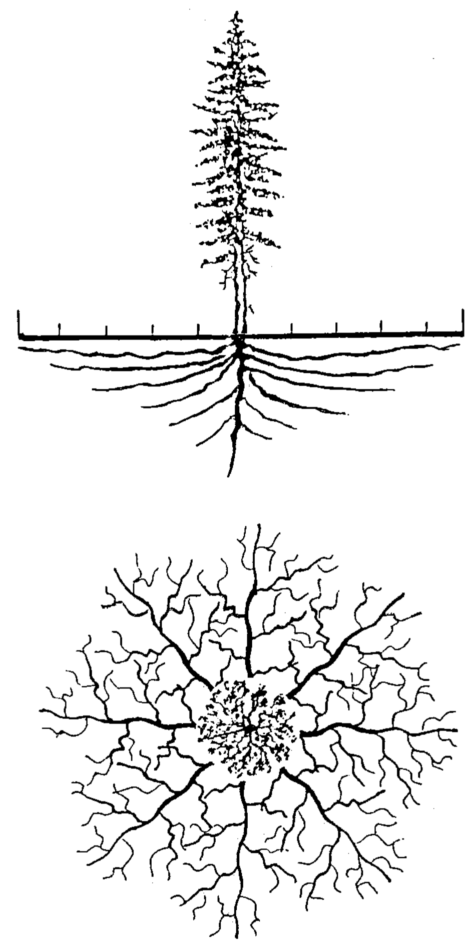


Figure 2. Conifer with a root spread five times the crown radius.

Figure 2 shows a conifer with a root spread of five times the crown radius. Figure 3 depicts a stand of conifers with a 300% root overlap at only 12% canopy closure. Field studies have verified full site occupancy at low crown closures. Seidel (1984) reported on a spacing trial in a 20-year-old stand of western larch and Engelmann spruce. During the last 10 years, diameter growth decreased as basal area increased. Diameter growth at 9-foot spacing was significantly less than at 15-foot spacing, all at canopy closures less than 100%.

In figure 4, people between the two ponderosa pines are standing at a soil pit which contains eight pine roots larger than 1/8 inch in diameter. The pit, located three crown radii distant, measures 2 feet square by 2 feet deep. It emphasizes the concept that crowns need not be touching for trees to be signicantly competing.

Figure 5 shows a similar relationship with Douglas-fir. The volume of roots four crown radii distant from the tree clearly emphasizes that crown closure is not required for full root occupancy and therefore full stocking. The stand in Figure 6 appears to be understocked. It is not. Instead it is a savanna environmental condition for ponderosa pine and Douglas-fir in which "fully stocked conditions" occur at crown closures between 12% and 25% for trees over 60 feet tall.

Leaf area index. Waring and Schlesinger (1985), in their text on forest ecosystem function, discuss leaf area index as a measure of site potential for producing biomass. Leaf area index (LAI) is an index of the

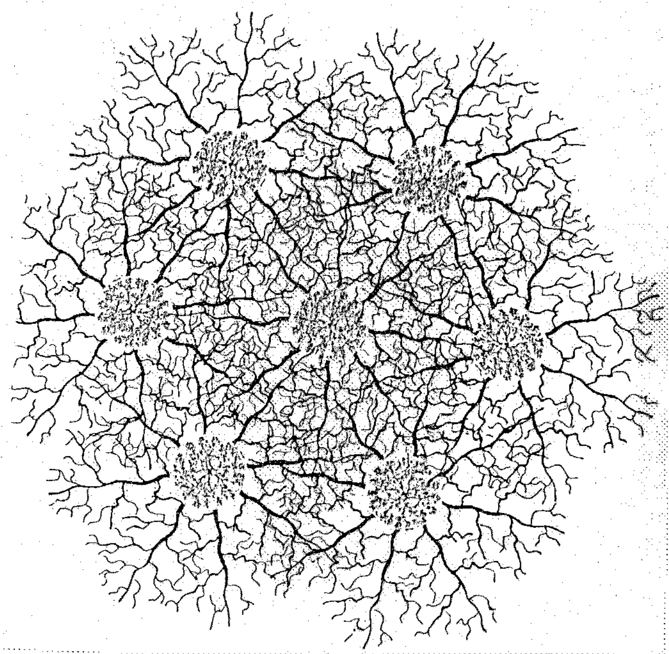


Figure 3. Conifers depicted in figure 2 at 300% root overlap and 12% canopy cover. A site can be fully occupied at less than 100% canopy cover.

surface area of all the leaves capable of being produced on a unit of land, i.e., 100% stocking. It is expressed as the ratio of leaf surface (ft^2) to ground area (ft^2). For example, an LAI of 4 means 4 ft^2 of leaf area per 1 ft^2 of ground covered. It represents the maximum leaf area and thus the maximum transpirational capability of a site. They report LAI's ranging from 1.5 for western juniper and 4 for ponderosa pine to 18 for Sitka spruce and western hemlock along the Pacific Ocean.

If 1 ft^2 of leaf area is contained in 3 ft^3 of crown volume (needles, branches, space between branches and needles, etc.), an LAI of 4 represents about 12 ft^3 of crown volume per 1 ft^2 of ground covered (Perry 1985). Figure 7 illustrates ponderosa pine LAI of 4 and the effects of tree height on canopy closure.

The assumption is made that this site can support only 12 ft^3 of pine crown volume per 1 ft^2 of ground area. Regeneration only 10 feet tall does not have sufficient height to produce maximum crown volume (and thus leaf area) to fully utilize the site, even at 100% or more canopy closure. By the time trees are 30 feet tall with 70% crown ratio, they can produce enough crown volume to fully utilize the site. Maximum crown volume occurs at 55% crown closure. At 60 feet tall, maximum crown volume occurs at 22% crown closure. Clearly, fully stocked conditions do not require a "closed crown canopy."

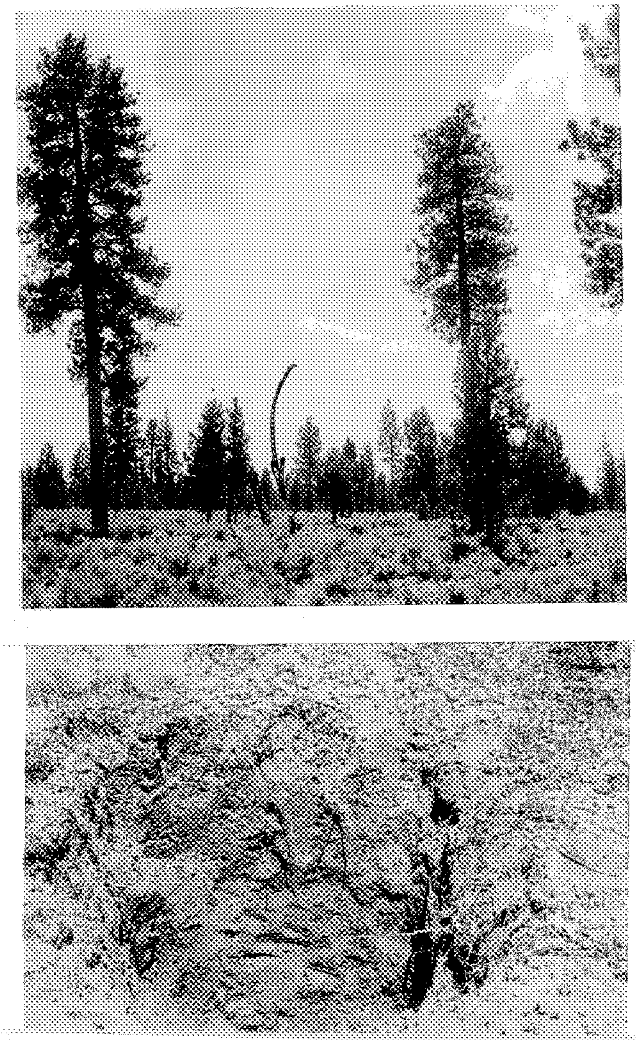


Figure 4. People (arrow) standing at a soil pit three crown radii from the ponderosa pine. The soil pit has eight pine roots larger than 1/8-inch diameter in two adjacent sides.

On this site with an LAI potential of only 4, a closed canopy would not be possible after trees exceed about 20 feet in height. As trees grow in height they produce longer crowns with increasing volume. Eventually they will be tall enough to reach site potential for crown volume. As they continue to grow taller, a gradual decrease in canopy closure should occur to maintain about the same crown volume (leaf area) per acre.

Diameter growth. These stand conditions are a primary reason for using rate of diameter growth as an index of intertree competition for GBA. The use of diameter growth as an index simply lets tree growth performance indicate how good a site is for stockability.

But just how good is diameter growth as an index of stockability and intertree competition? Most research studies and simulation models show an inverse relationship between stand density and rate of diameter growth (Barrett 1979, 1981, 1982; Brendt and Gibbons 1958; Cole 1984; Cole and Stage 1972; Cochran 1979b; Curtis et al. 1981; Dahms 1971a, 1971b, 1983; Harrington and Reukema 1983; Lynch 1958; Oliver 1972; Reukema 1979; Seidel 1980, 1982, 1984; Seidel and Cochran 1981; Tappeiner et al. 1982; Williamson 1982; Wykoff et al. 1982). Figure 8 illustrates two kinds of stand treatment. A Douglas-fir understory was released by logging and then commercially thinned 12 years later. Rate of diameter growth is clearly reflected in these treatments.

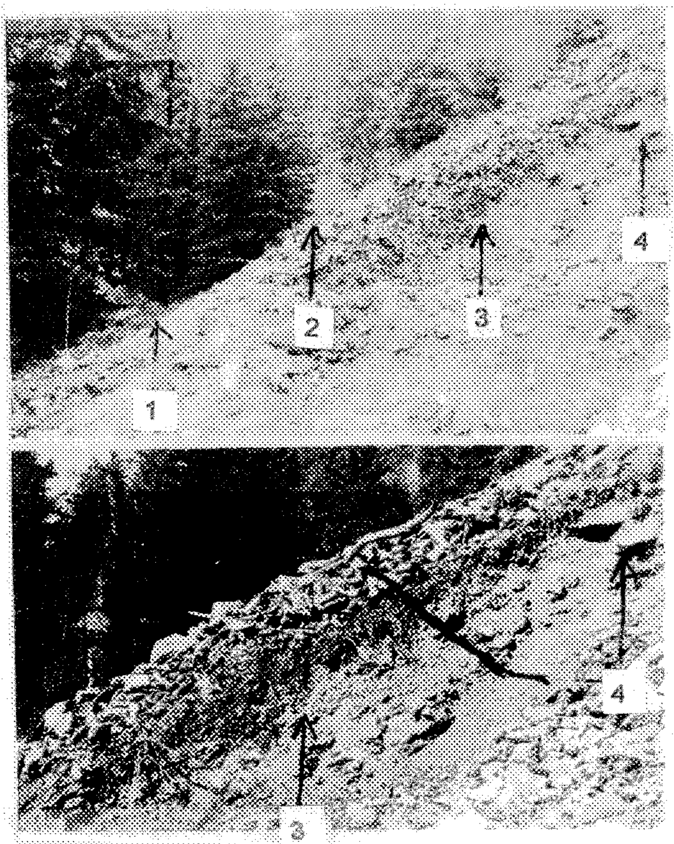


Figure 5. Root spread of a Douglas-fir exposed in a gravel pit. Top: Douglas-fir at left is marked off in crown radii. Bottom: Close view of rooting system between three and four crown radii from the tree demonstrates site occupancy.

Figure 6. Open, savanna conditions of ponderosa pine which can fully occupy a site at crown closures of 12% to 25%. Sagebrush dominates the ground vegetation.

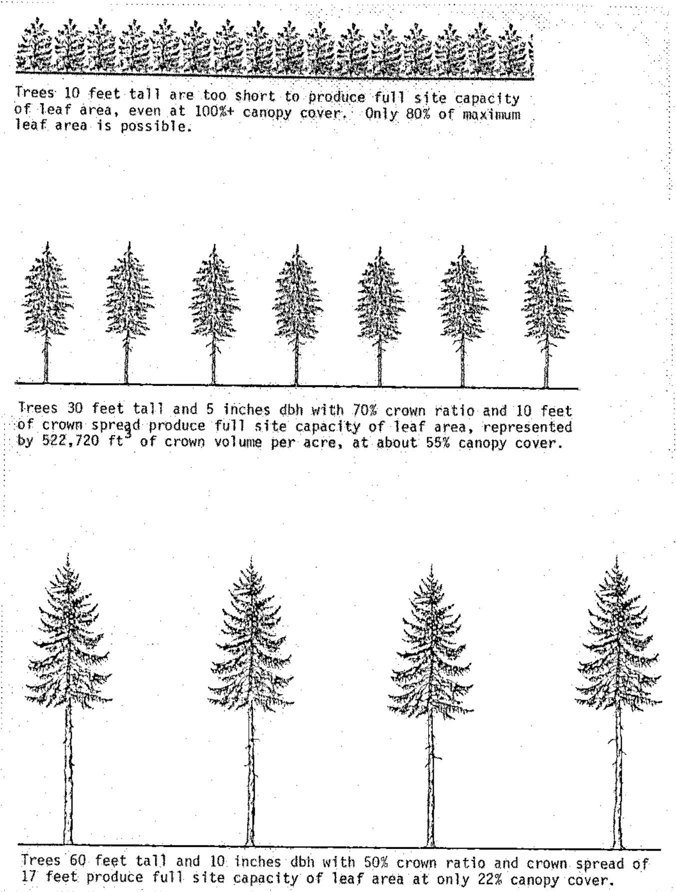


Figure 7. Relationship of tree height to canopy cover for a site with a leaf area index (LAI) of 4 ft^2 per ft^2. An LAI of 4 represents about 12 ft^3 of crown volume per ft^2 of ground covered or 522,720 ft^3 of tree crown volume per acre.

Figure 9 shows a precommercially thinned ponderosa pine stand. Site index is 70 for a normal BA of 189 ft^2/A (Meyer 1938). The stand was stagnated in 1963 at 140 ft^2 BA/A (75% of normal) at stand age 60 years. This age is approaching culmination of periodic annual increment , when stand growth should be at its maximum. Dominant trees were growing 0.8 in/dec. in diameter, and crown closure was 90% (the fact that the crown was not "closed" is evidenced by shadows in 1963).

Following heavy thinning in 1964, tree diameter growth reached a maximum of 2.8 in/dec. at 33 ft^2 BA/A 5 years later. Twenty years after thinning, diameter growth had slowed to 1.6 in/dec. at 65 ft^2 BA/A. Diameter growth decreased by 57% while BA/A increased by 51%. The increase in BA/A presumably caused a decrease in rate of diameter growth due to increasing competition, which occurred at canopy closures of only 50 to 60%.

GBA uses this stand density/diameter growth relationship to index the stockability of a site. As such,

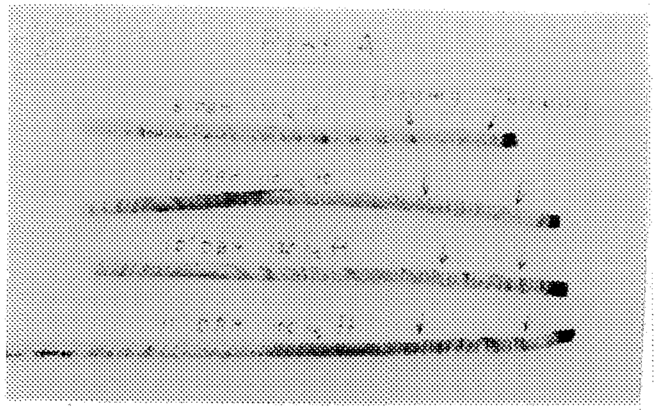


Figure 8. Response of Douglas-fir understory trees to overstory removal and commercial thinning 12 years later.

GBA is not indexed to normal yield tables or to relative density measures such as stand density index, tree area ratio, or crown competition factor (Curtis 1970). Instead, it is indexed to tree diameter growth performance as influenced by different sites.

Diameter Growth and Age

The stand density/diameter growth relationship is well documented and should be accepted in stands up to age 100. But this leaves the question of how old age affects the relationship, a topic essentially unresearched. One study, however (Williamson 1982), demonstrated that 127-year-old Douglas-fir has responded to both light and heavy commercial thinning.

Except for lodgepole pine, trees in reasonable or better vigor can respond to change in BA/A with a change in diameter growth up to at least age 250. Figure 10 shows a Douglas-fir released by a shelterwood cut at age 160. Diameter growth increased from 0.8 to 4.5 in/dec., the same rate at which diameter grew from age 20 to 40.

Figures 11 to 13 illustrate diameter growth responses to major changes in stand density for three species. Diameter growth increased fivefold to sixfold in trees from 140 to 240 years old.

Obviously, stand density is the major factor affecting diameter growth, with stand or tree age exerting relatively minor but significant influence. The challenge is to determine what the density/diameter growth relationship(s) is. How can diameter growth be predicted when stand density is changed? What shape does a curve of stand density/diameter growth take, and what is the equation?

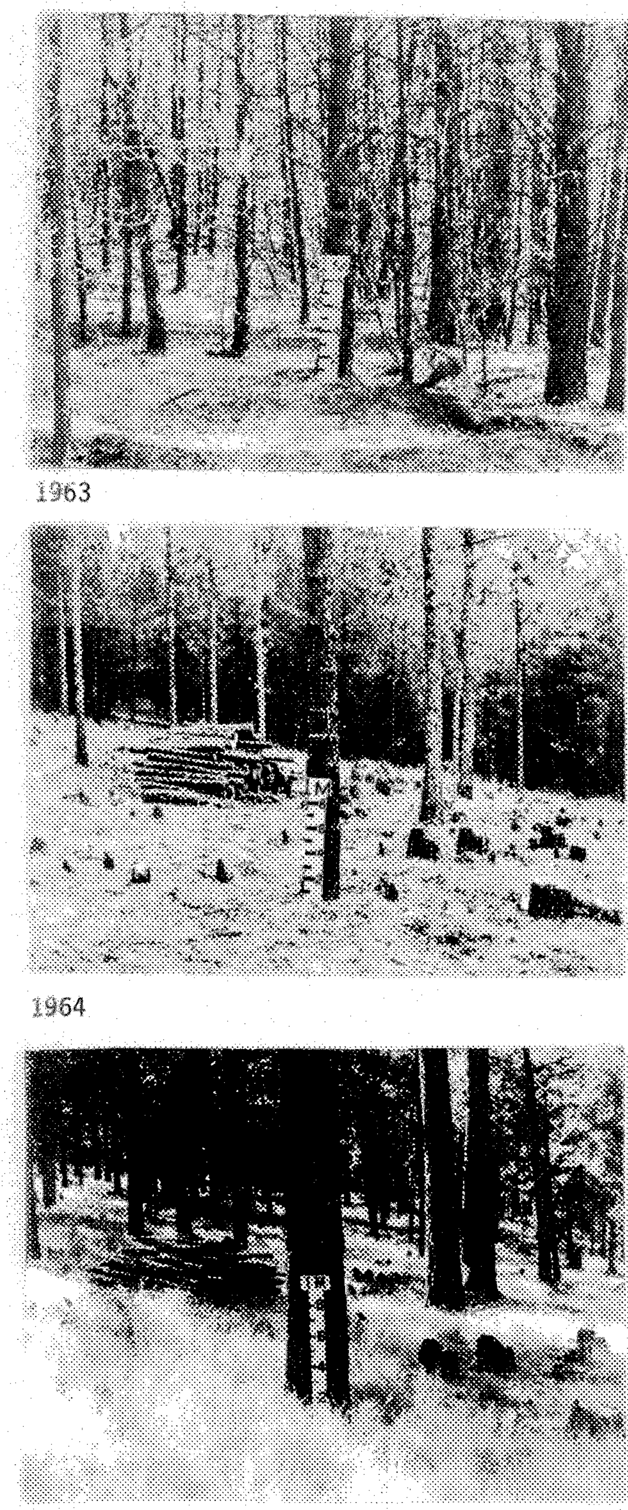


Figure 9. Stagnated ponderosa pine in 1963 to be precommercially thinned. Larger trees are 60 years old, smaller 40 years. Site index is 70 ft at age 100, BA/A in 1963 was 140 ft^2, 75% of normal at 90% crown closure. Diameter growth of dominants was 0.8 in/dec in 1963, which increased to 2.8 in/dec by 1969, than slowed to 1.6 in/dec by 1984 at 65 ft^2 BA/A and 55% canopy cover.

GBA Curve Development

Sampling to develop GBA curves was conducted east of the Cascade Crest in Oregon. Primary emphasis was devoted to dry sites supporting ponderosa pine, lodgepole pine, Douglas-fir, white fir, and Shasta red fir.

Concepts which were assumed to be valid are: A predictable relationship exists between BA/A and diameter growth; 1.0 in/dec. diameter growth implies sufficient competition to be usable as an index to compare stands; BA/A is a suitable measure of stand density; and different sites will have different stockability capacities regardless of canopy closure. A system was needed for converting current diameter growth to an index rate of 1.0 in/dec. and for concurrently adjusting current BA/A to that which would result in 1.0 in/dec. diameter growth.

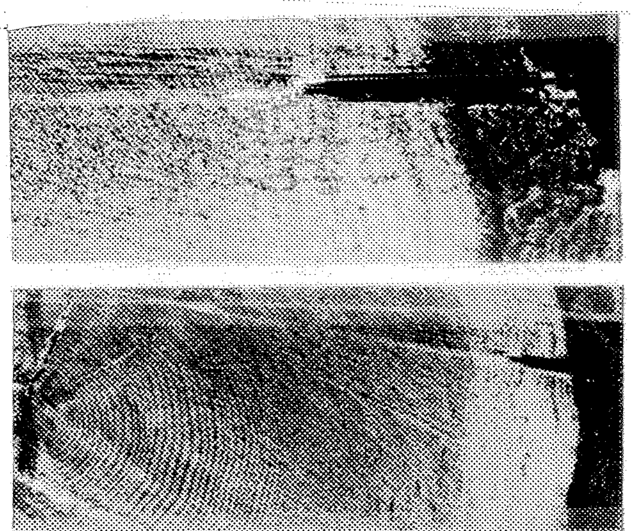


Figure 10. Douglas-fir released by shelterwood cut at age 160. Diameter growth rate changed from 0.8 to 4.5 in/dec., the same rate at which it grew at age 20.

For example, current diameter growth might be 0.6 in/dec. at 200 ft^2 BA/A. What BA/A would result in 1.0 in/dec. diameter growth and thus provide an index of stockability? A curve was developed with current diameter growth rate on the X axis and a conversion factor applied to current BA/A on the Y axis (figure 14). Diameter growth of 0.6 in/dec. occurs at 150% of GBA for a conversion factor (CF) of 0.67 (the reciprocal of 150%). One in/dec. diameter growth is faster than 0.6 in/dec., therefore the BA/A for 1.0 in/dec. must be less. The CF is multiplied times current BA/A for GBA:

$$\begin{aligned} GBA &= CF*BA/A \\ &= 0.67*200 \\ &= 134\ ft^2\ BA/A \end{aligned}$$

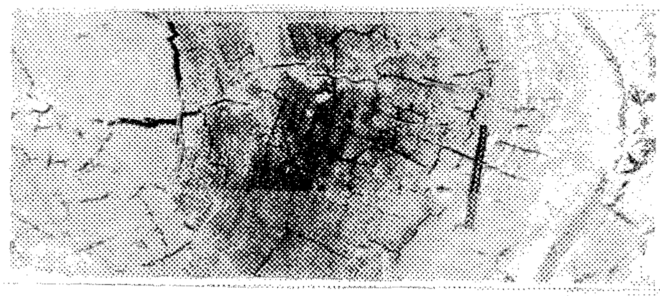


Figure 11. Ponderosa pine released by partial cut at age 240. Diameter growth changed from 0.6 to 3.6 in/dec.

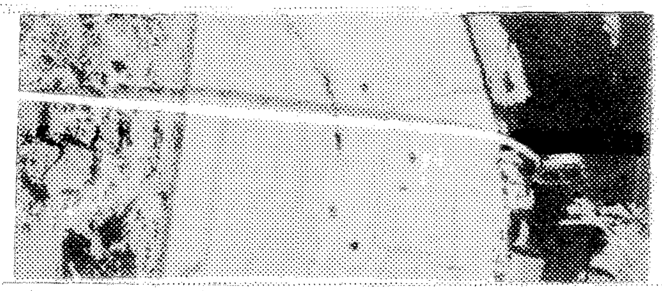


Figure 12. Grand fir released by overstory removal at age 160. Diameter growth changed from 0.7 to 3.7 in/dec.

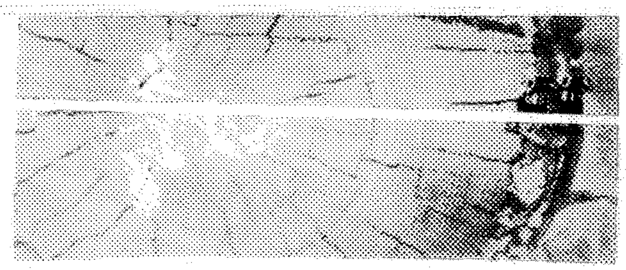


Figure 13. Western larch released by crown fire at age 140. Diameter growth changed from 0.7 to 3.7 in/dec.

Conversely, 0.6 in/dec. diameter growth should occur at 150% of the BA/A for 1.0 in/dec.

Stands selected for sampling were 80 to 250 years old, largely pure, even-aged, and originally stocked at wide spacing. They exhibited little observable mortality. Dead and down trees could account for no more than 5% of current BA/A. Mortality was observable because dry conditions east of the Cascade Crest prevent rapid deterioration of dead trees. Slow deterioration permits estimation of mortality for many years; stumps may remain intact for 80 years and 3-inch-diameter saplings can still be measured after 30 years (figure 15). Low initial stand density permits rapid diameter growth, which decreases over time as BA/A increases (figure 16).

For example, a stand of 90 trees per acre (TPA) and 9 inches quadratic mean dbh at 40 ft^2 BA/A might achieve 4.0 in/dec. diameter growth of dominant trees. As diameters increase, BA/A increases and

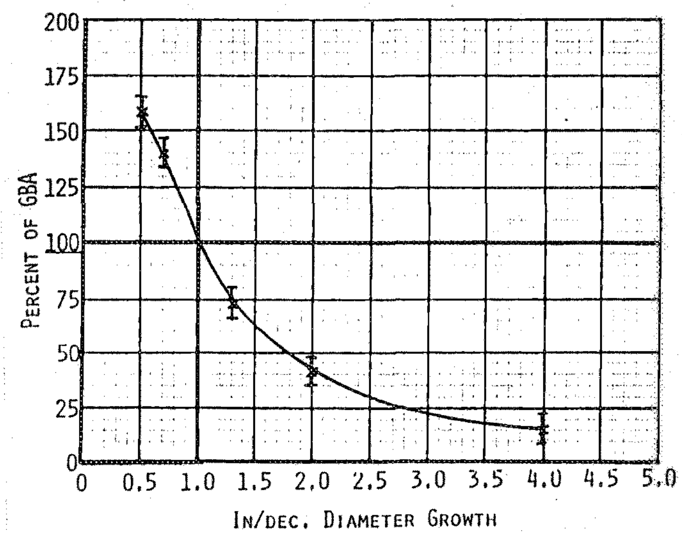


Figure 14. Ponderosa pine GBA curve with confidence intervals ($p = 0.01$) (Hopkins 1986), $n = 246$, for each of five growth points.

Figure 15. One of 12 stands sampled in Sumpter Valley, Oregon, to evaluate age effects on GBA. Measurements were taken on 80-year-old stumps from old growth ponderosa pine ranging in age from 180 to 240; on 22-year-old precommercial thinning slash and standing trees to appraise GBA at age 55 prior to thinning; and on the current stand at age 78 years. Note that evidence of past mortality can be recognized and measured for 25 to 80 years.

rate of diameter growth decreases so that at 13 inches dbh and 80 ft^2 BA/A, diameter growth has slowed to 2.0 in/dec. and at 18 inches dbh and 160 ft^2 BA/A, diameter growth is 1.0 in/dec. Figure 16 shows this relationship.

Field sampling involved increment coring trees at breast height. Three to five dominant trees within approximately a half-acre area were selected based on diameter and height. Dominant trees were selected because they exhibit the fastest diameter growth, thereby providing a single reference point for determining stockability of the site. They are often the same trees sampled for site index (SI), thereby

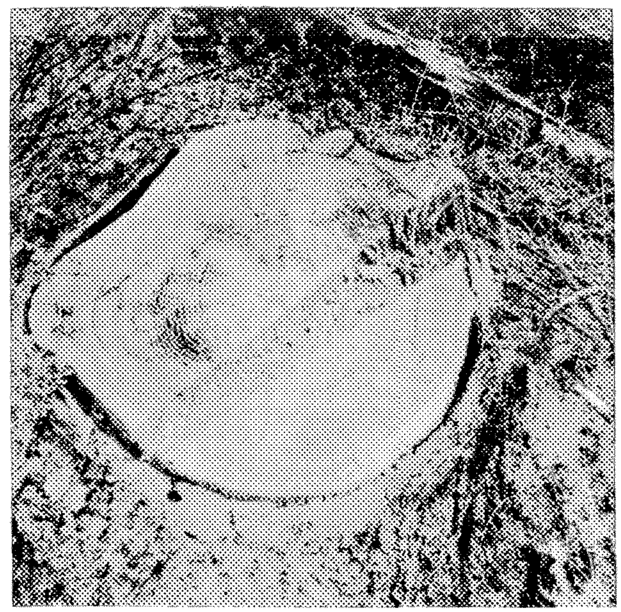


Figure 16. A Douglas-fir stump 20 inches in diameter showing rapid initial diameter growth which slowed to 0.6 in/dec. in the outer 1/2 inch. This stump is shown schematically in figure 18.

providing a focal point for using GBA as a stockability modifier for SI. At each tree sampled, BA/A was determined on either a 1/5-acre plot or by prism tally counting 8 to 12 trees.

The relationship between stand BA/A and dominant-tree diameter growth was evaluated in two phases: "horizontal" stand sectioning in ponderosa pine and evaluation of stand density/diameter growth relationships in other species.

Horizontal stand sectioning involved measuring dbh and increment coring all trees on a 1/5-acre plot that was centered on a dominant (GBA) tree. Current stand BA/A was determined and current rate of diameter growth on the GBA tree was measured. Then the increment core from the GBA tree was marked where three to five rings averaged diameter growths of 0.5, 0.7, 1.0, 1.3, 2.0, and 4.0 in/dec. Number of years before present were determined for each diameter growth rate to establish a date for each growth rate. Years before present were then marked on all other increment cores from the 1/5-acre plot so tree dbh at the six dates could be estimated. Stand BA/A was calculated using the reconstructed dbh's for each of the six diameter growth rates. In this way, stand development was recreated with respect to its dbh distribution and BA/A for each diameter growth rate. Finally, stand BA/A's for each diameter growth rate were taken as a percentage of the BA/A for 1.0 in/dec.

A simple shortcut was developed during this initial work. Percent of stand BA/A at each diameter growth rate was found to be highly correlated with percent of dominant tree BA (determined inside bark) for each growth rate. The recreated stand BA/A was taken as a percentage of the current BA/A for each diameter growth rate. Then the BA of the dominant tree (GBA tree) was determined (inside bark) for each of the diameter growth rates and BA was taken as a percentage of the BA at diameter inside bark (dib).

For example, current stand conditions might be 200 ft^2 BA/A with a 20-inch-dib dominant tree growing at 0.6 in/dec. This would be 100% stand BA/A at 100% tree BA dib. The growth rate of 1.0 in/dec. occurred 20 years previous at a recreated stand BA/A of 162 ft^2, or 81% of current BA/A, when the tree was 18 inches dib. Tree BA's were 2.18 ft^2 for current growth and 1.76 ft^2 at 1.0 in/dec. for 81% of current BA. The ratio, then, is 81% stand BA/A compared to 81% tree BA dib.

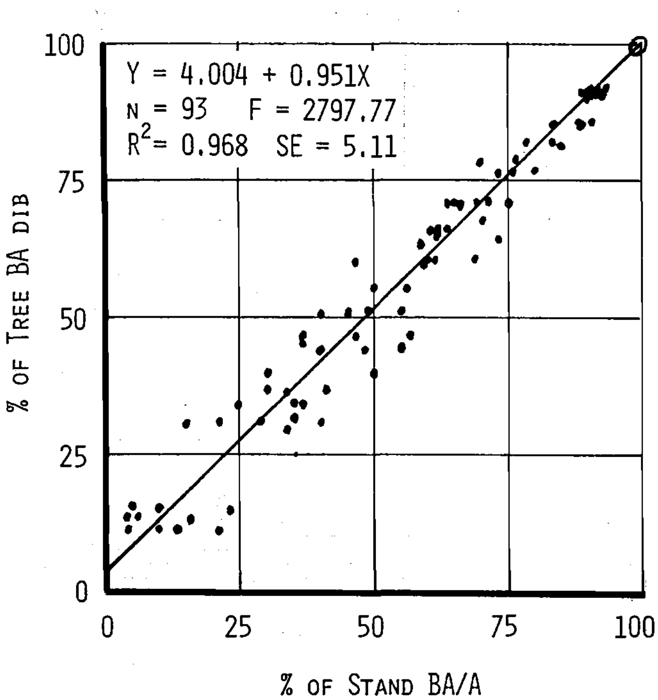


Figure 17. Regression of percent tree BA dib (Y) on percent stand BA/A (X) for 18 stands and 93 observations. This is a significant 1:1 correlation, meaning that percent tree BA can be used to estimate percent stand BA/A directly.

Percent stand BA/A was taken as the independent variable (X) and regressed with percent tree BA dib as the dependent variable (Y) (figure 17). The values of F = 2797.77, R^2 = 0.968, and a standard error of estimate = 5.11 were accepted as sufficient to warrant using percent tree BA dib as an estimate of stand BA/A for each diameter growth rate. In this way, only one tree had to be increment-cored per plot instead of 15 to 30, a significant savings in time. Forms for determining this relationship are in Appendix 5.

The current procedure is as follows: A dominant tree is selected and prism point is established halfway between the sample tree and its nearest neighbor to determine BA/A. The tree is increment-cored to the center on the same side as the prism point. Current rate of diameter growth is measured on the increment core. Then the core is marked where three to five rings average diameter growths of 0.5, 0.7, 1.0, 1.3, 2.0, and 4.0 in/dec. Diameter inside bark (dib) of the tree at each growth rate is determined to relate past BA to past diameter growth as shown in figure 18.

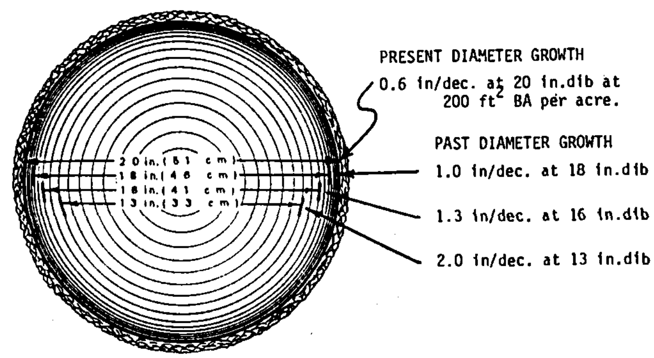


Figure 18. Technique used to evaluate diameter growth in regard to basal area. The measurements depicted are analyzed for GBA interpretation in table 1.

For example, current growth is 0.6 in/dec. at 200 ft^2 BA/A. Tree BA is 2.18 ft^2 at 20 inches dib. Diameter growth of 1.0 in/dec. occurred at 18 inches dib when the tree was 1.75 ft^2 BA, or 81% of its current BA. This means that 1.0 in/dec. diameter growth occurred at a stand density 81% of current, or about 160 ft^2 BA/A. Similarly, 1.3 in/dec. occurred at 16 inches dib when the tree was 1.39 ft^2 or 64% of its current BA, and 2.0 in/dec. occurred at 13 inches dib for 42% of current tree BA. Thus, 1.3 in/dec. occurred at 128 ft^2 BA/A, and 2 in/dec. occurred at 84 ft^2 BA/A.

Diameter growth of 1.0 in/dec. was selected as the growth rate index to evaluate stockability and establish a prediction curve. Basal areas for 0.5, 0.7, 1.3, 2.0, and 4.0 in/dec. were compared with it as

Table 1. Measurements depicted in figure 18 as they are analyzed for GBA.

In/dec.	In. dib	ft^2 BA	% BA	ft^2/A "GBA"	% GBA
0.6	20	2.18	100	200	123
1.0	18	1.76	81	162	100
1.3	16	1.39	64	128	79
2.0	13	.92	42	84	52

described above and shown in table 1. The BA for 1.0 in/dec. was assigned 100%. Then the BA for each other diameter growth rate was taken as a percentage of it, so that 0.6 in/dec. was 123%, 1.3 in/dec. was 79%, and 2.0 in/dec. was 52% of GBA. These percentages of GBA by diameter growth rate were treated in two ways: averaged by each growth rate by species, and submitted to regression analysis.

Figure 14 summarizes 246 ponderosa pine samples with confidence intervals (p = 0.01) (Hopkins 1986). The curve has been hand-drawn through the averages of each growth rate. Hopkins demonstrated that each tree species tends to have its own GBA curve shape (See Appendix 3 for four other species).

The curve is used as follows. A GBA pine is growing at 2.0 in/dec. at 100 ft^2 BA/A: Enter the graph at 2.0 in/dec., read up to the curve and left for about 45% GBA. This means that 2.0 in/dec. occurs at 45% of the BA/A for 1.0 in/dec. The Conversion Factor (CF) is the reciprocal of % GBA, which is 2.2:

GBA = CF*BA/A
= 2.2*100
= 220 ft^2 BA/A

Equations were developed by submitting all data (Hall 1983, Hopkins 1986) to regression analysis using % GBA (Y) as the dependent variable and diameter growth per decade (X) as the independent variable. The following forms of equations were tested:

(1) $\ln Y = a + bX$ (Intersected at 100.3% of GBA)

(2) $\ln Y = \ln a + bX$ (Intersected at 100.07% of GBA)

(3) $y = a\ln X^{bx}$ (Intersected at 100.05% of GBA)

(4) $\ln Y = a + b\ln X$ (Intersected at 97.2% of GBA)

(5) $Y = aX^b$ (Intersected at 86% of GBA)

Equations (1) and (3) fit the data fairly well. The natural logarithmic function (equation 1) was selected to test differences between species for two reasons: (1) It plots as a straight line, which permits simple calculation of R^2, variance, and the "a" and "b" coefficients. (2) Statistical tests for significant differences between species are simplified. Table 2 lists the results (Hopkins 1986).

Hopkins (1986) tested for significant differences between species by analysis of Equation (1). Analysis of variance, using Bartlett's test as described by Freese (1967), showed no significant difference between ponderosa and lodgepole pine or between white fir and Douglas-fir. Shasta red fir was different from white fir and from the pines but not from Douglas-fir. A second test of significant difference entails analysis of the "b" constant, or slope of the regression line. All species were significantly different (p = 0.05).

Figure 19 shows all six hand-drawn GBA curves. Clearly, this would not be usable on the GBA slide rule. Two curves were developed, one for "pine" and one for "fir" as shown in figures 20 and 21. This is a decision of expediency based upon measurement precision in the field and confidence intervals at each diameter growth rate. For example, a prism counting eight trees has a precision error of 12% of the mean BA/A. Confidence intervals at p = 0.05

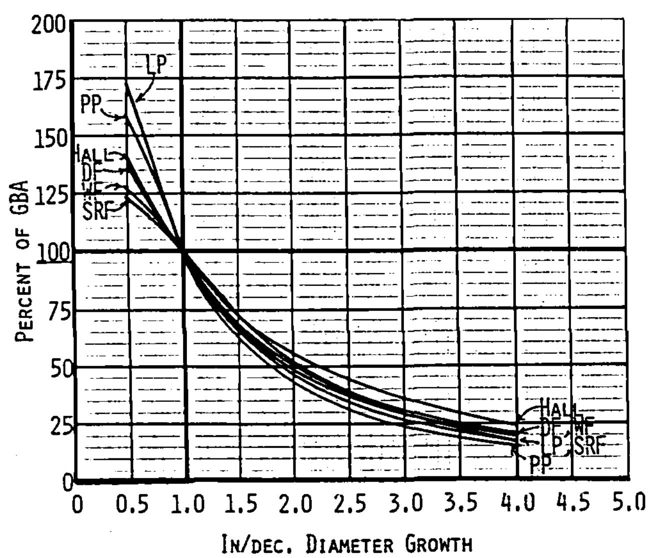


Figure 19. Six GBA curves overlaid to show differences: Hall (1983), ponderosa pine (PP), lodgepole pine (LP), white fir (WF), Douglas-fir (DF) and Shasta red fir (RF) (Hopkins 1986). Pine and fir curves were selected to represent shade-intolerant and shade-tolerant species (figures 20 and 21).

Table 2. Six regressions of percent GBA (Y) as a function of rate of diameter growth (X) expressed as in/dec. of the form lnY = a + bX.

Curve source	a	b	R^2	SE*	N
Hall[1]	5.10	- 0.492	0.98	.0894	365
Douglas-fir[2]	5.16	- 0.589	0.77	.0277	31
White (grand) fir[2]	5.19	- 0.628	0.68	.0219	94
Shasta red fir[2]	5.23	- 0.699	0.76	.0321	39
Lodgepole pine[2]	5.38	- 0.764	0.81	.0141	140
Ponderosa pine[2]	5.40	- 0.814	0.86	.0099	246

[1] Hall 1983
[2] Hopkins 1986
* Standard error of the estimate.

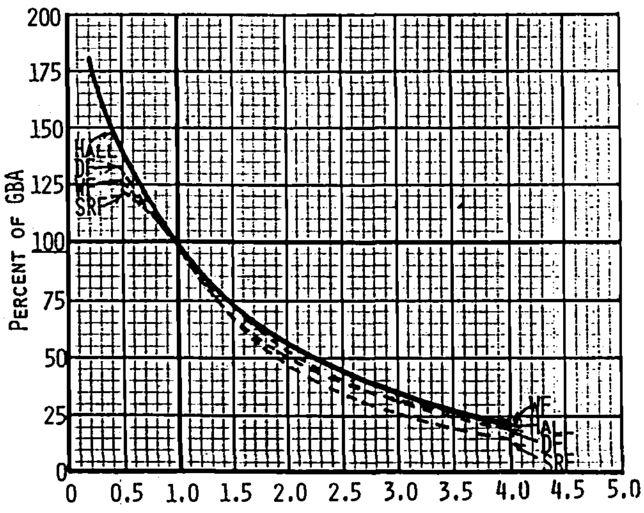


Figure 20. The Douglas-fir, white fir, Shasta red fir, Hall's curves (dotted lines) and the fir curve (solid line) used on the GBA slide rule and for data in table 13 and equations (6), (7), and (8).

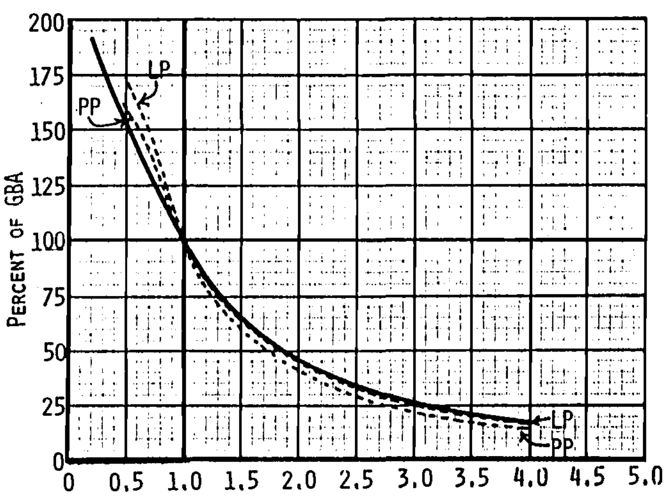


Figure 21. The ponderosa pine and lodgepole pine GBA curves (dotted lines) (Hopkins 1986) and the pine curve (solid line) used on the GBA slide rule and for data in table 13 and equations (6), (7), and (8).

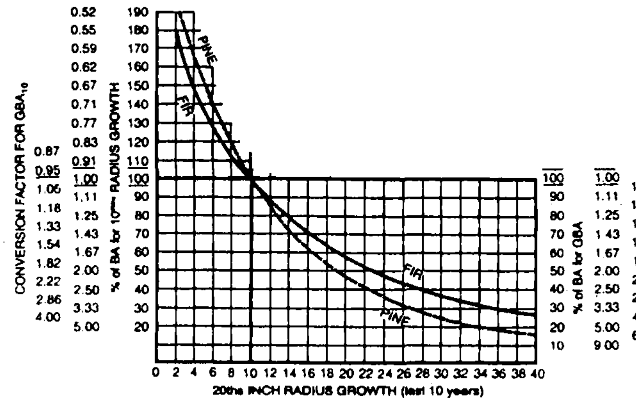


Figure 22. The pine and fir GBA curves as they appear on the slide rule.

suggested that species curves should be no closer to each other than about 8% of GBA. The curves developed in figures 20 and 21 are shown in figure 22.

The pine and fir curves were submitted to regression analysis to develop an equation for field use that would best fit the curve shape. Raw data were not used. Instead, values used in regression were taken from each curve. Units expressing diameter growth were changed from in/dec. to 20ths of an inch radius growth.[1/] Best fit was found with the form:

(6) $\ln Y = a + bX + cX^2$,

where Y is % GBA and X is radius growth for the last 10 years measured in 20ths of an inch.

Table 3 lists the coefficients for pine and fir. Values for F, R^2, and standard error of estimate are not given because regression data were taken from the curves.

Table 3. Pine and fir curve regressions of % GBA (Y) as a function of rate of diameter growth per decade (X) expressed as 20ths inch radius growth of the form: lnY = a + bX + cX².

Curve	a	b	c
Pine composite	5.488	- 0.0952	+ 0.000658
Fir composite	5.299	- 0.0740	+ 0.000584

[1/] Diameter growth is inferred by measuring the last 10 years' radial growth on increment cores in 20ths of an inch instead of 10ths of an inch. Radius growth must be doubled for diameter growth. Doubling is facilitated by measuring in 20ths (the doubling factor) and dividing by 10 for in/dec.--i.e., 0.8 in/dec. is measured as 8/20ths radius growth.

Determine % GBA by measuring the last decade radius growth in 20ths of an inch, enter the 20ths as X and X^2 in the equation, and solve for the natural log of % GBA; take the antilog for % GBA. For example, a GBA pine at 100 ft^2 BA/A is growing 2.0 in/dec. in diameter, which is 20/20ths radius growth:

ln% GBA = 5.488 - 0.0952*20 + 0.00065820**
= 3.847
The natural antilog Is 46.8% GBA

Knowing % GBA, find GBA by use of the conversion factor (CF) applied to current BA/A. The CF is the reciprocal of % GBA:

CF = 100/46.8
= 2.14

Determine GBA by adjusting current BA/A by the CF:

GBA = 2.14*100
= 214 ft^2 BA/A

The pine and fir GBA curves were also solved to obtain the Conversion Factor (CF) directly using equation (7):

(7) $Y = a + bX + cX^2$,

where Y is the CF (reciprocal of % GBA) and X is 20ths of an inch radius growth. Table 4 lists the coefficients.

Table 4. Pine and fir curve regressions of the Conversion Factor (Y) as a function of rate of diameter growth per decade (X) expressed as 20ths inch radius growth of the form: $Y = a + bX + cX^2$.

Curve	a	b	c
Pine composite	0.436 +	0.0235 +	0.00316
Fir composite	0.470 +	0.0440 +	0.00101

The CF can be determined by measuring the last decade's radius growth in 20ths of an inch, entering the 20ths as X and X^2 in the equation, and solving for CF, which is then used to calculate GBA for a stand. For example, a GBA pine is growing at 2.0 in/dec. at 100 ft^2 BA/A. The rate of 2.0 in/dec. is 20/20ths radius growth:

CF = 0.436 + 0.0235*20 + 0.0031620**
= 2.17

Determine GBA by adjusting current BA/A by the CF:

GBA = 2.17*100
= 217 ft^2 BA/A

And finally, data for the curves was rerun after substituting 20ths inch radius growth for Y and % GBA for X so that rate of diameter growth could be predicted from a percentage of GBA using equation (8):

(8) Y = a + b*lnX + clnX**

where Y is 20ths of an inch radius growth and X is % GBA. Table 5 lists the coefficients.

Table 5. Pine and fir GBA curve regressions of 20ths inch radius growth (Y) as a function of % GBA (X) of the form: $Y = a + b\ln X + c\ln X^2$.

Curve	a	b	c
Pine composite	109.07 -	31.134 +	2.0769
Fir composite	182.54 -	59.160 +	4.6963

Rate of diameter growth, expressed as 20ths of an inch radius growth, can be estimated from % GBA by entering the natural log of % GBA for X in the equation. Note that the natural log of % GBA is squared, not % GBA itself. For example, a pine stand has a GBA of 214 ft^2. How fast will dominant pine grow if thinned from below to 125 ft^2 BA/A? Determine % GBA:

% GBA = 125/214
= 58.4

The natural log of 58.4% GBA is 4.07: Substitute 4.07 for X:

20ths = 109.07 - 31.134*4.07 + 2.07694.07**
= 16.8 or 1.68 In/dec.

The curves in figures 20 and 21 have been combined on a single graph for field use. Figure 22 shows these curves as they appear on the GBA slide rule. They are used as follows: Enter at the measured rate of radius growth in 20ths of an inch, read up to either the pine or fir curve and left for % GBA and the CF. Taking the example used for equations (6) and (7), 2.0 in/dec. is 20/20ths radius growth at 100 ft^2 BA/A. Enter at 20/20ths, read up to the pine curve and left for about 47% GBA and a CF of 2.15: 2.15*100 = 215 ft^2 GBA. The illustration for equation (8) can be solved as follows:

Enter at 58% GBA, read right to the pine curve and down for about 16.5/20ths or 1.65 in/dec. diameter growth.

GBA Curve Validation

The concept of GBA curves and the shape of the curves have been validated in two ways: (1) measured plot data from 15 published studies were graphed and the appropriate GBA curve superimposed; (2) predicted values from six simulation models were graphed and the GBA curve superimposed. The major concern is shape of the curve, since nearly all studies clearly demonstrate predictable basal area/diameter growth relationships.

In figure 23, shape of the pine and fir curves is compared. In addition, shape of each GBA curve changes depending upon the value of GBA. In figure 24, change in shape of the pine curve varies as GBA changes from 50 to 400 ft^2 BA/A.

The appropriate curve was compared with measured plot data for ponderosa pine, lodgepole pine, western larch, and Douglas-fir. Only four examples are shown here, but Appendix 4 contains 12 more.

D/Dq diameter growth. Many reports provided only quadratic mean dbh (Dq), or average diameter growth. Dq diameter growth is less than dominant-tree diameter growth, therefore GBA calculated from Dq would be less than that calculated from dominant-tree growth. A ratio of dominant-tree diameter growth (d) to Dq diameter growth (d/Dq) was calculated from the studies shown in table 6 so that Dq diameter growth could be adjusted to dominant-tree diameter growth.

These data were submitted to regression analysis, which produced the equation:

$$\text{(9)}\quad Y = 1.73 - 0.19X \quad F = 10.636 \quad R^2 = 0.415 \quad SE = 1.774,$$

where Y is the d/Dq ratio and X is in/dec. Dq diameter growth (figure 25).

The d/Dq ratio decreases with increasing rate of Dq diameter growth such that the ratio is 1.54 at 1.0 in/dec. Dq diameter growth. This means that dominant trees (d) grow 1.54 times faster in diameter than Dq trees when Dq trees are growing at 1.0 in/dec. As Dq diameter growth increases, the ratio decreases to 1.16 at 3.0 in/dec., meaning that dominant trees now grow only 1.16 times faster than Dq trees. Apparently, as Dq diameter growth increases there are fewer trees in the stand and Dq

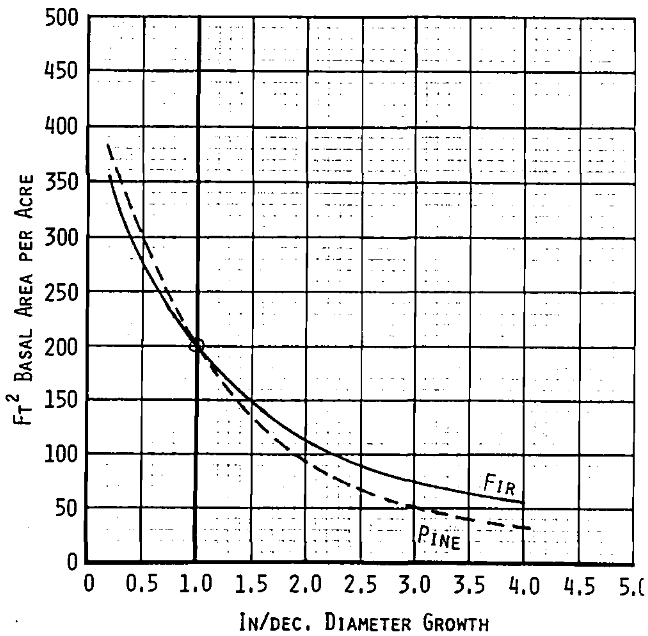


Figure 23. GBA curves for pine and fir for a GBA of 200 ft^2 BA/A. The fir curve suggests faster diameter growth for fir than pine at low stand densities, while the reverse is true at high stand densities.

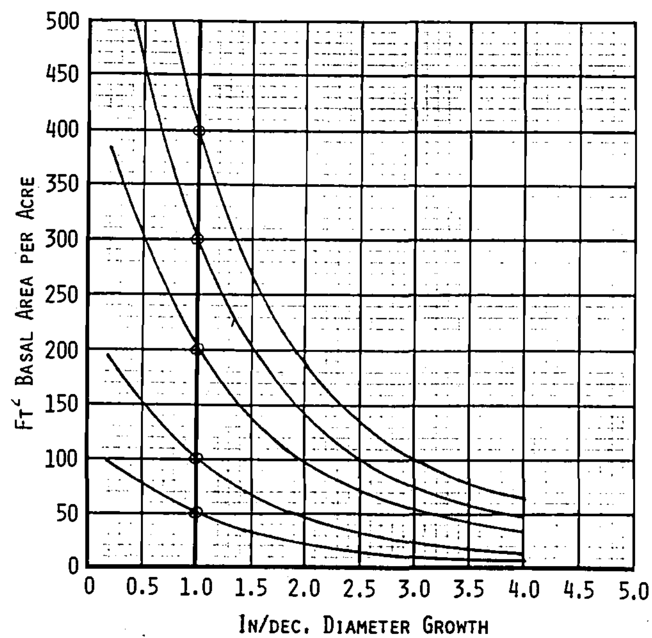
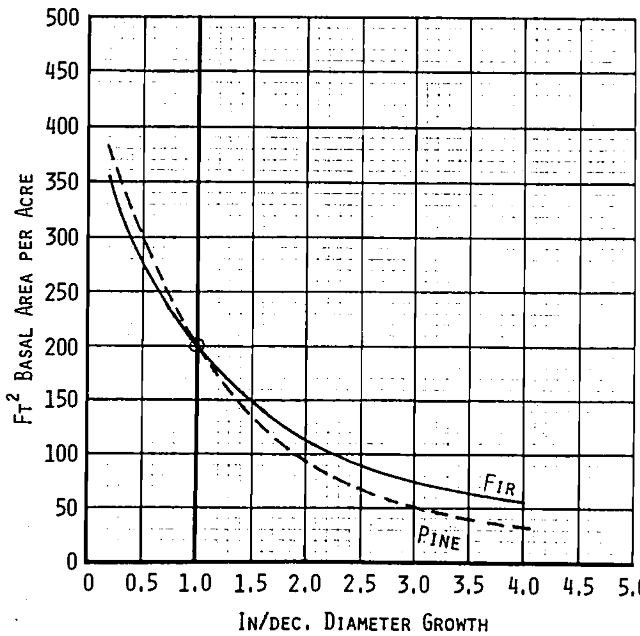


Figure 24. Change in shape of the pine GBA curve as GBA values vary from 50 to 400 ft^2 BA/A.

tends to approach dominant tree (d) dbh and diameter growth. Barrett (1972) reported thinning to 60 TPA--all dominant trees--so d and Dq were equal. The regression suggests this point is 3.8 in/dec. Dq diameter growth.

Dominant-tree diameter growth was calculated by substituting Dq diameter growth in equation (9). For example, a study (Ronco et al. 1985) might show Dq diameter growth of 1.3 in/dec. at 98 ft^2 BA/A:

Enter at 58% GBA, read right to the pine curve and down for about 16.5/20ths or 1.65 in/dec. diameter growth.



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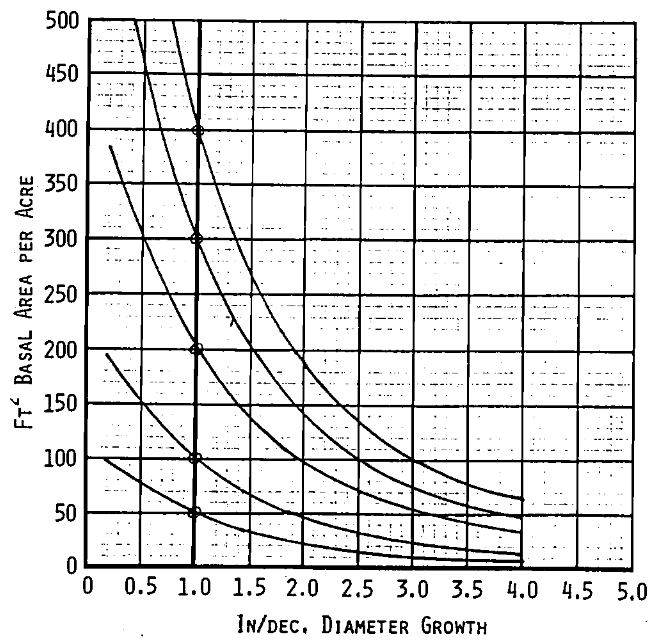

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D/Dq diameter growth. Many reports provided only quadratic mean dbh (Dq), or average diameter growth. Dq diameter growth is less than dominant-tree diameter growth, therefore GBA calculated from Dq would be less than that calculated from dominant-tree growth. A ratio of dominant-tree diameter growth (d) to Dq diameter growth (d/Dq) was calculated from the studies shown in table 6 so that Dq diameter growth could be adjusted to dominant-tree diameter growth.

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Dominant-tree diameter growth was calculated by substituting Dq diameter growth in equation (9). For example, a study (Ronco et al. 1985) might show Dq diameter growth of 1.3 in/dec. at 98 ft^2 BA/A:

Table 6. Relationship between diameter growth of quadratic mean dbh trees (Dq) and crop trees (d).

Publication	Dq in/dec.	d in/dec.	Ratio of d/Dq
Williamson 1976 D.fir	1.5	2.7	1.8
Harrington and Reukema 1983 D.fir	1.5	2.4	1.6
	1.9	2.6	1.4
	2.9	3.2	1.1
Barrett 1972 P.pine	1.5	2.5	1.7
	1.6	2.0	1.2
	1.9	2.2	1.2
	2.9	3.1	1.1
Seidel 1980 W.larch	1.2	1.7	1.4
	2.1	2.2	1.0
Heniger 1981 White fir	1.0	2.4	2.4
	2.1	3.0	1.4
	2.7	3.2	1.2
	3.6	3.8	1.1
	3.7	4.6	1.2
Barclay et.al 1982 D.fir	1.7	2.4	1.4
	2.2	2.7	1.2
	2.9	3.5	1.2
Cole and Stage 1972 LP pine	.7	1.2	1.7
	.9	1.4	1.5
	1.1	1.7	1.5
	1.3	1.9	1.5

d/Dq = 1.73 - 0.19*1.3
= 1.48

Dominant-tree diameter growth is 1.48 times faster than Dq diameter growth; to find dominant-tree diameter growth (d in/dec.):

d in/dec. = 1.48*1.3
= 1.92

Dominant trees would be growing at 1.92 in/dec. This value was graphed as 1.92 in/dec. at 98 ft^2 BA/A (Figure 26).

Measured plots. These calculations were applied to other plot data for the study (table 7) and the results graphed in figure 26. Then GBA was determined for each dominant-tree diameter growth rate at its BA/A, using equation (7) as follows (1.92 in/dec. is 19.2/20ths):

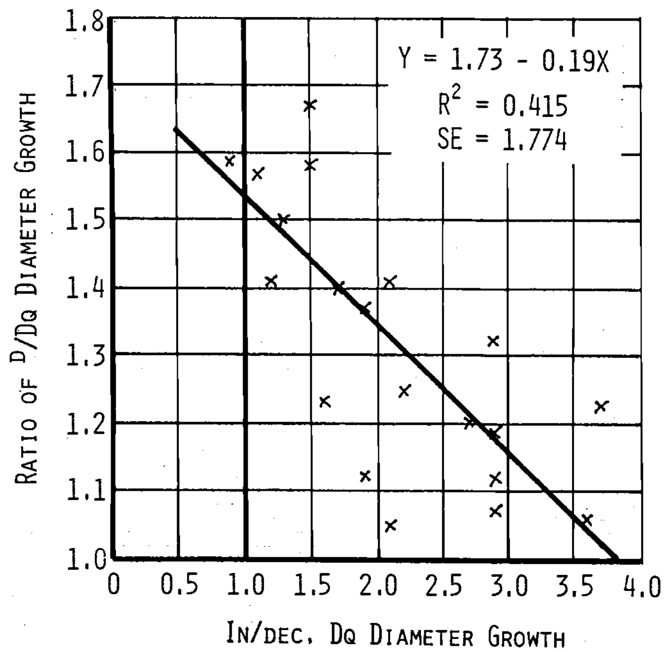


Figure 25. Relationship between rate of diameter growth of crop trees (d) and quadratic mean dbh trees (Dq) of the form Y = a + bX. The Y axis is the conversion factor applied to Dq diameter growth to estimate crop tree diameter growth.

CF = 0.436 + 0.0235*19.2 + 0.0031619.2**
= 2.052

Determine GBA by applying the CF to BA/A:

GBA = 2.052*98
= 201 ft^2 BA/A

GBA's for each dominant-tree diameter growth were then averaged for the study (table 7) and this average used as GBA for the curve overlaid on each graph. In table 7, the average for 35 estimates of GBA was 180.1 ft^2 BA/A with a standard error of 5.97 ft^2 and a confidence interval (p = 0.05) of 12.18 ft^2 BA/A, which is 6.8% of the mean.

Figures 26, 27, 28, and 29 show basal area/diameter growth data from studies of four species, respectively: ponderosa pine (Ronco et al. 1985); lodgepole pine (Dahms 1971a); western larch (Seidel 1982); and Douglas-fir (Harrington and Reukema 1983). All studies demonstrated that diameter growth decreases with increasing stand density. The GBA curves followed shape of the data points rather well. In addition, values are provided for calculation of a constant (K) used in the equation SI*GBA*K = ft^3/A/yr as a productivity index. The equation is discussed in Chapter 5 under "SI and GBA as Indicators of Site Productivity."

Simulation models. Studies like these provide the basic data for simulation models. Ek and Monserud (1981) discuss requirements for models and some of the regressions required for them to operate. One is a stand density/diameter growth relationship. Figure 30 plots their competition index/diameter growth multiplier curve with the % GBA curves. Competition index was equated with % GBA, assuming 200% GBA is a competition index of 100. The diameter growth multiplier was equated with rate of diameter growth, assuming 5.0 in/dec. to be no competition.

Table 7. Plot data from Ronco et al. (1985) for a stocking level study of ponderosa pine and values calculated to validate the pine GBA curve. Quadratic mean diameter (Dq) growth was converted to dominant tree (d) diameter growth by use of equation (9). GBA was determined with equation (7) using dominant tree calculated diameter growth and stand BA/A.

GSL[1]	Dq (in/dec)	d (in/dec)	BA/A (ft^2)	GBA (BA/A)
30	3.4	3.7	10	56
30	3.2	3.5	20	105
30	3.3	3.6	22	122
30	3.0	3.5	30	158
30	2.8	3.4	30	150
30	2.8	3.4	30	150
30	2.4	3.1	40	174
30	2.2	2.9	42	162
60	2.1	2.8	48	171
60	2.0	2.7	52	170
60	2.3	3.0	51	204
60	2.1	2.8	55	196
60	2.1	2.8	57	203
60	2.2	2.9	59	227
60	1.9	2.6	59	190
60	1.9	2.6	59	190
60	2.0	2.7	62	206
80	1.7	2.4	68	189
80	1.7	2.4	73	203
80	1.5	2.2	70	167
80	1.8	2.5	73	215
80	1.5	2.2	75	178
80	1.5	2.2	77	183
80	1.5	2.2	80	190
80	1.9	2.6	79	254
80	1.4	2.1	82	186
80	1.4	2.1	85	193
80	1.4	2.1	90	204
100	1.3	1.9	98	201
100	1.3	1.9	104	204
100	1.2	1.8	106	192
100	1.3	1.9	110	216
100	1.0	1.5	114	170
100	1.0	1.5	116	173
			Mean =	180.1
			SD =	35.33
			Sx =	5.97
			p=.05 CI =	12.18
			% CI of mean =	6.8

[1] GSL is growing stock level.

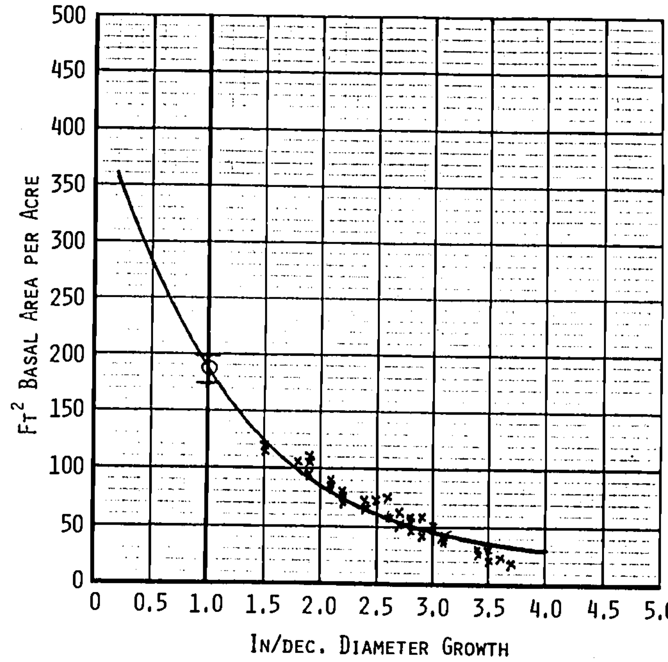


Figure 26. Ponderosa pine basal area/diameter growth data from Ronco et al. (1985) with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). GBA averaged 180 ft^2, n = 35, SD = 35 ft^2, CI = 12 ft^2 at 7% of the mean, SI = 73 ft, PAI = 69 ft^3, and K = 0.0052.

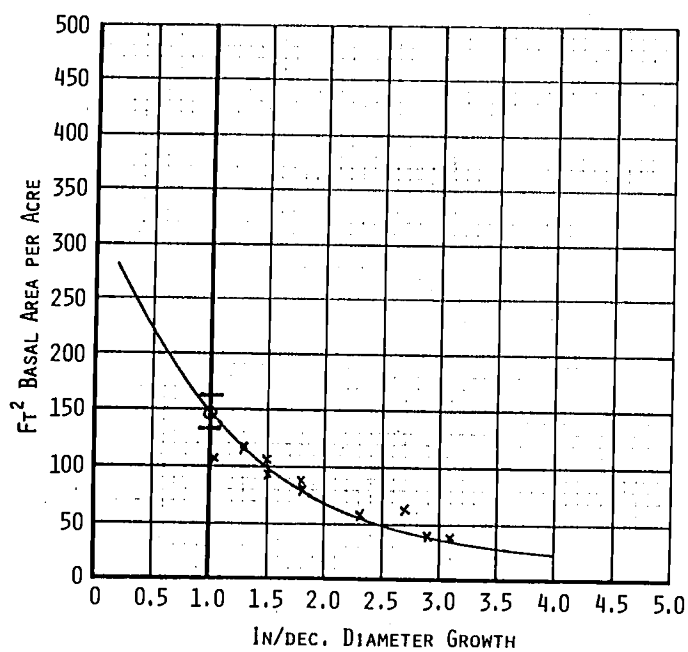


Figure 27. Lodgepole pine basal area/diameter growth data from Dahms (1971a) with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of Equation (9). GBA averaged 153 ft^2, n = 11, SD = 23 ft^2, CI = 15 ft^2 at 10% of the mean, SI = 112 ft (base age 100), MAI = 40 ft^3, and K = 0.0024.

The shape and concepts are similar, only the units and terminology differ.

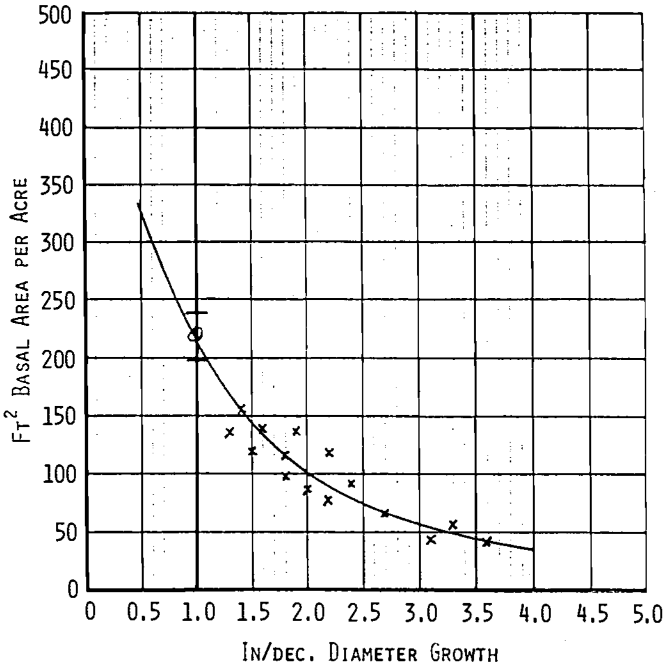


Figure 28. Western larch basal area/diameter growth data from Seidel (1982) with the pine GBA curve. Diameter growth was taken from crop trees. GBA averaged 218 ft^2, n = 15, SD = 37 ft^2, CI = 20 ft^2 at 9% of the mean, SI = 123 ft (base age 100), PAI = 134 ft^3, and K = 0.0050.

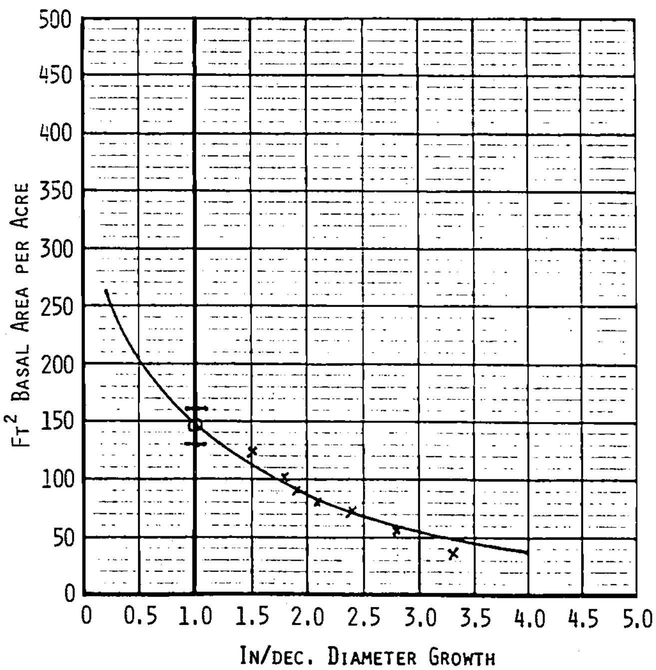


Figure 29. Douglas-fir basal area/diameter growth data from Harrington and Reukema (1983) with the fir GBA curve. Diameter growth was taken from crop trees. GBA averaged 145 ft^2, n = 7, SD = 18 ft^2, CI = 16 ft^2 at 11% of the mean, SI = 100 ft (base age 100), PAI = 106 ft^3, and K = 0.0073.

Figures 31 to 36 illustrate comparisons between GBA curves and values predicted from these simulation models: RMYLD (Edminster 1978); PROGNOSIS, version 15 (Wykoff et al. 1982); LPSIM (Dahms 1983); DFSIM (Curtis et al. 1981); and density management diagrams (Drew and Flewelling 1979, McCarter and Long 1983). All models contain stand density/diameter growth algorithms calculating

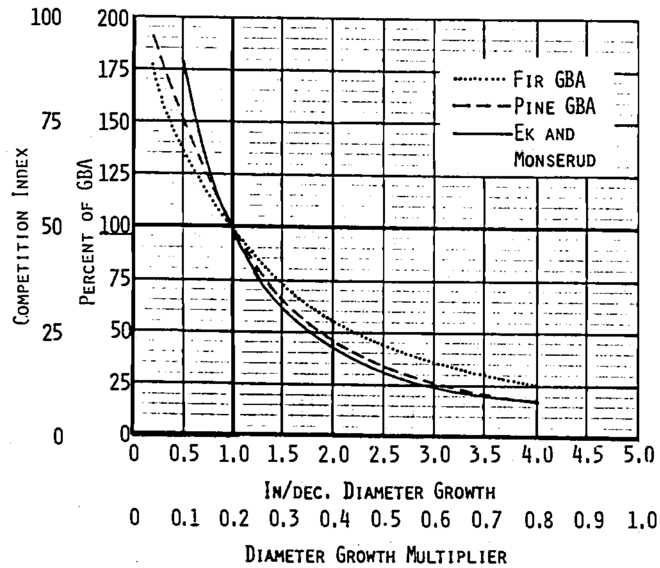


Figure 30. The competition index/diameter growth multiplier of Ek and Monserud (1981) compared with the pine and fir GBA curves.

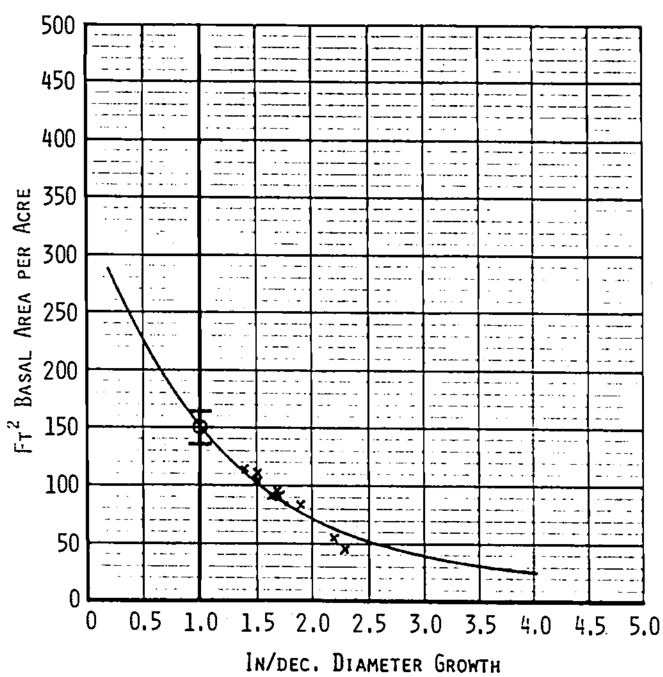


Figure 31. RMYLD (Edminster 1978) basal area/diameter growth data for ponderosa pine with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of Equation (9). GBA averaged 154 ft^2, n = 9, SD = 17 ft^2, CI = 13 ft^2 at 8% of the mean, SI = 70 ft, MAI = 55 ft^3, and K = 0.0051.

predictable change in diameter growth with change in stand density. DFSIM and McCarter and Long's SDI diagram seem to suggest a different shape of GBA curve. Six more graphs from three simulation models appear in Appendix 4.

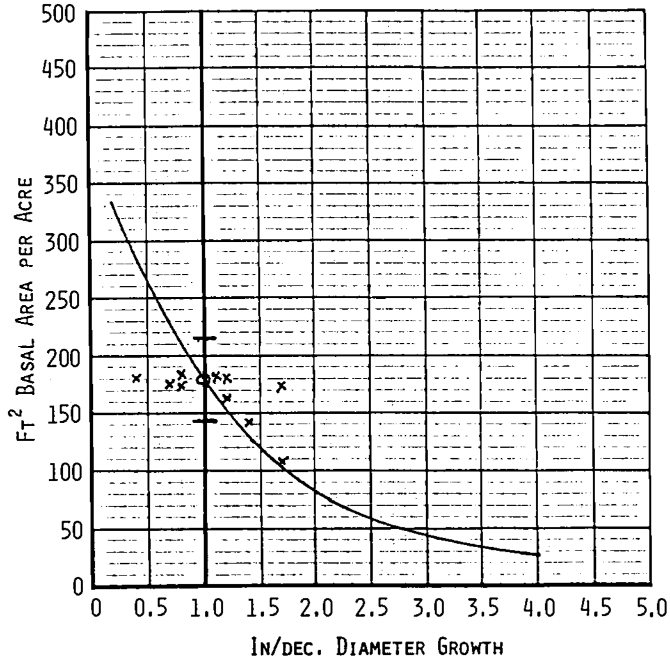


Figure 32. PROGNOSIS (Wykoff et al. 1982), version 15, basal area/diameter growth data for ponderosa pine with the pine GBA curve. Diameter growth was taken from crop trees. GBA averaged 181 ft^2, n = 10, SD = 50 ft^2, CI = 35 ft^2 at 19% of the mean, SI = 98 ft, MAI = 60 ft^3, and K = 0.0034.

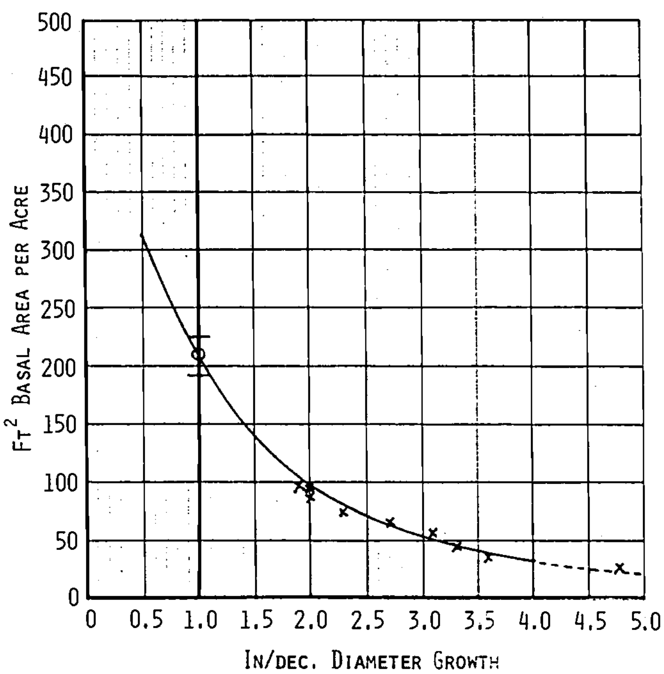


Figure 33. LPSIM (Dahms 1983) basal area/diameter growth data for lodgepole pine with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of Equation (9). GBA averaged 207 ft^2, n = 9, SD = 23 ft^2, CI = 17 ft^2 at 8% of the mean, SI = 90 ft (base age 100), MAI = 36 ft^3, and K = 0.0019.

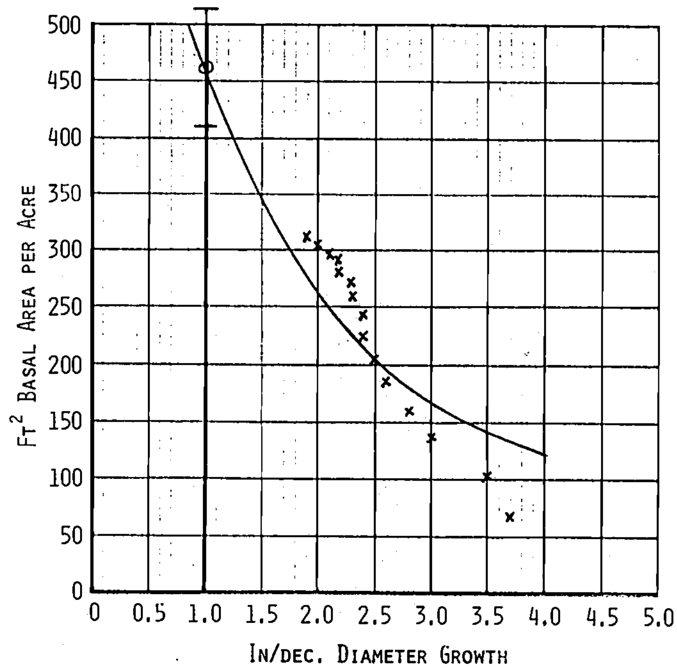


Figure 34. DFSIM (Curtis et al. 1981) basal area/diameter growth data for Douglas-fir with the fir GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of Equation (9). GBA averaged 462 ft^2, n = 15, SD = 93 ft^2, CI = 50 ft^2 at 11% of the mean, SI = 137 ft (base age 100), MAI = 153 ft^3, and K = 0.0025.

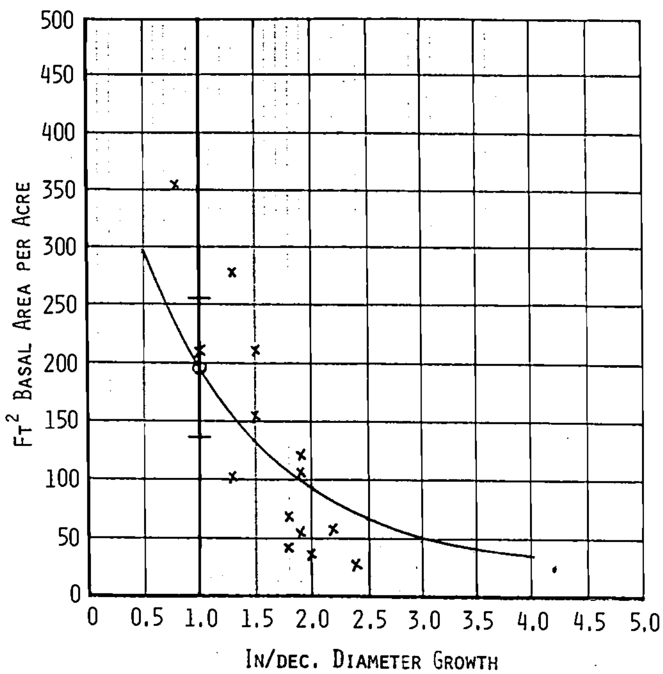


Figure 35. Stand density index management diagram of McCarter and Long (1983) for lodgepole pine showing estimated basal area/diameter growth data with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equatuon (9). GBA averaged 193 ft^2, n = 14, SD = 107 ft^2, CI = 61 ft^2 at 31% of the mean, SI = 80 ft (base age 100), MAI = 69 ft^3, and K = 0.0045.

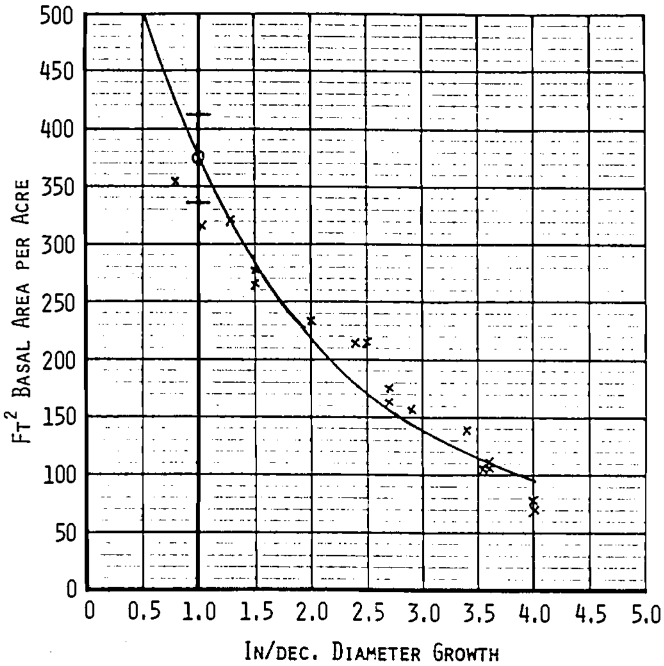


Figure 36. Density management diagram of Drew and Flewelling (1979) for Douglas-fir showing estimated basal area/diameter growth data with the fir GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of Equation (9). GBA averaged 373 ft^2, n = 13, SD = 63 ft^2, CI = 38 ft^2 at 10% of the mean, SI = 142 ft (base age 100), MAI = 223 ft^3, and K = 0.0042.

Stand Age Effects on GBA

Previous discussions have demonstrated dramatic diameter growth response to stand treatment for stands ranging in age from 15 to 240 years. Primary cause of change in diameter growth was change in stand density. Therefore, density will tend to mask the effects of age on diameter growth. Age (or tree size), however, should influence diameter growth as bole area changes with increasing diameter and height and trees become older and vigor declines. Stands of different ages, unless adjacent to each other, can seldom be compared satisfactorily for age effects on GBA because they may be on sites of different inherent GBA potential. The best way to evaluate age/GBA relationships is to calculate GBA at 10- or 20-year intervals over a long period for the same stand. Two approaches can be used: (1) Calculate GBA from published records of stands; (2) sample existing stands--for example, regenerated clearcuts where GBA can be determined on stumps and for the current natural stand.

Two long-term records of stand performance were selected: Norway spruce encompassing 120 years (Assmann 1970, p. 162, tables 51-I and 51-II), and ponderosa pine encompassing 50 years of measurements in pristine stands (Avery et al. 1976).

For Assmann (1970), thinnings were taken from below so "main crop" diameters were assumed to represent an average of dominant and codominant trees. This is only partly valid because some change in average main crop tree diameter can occur with tree removal (Reukema and Pienaar 1973). Knowing diameter growth and BA/A permitted calculation of GBA at 10-year intervals according the fir curve in figure 22. These GBA's are plotted in figure 37. GBA increased to about age 65, approximately at culmination of periodic annual increment. Thereafter it gradually declined at a rate of about 1% per decade.

Figure 37. Analysis of age effects on GBA using data from Assmann (1970) for Norway spruce over a 110-year period.

Avery et al. (1976) presented individual tree measurements on ponderosa pine over a 50-year period. Actual tree ages were not given. Size of trees and general age estimates, however, suggested stands ranging from 80 to 400 years old. They may not have been even-aged. Eighteen to twenty dominant trees were selected on each of 16 subplots for calculation of GBA at 10-year intervals. In all cases, BA increased and diameter growth decreased. Average GBA for all subplots and confidence intervals (p = 0.05) are plotted in figure 38.

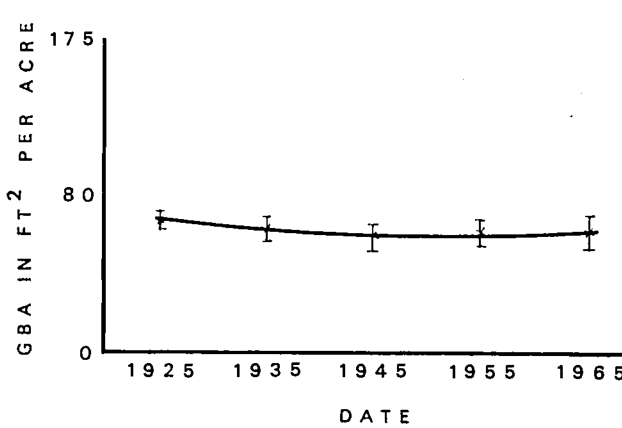


Figure 38. Analysis of age effects on GBA using data from Avery et al. (1976) for ponderosa pine over a 50-year period.

The slight dip in GBA between 1935 and 1945 possibly represents the drought of the 1930's. There did seem to be a slight decrease in GBA with age, even though it was not statistically significant.

Field sampling was the other method for evaluating age effects on GBA. It was accomplished in two ways: Measurement at three ages in treated stands (Sumpter Valley, Oregon) and stand sectioning (Cochran 1979a, 1979c).

Sumpter Valley was clearcut about 1900. It promptly regenerated to about 1,500 TPA, which by 1955 required precommercial thinning for stimulation of height and diameter growth. In 1978, 12 1/5-acre plots were established to determine GBA on stumps (old growth about 220 years old), just before thinning (age 55) and current stand conditions (age 78) (figure 15). Since site potential for GBA varied considerably, GBA for each age was taken as a percentage at age 55 just before thinning. GBA at age 78 averaged 104% of that at 55 with a confidence interval of 6% (p = 0.05). GBA of old growth, which varied from 180 to 240 years, averaged 77% of that for age 55 at a mean age of 220 years with a confidence interval of 7% (p = 0.05) (figure 39).

Cochran (1979a, 1979c) in conjunction with a comprehensive stand-sectioning study to evaluate growth, determined GBA at 10-year intervals for 26 of his stands (personal communication). His data with confidence intervals (p = 0.05) are plotted in figure 39. Similar to data from Assmann (1970) in figure 37, GBA increased from age 30 to 70 and peaked around age 80. After age 100, it decreased slowly.

Figure 40 compares the relationship between four estimates of stand age effects on GBA and the hand-drawn age index curve. Knowing stand age, one can estimate how GBA will change as time passes. The curve will also permit indexing GBA at a specified age, such as 50 or 100 years. This curve is the one appearing in the upper right-hand corner of the slide on the GBA slide rule (figure 51).

The curve was submitted to regression analysis. Data were evaluated in two parts: age 20 to 99, and age 100 to 300 which produced the following equations. Age correction (AC) factor for trees 20 to 99 yearls old.

(10) Y = 1.8115 - 0.02455*X + 0.0001651X**

where Y is the age correction factor and X is current tree age at dbh.

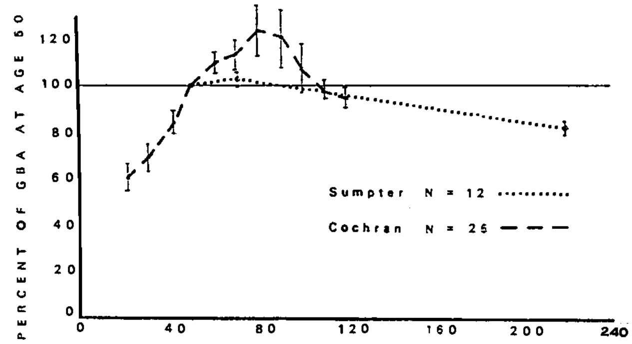


Figure 39. Data plotted from Cochran (personal communication) and Sumpter Valley showing age effects on GBA.

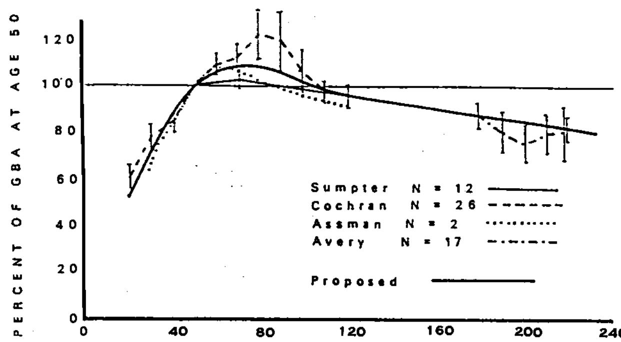


Figure 40. Four sources of age effects on GBA. The heavy solid line is the hand-drawn curve used to adjust GBA to age 50 or 100. This curve appears on the slide of the GBA slide rule and is the source of data for table 14 and equations (11) and (12).

Age correction factor for trees 100 to 300 years old:

(11) Y = 0.90 + 0.001*X

where Y is the age correction factor and X is tree age at dbh.

The curve or equations are used to adjust GBA determined at current tree age to age 50 or 100 as follows: Tree age is 80 years and GBA was calculated as 217 ft^2 BA/A. Enter 80 in equation (10) for X.

AC = 1.8115 - 0.02455*80 + 0.000165180**
= 0.9041

This means that current GBA must be reduced for age 50 or 100:

GBA = 217 *0.9041
= 196.2 ft^2 BA/A at age 50 and 100

GBA and Basal Area Growth

Because GBA is 1.0 in/dec. diameter growth at a specific BA/A, basal area growth might be indexed. When dbh is known, BA growth per tree and per acre can be estimated. For example, if GBA = 100 ft^2 and dbh is 10 inches, tree BA growth is 0.0054 ft^2/yr and stand BA growth is 2.035 ft^2/A/yr. BA growth per tree and per stand will be discussed using four rates of diameter growth (0.5, 1.0, 2.0, and 4.0 in/dec.) and three dbh classes (5, 10, and 20 inches). Data in each table are taken as a percentage of 1.0 in/dec. as a reference to GBA.

Table 8. Annual BA growth per tree as a function of diameter growth and tree dbh.

	in/dec. Diameter Growth				
	0.5	1.0	2.0	4.0	% of 10 in. dbh
Diameter increment (in.)	0.05	0.1	0.2	0.4	
% of 1.0 in/dec.	50	100	200	400	
5 in. dbh grows to (in.):	5.05	5.1	5.2	5.4	
BA growth (ft^2)	.00274	.00545	.01113	.02269	51
% of 1.0 in/dec.	50	100	204	416	
10 in. dbh grows to (in.):	10.05	10.1	10.2	10.4	
BA growth (ft^2)	.00547	.0110	.0220	.0445	100
% of 1.0 in/dec.	50	100	200	404	
20 in. dbh grows to (in.):	20.05	20.01	20.02	20.04	
BA growth (ft^2)	.01092	.02183	.0438	.08814	198
% of 1.0 in/dec.	50	100	201	404	

Table 9. Annual basal area growth per acre as a function of diameter growth and dbh for 100 ft^2 BA per acre.

	in/dec. Diameter Growth				
	0.5	1.0	2.0	4.0	% of 10 in. dbh
Diameter increment (in.)	0.05	0.1	0.2	0.4	
% of 1.0 in/dec.	50	100	200	400	
5 in. dbh: TPA	735	735	735	735	
BA growth (ft^2/A/yr)*	2.014	4.006	8.180	16.677	202
% of 1.0 in/dec.	50	100	204	416	
10 in. dbh: TPA	184	184	184	184	
BA growth (ft^2/A/yr)	1.012	2.035	4.070	8.234	100
% of 1.0 in/dec.	50	100	200	404	
20 in. dbh: TPA	46	46	46	46	
BA growth (ft^2/A/yr)	0.502	1.004	2.015	4.054	49
% of 1.0 in/dec.	50	100	201	404	

* BA growth per tree from table 8 times TPA.

Rate of tree BA growth increases with increasing diameter growth (table 8). BA growth for 0.5 in/dec. is 50% of that for 1.0 in/dec. and 25% of that for 2.0 in/dec. Tree BA growth also increases with increasing dbh: BA growth for 5-inch dbh is 50% of that for 10-inch and 25% of that for 20-inch dbh.

Rate of stand BA growth relationships are shown in table 9. BA growth per acre is tree BA growth from table 8 multiplied by the number of trees per acre in each dbh class required for 100 ft^2 BA/A.

Rate of BA growth per acre increases with increasing diameter growth: BA growth per acre for 0.5 in/dec. is 50% of that for 1.0 in/dec. and 25% of that for 2.0 in/dec.

But BA growth per acre decreases with increasing tree dbh when BA/A is held constant: 5 inch dbh is 202% of that for 10 inch and 400% of that for 20 inch dbh at the same 100 ft^2 BA/A.

These tables illustrate two important relationships: Tree BA growth increases with increasing dbh, but stand BA growth decreases with increasing dbh when BA/A is held constant.

In table 9, BA/A is held constant at 100 ft^2 and diameter growth and the resulting BA growth per acre are allowed to vary. This means that the GBA for each rate of diameter growth is different: For pine at 0.5 in/dec. GBA is 66 ft^2; at 1.0 in/dec. GBA is 100 ft^2; and at 2.0 in/dec. GBA is 208 ft^2.

In table 10, BA growth per acre is held constant at 2.035 ft^2 (the 10-inch dbh stand at 1.0 in/dec. of table 9); it shows BA/A required to grow this rate for the three dbh classes and four diameter growth rates.

The BA/A required to grow a fixed amount of BA/yr decreases as diameter growth increases: 0.5 in/dec. is 200% of the BA/A for 1.0 in/dec., and 400% of that for 2.0 in/dec. This relationship illustrates the density/diameter growth concept of full site utilization over a range of stocking.

Assume a site has the capability of growing 2.0 ft^2 BA/A/yr at an average stand diameter of 10 inches dbh. High stocking, such as 200 ft^2 BA/A, should result in slow diameter growth--i.e., 0.5 in/dec.--whereas half the density, 100 ft^2 BA/A, should result in double the diameter growth. This also illustrates the GBA assumption that diameter growth indexes intertree competition--as BA/A changes on a site there will be a concurrent and opposite change in diameter growth.

The data from table 10 are plotted in figure 41 and compared with the GBA curves. Note the similarity between figure 41 and figure 30 (page 18), which shows Ek and Monserud's (1981) competition index/diameter growth multiplier curve.

Table 10 also illustrates that BA/A must increase with increasing dbh if a constant rate of BA growth per acre is maintained. BA/A for 10 inch and 20-

Table 10. Basal areas per acre required to grow 2.00 ft^2 BA/A/yr at four rates of diameter growth and three dbh's*.

	in/dec. Diameter Growth				
	0.5	1.0	2.0	4.0	% of 10 in. dbh
5 in. dbh: TPA	730	365	180	88	
BA per acre (ft^2)	99.5	50.0	24.5	12.0	50
% of 1.0 in/dec.	199	100	49	24	
10 in. dbh: TPA	366	183	91	45	
BA per acre (ft^2)	199.6	100.0	49.6	24.5	100
% of 1.0 in/dec.	200	100	50	24	
20 in. dbh: TPA	183	92	46	23	
BA per acre (ft^2)	399.2	200.7	100.4	50.2	200
% of 1.0 in/dec.	199	100	50	25	

* Computations require data from table 8: TPA = 2.00 ft^2 divided by the BA growth rate for eadh diameter growth class, i.e. 2.00/.00274 = 730 trees per acre for 0.5 in/dec. at 5" dbh. BA per acre = trees per acre times BA of each diameter class, i.e. 730 X 0.1363 = 99.5 ft^2 BA/A. Tree BA's are: 5" dbh = 0.1363, 10" = 0.5454, 20" dbh = 2.1817.

inch dbh is 200% and 400% of that for 5 inch dbh, respectively. As a result, GBA also varies by dbh class in table 10: 50 ft^2 for 5 inch, 100 ft^2 for 10 inch, and 200 ft^2 for 20 inch dbh (using the 1.0 in/dec. diameter growth column). GBA also varies in table 9. These tables suggest that both tree and stand BA growth vary within a GBA class as a function of dbh.

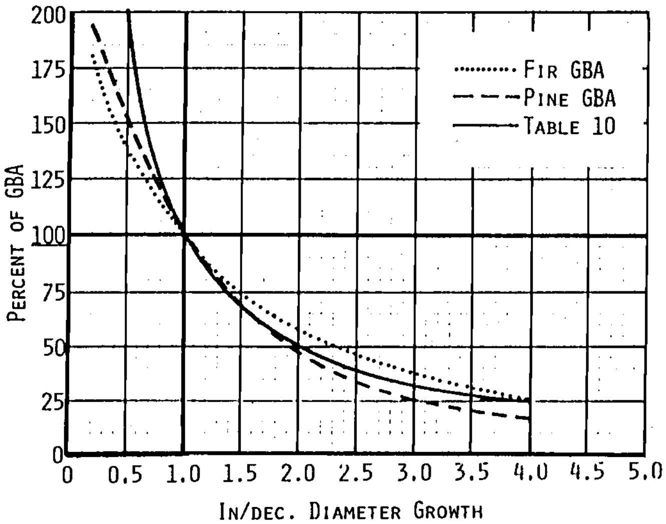


Figure 41. Table 10 data for 10-inch-dbh trees plotted as percent of 1.0 in/dec. diameter growth and compared with the pine and fir GBA curves. Greatest curve divergence occurs at diameter growth rates slower than 0.8 in/dec. For example, 0.5 in/dec. from table 10 is 200% of the basal area for 1.0 in/dec., compared with 152% for pine and only 132% for fir. Compare with figure 30.

Table 11 lists tree and stand BA growth per year for GBA 100, the 10 inch dbh class at 1.0 in/dec. of tables 8, 9, and 10. In table 11, BA/A is determined by the rate of diameter growth: 200 ft^2 for 0.5 in/dec., 100 ft^2 for 1.0 in/dec., 50 ft^2 for 2.0 in/dec., and 25 ft^2 for 4.0 in/dec. (table 10). Variables are tree and stand BA growth as shown in the "% of 5 in. dbh" column. Stand BA growth remains constant for a dbh class regardless of tree diameter growth rate, but decreases with increasing dbh for all diameter growth rates.

Decreasing stand BA growth with increasing dbh at the same BA/A has another implication. Since stand BA growth at 20-inch dbh is 25% of that for 5-inch-dbh, stand BA/A at 20-inch. dbh will accumulate at one-fourth the rate it would at 5-inch-dbh. This slower accumulation of BA/A will result in a slower rate of decrease in diameter growth. For example, a 20-inch-dbh stand at 1.0 in/dec. at 100 ft^2 BA/A would slow to 0.6 in/dec. at 130 ft^2 BA/A. At an accumulation rate of 1.0 ft^2 BA/A/yr, this would take 30 years. In contrast, the 5-inch-dbh stand would accomplish the same change in only 7 years. Thus the 5 in. dbh stand would have a four times faster rate of decline in diameter growth.

This is one reason why stands less than 5 inches dbh should be avoided when sampling for GBA. The other reason is obtaining a suitable estimate of BA/A with a prism.

Table 11. Relationships of tree and stand BA growth per year to dbh and rate of diameter growth for a GBA of 100 ft^2 BA per acre.

	in/dec. Diameter Growth				
	0.5	1.0	2.0	4.0	% of 5 in. dbh
BA per acre (Table 10)	200	100	50	25	
5 in. dbh: Tree BA growth (ft^2)	.00274	.00545	.01113	.02269	100
% of 1.0 in/dec.	50	100	204	416	
Trees per acre	1466	733	366	183	
*Stand BA growth (ft^2/A)	4.107	3.998	4.074	4.152	100
10 in. dbh: Tree BA growth (ft^2)	.00547	.0110	.0220	.0445	202
% of 1.0 in/dec.	50	100	200	404	
Trees per acre	366	183	91	45	
*Stand BA growth (ft^2/A)	2.002	2.013	2.002	2.003	50
20 in. dbh: Tree BA growth (ft^2)	.01092	.02183	.0438	.08814	400
% of 1.0 in/dec.	50	100	200	404	
Trees per acre	92	46	23	11	
*Stand growth (ft^2/A)	1.005	1.004	1.007	0.970	25

* Trees per acre times tree BA growth.

GBA influences. Figure 41 demonstrates that GBA curves diverge from the table 10 curve, which was mathematically calculated. This is apparently due to environmental influences on tree physiology that affect biological growth. This divergence was applied to the 10-inch-dbh data in table 10 by calculating BA/A by diameter growth rate according to the GBA curves for pine and fir (table 12). Hence, BA/A for 0.5 in/dec. for pine is not 199.6 ft^2 but 152 ft^2 and for fir 132 ft^2. Similar differences occur for 2.0 and 4.0 in/dec. As a result, the BA growth per acre also differs: At 0.5 in/dec. it is 1.526 ft^2 for pine instead of 2.035 ft^2 and only 1.362 ft^2 for fir. These data are plotted in figure 42.

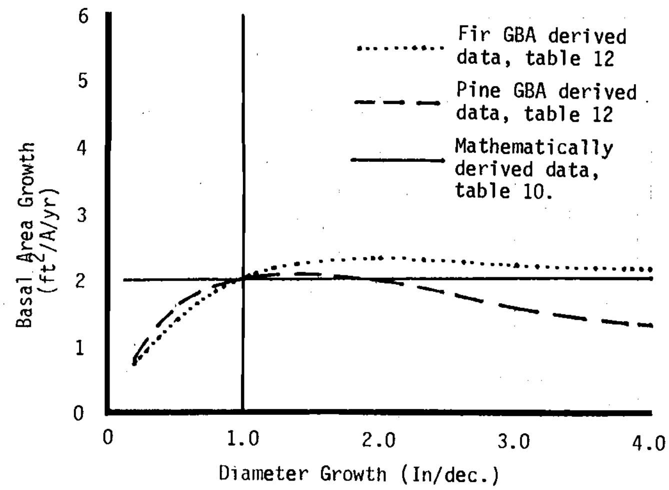


Figure 42. Data from table 12 showing divergence of stand BA/A growth when BA/A is determined by use of the pine and fir GBA curves compared with the mathematically derived basal area growth of table 10.

Both pine and fir are somewhat similar to the calculated line at growth rates faster than 1.0 in/dec. But at slower diameter growth rates, both tend to fall rather rapidly. This may be a reflection of severe competition, wherein partitioning of carbon between growth and transpiration becomes critical.

Presumably, between 0.6 and 0.2 in/dec., competition is so severe that maintenance of physiological function takes precedence over growth.

In summary, both tree and stand BA growth change for a given GBA according to dbh and rate of diameter growth. Stand BA growth decreases with increasing dbh, while tree BA growth increases with increasing dbh. GBA alone can not index BA growth; dbh must be known. GBA indexes stockability by assuming that rate of diameter growth is a measure of intertree competition.

Table 12. BA growth per acre per year for the 10 inch dbh stand of table 10 when BA/A is taken from the pine and fir GBA curves.

	In/dec. Diameter Growth					
	0.2	0.5	1.0	2.0	3.0	4.0
10 in. dbh of table 10.						
*BA per acre (ft^2)		199.6	100	49.6		24.5
Trees per acre		366	183	91		45
Stand BA growth (ft^2/A/Yr)		2.00	2.00	2.00		2.00
% of 1.0 in/dec.		100	100	100		100
Pine GBA Curve						
*BA per acre (ft^2)	192	152	100	48	25	16
Trees per acre	352	279	183	88	46	29
Stand BA growth (ft^2/A/Yr)	0.769	1.526	2.035	1.936	1.472	1.291
% of 1.0 in/dec.	38	76	100	96	73	64
Fir GBA Curve						
*BA per acre (ft^2)	180	132	100	58	36	26
Trees per acre	330	249	183	106	66	48
Stand BA growth (ft^2/A/Yr)	0.721	1.361	2.013	2.331	2.191	2.136
% of 1.0 in/dec.	36	68	100	116	109	106

* BA/A for 1.0 in/dec. is set at 100 ft^2 (GBA). BA/A for 0.2, 0.5, 2.0, 3.0, and 4.0 in/dec. is calculated by equation (7) for pine and fir (or curves of figure 22, or table 11). Diameter growth of 0.5 in/dec. is 5/20ths which is 132% GBA for fir and 152% GBA for pine. Since GBA is 100 ft^2, 0.5 in/dec. diameter growth occurs at 152 ft^2 BA/A for pine and 132 ft^2 BA/A for fir.

Determination of GBA

GBA is a method for indexing stockability of sites in the field. It is also a method for identifying sites as they are characterized in simulation models, managed yield tables, or productivity levels within SI classes. Determining stockability or identifying various sites is influenced by stand conditions, method of sampling, and calculation of GBA.

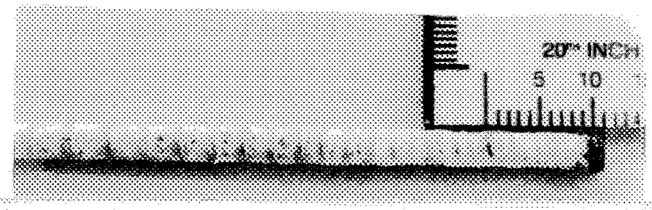


Figure 43. Decreasing rate of radius growth required for determination of GBA. Last-decade radius growth is measured in 20ths of an inch (8/20ths).

Stand Conditions

Stand conditions influence GBA sampling methodology and interpretation of the data. Three types of stands cannot be sampled for GBA:

1. Stands that are less than 20 years old. In young stands, the relationship of change in GBA with age is poorly established.

2. Stands that are less than 5 inches dbh. In small-diameter stands, estimation of BA/A is difficult, stand BA/A changes very rapidly, and rate of diameter growth changes quickly, requiring measurement of less than 5 years' radius growth.

3. Stands where diameter growth is not decreasing. A decreasing rate is usually required to satisfy the assumption that increasing BA/A is causing decreasing diameter growth. An increasing rate of diameter growth suggests trees are still recovering from stand treatment or disturbance. When tree competition becomes significant, rate of diameter growth should stabilize and then decrease. Figure 43 shows the decreasing rate of diameter growth usually required to determine GBA.

There is one exception to the requirement for decreasing diameter growth. Stands so dense (stagnated) that BA/A remains reasonably constant because mortality equals growth will tend to have a reasonably constant rate of diameter growth. The growth will fluctuate inversely with the amount of mortality. In these cases, the stand has reached the maximum amount of BA/A that the site can produce. Under conditions found east of the Cascade Crest, radius growth will be less than 8/20ths, usually between 2 and 5/20ths.

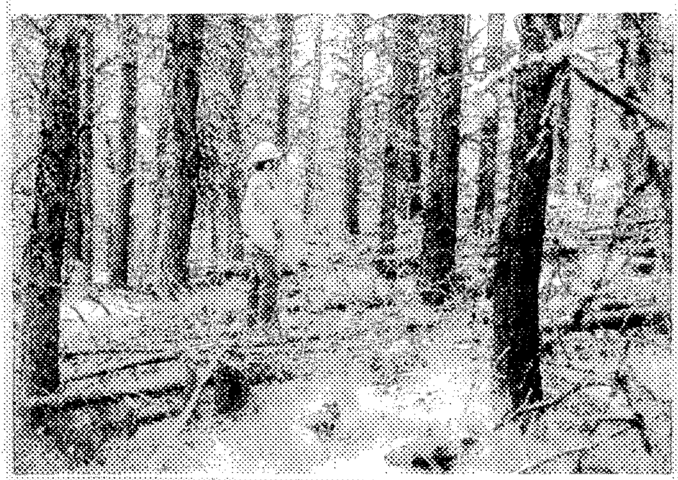


Figure 44. Even-aged stand of ponderosa pine thinned 12 years previously. GBA can be determined if rate of diameter growth is declining, which assumes that trees in the stand are in significant competition.

Recent thinning or mortality in a stand influences sampling for and interpretation of GBA (figure 44). The requirement for decreasing diameter growth is essential in evaluating these stands. The investigator must ask several questions: Has the stand responded by increased rate of diameter growth? If the answer is no, the prethinned BA/A and diameter growth rate can be used. If the answer is yes, has rate of diameter growth started to decrease? Figure 45 depicts a situation where the tree has responded to thinning but rate of diameter growth has not started to decline. In this case, the rate and stand BA/A prior to thinning can be used for calculating GBA. If rate of diameter growth since thinning has started to decline (figure 46), the current BA/A can be used.

In many cases, rate of decrease in diameter growth in small-diameter stands will be quite rapid. Instead of measuring radius growth for the last 10 years, the investigator can measure the last 5 years and double the value (figure 45).

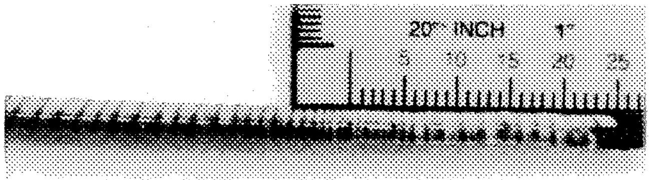


Figure 45. Radius growth response to thinning where the rate of growth has not started to decrease adequately for GBA determination. Prethinning stand BA/A and radius growth can be used. Where the rate changes rapidly, the last 5 years' growth can be measured and the 20ths of an inch doubled-- i.e., 8/20ths radius growth.

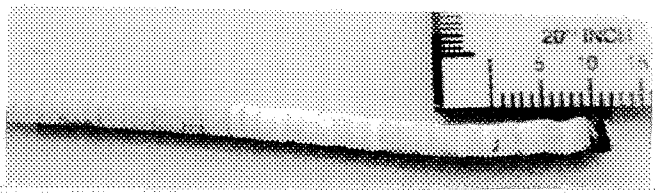


Figure 46. Radius growth response to thinning where the rate of growth has started to decline adequately for GBA determination. The last decade's radius growth in 20ths of an inch can be measured.

Disease and insect attack can have effects similar to thinning. Diameter growth is a function of all environmental factors: intertree competition, insects, disease, precipitation, temperature, soil, and other competing vegetation. The investigator must separate long-term and short-term impacts on the stand.

Root rot or mistletoe, which remain in the stand for years and afford few control opportunities, have long-term impacts; GBA should be determined taking them into account. If and when such pathogens can be controlled or eliminated, a new estimate of GBA is appropriate.

Short-term effects may be caused by defoliators such as tussock moth and spruce budworm, or borers such as mountain pine beetle. These will dramatically reduce diameter growth, resulting in a low GBA estimation. GBA should be determined by sampling pre-insect attack stand conditions for rate of diameter growth and BA/A. If the attack is less than 10 years old, mortality should still be recognizable and pre-attack radius growth easy to sample. Insect-caused mortality should be included in pre-attack BA/A estimates.

Other stand conditions influence sampling for and interpretation of GBA. For example, stands may be: pure, even-aged; pure, uneven-aged; mixed species, even-aged; and mixed species, uneven-aged. GBA was developed in pure, even-aged stands (figure 44), and it is these stands where GBA is easiest to sample and most straightforward to interpret.

Mixed-species, even-aged stands (figure 47) provide challenges for determining GBA. Each species will often have its own diameter growth rate and thus its own GBA unique to the site. GBA may be determined for most species in the stand.

In general, sampling five individuals of each species is necessary to obtain an adequate GBA estimate. A common recommendation, however, is to sample five individuals of the dominant species and apportion sampling of other species according to their percentage of BA/A in the stand. For example, a stand might be 50% ponderosa pine, 30% Douglas-fir, and 20% white fir. The recommendation would be five ponderosa pine and three Douglas-fir. Any species that accounts for less than 20% of the stand BA/A is of questionable value in estimating GBA.

A word of caution is in order when interpreting GBA for different species in the same stand. In the illustration above, ponderosa pine might have a GBA of 150 ft^2 BA/A and Douglas-fir 180 ft^2 BA/A. With Douglas-fir accounting for only 30% of the stand BA, it is not experiencing intertree competition similar to a pure stand of Douglas-fir. A pure stand would probably have a lower GBA, perhaps 160 to 170 ft^2.

The most severe intertree competition for a species comes from other individuals of that same species because their demands are identical and they use the same site factors. While pine and Douglas-fir do compete, the competition is less intense because their demands are slightly different. This kind of difference was demonstrated for height growth by Deitschman and Green (1965). When interpreting GBA in mixed species stands, be skeptical of a species' GBA that is more than twice or less than

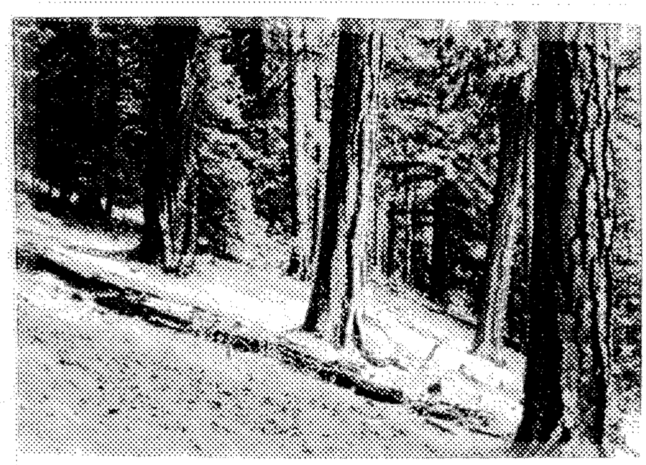


Figure 47. Mixed-species, even-aged stands, such as ponderosa pine and fir, usually have different GBA's for each species. The species with a higher diameter growth rate will have a higher GBA.

half of the dominant species' GBA. This is particularly important for any species that is less than 20% of the stand BA/A.

Pure, uneven-aged stands pose a problem interpreting GBA when trees of significantly different sizes and ages are competing with each other (figure 48). GBA estimated from dominant trees will probably be higher compared with even-aged conditions. This may be an important bias when crown volumes of the overstory trees are less than half of the total stand crown volume. At present there is no correction factor or rule of thumb by which GBA can be "adjusted" for these uneven-aged stands.

Mixed-species, uneven-aged stands pose a compound problem. A GBA can be calculated, but its value for depicting stockability or prescribing stand treatment is extremely questionable. At this time, determining GBA in mixed-species, uneven-aged stands cannot be recommended.

Clumped tree distribution as depicted in figure 48 creates GBA sampling problems. The problem is twofold: (1) How to estimate stand BA in an unbiased manner, and (2) where to increment-core trees--toward an opening, at right angles to an opening, or toward the center of the clump.

Discussion in Chapter 2 on forestland stockability demonstrated that clumped stands can fully occupy a site. The "holes" in the stand must be part of BA/A determination.

Systematic placement of sample points is used to reduce bias in estimating BA/A in clumped stands.

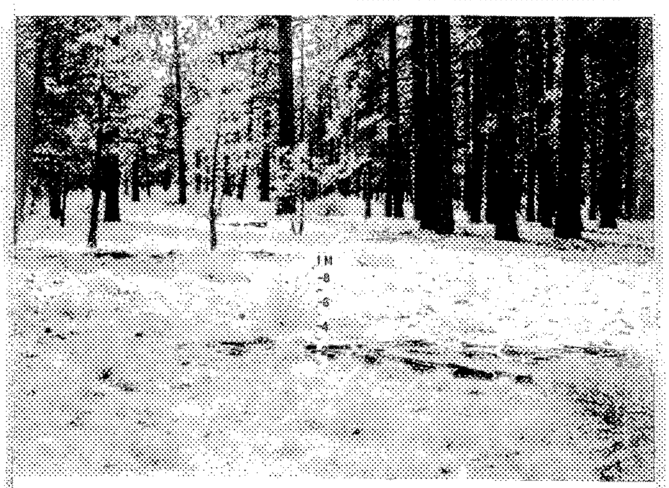


Figure 48. A clumped, uneven-aged stand of ponderosa pine. Clumped stands pose problems for determining stand BA/A because the holes in the stand must be included. Uneven-aged conditions pose problems when interpreting diameter growth relationships between large and small trees.

Trees should be increment-cored at right angles to the stand opening to sample an average rate of diameter growth. A tree will often grow faster in diameter on the side facing the hole because root competition is less.

GBA may be approximated in clearcut stands. However, a GBA estimate will probably be higher when radius growth is determined at stump height instead of breast height. Radius growth should be measured on the highest part of the stump and age determined. The BA/A can be estimated by counting (or measuring) diameter inside bark of the stumps. Care should be taken to find all stumps in the unit because they are often hidden by brush. When age, BA/A, and radius growth are known, GBA can be determined.

GBA Sampling Systems

GBA sampling entails two primary considerations: (1) tree selection for increment coring, and (2) determination of stand BA/A. The latter can be determined either by variable- or fixed-radius sampling systems.

BA/A determination. For variable-radius sampling, a prism should be selected that will count 8 to 12 trees. A tendency toward underestimating BA/A occurs when more than 12 trees are counted, due to missed trees. If fewer than eight trees are counted, measurement precision is sacrificed.

For example, with a six-tree count, the precision error is plus or minus 17% of the BA/A being estimated. If fixed- radius sampling is used, such as 1/10- to 1/5-acre plot, the plot should contain 6 to 10 of the larger trees in the stand to facilitate choice of a GBA tree and to encompass a good sample of stand BA/A. Fixed area plots may be desirable in dense brushy sites where prism sampling tends to miss trees.

GBA is extremely sensitive to site quality and therefore can vary considerably over the landscape. For that reason, GBA sampling should be stratified according to site quality and stand conditions. Similar species composition in the plant community--trees, shrubs, and herbs--is a good first clue to similarity in site potential. Likewise, similarity in species dominance is often an excellent indicator of site homogeneity.

A systematic sample is strongly recommended, particularly in stands with clumped tree distribution. At least five sample plots are recommended per species. An increased number of samples may be required if specified accuracy levels are established, for example plus or minus 20% of the mean GBA at p = 0.05. Any plot layout is acceptable, particularly to stay within the same site and stand. Figure 49 depicts two five-plot sampling systems: clustered sample plots and a line of plots. A fixed distance between plots must be established, depending on tract size, number of plots, and stand dbh. In many cases, 70 feet is adequate. Plots should be spaced far enough apart to avoid counting the same tree in adjacent samples.

Tree selection. The form in figure 50 provides GBA and SI data for five sets of tree measurements. A separate form is required for each species--up to three forms for a three-species stand. The investigator should proceed as follows (figure 50):

At each plot center determine live BA by species, then record and total (DF@200 ft^2, PP@20 ft^2 = 220 ft^2 in "TBA"). From the trees tallied, select the largest diameter individual with no observable damage as a GBA tree. Largest diameter trees are selected assuming they are growing fastest in diameter (the reason they are largest) and all other trees are growing at equal or slower rates. If SI is to be combined with GBA, trees sufficient to satisfy the SI criteria should be selected. Record the species

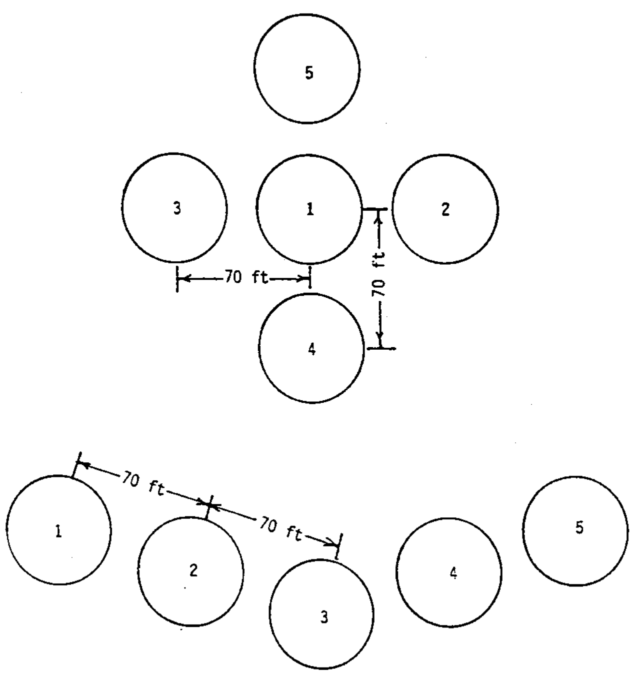
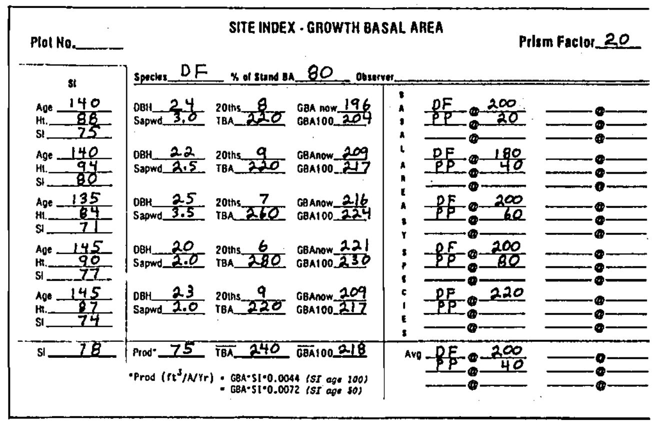


Figure 49. Alternative methods for establishing five points or plots when sampling for GBA. A fixed distance between plots is required to reduce bias in clumped stands for BA/A determination.



SITE INDEX - GROWTH BASAL AREA

Plot No._____ Prism Factor 20

Species DF % of Stand BA 80 Observer_____

SI				BASAL AREA BY SPECIES	
Age 140, Ht. 88, SI 75	DBH 24, Sapwd 3.0	20ths 8, TBA 220	GBA now 196, GBA100 204	DF @ 200, PP @ 20, @	@, @, @
Age 140, Ht. 94, SI 80	DBH 22, Sapwd 2.5	20ths 9, TBA 220	GBAnow 209, GBA100 217	DF @ 180, PP @ 40, @	@, @, @
Age 135, Ht. 84, SI 71	DBH 25, Sapwd 3.5	20ths 7, TBA 260	GBAnow 216, GBA100 224	DF @ 200, PP @ 60, @	@, @, @
Age 145, Ht. 90, SI 77	DBH 20, Sapwd 2.0	20ths 6, TBA 280	GBAnow 221, GBA100 230	DF @ 200, PP @ 80, @	@, @, @
Age 145, Ht. 87, SI 74	DBH 23, Sapwd 2.0	20ths 9, TBA 220	GBAnow 209, GBA100 217	DF @ 220, PP @, @	@, @, @
SI 78	Prod* 75	$\overline{\text{TBA}}$ 240	$\overline{\text{GBA}}$100 218	Avg DF @ 200, PP @ 40, @	@, @, @

*Prod (ft^3/A/Yr) = GBA*SI*0.0044 *(SI age 100)*
= GBA*SI*0.0072 *(SI age 50)*

Figure 50. Field form for recording GBA data. Provision is made for site index and leaf area index. Five trees may be recorded across the sheet. In this example, GBA averaged 218.4 ft^2 with a standard error of 4.34 and a confidence interval of 11.16 (p = 0.05).

and its dbh (DBH = 24 inches). Increment-core to the tree center, determine tree age at dbh (140 years), and measure the last 10 years' radius growth in 20ths of an inch (20th = 8) (figure 43). In some cases, the last 5 years' radius growth should be measured and doubled if rate of diameter growth is changing rapidly or where thinning or other stand disturbance has created a change in rate of diameter growth during the last few years (figure 45). Determine GBA according to the next section.

When sampling a mixed-species stand, use a second data form. Select the largest diameter individual of the second species on those sample points where the species contributes more than 20% to stand BA/A and occupies a dominant or codominant position.

If SI is desired, measure height of the GBA trees (Ht = 88 ft). Determine SI with appropriate tables or curves (SI = 75). For some SI calculations, total tree age (not breast height age) is required.

Estimate number of years to breast height by counting the number of rings from the pith outward for a distance of 1 inch and assume this number as years to breast height.

Rings per inch at tree center is an indication of tree vigor at 5 to 10 feet tall. It is used for adjusting grand fir SI curves according to degrees of early suppression (Stage 1959). A few rings (e.g., three to five) suggest rapid, uninhibited seedling growth, whereas many rings (e.g., 20 to 25) suggest seedling suppression and slow growth to breast height.

"Sapwd" is an entry for sapwood thickness (Sapwd = 3.0 inches), which can be used in conjunction with dbh and BA/A to estimate leaf area index (Waring and Schlesinger 1985).

GBA can be used in conjunction with other forest inventory systems. It can be calculated with any of these systems, as long as the following conditions are met:

1. Dominant individuals of each species are increment-cored for radius growth.

2. An unbiased estimate of stand basal area is obtained.

3. A suitable sampling stratification is employed to allocate sample plots to similar sites.

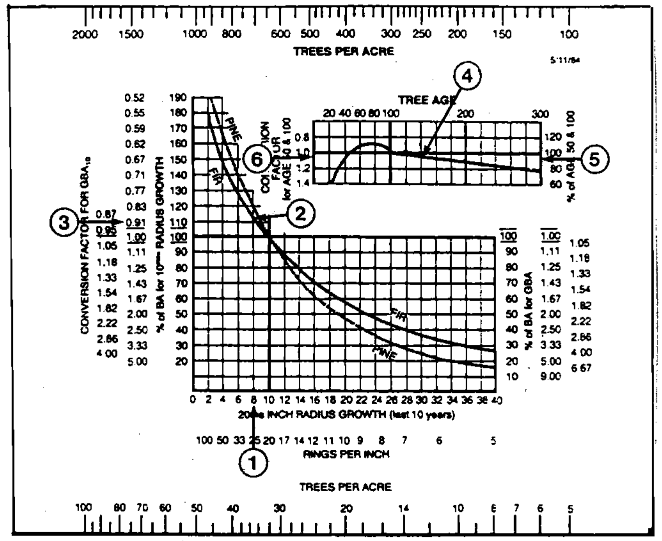


Figure 51. Steps required to determine GBA with age adjustment to 100 years (see text for details).

Determing GBA

Three sources of Conversion Factors (CF) are available for adjusting current BA/A to GBA according to current 20ths of an inch radius growth: (1) the GBA curves (figure 51); (2) equation (7) (Chapter 2); and (3) table 13. The curves that appear on the GBA Slide Rule are designed for field use. Table 13 is more precise and is useful in the office. Equation (7) is suitable for a hand-held calculator and is particularly useful with a programmable unit. GBA curves will be used with this illustration.

Figure 50 represents a five-point sample of Douglas-fir growing on a moderately dry site east of the Cascade Crest. Measurements from point number one are entered across the uppermost data set. GBA is determined by use of 20ths of an inch radius growth (8/20ths), total stand basal area (TBA = 220 ft^2), and tree age (140 years):

A. Using figure 51: (1) Enter the GBA graph at 8/20ths, (2) intersect the fir curve and (3) read left for a conversion factor of 0.89, which is also 112% of GBA. Since 8/20ths is slower radius growth than 10/20ths, current BA/A exceeds GBA. The GBA curve indicates 112%; therefore, current BA/A must be reduced by 0.89.

If one of the other alternatives is used, proceed as follows:

1) Equation (7):

CF = 0.470 + 0.044*8 + 0.001018**
= 0.887 for fir.

2) Table 13: 8/20ths for fir is a CF of 0.89.

B. Multiply the conversion factor times current stand BA/A for GBA at current stand age:

GBA = 0.89*220
= 196 ft^2 BA/A.
This "GBA" is for age 140.

C. Convert GBA to breast height age 100 (figure 51, equation (11), or table 14): (4) Age 140 is about (5) 96% of GBA for age 100 and (6) the conversion factor is 1.04:

1) Equation (11):

AC = 0.90 + 0.00*140
= 1.04

2) Table 14: age 140 is an AC of 1.04.

GBA_{100} = 1.04*196
= 204 ft^2 BA/A

So GBA for this Douglas-fir at age 100 is 204 ft^2 BA/A.

D. Repeat this procedure for four more trees and average the results. The example average is 218.4 ft^2 GBA for the stand. The standard error is 4.34 ft^2 and the confidence interval at p = 0.05 is 11.16 ft^2, a reasonably accurate estimate.

However, three precision errors must be understood: (1) A 20-factor prism counts stand BA/A in 20-ft^2 increments, which is twice the confidence interval. (2) A prism counting 8 to 12 trees averages a 10% precision error. (3) The difference between the conversion factors for 8 and 9/20th is 6% (from 0.89 to 0.95). Each 20th of an inch introduces a 6% precision error at about 10/20ths; this increases to 14% at 40/20ths. These errors suggest that GBA can be measured no more precisely than to about 10% of the mean. In the example, GBA is someplace between 200 and 240 ft^2 BA/A ($p = 0.05$) rather than between 207.24 and 229.56 ft^2.

Table 13. Relationship of diameter growth, shown as 20ths inch radius growth, to percent GBA and conversion factors (CF) for pine and fir GBA curves.

20ths Radius Growth	Pine % GBA	Pine CF	Fir % GBA	Fir CF
2	192	0.50	180	0.55
3	181	0.55	162	0.62
4	166	0.59	149	0.67
5	152	0.66	132	0.76
6	141	0.70	127	0.79
7	129	0.77	120	0.83
8	121	0.84	112	0.89
9	109	0.92	105	0.95
10	100	1.00	100	1.00
11	93	1.07	93	1.07
12	85	1.18	88	1.14
13	78	1.28	83	1.20
14	72	1.39	79	1.27
15	67	1.49	74	1.35
16	62	1.61	71	1.41
17	58	1.72	67	1.49
18	54	1.85	64	1.56
19	51	1.96	61	1.64
20	48	2.08	58	1.72
21	44	2.27	55	1.82
22	42	2.38	52	1.92
23	39	2.56	50	2.00
24	36	2.78	48	2.08
25	34	2.94	46	2.17
26	31	3.22	43	2.32
27	30	3.33	41	2.44
28	28	3.57	39	2.56
29	26	3.85	38	2.63
30	25	4.00	36	2.78
31	23	4.35	35	2.86
32	22	4.54	34	2.94
33	21	4.76	33	3.03
34	20	5.00	32	3.12
35	19	5.26	31	3.23
36	17.5	5.37	30	3.33
37	18	5.63	29	3.45
38	17	5.86	28	3.56
39	16.5	6.15	27	3.70
40	16	6.26	26	3.84

Table 14. Relationship of stand age to GBA and conversion factors.

Stand Age	GBA at age 50 and 100: Percent	Conversion
20	60	1.40
30	78	1.22
40	93	1.07
50	100	1.00
60	108	0.92
70	111	0.89
80	111	0.89
90	106	0.94
100	100	1.00
120	98	1.02
140	96	1.04
160	94	1.06
180	92	1.08
200	90	1.10
220	88	1.12
240	86	1.14
260	84	1.16
280	82	1.18
300	80	1.20

How to Use GBA

This chapter deals with how GBA may be used for prescribing stand treatment and how stand density, as indexed by GBA, influences timber management. The Douglas-fir-dominated stand sampled for GBA determination will be used to illustrate treatment prescription. Tree measurements are shown in figure 50. GBA for the stand averaged 218 ft^2 BA/A.

Estimating Precommercial Thinning

The stand just sampled for GBA will be regenerated. A critical question is how many trees to leave following precommercial thinning. The first requirement is to specify stand conditions desired at first commercial entry. A manager has decided on a quadratic mean stand diameter (Dq) of 10 inches dbh at age 40 and a diameter growth on dominant trees of 15/20ths (1.5 in/dec.).

Utilizing the slide rule illustrated in figure 52, three steps are required:

1. Adjust GBA to age 40 (i.e., 203 ft^2 BA/A).

2. Determine BA/A for 15/20ths radius growth (i.e., 152 ft^2 BA/A).

3. Determine trees per acre (TPA) for optimum stand conditions (i.e., 290 TPA at 10 inches dbh).

This is the number of trees to leave following precommercial thinning assuming no mortality between age at thinning and first commercial entry. Spacing for 290 TPA is about 12 feet.

Alternatives to using the GBA curves are the regression equations for pine and fir or tables 13 and 14. For example, table 14 may be used to determine the age adjustment from 100 to 40 years (i.e., 0.93). Table 13 may be used to determine % GBA for 15/20ths (i.e., 74%). Equation (6) may be used to determine % GBA:

ln% GBA = 5.299 - 0.074*15 + 0.00058415**
= 4.3204, the antilog is 75.22 % GBA.

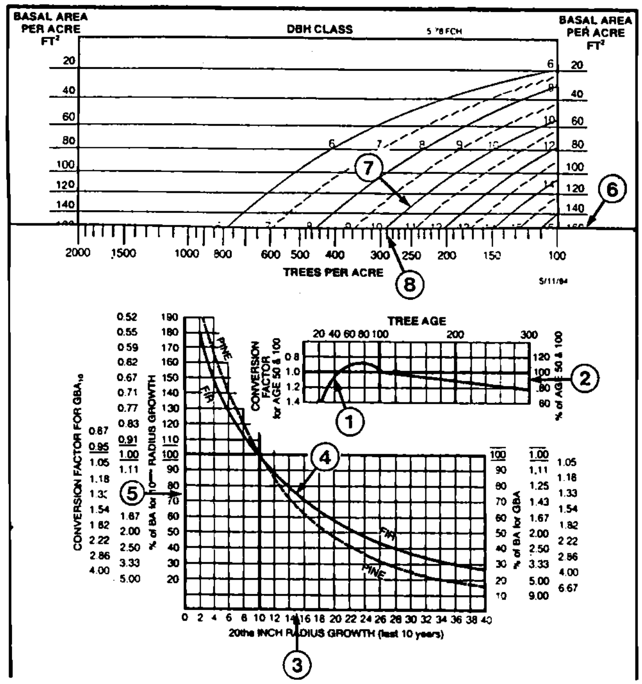


Figure 52. Procedure for determining precommercial thinning to attain a 10-inch Dq dbh stand with dominants growing at 15/20ths (GBA = 218 ft^2). First adjust GBA to age 40; (1) enter the graph at age 40, (2) read right to 93% of age 100. Then: 0.93*218 = 203 ft^2 (at age 40, dominants will average 1.0 in/dec. at 203 ft^2 BA/A). Next, (3) enter the GBA graph at 15/20ths, (4) read up to the fir curve and (5) left to 75% of GBA . Then: 0.75*203 = 152 ft^2 BA/A. Finally, (6) set the slide at 152 ft^2 BA/A, (7) find the 10- inch-dbh curve and (8) read 290 TPA. Thin to 290 TPA, about a 12-foot spacing.

Estimating Planting Density

Planting density can be estimated from calculations for precommercial thinning by increasing precommericial thinning TPA according to expected mortality. For example, if an established plantation will contain 60% of the planted stock, precommercial thinning density can be increased by 140%: 1.40 *290 = 460 TPA planting density.

Prescribing Thinning

We will assume first commercial entry stand conditions described above: i.e., 290 TPA averaging 10 inches dbh at 152 ft^2 BA/A with dominants growing at 15/20ths. One goal might be to prescribe thinning to attain 25/20ths radius growth. Recall that GBA at age 40 is 203 ft^2.

Two steps are required using figure 53:

1. Determine % GBA for 25/20th radius growth (i.e., 45%), and

2. Determine BA/A to leave following thinning (i.e., 93 ft^2 BA/A).

The stand will initially average 25/20ths radius growth of dominant trees when thinned from below to 93 ft^2 BA/A. Since GBA is based on diameter growth of dominants, these trees must remain after thinning. In this way, the largest, fastest growing trees in the stand continue to accumulate maximum volume.

There are two alternatives: Using table 13: 25/20ths is 46% of GBA for fir. Or, using equation (6):

ln% GBA = 5.299 - 0.074*25 + 0.00058425**
= 3.814, the antilog is 45.33% GBA.

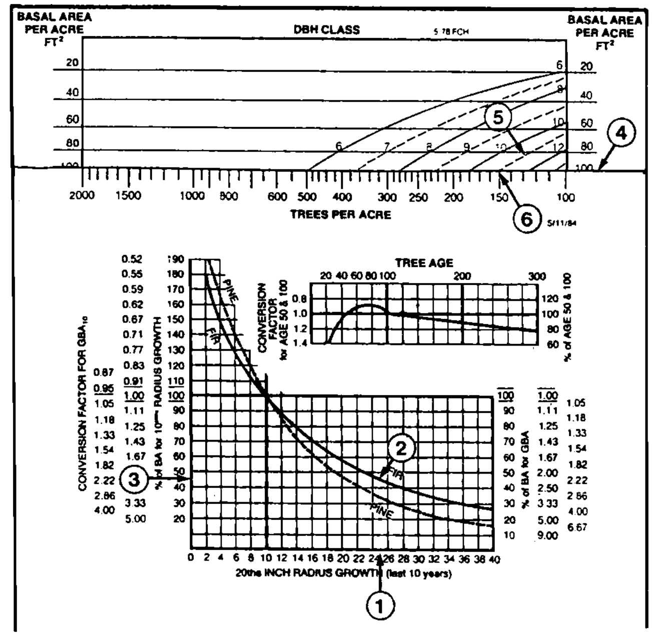


Figure 53. Procedure for prescribing thinning to attain 25/20ths radius growth (GBA = 203 ft^2). First, (1) enter the GBA graph at 25/20ths, (2) read up to the fir curve and (3) left for 45% of GBA . Then: 0.45*203 = 93 ft^2 BA/A. Thin to leave 93 ft^2 BA/A. See text for other steps.

Approximating 20 Years' Diameter Growth

The GBA slide rule can be used to approximate future diameter growth of trees. "Approximate" is stressed because dominant tree dbh is used for diameter growth but is treated on the slide rule as Dq dbh when dealing with TPA and BA/A. The stand will be projected for 20 years. To illustrate, assume that average dominant tree dbh is 11 inches and that 93 ft^2 BA/A remained after thinning. Using figure 53, proceed as follows:

(4) Set the slide at 93 ft^2 BA, (5) find the 11-inch dbh curve, and (6) read about 150 TPA .

The first-decade diameter growth is calculated as follows (figure 54): Radius growth of 25/20ths is 2.5 in/dec. diameter growth. Add 2.5 inches to 11 inches dbh for 13.5 inches dbh at 150 TPA. (1) Find the 13.5-inch-dbh curve, (2) adjust the slide so 150 TPA intersects the 13.5-inch-dbh curve, and (3) read BA/A (about 145 ft^2). Now, determine percent of GBA and corresponding 20ths: 145/203 = 72% of GBA. In figure 54, (4) enter the GBA graph at 72% (5), read over to the fir curve and (6) down for 15.5/20ths radius growth.

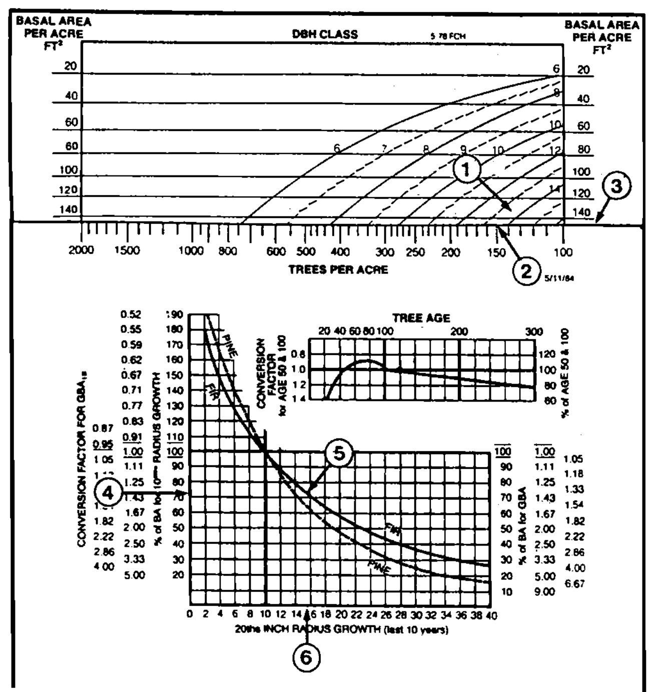


Figure 54. First steps in approximating 20 years' diameter growth following the thinning depicted in figure 53. Additional steps are shown in figures 55 to 57.

There are two alternatives: Using table 13: Find 72% GBA for fir, look left to 15.5/20ths. Or, using equation (8):

20ths = 182.54 - 59.160*ln72 + 4.6963ln72**
= 15.43

The next step is to take the average between 15.5/20ths and 25/20ths (i.e., 20/20ths); add 2.0 inches to 11 inches dbh for 13 inches dbh at 150 TPA. Dominant trees would grow only 15.5/20ths at 145 ft^2 BA/A. They would not grow at 25/20ths for this entire decade.

Next, using figure 55, (1) find the 13-inch-dbh curve, (2) adjust the slide to intersect at 150 TPA, and (3) read BA/A (about 135 ft^2).

Now, take the percentage of GBA: 135/203 = 67% of GBA: (4) enter the GBA graph at 67% , (5) read over to the fir curve, and (6) down to 17/20ths radius growth. At the end of the first decade, the stand averaged about 21/20ths radius growth, starting at 25/20ths and ending at 17/20ths. Stand conditions after the first decade are: 150 TPA at 135 ft^2 BA/A with dominants growing at 17/20ths radius growth.

There are two alternatives: Using table 13, find 67% GBA for fir, look left for 17/20ths. Or, using equation (8):

20ths = 182.54 - 59.16*ln67 + 4.6963ln67**
= 16.8.

For the second decade, repeat the same procedure as follows: 17/20ths is 1.7 in/dec. diameter growth added to 13 inches dbh for 14.7 inches dbh at 150 TPA. Using figure 56, (1) find the 14.7-inch-dbh

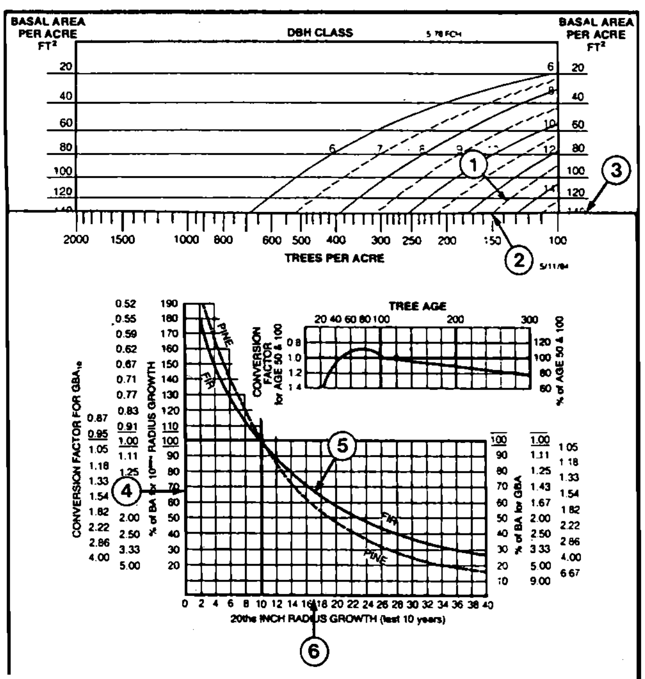


Figure 55. Second set of steps for approximating 20 years' diameter growth. See text for details and figures 54, 56, and 57.

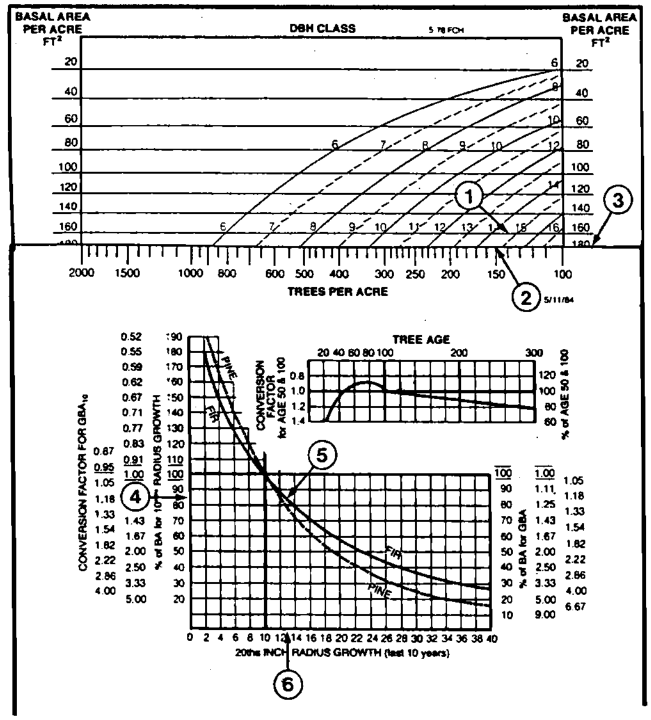


Figure 56. Third set of steps for approximating 20 years' diameter growth.

curve, (2) adjust the slide to intersect at 150 TPA, and (3) read about 175 ft^2 BA/A. Determine percent of GBA: 175/203 = 86% of GBA. Then (4) enter the GBA graph at 86%, (5) read over to the fir curve and (6) down to 13/20ths. Average 17/20ths and 13/20ths for 15/20ths, or an average of 1.5 in/dec. diameter growth. Add 1.5 inches to 13 inches dbh for 14.5 inches dbh at 150 TPA (figure 57): (1) find the 14.5-inch-dbh curve, (2) adjust the slide to intersect at 150 TPA, and (3) read about 170 ft^2 BA/A . Determine percent of GBA: 170/203 = 84% of GBA. Then (4) enter the GBA graph at 84% , (5) read to the fir curve and (6) down to 13/20ths. At the end of two decades, dominants are about 14.5 inches dbh and are growing at approximately 13/20ths at 170 ft^2 BA/A. Stand age is now 60 instead of 40, which suggests 10% higher GBA. Therefore, diameter growth would probably be about 10% higher (i.e., 14/20ths instead of 13/20ths). This same procedure may be applied to several more decades of growth.

Predicting Diameter Growth After Thinning

This stand, with dominants now growing about 1.4 in/dec. in diameter at 170 ft^2 BA/A, is ready for a second commercial thinning. Let's assume economic constraints require at least 60 ft^2 BA/A must be harvested from below, which would leave 110 ft^2 BA/A. Using figure 58, three steps are required to predict rate of diameter growth following commercial thinning:

1. Adjust GBA to age 60 (i.e., 235 ft^2 BA/A;

2. Determine % GBA after thinning (i.e., 47%); and

3. Estimate rate of diameter growth (i.e., 24/20ths or 2.4 in/dec.).

Alternatives to using GBA curves are the regression equations or tables 13 and 14. For example, table 14 shows the age adjustment for fir from 100 to 60 years is 108%. Table 13 shows that 47% GBA for fir is 24/20ths radius growth. Using equation (8):

20ths = 182.54 - 59.15*ln47 + 4.6963ln47**
= 24.42.

Another way to estimate change in rate of diameter growth is to remove a percentage of existing basal area. For example, the stand is growing at 14/20ths at 170 ft^2 BA/A, which is 72% of GBA at age 60. If 35% of the BA is cut, 65% would remain: 0.65*.72 = 46% of GBA. Using figure 58, (3) enter at 46% of GBA, (4) read to the fir curve and (5) down to 24/20ths radius growth.

Estimating Maximum and Minimum Stocking

When evaluating regeneration alternatives, a manager might consider three stocking parameters: maximum, optimum, and minimum acceptable stocking (Barrett 1979, Sassaman et al. 1977, Seidel and Cochran 1981).

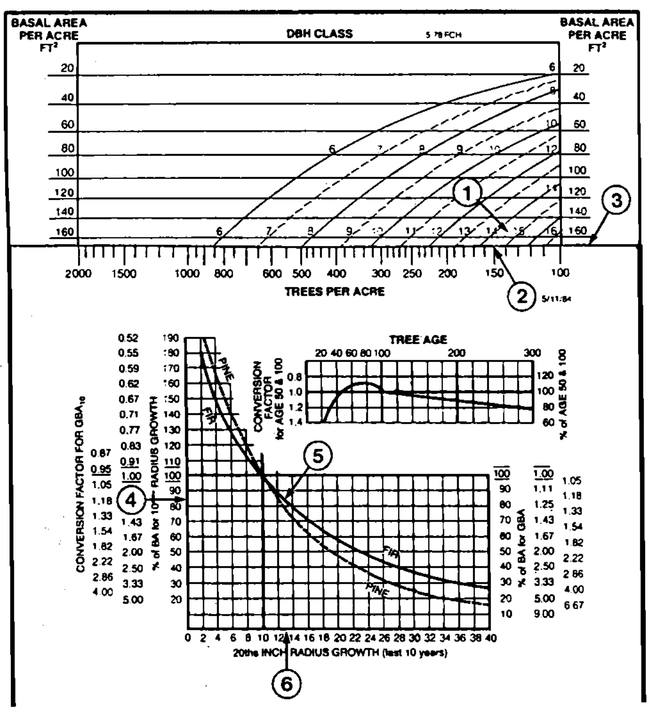


Figure 57. Final steps in approximating 20 years' diameter growth.

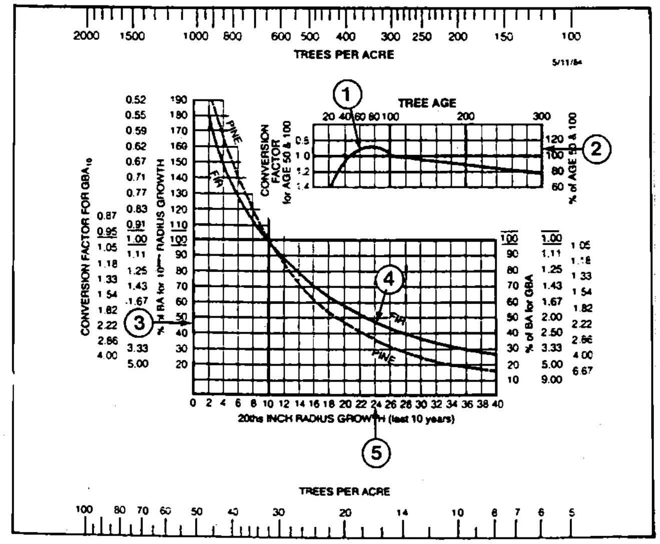


Figure 58. Procedure for predicting radius growth following thinning (GBA = 218 ft^2). First, adjust GBA to age 60; (1) enter the age graph at age 60 and (2) read right to 108% . Then: 1.08*218 = 235 ft^2 BA/A (at age 60, dominant trees will average 1.0 in/dec. at 235 ft^2). Next, determine % GBA after thinning to 110 ft^2 BA/A: 110/235 = 47% of GBA. Finally, estimate rate of diameter growth; (3) enter the GBA graph at 47% of GBA, (4) read right to the fir curve and (5) down for 24/20ths. Dominants will increase to 24/20ths radius growth (2.4 in/dec.) following thinning to 110 ft^2 BA/A.

Optimum is that stocking which will result in reaching specified stand conditions for first commercial entry in the desired period of time. Maximum stocking is that which requires precommercial thinning. Minimum stocking is that which requires replanting.

Let's use the Douglas-fir stand just illustrated as an example. GBA was 218 ft^2/A, optimum stand condition at first commercial entry was 10 inches Dq with dominants growing at 1.5 in/dec. diameter growth at age 40 years. Optimum stocking was 290 TPA following precommercial thinning. This could also be optimum stocking for an established plantation (established means 290 well-spaced trees per acre over 4.5 feet tall).

Maximum stocking requires that the manager decide how much time is acceptable before commercial thinning can take place (assuming that 10 inches Dq is the minimum acceptable commercial size). More than 290 TPA will result in a slower rate of diameter growth, requiring more years to first commercial entry. Assuming a 20-year delay in first entry, stand conditions would be 10 inches Dq with dominants growing at 0.7 in/dec.: 0.7 in/dec. (7/20ths) is 120% of GBA, meaning 262 ft^2 BA/A for a maximum stocking of 500 TPA. Precommercial thinning to 290 TPA would be appropriate for stands with more than 500 TPA.

Minimum acceptable stocking is also an administrative decision regarding how much volume and how many commercial thinnings can be given up as a tradeoff for not replanting the tract. Assume as being acceptable a regeneration harvest program (no thinning) with Dq stand diameter of 24 inches and dominants growing at 0.7 in/dec: 0.7 in/dec. is 120% of GBA, meaning 262 ft^2 BA/A for a minimum acceptable stocking of 84 TPA. A tract with fewer than 84 well-spaced trees per acre would require replanting to attain 290 TPA over 4.5 feet tall.

Stocking guides. The concept of maximum and minimum acceptable stocking is employed in the Forest Service stocking guides based on the Gingrich concept (figure 59) (Ernst and Knapp 1985). These guides provide upper and lower limits to a management zone within which stocking levels can be chosen to optimize different management objectives. This management zone falls below the average maximum density level and above the reference level of no significant competition. The maximum density level varies according to the tree species or forest type, plant association (habitat type), or other forest type classification (such as site index). Average stand diameter, trees per acre, and basal area per acre are provided in a format different from the GBA slide rule.

The relationship of GBA to stocking level guides is shown in figure 59 and table 15. Average stand dbh of 10 inches was chosen for illustration. In figure 59, a maximum density of 250 ft^2 BA/A was assumed to be 0.4 in/dec. diameter growth, which is 149% of GBA for fir (166% for pine). This means fir GBA is 167 ft^2 BA/A. At 1.0 in/dec. diameter growth, each dbh class could be multiplied by 10 years to estimate stand age (i.e., 4 inches is 40 years, 6 inches is 60 years, etc.). The curve in figure 59 represents stand age effects on dominant-tree diameter growth from age 40 to 240 according to the age correction curve on the slide rule, table 14, or equations (10) and (11).

Table 15. Relationship of Gingrich guide stand densities to rate of diameter growth for a fir GBA of 167 ft^2 at 10 inches dbh. Maximum density would be about 250 ft^2 BA/A at 0.4 in/dec. diameter growth.

Stocking level	ft^2/A @ 10 in. dbh	% max. density	% GBA	In/dec. diameter growth
Maximum	250	100	150	0.4
Upper level	205	82	123	0.7
GBA	167	67	100	1.0
Lower level	135	54	81	1.4
No competition	72	30	45	2.5

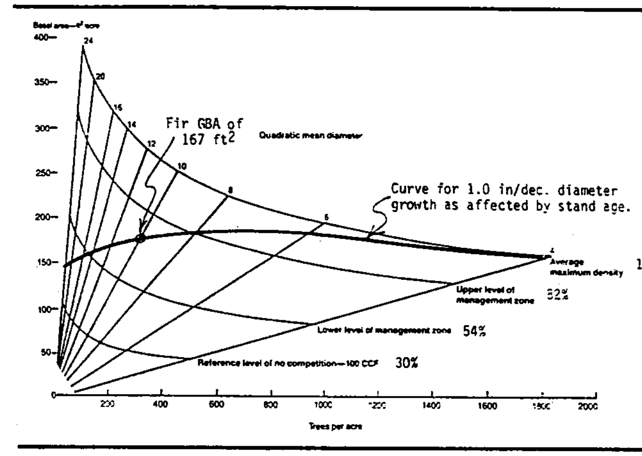


Figure 59. The Gingrich graph for depicting Forest Service stocking guides. A curve has been added showing GBA-derived diameter growth. A maximum density of 250 ft^2 BA/A for a 10-inch-dbh stand would be a GBA of 167 ft^2 for fir if maximum density is assumed to be 0.4 in/dec. diameter growth. Stand age effects on diameter growth were taken from the age correction curve on the slide rule (or from table 14). Each diameter class was multiplied by 10 years as an estimate of stand age (i.e., 8 inches is 80 years, 10 inches is 100 years, etc.).

Table 15 lists the relationship of stocking level to rate of diameter growth assuming a fir GBA of 167 ft^2 at 10 inches dbh.

These Gingrich-type stocking guides can be constructed for various GBA's by assuming that maximum density represents 0.4 in/dec. diameter growth. Take 149% of GBA for fir and 166% of GBA for pine to establish the maximum density at 10 inches dbh. Upper and lower management levels represent 82% and 54% of maximum; no significant competition is 30%.

Management Implications of Stand Density

As an index of forestland stockability, GBA has other uses besides prescribing stand treatment. It indexes stand density. Stand density affects rate of tree height growth, and therefore SI determination. It also affects periodic and mean annual increment, tree vigor, and susceptibility to insects and disease.

Density and height growth. High stand densities tend to reduce height growth (Alexander et al. 1967; Barrett 1969, 1979, 1981, 1982; Curtis and Reukema 1970; Dahms 1971b; Harrington and Reukema 1983; Lynch 1958; Oliver 1972; Reukema and Bruce 1977; Reukema 1979; Schmidt 1978; Seidel 1982). Reduction can be dramatic enough to require adjustment of SI curves for lodgepole pine (Alexander 1966), ponderosa pine (Lynch 1958), and grand fir (Stage 1959).

Some studies have provided enough data to relate reduction in height growth to diameter growth. Seidel (1982) and Schmidt (1978) found reduced height growth in dominant western larch trees at 1.3 in/dec. diameter growth, but not at 2.5 in/dec. Apparently, height growth was reduced at 60% to 80% of GBA.

Effect of stand density on ponderosa pine is shown in figure 60. Barrett's (1981) results in the Methow Valley of Washington were different from those at Pringle Falls in Oregon (Barrett 1982). Oliver's (1972) data from Idaho showed results similar to those from Pringle Falls--i.e., height growth of dominant trees was reduced to 30% of maximum at 1.0 in/dec. Dq diameter growth. This would calculate as 1.5 in/dec. diameter growth of dominant trees using equation (9) (67% of GBA). Both tree and shrub competition resulted in slower rates of diameter and height growth. Barrett (1968) also found that pruning live crowns in ponderosa pine to a 45% crown ratio reduced height and diameter growth, the latter to 1.7 in/dec. or slower.

Alexander et al. (1967), in discussing adjustment of lodgepole pine SI by crown competition factor (CCF), did not provide diameter growth data. However, diameter growth has been presented in conjunction with CCF in other studies (Dahms 1966, 1971a, 1971b, 1973b). No adjustment for stand density was deemed necessary at CCF's below 125 (Alexander 1966), which were associated with 0.7 to 1.0 in/dec. Dq diameter growth. Apparently, lodgepole pine height growth is affected at dominant-tree diameter growth rates between 1.1 and 1.9 in/dec. (equation (9), or 93% to 51% of GBA.

Figure 61 illustrates the effect of stand density on Douglas-fir height growth. Curtis and Reukema (1970) and Reukema (1979) discussed the effects of stand density on SI determination in a Wind River, Washington, plantation. Height growth of dominant trees was reduced to about 80% of maximum at 1.0 in/dec. Dq diamter growth (1.5 in/dec. of dominant trees or 74% of GBA). Harrington and Reukema (1983), on the other hand, found height growth reduced to about 50% of maximum at 1.0 in/dec. Dq diameter growth and about 80% of maximum at 2.0 in/dec. Dq diameter growth. These Dq diameter growth rates represent 1.5 and 2.7 in/dec. diameter growth of dominant trees (equation (9)) or 74% and 41% of GBA. These studies suggest that height growth of ponderosa pine, lodgepole pine, larch, and Douglas-fir is reduced at 40% to 70% of GBA.

Density and stand growth. Stand density also affects stand volume growth. Volume growth is usually divided into several categories: total cubic stem,

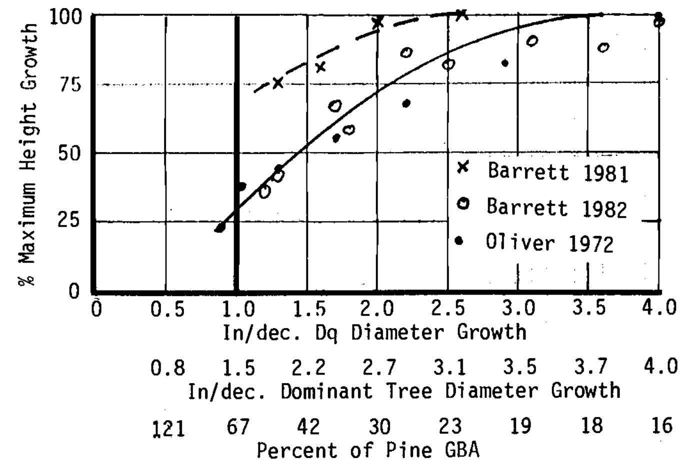


Figure 60. Ponderosa pine height growth as affected by stand density. Density is expressed as: (1) in/dec. diameter growth of quadratic mean (Dq) dbh trees, (2) diameter growth of dominant trees estimated by use of equation (9), and (3) percent of GBA.

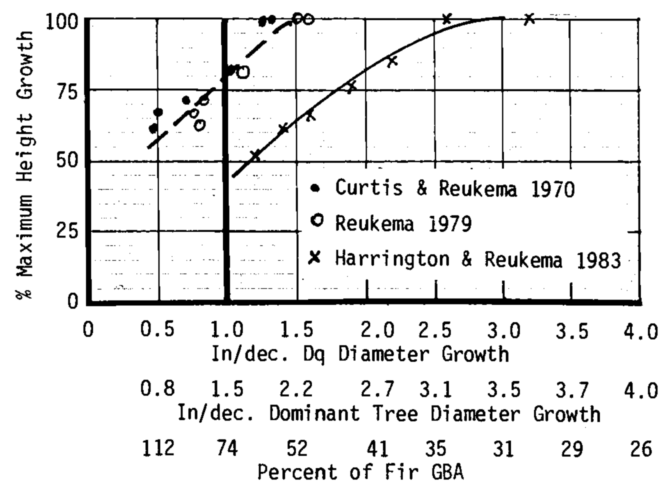


Figure 61. Douglas-fir height growth as affected by stand density. Density is expressed as: (1) in/dec. diameter growth of quadratic mean (Dq) dbh trees, (2) diameter growth of dominant trees estimated by use of equation (9), and (3) percent of GBA.

merchantable cubic stem, and merchantable board-foot volume and volume growth. Merchantable volume is that volume in logs of specified lengths from a given stump height to a set of top diameters such as 4, 6, or 8 inches. Board-foot volume is the volume in logs 9 inches in diameter or greater. Volume and growth by each of these categories are further divided into gross and net amounts (Reukema and Bruce 1977). Gross is the total amount of volume and growth produced on the site, including unusable mortality. Net is the amount that can be harvested for products.

Many thinning studies test the effects of stand density and thinning on production of usable wood products. The objective is to find stand treatments that will maximize net volume and growth by utilizing as much gross volume and growth as possible.

In general, maximum gross cubic volume and periodic annual increment are attained with maximum stand density (i.e., unthinned conditions or densest possible spacing). Maximum net cubic volume is often produced at slightly wider spacings or in lightly thinned stands because mortality is less. Board-foot volume, since it requires a certain minimum dbh, is often maximized at still wider **initial** spacings until trees reach merchantable size, then with light thinning to maintain maximum stand density without mortality. Generally, the lower the stand density, the lower the net and gross growth and volume produced (Alexander and Edminster 1980, Assman 1970; Barrett 1968, 1979, 1981, 1982; Cole 1984; Cole and Edminster 1985; Curtis et al. 1981; Dahms 1971a, 1971b, 1973b; Drew and Flewelling 1979; Graham et al. 1985; Harrington and Reukema 1983; Hilt et al. 1977; Oliver 1972; Reukema 1979; Reukema and Piennar 1973; Sassaman et al. 1977; Seidel 1980, 1982; Seidel and Cochran 1981; Tappeiner et al. 1982; Wiley and Murray 1974; Williamson 1982).

Calculations from some of these studies suggest that 95% to 100% maximum net cubic volume productivity is attained at dominant-tree diameter growth rates of 0.7 to 1.4 in/dec., or 120% to 70% of GBA. Volume productivity per acre decreases as diameter growth rates of dominant trees exceed 1.4 in/dec., or less than 70% of GBA. Calculations have also suggested that only 60% of maximum productivity is attained at diameter growth rates of 3.0 to 4.0 in/dec., or 35 to 20% of GBA. (Barrett 1982; Cole 1984; Dahms 1971b, 1973b; Harrington and Reukema 1983; Seidel 1980, 1982). The land manager must balance maximizing net cubic volume growth with attaining merchantable tree size in a reasonable period of time.

Density and CMAI. Culmination of mean annual increment (CMAI) is influenced by stand density and stand treatment. For example, in ponderosa pine at 900 TPA and SI 78, CMAI occurs at age 55 without thinning (Sassaman et al. 1977). With precommercial thinning to a 2-inch-dbh tree, CMAI occurs at age 130; to a 4-inch-dbh tree, at age 140; and to an 8-inch-dbh tree, at age 150. Mean annual increments (MAI) at the culmination ages are: 52, 50, 46, and 39 ft^3/A/yr, and merchantable cubic volumes at age 160 are: 2,409, 5,850, 5,385, and 4,411 ft^3/A, respectively.

Reukema (1979), working on poor-site Douglas-fir at Wind River, Washington, found that 4-foot and 5-foot square spacing resulted in culmination of MAI at age 50, and that 10-foot and 12-foot square spacing still showed increasing MAI at age 53.

Density, insects and disease. Stocking level control, which influences tree vigor, may be used to ameliorate effects of insects and disease. For example, Indian paint fungus impacts may be reduced in grand fir and Douglas-fir by maintaining fast diameter growth (Filip et al. 1984). Rapid growth in both height and diameter seem to reduce effects of dwarf mistletoe on ponderosa pine (Barrett and Roth 1985, Childs and Edgren 1967, Roth and Barrett 1985, Shea 1964) and lodgepole pine (Van der Kamp and Hawksworth 1985).

Fast growth also seems to reduce effects of beetle attack or even to prevent it. Lodgepole pine may be an exception, where Anman and Safranyik (1985) found that wide annual rings in conjunction with dbh greater than 10 inches seem to increase susceptibility to mountain pine beetle attack. Ponderosa pine becomes more resistant to beetles when stand density is low and diameter growth fast (Johnson 1967, Sartwell 1971). Effects of Douglas-fir beetle and fir engraver beetle are reduced with rapid diameter growth (Johnsey 1984), and good tree vigor seems to deter spruce budworm damage (Fellin et al. 1984, Williams 1967).

Knowing GBA for a site affords the manager an opportunity to prescribe suitable treatment. For example, diameter growth faster than 1.8 in/dec. can be attained by thinning to less than 50% GBA.

Fertilization and vegetation control. Two other aspects of management related to GBA are fertilization and control of competing vegetation, both of which may increase GBA and SI. Control of nontree vegetation can result in increased diameter and height growth of ponderosa pine (Barrett 1979, 1982; Gordon 1962; Van Sickle 1959) at stand ages ranging from 15 to 50 years. Fertilization has been shown to increase height and diameter growth for three to six seasons after application in lodgepole pine (Cochran 1979b, Wheetman et al. 1985), ponderosa pine (Barrett 1979, Agee and Biswell 1970), Douglas-fir (Barclay et al. 1982, Harrington and Miller 1979), and white fir (Heninger 1981).

Thus, GBA may be used as a guide to stand management alternatives. On one hand, high stand densities, such as 70% to 120% of GBA, tend to maximize stand growth and cubic volume of small-diameter logs. On the other hand, low stand densities, such as 30% to 50% of GBA, tend to reduce insect- and disease-related mortality and produce larger logs, but achieve only 60% to 80% of maximum volume. By knowing GBA for the site, the manager can decide which stand conditions best meet his needs, prescribe treatment to attain those conditions, and apply the treatments in the field.

CHAPTER 5

GBA and Stand Growth

GBA, as a measure of stockability, can be used to refine estimates of stand growth when used in conjunction with SI tables and simulation models. The relationship of GBA to stand BA/A growth was discussed in Chapter 2, and the effect of stand density on stand growth was reviewed in Chapter 4. This Chapter will discuss (1) GBA in relation to stand growth using data calculated in Chapter 2 in the "GBA and Basal Area Growth" section, (2) combining of SI with GBA to index stand growth potential, and (3) interpretiang SI/GBA relationships.

GBA and Stand Growth

Stand volume growth is the sum of the growth of all trees in the stand. Tree growth is a function of current tree size, rate of diameter growth, rate of height growth, and tree form.

Tree volume growth. The following computations illustrate growth components of a 10-inch-dbh tree 60 feet tall growing at the rate of 1.0 in/dec. in diameter and 1.0 ft/yr in height :

Components:

f = form factor of 0.39 (the constant used to change the volume in a cylinder to a cone)

H = tree height of 60 ft

dH/dt = tree height growth per year of 1.0 ft

B = 10-inch-dbh basal area of 0.5454 ft^2

dB/dt = basal area growth per year of 0.0110 ft^2

dV/dt = cubic volume growth rate per tree per year

Volume growth per year (Curtis and Marshall 1986):

(12) $$dV/dt = f{*}B{*}dH/dt + f{*}H{*}dB/dt = 0.39{*}0.5454{*}1.0 + 0.39{*}60{*}0.011 = 0.2127 + 0.2574 = 0.4701\ ft^3 \text{ per year per tree}$$

Growth accounted for by height increment:

(13) $$dH/dt = f{*}B{*}dH/dt = 0.2127$$

Growth accounted for by diameter increment:

(14) $$dB/dt = f{*}H{*}dB/dt = 0.2574$$

Table 16. Effects of different rates of height and diameter increment on the volume growth of a 10 in. dbh tree 60 feet tall. Growth rates are 1.0 and 2.0 ft/yr in height and 1.0 and 2.0 in/dec. on diameter.

	1 ft/yr 1.0 in/dec	2 ft/yr 1.0 in/dec	1 ft/yr 2.0 in/dec	2 ft/yr 2.0 in/dec
Total: (ft^3/tree/yr)(Eq. 12)	0.4701	0.6828	0.7275	0.9402
% of 1 ft & 1.0 in/dec.	100	145	155	200
Height growth proportion:				
ft^3/tree/yr (Eq. 13)	0.2127	0.4254	0.2127	0.4254
% of total	45	62	29	45
% of 1 ft & 1.0 in/dec.	100	200	100	200
Diameter growth proportion:				
ft^3/tree/yr (Eq. 14)	0.2574	0.2574	0.5148	0.5148
% of total	55	38	71	55
% of 1 ft & 1.0 in/dec.	100	100	200	200

Summary:

Growth by height	= 0.2127	45%
Growth by diameter	= 0.2574	55%
Total growth	= 0.4701	100%

These percentage relationships between growth accounted for by height and diameter vary according to the rates of height and diameter growth. Table 16 summarizes effects of varying both rates.

Doubling the rate of height growth increases tree productivity 145%, while doubling diameter growth increases tree productivity 155%--roughly a 1.5-fold increase in volume productivity when one of the two growth components doubles. When both double, productivity doubles. The amount of tree productivity accounted for by height and diameter growth changes as these components change. When height growth doubles, tree productivity accounted for by height growth changes from 45% to 62%. When diameter growth doubles, productivity accounted for changes from 55% to 70%.

Tree size also influences growth rate per tree. Table 17 lists characteristics of three tree sizes.

The 10-inch-dbh tree grows four times more volume than the 5-inch tree, and the 20-inch-dbh tree grows 16 times more volume than the 5-inch tree at the same rate of height and diameter increment. Likewise, BA growth of a 10-inch-dbh tree is 200% greater than that of a 5-inch tree, and BA growth of a 20- inch-dbh tree is 400% greater.

A similar relationship holds for the ratios of cubic foot wood produced per square foot of BA growth. The 10- inch-dbh tree has double the volume and the 20- inch- dbh tree has four times the volume of a 5-inch-dbh tree. This seems logical, since the 20-inch-dbh tree is four times taller.

Stand volume growth is the summation of all tree growths. For illustration, let's assume all trees perform similarly and have similar measurement characteristics. Table 18 lists annual cubic volume and basal area growth per acre for stands of 5-, 10-, and 20-inch-dbh trees stocked at 100 ft^2 BA/A each.

Stand volume growth per acre per year, 86 ft^3, is the same for all tree sizes, while BA growth per acre per year decreases with increasing tree diameter. Volume growth per acre per year was intentionally made similar by selecting tree height at each dbh to produce 86 ft^3/A/yr. Table 18 demonstrates that BA growth per acre does not index stand productivity unless dbh and height are specified. These data are plotted in figure 62 and compared with the SI 100 curve for eastside Douglas-fir (Cochran 1979c), which has a culmination of mean annual increment (CMAI) of 90 ft^3/A/yr (Cochran 1979a).

The fact that BA growth per acre per year decreases with increasing dbh while producing the same cubic volume growth per acre per year reflects the effect of tree size on tree productivity (table 17). As trees increase in size (dbh and height) they greatly increase in growth when height and diameter increment are constant. If the same stand volume growth is produced over a range of tree sizes, BA growth per acre per year must decrease with increasing tree size because the volume of wood produced per square foot of BA growth increases with increasing tree height (table 17). If a reasonably similar rate of diameter growth could be maintained at the same BA/A over a range of tree sizes (ages), volume productivity should be directly related to the SI curve and would tend to fall with increasing age as rate of height growth declines.

Stand productivity seems to be influenced by stand density even though rate of height growth and BA growth per acre per year remain constant at a given

Table 17. Differences in annual growth between trees of three sizes, 5, 10, and 20 in. dbh, growing at rates of 1.0 in/dec. in diameter and 1.0 ft/yr in height.

dbh (in)	Height (ft)	Volume Ft^3/yr	% of 5 in. dbh	BA ft^2/yr	% of 5 in. dbh	Ft^3/Ft^2 Ratio*	% of 5 in. dbh
5	31	0.1176	100	0.00545	100	21.56	100
10	61	0.4701	400	0.0110	201	42.74	199
20	122	1.8843	1602	0.0218	400	86.44	401

* Ratio of cubic volume of wood produced per square foot of basal area growth.

Table 18. Stand growth characteristics for trees of 5, 10, and 20 inch dbh stocked at 100 ft^2 BA per acre and growing at rates of 1.0 in/dec. in diameter and 1.0 ft/yr in height.

			Annual Growth			
dbh (in.)	Tree height (ft)	Trees /acre	Tree (ft^3)	Stand* (ft^3/A)	Stand (ft^2/A)	% of 5 in. dbh BA growth
5	31	733.4	0.1176	86.25	4.00	100
10	61	183.5	0.4701	86.26	2.02	50
20	122	45.8	1.8843	86.30	1.00	25

* Stand growth is calculated by multiplying number of trees per acre times tree growth; table 17 for volume and BA growth.

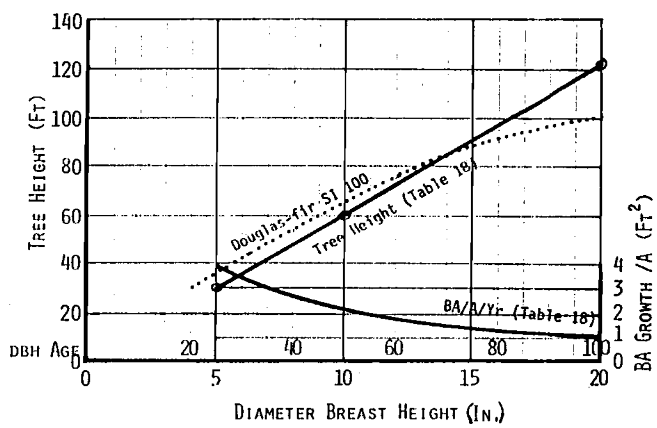


Figure 62. Stand growth data from table 18 plotted with the Douglas-fir SI 100 curve (Cochran 1979c). Stands were 5, 10, and 20 inches dbh, stocked at 100 ft^2 BA/A and grown for 1 year at 1.0 in/dec. in diameter and 1.0 ft/yr in height; this produced 86 ft^3/A/yr, approximately the productivity of Douglas-fir SI 100.

dbh (Buckman 1962, Tappeiner et al. 1982). Table 19 illustrates this relationship for four stand densities, using 60-foot-tall, 10-inch-dbh trees growing 1.0 ft/yr in height. Productivity at 1.0 in/dec. is used as a reference point: 86.26 ft^3/A/yr and 2.03 ft^2 BA/A/yr growth at 100 ft^2 BA/A. Data from 10-inch-dbh trees in table 10 were used for TPA and BA/A.

Stand volume growth was calculated by multiplying TPA times tree volume growth determined by equation (12). BA per acre per year growth was calculated by multiplying BA growth per tree for 10-inch-dbh trees in table 8 times TPA.

Stand productivity varies by stand density even though BA growth per acre per year, height growth, and tree size are all constant. Tappeiner et al. (1982) reported a similar relationship for a spacing study in Coast Range Douglas-fir. The relationship between rate of diameter growth and productivity is shown in figure 63.

GBA effect. Table 19, however, does not have "GBA effect" reflected in stand BA/A for each diameter growth rate. Figure 41 (page 24) compares the curve used to calculate BA/A in table 19 with the pine and fir GBA curves. Basal areas per acre in table 19 were replaced with those derived from the pine and fir GBA curves in figure 41, and stand growth was recalculated in table 20 and graphed in figure 63.

Figure 63 shows that GBA-derived stand BA growth, like volume growth, diverges from the mathematically calculated table 19 data. Fir BA growth, however, approximates mathematical data at diameter growth rates faster than 1.0 in/dec. Pine BA growth per

Table 19. Mathematically calculated effect of stand density, expressed as diameter growth, on volume productivity for a stand 60 feet tall and 10 inches dbh growing at 1.0 ft/yr in height.

	In/dec. Diameter Growth			
	0.5	1.0	2.0	4.0
BA/A (table 10) (ft^2)	199.6	100.0	49.6	24.5
TPA (table 10)	366	183	91	45
Stand growth (ft^3/A/yr)	125.47	86.26	66.98	57.21
% of maximum growth	100	69	53	46
BA growth (ft^2/A/yr)	2.002	2.013	2.002	2.003

acre per year gradually diverges from mathematically calculated growth as stand density decreases. At diameter growth rates slower than 1.0 in/dec., stand BA growth for both pine and fir decreases sharply. A decrease in stand BA growth is required if approximately the same stand volume growth is produced as stand density increases. Both pine and fir produced 85 to 95 ft^3/A/yr as stand density increased from 100 ft^2 to 190 ft^2 BA/A (diameter growth rates from 1.0 to 0.2 in/dec.). Stand density increased 80-90% while BA growth per acre per year decreased 60-65%.

Figure 63 also illustrates the difference between mathematically and GBA-derived stand volume growth. The table 19 curve for mathematically calculated volume production diverges dramatically from the curves of production derived using BA/A from the pine and fir GBA curves at diameter growth rates slower than 1.0 in/dec. The divergence reflects stand reaction to increasing competition stress indexed by shape of the GBA curves. Shape is also the cause for differences in stand productivity between pine and fir at various stand densities, even though they are both indexed at 86 ft^3/A/yr at 1.0 in/dec. diameter growth and 100 ft^2 BA/A (GBA = 100).

Reasons for differences in GBA curves among species will not be addressed here. However, Waring and Schlesinger (1985) devote three chapters in their text on forest ecosystems to discussion of tree physiology and competition using, among other things, leaf area index. They point out differences among species in wood produced per unit of leaf area and changes in the growth efficiency index with changes in stand density. Differences in efficiency among species might account for variation in productivity at lower stocking densities. And changes in carbon allocation reflected by the growth efficiency index might account for shape of the productivity curves at diameter growth rates lower than 1.2 in/dec. Under extreme stress, such as diameter growth less than 0.8 in/dec., partitioning of carbon between maintenance and construction functions becomes critical.

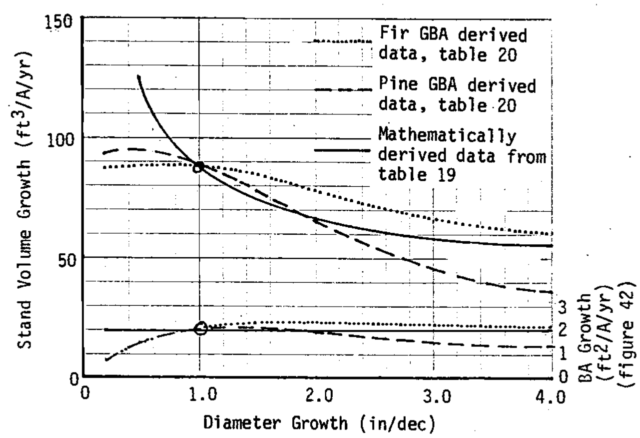


Figure 63. Relationship of stand growth to stand density, indexed by rate of diameter growth, comparing values calculated using GBA data (table 20) and mathematical values (table 19).

Table 20. Effects of stand density on stand growth using BA/A derived from the pine and fir GBA curves for a stand 60 feet tall and 10 inches dbh growing at 1.0 ft/yr in height.

	In/dec. Diameter Growth					
Pine GBA curve	0.2	0.5	1.0	2.0	3.0	4.0
BA/A (ft^2)	192	152	100	48	25	16
Trees per acre @ 10" dbh	352	279	183	88	46	29
Stand growth (ft^3/A/yr)	93.14	95.64	86.26	64.77	46.12	36.80
% of 1.0 in/dec. (GBA)	107	110	100	75	57	43
Stand BA growth (ft^2/A/yr)	0.769	1.526	2.013	1.936	1.472	1.291
% of 1.0 in/dec. (GBA)	38	76	100	96	73	64
Fir GBA curve						
BA/A (ft^2)	180	132	100	58	36	26
Trees per acre @ 10" dbh	330	249	183	106	66	48
Stand growth (ft^3/A/yr)	87.32	85.35	86.26	78.03	66.17	60.91
% of 1.0 in/dec. (GBA)	101	99	100	90	82	71
Stand BA growth (ft^2/A/yr)	0.721	1.362	2.013	2.332	2.191	2.136
% of 1.0 in/dec. (GBA)	36	68	100	116	109	106

The flat shape of the volume production curves (figure 63) from 1.2 to 0.2 in/dec. suggests a delicate balance between survival and death (mortality).

Mortality in relationship to diameter growth was evaluated using data from Avery et al. (1976), whose 50 years of remeasurements on Arizona ponderosa pine included documentated mortality. Suppressed pine started dying at 0.8 in/dec. diameter growth of dominant trees, and reached a model maximum at 0.45 in/dec. In several stands, dominant trees were growing only 0.2 in/dec. and surviving.

SI and GBA as Indicators of Site Productivity

GBA can be combined with SI to index stand productivity. Between them, they include three elements of stand growth: height growth indexed by SI, diameter growth indexed by "G" of GBA, and BA/A indexed by "BA" of GBA (figure 64). The elements missing are tree height and dbh. These may be approximated by tree size at SI age. For example, for SI 100 at base age 100, dominants in a managed stand growing at 1.0 in/dec. for 100 years would be about 10 inches dbh and 100 feet tall.

Variable productivity within an SI class. But the combination SI and GBA is of interest only if an SI class has a range of stockabilities within it, and therefore a range of productivity. Research in Europe has clearly documented a range in producivity so broad that three levels have been established within a site index (height/site) class (Assmann 1970, Bradley et al. 1966, Franz 1967). Recognition of multiple productivity levels has been slow in the United States.

SI was recognized early as only a mediocre indicator of stand productivity. Beginning in 1913, the Society of American Foresters (SAF) attempted to adopt a single measure of site potential for the United States. SI was proposed, among other measures, but was known to be so unreliable that heated discussion lasted for 10 years (Bates 1918, Frothingham 1918, Roth 1916, 1918, Watson 1917, Zon 1913). Finally the SAF (1923) suggested: "Your committee does not recommend the adoption of any one method of determining site-quality, but is inclined to look with favor on the use of height-growth of dominants, in stands above the juvenile stage, if neither too open nor too crowded."

The result was development of a single set of data per SI class called normal yield tables (McArdle et al. 1949; Meyer 1938). This precedent of a single data set, (ft^3, BA/A, dbh, TPA, etc.) per SI class still

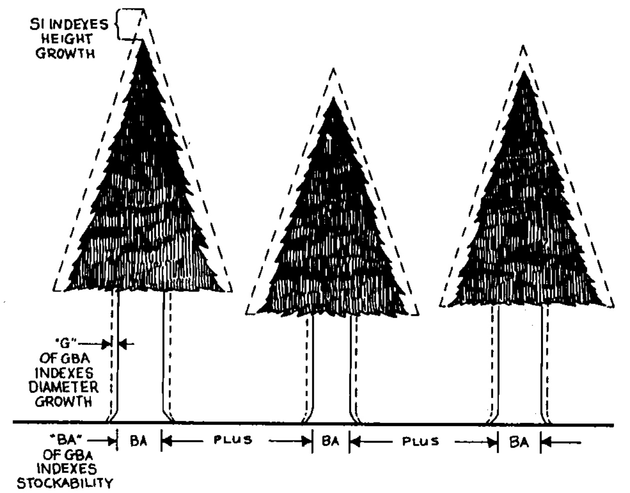


Figure 64. The combination of GBA with SI provides three measures of stand growth: rate of height growth, indexed by SI; rate of diameter growth, indexed by "G" of GBA; and stand density, indexed by "BA" of GBA. Stand growth components missing are stand height and dbh.

tends to be followed (Alexander and Edminster 1980, Cochran 1979a, Curtis et al. 1982, Dahms 1973b, Sassaman et al. 1977), perhaps because a convenient method for identifying different productivity classes in the field has not been available.

The concept of a range in productivity within an SI class is receiving increased attention in the United States. Hagglund (1981) discussed site evaluation by SI, mean annual increment, and soil/topographic characteristics, as did Carmean (1975). Curtis (1981) discussed yield tables past, present, and future, and predicted multiple productivities per SI class. Recently, Monserud (1984) dealt directly with the problems of SI as a site indicator and discussed reasons for multiple yield classes.

Tree physiology supports the concept of a range in productivity within an SI class. Kozlowski (1971) treated tree growth in detail in his two-volume work. Zimmerman and Brown (1971) devoted separate chapters to terminal and cambial growth, and discussed reasons why diameter growth is different from height growth. If they are different, there should by physiological reasons why an SI class could have more than one stockability level within it. Height growth is stimulated by different auxins and tends to be preconditioned by the previous season's growing conditions. It starts earlier and ends earlier than diameter growth, often setting terminal buds prior to onset of severe environmental conditions. Height growth tends to use stored food reserves, while diameter growth tends to use currently produced food.

Evidence for multiple yield classes is mounting. Dahms (1966) showed productivities for SI 78 lodgepole pine (index age 100) of 87 and 137 ft^3/A/yr. Later he compared Rocky Mountain and central Oregon lodgepole pine, finding 104 versus 64 ft^3/A/yr for SI 80 (Dahms 1973a). Most recently, Cole and Edminster (1985) showed significantly different productivities for SI 80 lodgepole pine. Their northern model estimated 71 ft^3 and their central model 105 ft^3/A/yr. These three references imply a range from 64 to 137 ft^3/A/yr for SI 80 lodgepole pine, a variation of 215%.

MacLean and Bolsinger (1973) proposed taking old growth BA/A as a percentage of normal to estimate productivity of dry-site ponderosa pine stands when evidence suggested they differ significantly from normal. Recently, McKay (1985) presented an equation to estimate different stockabilities within an SI class for northern California. In the East, Page (1970) found two productivity levels per SI class for black spruce and balsam fir in Newfoundland. Apparently, lack of a method to simultaneously characterize different stockabilities within an SI class and to identify those site potentials in the field has hindered application of multiple productivity levels.

Empirically, Hall (l971) tested SI and GBA against 31 site factors such as elevation, percent slope, soil texture, soil depth, etc. for six plant community types. Variability accounted for by step-wise regression ranged from 64 to 89 percent (R^2 of 0.64 to 0.89). Thirteen environmental factors proved significant (accounted for at least 10% of the variability) in the six community types for SI, and 12 factors proved significant for GBA. However, only four factors were significantly associated with both SI and GBA out of a total of 21. This suggests that SI and GBA are significantly associated with different site factors, supporting the concept of at least some independence between GBA and SI.

Diameter growth is known to be more sensitive to stand density than height growth, suggesting different physiological reactions to crowding. This is one reason why SI has been popular as a site indicator--it tends to be independent of stand density and can be easily measured in most stands. GBA uses the sensitivity of diameter growth to identify sites of different stockability regardless of SI class. When both SI and GBA for a site are known, a refined estimate of stand growth potential is available.

SI-GBA identifies sites. For example, 100-100 means SI = 100 ft and GBA = 100 ft^2 BA/A at 1.0 in/dec. diameter growth, both at age 100. Table 18 and figure 62 represent an approximation of this site potential, which was mathematically calculated to produce 86 ft^3/A/yr, while table 20 and figure 63 show the effects of GBA.

Both SI and GBA are determined in the field according to stand growth performance--SI according to tree age and height, GBA according to tree diameter growth and stand BA/A. Since both tend to be influenced by past stand history, selection of SI and GBA trees is critical to sound site appraisal.

The number of GBA classes (stockability classes) within an SI class depends on the range of stockability. An SI class can have more than three GBA classes and therefore more than three productivity levels. Figure 65 illustrates SI-GBA combinations for lodgepole pine (Hall 1985).

SI-GBA and productivity. The challenge is to determine how much volume is produced for a given SI-GBA. There are several methods, each with its own advantages and disadvantages.

MacLean and Bolsinger (1973) suggested a practical approach: For an SI class, take old growth BA/A as a percent of normal yield table BA/A and apply the percent to normal volume production. GBA may be substituted for old growth BA/A. For example, SI 100 for ponderosa pine has a normal BA/A of 228 ft^2 and a culmination of mean annual increment (CMAI) of 102 ft^3/A/yr (Meyer 1938). The GBA of an SI-GBA of 100-100 would be 44% of normal. Productivity would be estimated at 44% of 102 ft^3, or 45 ft^3/A/yr. For SI 100 Douglas-fir, normal BA/A is 268 ft^2 and CMAI 98 ft^3/A/yr (McArdle et al. 1949); GBA 100 is 37% of normal so estimated productivity would be 36 ft^3/A/yr.

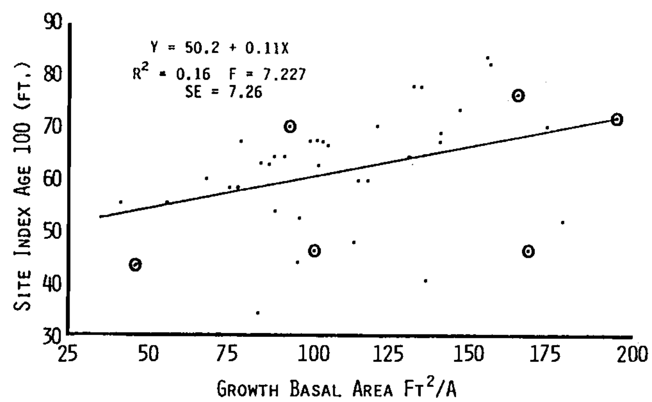


Figure 65. Relationship of lodgepole pine SI to GBA for 39 plant associations in Oregon and Washington (Hall 1985). The circled points suggest that SI class 45 has GBA's of 45, 100, and 170 ft^2 BA/A, and SI class 70 has GBA's of 90, 170, and 200 ft^2. GBA classes 90-100 and 170 occurred in both SI 45 and 70. SI accounted for only 16% of the variability in GBA. The six circled associations are shown in table 24.

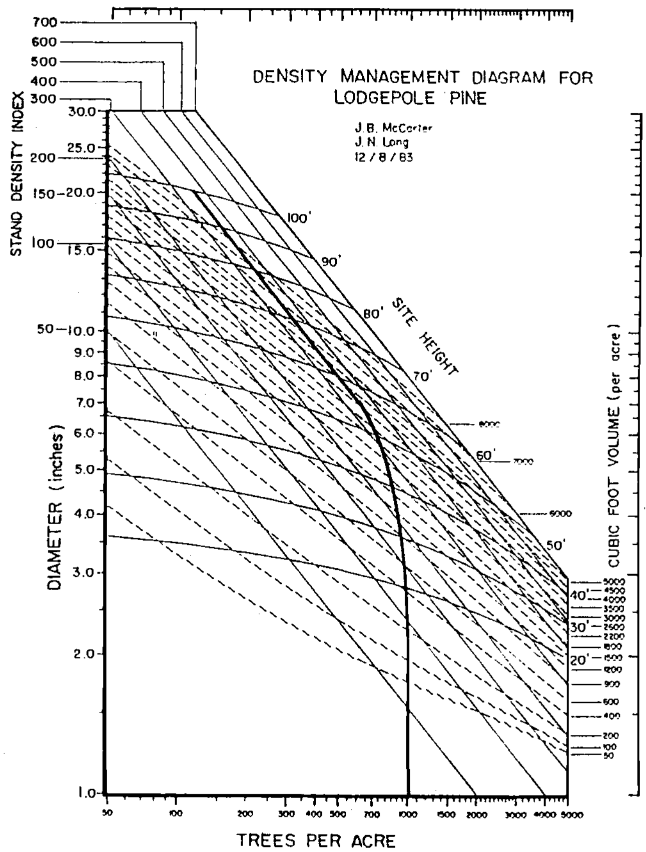


Figure 66. SDI management diagram for lodgepole pine (McCarter and Long 1983) with the probable performance of an SI-GBA site of 100-100 with no thinning. The maximum BA/A for a pine GBA of 100 ft^2 would be 166 ft^2 for an SDI of 308, because at this density mortality tends to equal growth.

The advantage is simplicity; the disadvantage is that normal BA/A often does not represent 1.0 in/dec. diameter growth; therefore, the percentage applied to normal volume production is inaccurate.

This inaccuracy can be reduced if GBA is taken as a percentage of the GBA of simulation models. Again using the 100-100 example, density/diameter growth values calculated for Douglas-fir were graphed from DFSIM SI 100 (at age 100, SI 74 at age 50) (Curtis et al. 1981). A GBA of 290 ft^2 was estimated after adjusting average stand diameter growth to dominant-tree diameter growth with equation (9). GBA 100 was 34%, so productivity was estimated as 34% of the predicted 91 ft^3/A/yr, or 31 ft^3/A/yr net growth (see Chapter 2, "GBA Curve Validation").

The same approach may be used for lodgepole pine with LPSIM (Dahms 1983). Simulator GBA was 130 ft^2 for SI 100, and the example was 77% for 28 ft^3/A/yr. Douglas-fir was also evaluated with PROGNOSIS (Wykoff et al. 1982), where simulator GBA was 180 ft^2 and the example was 56% for 33 ft^3/A/yr. Ponderosa pine was evaluated with RMYLD (Alexander and Edminster 1980) for SI 90 with a simulator GBA of 170 ft^2. The example was 59% for 53 ft^3/A/yr.

The advantage of taking stand GBA as a percentage of simulator GBA is a more precise estimate of volume growth; the disadvantage is time required to estimate simulator GBA.

A similar approach may be used with density management diagrams (Drew and Flewelling 1979, Long 1985, Long and McCarter 1985). A percentage is taken of the BA/A calculated from the diagram, but the percentage is not GBA--instead it is the BA/A for 0.4 in/dec. diameter growth (166% for pine GBA and 149% for fir GBA). This roughly corresponds to a relative density (RD) of 1.0 as it relates to productivity potential of the site sampled. For the 100-100 example, GBA 100 for pine is 166 ft^2 BA/A, and for fir 149 ft^2 BA/A.

BA/A's calculated from Drew and Flewelling's density management diagram (1979) range from 290 to 380 ft^2 as dbh's change from 8 to 24 inches. Using an average of 335 ft^2 BA/A, GBA 100 is 44% for Douglas-fir, which is an RD of 0.4. This 0.4 RD represents the maximum density line for the GBA 100 site, which means the site potential is 44% of maximum density. Net volume calculated from the diagram would be 44% for the 100-100 example. In addition, size of product estimated from the diagram would be significantly larger than could be produced by the real stand.

The same procedure applies to stand density index (SDI) density management diagrams (Long 1985, Long and McCarter 1985). For lodgepole pine, maximum density is an SDI of 700, which corresponds to 382 ft^2 BA/A for a 10-inch Dq diameter stand. Pine maximum density for the 100-100 site, at 166 ft^2 BA/A, is an SDI of about 308, or 44% of maximum. The SDI estimated by GBA can be used to set upper and lower limits for growing stock. But again, product size estimated by the diagram will probably be larger than can be produced by the real stand. The 100-100 example is shown in figure 66 for lodgepole pine on McCarter and Long's SDI Management diagram (1983).

The advantage of this system is ease in calculating percent of stand growth; the disadvantage is difficulty in adjusting size of trees (timber products) downward to those actually producible on the site.

The SI*GBA*K function. A quite different approach to estimating stand productivity for an SI-GBA class involves adjusting the product of SI and GBA by a constant. For example, the 100-100 site was indexed at 31 to 36 ft^3/A/yr for Douglas-fir. If SI is multiplied times GBA and this product adjusted by a constant (K), productivity may be indexed (PI):

(15) PI = SI*GBA*K,

where PI is a productivity index in ft^3/A/yr, SI is based on age 100 measured in feet, GBA is based on 1.0 in/dec. diameter growth adjusted to age 100 and measured in ft^2/A, and K adjusts the product of SI and GBA to an index of productivity.

PI = 100*100*0.0035
= 35 ft^3/A/yr

Table 21 shows calculated productivity for ponderosa pine for four SI classes over five ages at a GBA of 100 ft^2. The same assumptions apply as used in table 18: All trees in the stand are the same size and perform the same in growth. Tree height and rate of height growth are taken from ponderosa pine SI curves (Barrett 1978), and dbh is based on 1.0 in/dec. diameter growth (which assumes periodic thinning to maintain 100 ft^2 BA/A). Growth was calculated using equation (12).

Stand volume growth decreases with age in direct proportion to shape of the SI curve. If volume growth at age 100 is used as an index, the K factor applied to the product of SI and GBA is 0.0087: 80*100*.0087 = 69.6 ft^3/A/yr and 120*100*.0087 = 104.4 ft^3/A/yr. But table 21 assumes all trees grow the same, which is unrealistic. A better constant is required.

Many studies provide data that can be used to calculate a K value. Essential are: dbh by decade or rate of diameter growth and stand BA/A to calculate GBA, SI (or tree age and height by which SI can be determined), and stand volume and/or volume growth by which PAI or MAI can be calculated. Knowing GBA, SI, and MAI or PAI permits calculation of K. In some cases, MAI could not be determined, particularly in thinning studies, because volume or growth prior to treatment was not available. In these cases, PAI was used to calculate K.

Some reports listed only quadratic mean dbh (Dq) diameter growth. Dominant-tree diameter growth is required to calculate GBA. Therefore, equation (9), discussed in Chapter 2 and depicted in figure 25, was used to estimate dominant-tree diameter growth from Dq diameter growth. For example, a study may

Table 21. Calculated stand productivity for ponderosa pine SI 80, 100, 120, and 140 at GBA = 100 ft^2 BA per acre from age 40 to 120. Diameter growth for all calculations is 1.0 in/dec. at 100 ft^2 BA per acre.

	Age (yrs)	40	60	80	100	120	
	TPA	733	374	226	152	108	SI*GBA
	dbh(in.)	5	7	9	11	13	K
SI 80:							
Tree ht. (ft)		38	57	70	80	86	
Ht.growth (ft/yr)		.95	.65	.50	.30	.20	
*PAI (Ft^3/A/yr)		98.38	87.42	80.87	69.14	59.43	.0087
SI 100:							
Tree ht. (ft)		54	74	89	100	109	
Ht growth (ft/yr)		1.00	.75	.55	.40	.30	
*PAI (Ft^3/A/yr)		125.61	113.08	99.40	87.43	76.57	.0087
SI 120:							
Tree ht. (ft)		69	91	107	120	129	
Ht growth (ft/yr)		1.10	.80	.65	.45	.35	
*PAI (Ft^3/A/yr)		153.29	143.15	119.05	103.72	91.12	.0086
SI 140:							
Tree ht. (ft)		83	107	126	140	150	
Ht growth (ft/yr)		1.25	.95	.70	.50	.40	
*PAI (Ft^3/A/yr)		181.42	158.12	137.59	120.00	105.67	.0086

* Periodic annual increment.

show 1.3 in/dec. Dq diameter growth for fir at 230 ft^2 BA/A. Substituting 1.3 in/dec. in equation (9) yields:

$$
\begin{aligned}
\mathbf{d/Dq} &= \mathbf{1.73 - 0.19*1.3} \\
&= \mathbf{1.48}
\end{aligned}
$$

Dominant-tree diameter growth is 1.48 times faster than Dq diameter growth. Dominant-tree diameter growth is:

$$
\begin{aligned}
\mathbf{d\ in/dec.} &= \mathbf{1.48*1.3} \\
&= \mathbf{1.92}
\end{aligned}
$$

Dominant-tree diameter growth is 1.92 in/dec. at 230 ft^2 BA/A. GBA for fir is determined by the CF for 1.92 in/dec. (19/20ths). The conversion factor is 1.64 (table 13, equation (7), or figure 22):

$$
\begin{aligned}
\mathbf{GBA} &= \mathbf{1.64*230} \\
&= \mathbf{377\ ft^2\ BA/A}
\end{aligned}
$$

This value was then used in conjunction with SI and MAI to calculate K. Determination of GBA from published studies and simulation models was discussed in Chapter 2, "GBA Curve Validation."

Ideally, the K factor should represent culmination of mean annual increment (CMAI). However, most reports did not document CMAI. In stands younger than age at culmination, MAI would be less than CMAI, resulting in slightly lower K values. PAI prior to age 80 to 100 is usually higher than MAI or CMAI. Prior to age 60, PAI may estimate CMAI, and might therefore provide an estimate of K. I was not able to develop a correction factor for adjusting MAI or PAI. The variation in K shown in figure 67 represents both differences in site quality and effects of age on PAI and MAI. It is hoped the average adequately estimates a usable K value.

Table 22 lists results from 26 reports on five tree species. The K values averaged 0.0044 with a confidence interval (CI) of = 0.00030 (7%) (p = 0.05) for the 92 observations. Figure 67 shows the frequency distribution. Average K values by species are: Norway spruce @ 0.0065; ponderosa pine @ 0.0042, CI = 0.00043 (10%); western larch @ 0.0050, CI = 0.00094 (19%); Douglas-fir @ 0.0040, CI = 0.00051 (13%); and lodgepole pine @ 0.0045, CI = 0.00095 (21%). Norway spruce, at only three samples, did not have a confidence interval calculated. There was no significant difference between species at p = 0.05.

A constant of 0.0044 is suggested to index stand productivity with the SI*GBA equation when SI is based on age 100. A K factor of 0.0072 may be used when SI is based on age 50.

INDEX is emphasized when using the SI*GBA*K equation for several reasons.

1. Normal yield tables and several simulation models show differences in stand growth between species at similar SI and GBA (Edminster 1978, McArdle et al. 1949, Meyer 1938, Wykoff et al. 1982).

2. Several thinning studies document differences in stand productivity depending upon stand density and thinning treatment. Therefore, stand growth for the same species at the same SI and GBA will differ depending upon stand management (see Chapter 4, "Management Implications").

3. SI and GBA index only three of several stand variables required to calculate stand growth--height growth, diameter growth, and BA/A--which omits both stand height and dbh.

The INDEX (PI) calculated with the SI*GBA*K equation is useful for approximating site potential and for comparing different stands for their relative rates of growth. Advantages of the SI*GBA*K equation are simplicity and apparent application to any species; the disadvantage is lack of precision in indexing stand productivity.

GBA is related to stand growth primarily through its association with SI. It provides a convenient means for indexing different PI levels within an SI class and facilitates identification of these PI levels in the field. The SI-GBA concept will be strengthened considerably after studies designed to evaluate the relationship are completed. Some indication of the magnitude of variation in SI-GBA is presented in the next section.

SI-GBA Productivity Levels

The SI-GBA system of characterizing forest sites has been extensively applied on National Forest lands in Oregon and Washington by the Region 6 ecological program. Plant communities are classified into associations according to their potential natural species dominance, productivity, management characteristics, and ease of identification in the field under disturbed conditions. Some of these plant associations were selected to illustrate the SI-GBA concept.

Productivity does vary within an SI class, sometimes by as much as five times. Differences in SI, GBA, and PI among species within a plant association indicate their suitability for a site. SI characteristics imply a species' ability to become dominant in height, GBA characteristics imply a species' ability to become dominant in BA/A and its response to thinning, and PI is an intergrating index useful for ranking various species' general suitability for a site.

Table 22. Sources of the factors for the equation: SI*GBA*K = ft^3 per acre per year. See figures 26 to 36 and appendix 4 for derivation of GBA K values.

Publication (species)	Treatment	SI (age 100(ft)	GBA (ft^2/A)	MAI (ft^3/A/yr)	PIA (ft^3/A/yr)	K
Assman 1970 (spruce)	#49	127	330	257		.0061
	#51a	108	237	167		.0065
	#51b	93	194	127		.0070
Barrett 1981 (P.pine)		80	169		55	.0040
Barrett 1982 (P.pine)	Vegetation	120	225		46	.0017
	No Vegetation	130	333		60	.0014
Barrett 1972 (P.pine)	8.8 ft	78	196		89	.0058
	12.2 ft	78	185		73	.0051
	12.5 ft	78	173		75	.0056
	17.6 ft	78	224		74	.0042
Oliver 1972 (P.pine)	53 ft^2	80	209		48	.0029
	50 ft^2	70	189		46	.0036
	75 ft^2	65	180		48	.0041
	131 ft^2	65	189		75	.0061
	148 ft^2	65	189		77	.0063
	193 ft^2	65	176		75	.0065
Alexander and Edminster 1980 (P.pine)	(SI)	50	177	40		.0045
		60	182	51		.0047
		70	207	64		.0043
		80	215	77		.0045
		90	237	90		.0042
Ronco et al. 1985 (P.pine)		73	180		69	.0052
Edminster 1978 (P.pine) RMYLD		70	154	55		.0051
Wykoff et al. 1982 (P.pine)	(SI)	98	181	60		.0034
PROGNOSIS 15		128	230	77		.0026
		78	120	48		.0051
		79	100	36		.0046
PROGNOSIS 25		78	220	66		.0038
		81	110	22		.0025
Meyer 1983 (P.pine)	(SI)	40	141	30		.0053
Normal Yield		80	198	68		.0043
		120	258	141		.0046
		160	318	234		.0046
					Mean =	.0042
					N =	30
					Sx =	.00021
					p=.05 CI =	.00043

Table 22. (Cont.)

Publication (species)	Treatment	SI (age 100(ft)	GBA (ft^2/A)	MAI (ft^3/A/yr)	PIA (ft^3/A/yr)	K
Cole 1984 (W. larch)	D + 4	84	87		58	.0079
	CROWN	84	128		62	.0057
	Control	84	157		69	.0052
Seidel 1982 (W. larch)	5M ft^2	123	198		78	.0032
	10M ft^2	123	180		113	.0051
	15M ft^2	123	186		121	.0053
	20M ft^2	123	218		134	.0050
	25M ft^2	123	175		157	.0073
Seidel 1980 (W. larch)	65 ft^2	127	144		73	.0040
	100 ft^2	127	106		85	.0063
	150 ft^2	127	159		72	.0036
	200 ft^2	127	249		93	.0029
					Mean =	.0050
					N =	12
					Sx =	.00043
					p=.05 CI =	.00094
Dahms 1971a (L.P.pine)	16M ft^2	112	132		35	.0024
	21M ft^2	112	153		40	.0024
	26M ft^2	112	106		44	.0037
Dahms 1971b (L.P.pine)	Control	88	84		33	.0045
	16 ft	88	61		26	.0048
	12 ft	88	81		40	.0056
Dahms 1973b (L.P.pine)	16M ft^2	80	85		40	.0058
	25M ft^2	80	108		68	.0078
	26M ft^2	80	84		51	.0076
Cole and Edminster		50	142		25	.0035
1985 (L.P.pine)		80	259		70	.0034
	North	80	101		71	.0088
	South	80	167		105	.0079
Edminster 1978 (LP pine) RMYLD	GSL120	70	169		68	.0069
Dahms 1983 (L.P.pine) LPSIM		90	207		36	.0019
Long and McCarter 1985 SDI Density Mgt.	(SI)	40	63		12	.0048
		60	112		34	.0051
		80	193		69	.0045
		100	400		100	.0025
					Mean =	.0045
					N =	19
					Sx =	.0045
					p=.05 CI =	.00095

Table 22. (Cont.)

Publication (species)	Treatment	SI (age 100(ft)	GBA (ft^2/A)	MAI (ft^3/A/yr)	PIA (ft^3/A/yr)	K
Reukema and Pienaar 1973 (D.fir)	Control	208	461		285	.0030
	Thinned	195	502		245	.0025
Reukema 1979 (D.fir)	4 ft	82	198	87		.0053
	5 ft	77	178	80		.0058
	6 ft	86	171	87		.0059
	8 ft	97	199	83		.0043
	10 ft	119	270	139		.0043
	12 ft	119	227	120		.0044
Berg and Bell 1979 (D.fir)	170 ft^2	145	578		437	.0052
	160 ft^2	145	534		378	.0049
	260 ft^2	145	430		418	.0067
Harringtin and Reukema 1983 (D.fir)		100	145		106	.0073
Curtis et al. 1981 (D.fir) DFSIM	(SI)	94	427	104		.0026
		113	324	105		.0028
		125	467	140		.0024
		137	462	153		.0025
		196	644	257		.0021
		196	591	281		.0024
Drew and Flewelling 1979: density mgt. (D.fir)	300 TPA	98	221	93		.0043
	300 TPA	142	373	223		.0042
	300 TPA	187	575	339		.0032
	500 TPA-thin	98	221	102		.0047
	500 TPA-thin	142	411	231		.0040
	500 TPA-thin	187	778	391		.0027
McArdle et al. 1949 Normal Yield	(SI)	85	202	58		.0034
		110	245	98		.0036
		140	283	142		.0036
		170	301	181		.0035
		200	312	208		.0033
					Mean =	.0040
					N =	29
					Sx =	.00025
					p=.05 CI =	.00051
			All Samples:		Mean =	.0044
					N =	92
					Sx =	.00015
					p=.05 CI =	.00030

Ponderosa pine is a good example of a species with different PI levels within an SI class, possibly because of its great ecological amplitude. This amplitude varies from climax status in the savanna transition from nonforest to seral status on white fir climax sites. On dry sites ponderosa pine cannot approach a closed crown canopy, while on moist sites it may reach 125% canopy cover. Table 23 lists

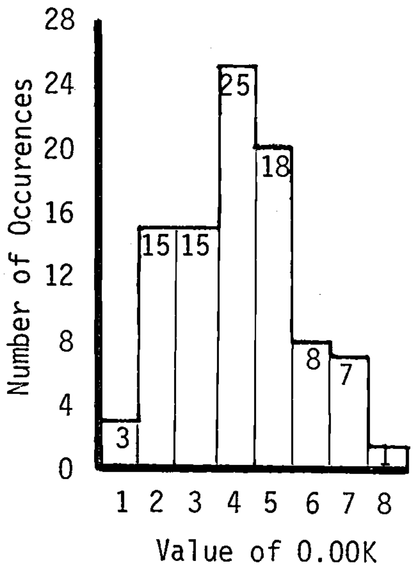


Figure 67. Frequency distribution of K factors used in the equation SI*GBA*K = ft^3/A/yr (table 22 data).

selected ponderosa pine associations with their SI, GBA, and PI. The PI is not the same as published in the cited references because it was calculated here with a K factor of 0.0044 instead of 0.005 as used in the references.

Ponderosa pine SI class 60 ranges in PI from 7 to 19 ft^3/A/yr--from 17% to 40% of the normal 46 ft^3. SI class 70 has several PI levels ranging from 17 to 47 ft^3 (31% to 80% of normal), while SI class 80 has three PI levels ranging from 15 to 42 ft^3/A/yr (20% to 55% normal). Note that GBA classes 45-55 ft^2 and 65-75 ft^2 BA/A occur in SI classes 60, 70, and 80. Tables 24, 25, and 26 further demonstrate multiple PI levels within an SI class.

Management Interpretations

Williams and Lillybridge (1983) provide data on both ponderosa pine and Douglas-fir in three of their associations (table 23). SI's are within 4 feet of each other in each association (average 69), but GBA's and PI's vary considerably. In PIPO-PSME/AGIN, ponderosa pine is about 25% more productive than Douglas-fir, while in PSME/VACCI Douglas-fir is 33% more productive than ponderosa pine.

These differences may be interpreted as follows: (1) Favor ponderosa pine in PIPO-PSME/AGIN, Douglas-fir in PSME/VACCI, and both in PSME/ARUV-PUTR for regeneration and precommercial thinning to help produce maximum fiber. (2) When thinning, ponderosa pine will grow about 33% faster in diameter than Douglas-fir in PIPO-PSME/AGIN, while Douglas-fir will grow about 20% faster than ponderosa in PSME/VACCI. (3) Neither species will tend to become dominant in height over the other on any of these sites.

Recall figure 65, which depicted lodgepole pine SI-GBA for 39 plant associations in Oregon and Washington. Eight of these associations are shown in table 24, representing SI classes 47, 60, and 75 feet at base age 100. Normally, lodgepole pine SI is based on age 50. However, to facilitate comparison with other tables, SI was adjusted to age 100 according to curves by Alexander (1966). SI 75-80 has PI's of 30, 60, and 65 ft^3/A/yr. Dahms (1966) documented productivities of 87 and 137 ft^3 in Oregon

Table 23. Ponderosa pine plant associations listing SI, GBA, and the productivity index (PI)*.

Association	SI (ft)	GBA (ft^2/A)	PI (ft^3/A/yr)
PIPO/AGSP[1]	57	29	7
PIPO/FEID[1]	61	55	15
PIPO/PUTR/CARO[1]	64	69	19
PIPO/PUTR/BUNCH[4]	72	55	17
PIPO/PUTR-ARPA/FEID[4]	71	80	25
Conifer/CARU[1]	72	109	35
PIPO-PSME/PHMA[1]	72	129	41
PIPO-PSME/SYAL[1]	72	149	47
PIPO-PSME/AGIN[3]			
PIPO	68	97	28
PSME	65	71	21
PSME/ARUV-PUTR[3]			
PIPO	70	98	30
PSME	66	85	25
PSME/VACCI[3]			
PIPO	70	119	37
PSME	73	144	46
PIPO/PUTR-ARPA/ SEDGE[4]	82	42	15
PIPO/PUTR/STOC[4]	80	70	25
PIPO/WYMO[2]	78	100	34
PIPO-POTR/POPR[2]	78	124	42

* The K factor used with SI(GBA) is 0.0044 (not 0.005 as used in cited references).

[1] Hall 1973, [2]Hopkins 1979, [3]Williams and Lilybridge 1983, [4]Volland 1985.

See Table 26 for plant code names.

and 104 and 64 ft^3 in Rocky Mountain and central Oregon lodgepole SI 80 stands, respectively (Dahms 1973a). Apparently, SI 75-80 for lodgepole pine can range from 30 to 137 ft^3/A/yr, nearly a fivefold difference.

This range in productivity for an SI class has not been reported in the literature. Is it possible? Consider measurements for SI class 45-50, showing a fourfold difference in PI (table 24). Dominant trees of the PICO/ARNE type were measured at 0.4 to 1.2 in/dec. diameter growth at 46 ft^2 to 88 ft^2 BA/A (Volland 1985), while for ABLA/VASC they were measured at 0.4 to 1.2 in/dec. at 122 ft^2 to 313 ft^3 BA/A (Williams and Lillybridge 1983). GBA's were 46 ft^2 and 173 ft^2 BA/A and PI's were 9 ft^3 and 37 ft^3/A/yr. The critical question is: "What silvicultural treatment can be prescribed to increase both rate of diameter growth and BA/A on PICO/ARNE to equal that on ABLA/VASC?" There is no such treatment because the two sites, while equal in SI, are not equal in stockability.

Table 25 lists white and grand fir SI-GBA data and compares them to ponderosa pine in four associations. As usual, each SI class has several PI levels. For example, SI class 85 has four levels ranging from 50 to 96 ft^3/A/yr.

Table 24. Lodgepole pine plant associations listing SI[*], GBA, and the productivity index (PI)[**].

Association	SI (ft)	GBA (ft^2/A)	PI (ft^3/A/yr)
PICO/ARNE[4]	45	46	9
PICO/VAME[1]	48	104	22
ABLA/VASC[3]	48	173	37
PICO/STOC-CAPE[2]	60	79	21
PICO/CARU-VASC[1]	62	118	32
PICO/ARUV[4]	72	94	30
PICO/CAPE-LUP-PEEU[4]	80	170	60
ABLA/CARU[3]	74	201	65

[*] SI at age 100 (not 50) to facilitate comparison with other tables.
[**] The K factor used with SI*GBA is 0.0044 (not 0.005 as used in cited references).
[1] Hall 1973, [2]Hopkins 1979, [3]Williams and Lillybridge 1983, [4]Volland 1985.
See Table 26 for plant code names.

But these associations were selected to document differences between species in the same association. ABCO-PIPO-PILA/CAPE shows SI 94 and GBA 241 for white fir, compared with SI 79 and GBA 104 for ponderosa pine. Ponderosa is 80% of white fir SI and only 43% of fir GBA. White fir will outgrow ponderosa pine in both height and diameter meaning it will become dominant over ponderosa pine (a shade intolerant species) and will clearly dominate larger diameter classes under stand management. Fiber production with white fir would apparently be about three times greater than with pine.

Table 26 lists SI and GBA data for six high-elevation, Cascade Range, silver fir zone plant associations. Differences in PI within an SI class are shown and differences between species in the same association are apparent.

Summary

GBA, the basal area at which dominant trees grow at the rate of 1.0 in/dec. in diameter, is a means for

Table 25. White and grand fir plant associations listing SI[*], GBA, and the PI[**].

Association	SI (ft)	GBA (ft^2/A)	PI (ft^3/A/yr)
CONIFER/SYAL/CARU[1]			
ABGR	87	170	65
PIPO	85	133	50
ABGR/VAME[1]			
ABGR	83	177	65
ABGR/LIBO-FORB[1]			
ABGR	85	231	86
ABCO-PIPO-LIDE/AMAL[2]			
ABCO	82	265	96
PIPO	80	126	44
ABCO-PIPO-PILA/CAPE[2]			
ABCO	94	241	100
PIPO	79	104	36
CONIFER/SYAL-FORB[3]			
ABCO	120	260	137
PIPO	99	217	94

[*] SI at age 100 for both species to facilitate comparison.
[**] The K factor used with SI*GBA is 0.0044 (not 0.0005 in cited references).
[1] Hall 1973, [2]Hopkins 1979, [3]Volland 1985.

identifying site potential for stockability. It also provides a basis for prescribing stocking levels to attain desired timber products. When combined with SI, it is a means for characterizing different productivity levels within an SI class and for identifying these productivity potentials in the field.

Table 26. Silver fir zone plant associations listing SI*, GBA, and the PI**, (Hemstrom et al. 1982).

Association		SI (ft)	GBA (ft^2/A)	PI ($ft^3/A/yr$)
ABAM/MEFE				
	PMSE	73	282	91
ABAM/VAAL-GASH				
	PMSE	73	420	135
ABAM/RHMA/XETE				
	PMSE	96	341	144
	ABPR	96	501	212
ABAM-TSHE/RHMA/GASH				
	PMSE	101	276	123
ABAM/VAAL/COCA				
	PSME	102	394	177
	ABPR	110	407	197
ABAM/OPHO				
	PMSE	123	375	203
	ABPR	135	500	297

* SI at age 100 (not 50) to facilitate comparison.
** The K factor used with SI*GBA is 0.0044 (not 0.005 used in cited references).

Table 27. Plant acronym codes with their species.

ABAM	Abies amabilis
ABCO	A. concolor
ABGR	A. grandis
ABLA	A. lasiocarpa
ABPR	A. procera
AGIN	Agropyron inerme
AGSP	A. spicatum
AMAL	Amelanchier alnifolia
ARNE	Arctostaphylos nevadensis
ARPA	A. patula
ARUV	A. uva-ursi
BUNCH	Bunchgrasses (Agropyron, Festuca)
CAPE	Carex pennsylvanica
CARO	C. rosii
CARU	Calamagrostis rubescens
COCA	Cornus canadensis
Conifer	Abies, Pseudotsuga, Pinus
FEID	Festuca idahoensis
Forb	Variety of forbs
GASH	Gautheria shallon
LIBO	Linnaea borealis
LIDE	Libocedrus decurrens
LUP	Lupinus species
MEFE	Menziesia ferruginea
OPHO	Oplopanax horridus
PEEU	Penstemon euglaucus
PHMA	Physocarpus malvaceus
PICO	Pinus contorta
PILA	P. lambertiana
PIPO	P. ponderosa
POPR	Poa pratensis
POTR	Populus trichocarpa
PSME	Pseudotsuga menziesii
PUTR	Purshia tridentata
RHMA	Rhododendron macrophyllum
Sedge	Cares species (dryland)
STOC	Stipa occidentalis
SYAL	Symphoricarpos alba
TSHE	Tsuga heterophylla
VAAL	Vaccinium alaskense
VACCI	Vaccinium species
VAME	V. membranaceum
VASC	V. scoparium
WYMO	Wyethia mollis
XETE	Xerophyllum tenax

Literature Cited

Agee, J.K. and H.H. Biswell. 1970. Some effects of thinning and fertilization on ponderosa pine and understory vegetation. Jour. For. 68(11):709-711.

Alemdag, I.S. 1978. Evaluation of some competition indexes for the prediction of diameter increments in planted white spruce. Canadian For. Serv., Dept. of Environment, For. Mgt. Inst., Information Report FMR-Y-108, Ottawa, Ontario. 39pp.

Alexander, R.R. 1966. Site indexes for lodgepole pine, with corrections for stand density: instructions for field use. USDA, For. Serv., Rocky Mtn. For. and Range Exp. Stn., Res. Pap. RM-24. 7pp.

Alexander, R.R. and C.B. Edminster. 1980. Management of ponderosa pine in even-aged stands in the Southwest. USDA, For. Serv., Rocky Mtn. For. and Range Exp. Stn., Res. Paper RM-225. 11pp, illus.

Alexander, R.R., D. Tackle, W.G. Dahms. 1967. Site indexes for lodgepole pine, with corrections for stand density: methodology. USDA, For. Serv., Rocky Mtn. For. and Range Exp. Stn., Res. Pap. RM-29. 18pp, illus.

Anman, G.D. and L. Safranyik. 1985. Insects of lodgepole pine: impacts and control. **In:** Lodgepole Pine. The Species and Its Management (Symposium Proceedings). Wash. State Univ., Cooperative Extension, Pullman. pp107-124.

Assmann, E. 1970. The principles of forest yield study. Studies in the organic production, structure, increment and yield of forest stands. Pergamon Press, New York. 506pp, illus.

Avery, C.C., F.R. Larson, and G.H. Schubert. 1976. Fifty-year records of virgin stand development in southwestern ponderosa pine. USDA, For. Serv., Rocky Mt. For. and Range Exp. Stn., Gen. Tech. Rep. RM-22. 71pp.

Barclay, H., H. Brix, and C.R. Layton. 1982. Fertilization and thinning effects on a Douglas-fir ecosystem at Shannigan Lake. 9-year growth response. Environment Canada, Can. For. Serv., Pacific For. Res. Cent. Pub. BC-X 238, Victoria, B.C. 35pp, illus.

Barrett, J.W. 1968. Pruning of ponderosa pine--effect on growth. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-68. 9pp, illus.

Barrett, J.W. 1969. Crop-tree thinning of ponderosa pine in the Pacific Northwest. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Note PNW-100. 13pp, illus.

Barrett, J.W. 1972. Large-crowned planted ponderosa pine respond well to thinning. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn. Res. Note PNW-179. 12pp, illus.

Barrett, J.W. 1978. Height growth and site index curves for managed, even-aged stands of ponderosa pine in the Pacific Northwest. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-232. 13pp, illus.

Barrett, J.W. 1979. Silviculture of ponderosa pine in the Pacific Northwest: the status of our knowledge. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Gen. Tech. Rep. PNW-97. 106pp, illus.

Barrett, J.W. 1981. Twenty-year growth of thinned and unthinned ponderosa pine in the Methow Valley of northern Washington. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-286. 13pp, illus.

Barrett, J.W. 1982. Twenty-year growth of ponderosa pine saplings thinned to five spacings in central Oregon. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-330, 15pp, illus.

Bates, C.G. 1918. Concerning Site. Jour. For. 16:383-388.

Berg, A. B. and J.F. Bell. 1979. Levels-of-growing stock cooperative study on Douglas-fir. Report No. 5--The Huskins Study 1963-1975. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-257. 29pp, illus.

Bradley, R.T., J.M. Christie, and D.R. Johnston, 1966. Forest management tables, (Brit.) Forest. Comm. Booklet 16. London. 212pp.

Brendt, H.W. and R.D. Gibbons. 1958. Root distribution of some native trees and understory plants growing on three sites within ponderosa pine watersheds in Colorado. USDA, For. Serv., Rocky Mtn. For. and Range Exp. Stn., Res. Pap. RM-37. 14pp, illus.

Buckman, R.E. 1962. Three-growting stock density experiments in Minnesota red pine. A progress report. USDA, For. Serv., Lake States For. Exp. Stn., Paper No. 99. 10pp, illus.

Carlson, C.E. and E.E. McCaughey. 1982. Indexing western spruce budworm activitiy through radial increment analysis. USDA, For. Serv., Intermountain For. and Range Exp. Stn., Res. Pap. INT-291. 10pp, illus.

Carmean, W.H. 1975. Forest site quality evaluation in the United States. Advances in Agronomy 27:209-269.

Childs, T.W. and J.W. Edgren. 1967. Dwarfmistletoe effects on pondersoa pine in southern Idaho. USDA, For. Serv., Intermountain For. and Range Exp. Stn., Res. Note INT-46.

Cochran, P.H. 1979a. Gross yields for even-aged stands of Douglas-fir and white or grand fir east of the Cascades in Oregon and Washington. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-263. 17pp, illus.

Cochran, P.H. 1979b. Response of thinned lodgepole pine after fertilization. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Note PNW-335. 6pp.

Cochran, P.H. 1979c. Site index and height growth curves for managed, even-aged stands of Douglas-fir east of the Cascades in Oregon and Washington. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-251. 16pp, illus.

Cole, D.M. 1984. Crop-tree thinning a 50-year-old western larch stand: 25-year results. USDA, For. Serv., Intermtn. For. and Range Exp. Stn., Res Pap. INT-328. 9pp.

Cole, D.M. and C.B. Edminster. 1985. Growth and yield of lodgepole pine. **In**: Lodgepole Pine: The Species and Its Management (Symposium Proceedings), Wash. State Univ., Cooperative Extension, Pullman. pp263-290.

Cole, D.M. and A.R. Stage. 1972. Estimating future diameters of lodgepole pine trees. USDA, For. Serv., Intermtn. For. and Range Exp. Stn., Res. Pap. INT-131. 20pp.

Curtis, J.D. 1964. Roots of a ponderosa pine. USDA, For. Serv., Intermtn. For. and Range Exp. Stn., Res. Pap. INT-9. 10pp, illus.

Curtis, R.O. 1970. Stand density measures: an interpretation. For. Sci. 16:403-414.

Curtis, R.O. 1981. Yield tables past and present. in: Forestry Predictive Models: Problems in Application, Wash. State Univ., Cooperative Extension, Pullman. pp1-8.

Curtis, R.O. and D.L. Reukema 1970. Crown development and site estimates in a Douglas-fir plantation spacing test. For. Sci. 16:287-301.

Curtis, R.O., G.W. Clendenen, and D.J. DeMars. 1981. A new stand simulator for coast Douglas-fir: DFSIM user's guide. USDA, For. Serv., Pac. N.W. For. and Range. Exp. Stn., Gen. Tech. Rep. PNW-128. 79pp, illus.

Curtis, R.O., G.W. Clendenen, D.L. Reukema, and D.J. Demars. 1982. Yield tables for managed stands of coast Douglas-fir. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Gen. Tech. Report PNW-135. 182pp.

Curtis, R.O. and D.D. Marshall, 1986. Levels-of-growing-stock cooperative study in Douglas-fir: Report No. 8 -- the LOGS study: twenty year results. USDA, For. Serv., Pac. N.W. Res. Stn., Res Pap. PNW-356. 113pp, illus.

Dahms, W.G. 1966. Relationship of lodgepole pine volume increment to crown competition factor, basal area, and site index. For. Sci. 12:74-82.

Dahms, W.G. 1971a. Growth and soil moisture in thinned lodgepole pine. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-127. 32pp, illus.

Dahms, W.G. 1971b. Fifty-year-old lodgepole pine responds to thinning. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Note PNW-141. 13pp.

Dahms, W.G. 1973a. Gross yield of central Oregon lodgepole pine. **In**: Management of Lodgepole Pine Ecosystems, Symposium Proceedings, Washington State Univ., Pullman. pp208-232.

Dahms, W.G. 1973b. Tree growth and water use response to thinning in a 47-year-old lodgepole pine stand. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Note PNW-194, 14pp.

Dahms, W.G. 1983. Growth-simulation model for lodgepole pine in central Oregon. USDA, For. Serv., Pac. N.W. For. and Range. Exp. Stn., Res. Pap. PNW-302, 22pp, illus.

Deitschman, G.H. and A.W. Green. 1965. Relations between western white pine site index and tree height of several associated species. USDA, For. Serv., Intermountain For. and Range Exp. Stn., Res. Pap. INT-22. 28pp, illus.

Drew, T.J. and J.W. Flewelling 1979. Stand density management: an alternative approach and its application to Douglas-fir plantations. For. Sci. 25:518-532.

Edminster, C.B. 1978. RMYLD:Computation of yield tables for even-aged and two-storied stands. USDA, For. Serv., Rocky Mtn. For. and Range Exp. Stn., Res. Paper RM-199, 26pp, illus.

Eis, S. 1970. Natural root grafts in conifers and the effect of grafting on tree growth. **In**: Tree Ring Analysis With Special Reference to Northwest America. Univ. British Columbia, Faculty of Forestry, Bull. No. 7, Vancouver, B.C., Canada. pp25-29.

Ek, A.R. and R.A. Monserud 1981. Methodology for modeling forest stand dynamics. **In**: Forestry Predictive Models: Problems in Application. Wash. State Univ., Cooperative Extension, Pullman. pp19-31.

Ernst, R.L. and W.H. Knapp. 1985. Forest stand density and stocking: concepts and the use of stocking guides. USDA, For. Serv., Gen. Tech. Rep. WO-44. 8pp, illus.

Fellin, D.G., W.C. Schmidt, and C.E. Carlson. 1984. The western spruce budworm in the northern Rocky Mountains--ecological relations and silvicultural strategies. **In**: Silvicultural and Management Strategies for Pests of the Interior Douglas-fir and Grand Fir Forest Types. Wash. State Univ., Cooperative Extension, Pullman. pp81-94.

Filip, G.M., P.E. Aho, and M.R. Wiitala. 1984. Strategies for reduction of decay in the interior Douglas-fir and Grand Fir Forest Types. **In**: Silvicultural and Management Strategies for Pests of the Interior Douglas-fir and Grand Fir Forest Types. Wash. State Univ., Cooperative Extension, Pullman. pp73-80.

Ford-Robertson, F.C. 1971. Terminology of forest science, technology, practice and products. English-Language Version, Soc. of Amer. For., Multilingual Forestry Terminology Series No. 1, Washington, D.C. 349pp, illus.

Franz, F. 1967. Verfahren zur herleitung von ertragshiveau-schatzwerten fur die fichte aus einmalig erhobenen bestandesgrossen. (Methods for deviation of production class estimates for spruce from single measurements of stand values). IUFRO, XIV Congress, Munich, Sec. 25, VI:287:303.

Freese, F. 1967. Elementary statistical methods for foresters. USDA, Agric. Hndbk. 317, 87pp.

Frothingham, E.H. 1918. Height growth as a key to site. Jour. For. 16:754-760.

Gordon, D.T. 1962. Growth response of eastside pine poles to removal of low vegetation. USDA, For. Serv., Pac. S.W. For. and Range Exp. Stn., Res. Note 209.

Graham, J.N., J.F. Bell, and F.R. Herman 1985. Response of Sitka spruce and western hemlock to commercial thinning. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Paper PNW-334. 17pp. illus.

Hagglund, Bjorn. 1981. Evaluation of forest site productivity. Forestry Abstracts 42(11):515-527.

Hall, F.C. 1971. Some uses and limitations of mathematical analysis in plant ecology and land management. **In**: Statisical Ecology, Vol. 3, Many Species Populations, Ecosystems, and Systems Analysis. pp 377-395. Penn. State Univ. Press, University Park.

Hall, F.C. 1973. Plant Communities of the Blue Mountains in eastern Oregon and southeastern Washington. USDA, For. Serv., Pac. N.W. Region, R-6 Area Guide 3-1. Portland, OR. 62pp, illus.

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

Hall, F.C. 1985. Stockability and management of lodgepole pine using growth basal area. **In**: Lodgepole Pine. The Species and Its Management (Symposium Proceedings), Wash. State Univ., Cooperative Extension, Pullman. pp243-250.

Harrington, C.A. and R.E. Miller, 1979. Response of a 110-year-old Douglas-fir stand to urea and ammonium nitrate fertilization. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Note PNW-336. 7pp.

Harrington, C.A. and D.L. Reukema. 1983. Initial shock and long-term stand development following thinning in a Douglas-fir plantation. For. Sci. 29:33-46.

Hemstrom, M.A., W.E. Emmingham, N.M. Halverson, S.E. Logan, and C. Topik. 1982. Plant association and management guide for the Pacific Silver Fir Zone, Mt. Hood and Willamette National Forests. USDA, For. Serv., Pac. N.W. Region, R-6 Ecol 100-1982a. Portland, OR. 104pp, illus.

Heninger, R.L. 1981. Response of **Abies concolor** to intensive management. **In**: Proceedings of the Biology and Management of True Fir in the Pacific Northwest (Symposium Proceedings). Univ. Wash., Coll. Forest Resources, Institute of Forest Resources Contribution No. 45., Seattle. pp 319-323.

Hilt, D.E., F.R. Herman, and J.F. Bell, 1977. A test of commercial thinning on the Hemlock Experimental Forest: USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Paper PNW-225. 11pp.

Hopkins, W.E. 1979. Plant associations of the Fremont National Forest. USDA, For. Serv., Pac. N.W. Region, R-6 Ecol. 79-004. Portland, OR. 106pp, illus.

Hopkins, W.E. 1986. A comparison of the growth basal area stocking level curve to a number of curves developed from south-central Oregon tree data. Can. Jour. For. Res. 16:508-512.

Johnsey, R. 1984. Bark beetles of interior Douglas-fir - Grand Fir Forest Type. **In**: Silvicultural and Management Strategies for Pests of the Interior Douglas-fir and Grand Fir Forest Types. Wash. State Univ., Cooperative Extension, Pullman. pp103-107.

Johnson, P.C. 1967. Distribution of bark beetle attacks on ponderosa pine trees in Montana. USDA, For. Serv., Intermtn. For. and Range Exp. Stn., Res. Note INT-62.

Kozlowski, T.T. 1971. Growth and development of trees. Vols. I & II. Academic Press, New York.

Long, J.N. 1985. A practical approach to density management. For. Chron., Feb. 1985. pp23-27.

Long, J.N. and J.B. McCarter. 1985. Density management diagrams: a practical approach. **In**: Proceedings - Growth and Yield and Other Mensurational Tricks: A Regional Technical Conference. USDA, For. Serv., Intermtn. For. and Range Exp. Stn., Gen. Tech. Rep INT-193. pp25-29.

Lynch, D.W. 1958. Effects of stocking on site measurement and yield of second-growth ponderosa pine in the Inland Empire. USDA For. Serv., Intermtn. For. and Range Exp. Stn., Res. Pap. 56. 36pp, illus.

MacLean, C.D. and C.L. Bolsinger. 1973. Estimating productivity on sites with a low stocking capacity. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-152. 18pp, illus.

McArdle, R.E., W.H. Meyer, and D. Bruce. 1949. The yield of Douglas-fir in the Pacific Northwest. USDA, Tech. Bull. No. 201, Washington, D.C. 74pp, illus.

McCarter, J.B. and J.N. Long 1983. Density management diagram for lodgepole pine. College Nat. Resources, Utah State Univ., Logan. 2pp.

McKay, N. 1985. A stockability equation for forest land in Siskiyou County, California. USDA, For. Serv., Pacific N.W. For. and Range Exp. Stn, Res. Note PNW-435. 6pp.

Meyer, W.H. 1938. Yield of even-aged stands of ponderosa pine. U.S. Dept. Agric., Tech. Bull. 630, 59 p. rev. 1961.

Monserud, R.A. 1984. Problems with site index: an opinionated review. **In**: Proceedings of the Symposium Forest Land classification: Experience, Problems, Perspectives. J.A. Backheim, Ed. Univ. Wis., Wis. Center, Madison. pp167-180, illus.

Oliver, W.W. 1972. Growth after thinning ponderosa pine stands in northwestern California. USDA, For. Serv., Pac. S.W. For. and Range Exp. Stn., Res. Pap. PSW-85. 8pp, illus.

Page, G. 1970. Silviculture. Minister, Dept. Fisheries and Forestry, Bimonthly Research Notes 26(1): 6-7, Ottawa, Canada.

Perry, D. A. 1985. The competition process in forest stands. in: Attributes of trees as crop plants, M. G. R. Cannel and J. E. Jackson, eds. Inst. Terrestrial Ecol., Abbots Ripten, Hunts, England. pp 481-505.

Reynolds, E.R.C. 1970. Root distribution and the cause of its spacial variability in **Pseudotsuga taxifolia** (Poir) Britt. Plant and Soil 32:501-517.

Reukema, D.L. 1979. Fifty-year development of Douglas-fir stands planted at various spacings. USDA, For. Serv., Pac. N.W. For. and Range. Exp. Stn., Res. Pap. PNW-253. 21pp, illus.

Reukema, D.L. and D. Bruce. 1977. Effects of thinning on yields of Douglas-fir. Concepts and some estimates obtained from simulation. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Gen. Tech. Rep. PNW-58. 36pp, illus.

Reukema, D.L. and L.V. Pienaar. 1973. Yield with and without repeated commercial thinnings in a high-site-quality Douglas-fir stand. USDA, For. Serv., Pac. N.W. For. and Range. Exp. Stn., Res. Pap. PNW-155. 15pp.

Ronco, Frank, Jr., C.B. Edminster, and D.P. Trujilla. 1985. Growth of ponderosa pine thinned to different stocking levels in northern Arizona. USDA, For. Serv., Rocky Mtn. For. and Range Exp. Stn., Res. Pap. RM-262. 15pp, illus.

Roth, F. 1916. Concerning site. For. Quart. 15:3-13.

Roth, F. 1918. Another word on site. Jour. For. 16:749-753.

Roth, L.F. and J.W. Barrett. 1985. Response of dwarf mistletoe-infected ponderosa pine to thinning: 2. Dwarf mistletoe propagation. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Paper PNW-331. 20pp, illus.

Sartwell, C. 1971. Thinning ponderosa pine to prevent outbreaks of mountain pine beetle. In: Precommercial Thinning of Coastal and Intermountain Forests in the Pacific Northwest. Wash. State Univ., Coop. Extension Serv., Pullman. pp 41-52.

Sassaman, R.W., J.W. Barrett, and A.D. Twombly. 1977. Financial precommercial thinning guides for northwest ponderosa pine. USDA, For. Serv., Pac. N.W. For. and Range. Exp. Stn., Res. Pap. PNW-226. 27pp, illus.

Schmidt, W.C. 1978. Some biological and physical responses to forest stand density. 8th World Forestry Congress, FQL/25-2, Jakarta, Indonesia. 12pp, illus.

Seidel, K.W. 1980. Growth of western larch after thinning from above and below to several density levels: 10-year results. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Note PNW-366. 20pp, illus.

Seidel, K.W. 1982. Growth and yield of western larch; 15-year results of a levels-of-growing-stock study. USDA, For. Serv., Pac. N.W. For. and Range. Exp. Stn., Res. Note PNW-398. 14pp, illus.

Seidel, K.W. 1984. A western larch-Engelmann spruce spacing study in eastern Oregon: results after 10 years. USDA, For Serv., Pac. N.W. For. and Range. Exp. Stn., Res. Note PNW-409. 6pp, illus.

Seidel, K.W. and P.H. Cochran. 1981. Silviculture of mixed conifer forests in eastern Oregon and Washington. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Gen. Tech. Rep. PNW-121. 70pp, illus.

Shea, K.R. 1964. Diameter increment of ponderosa pine infected with dwarf mistletoe in south central Oregon. Jour. For. 62(10):743-748.

Smith, J.H.G. 1964. Rootspread can be estimated from crown width of Douglas-fir, lodgepole pine and other British Columbia tree species. For. Chron. 40:456-473.

Smith, S.H. and J.F. Bell. 1983. Using competitive stress index to estimate diameter growth for thinned Douglas-fir stands: For. Sci. 29:491-499.

Society of American Foresters. 1923. Classification of forest sites. Jour. For. 21:139-147.

Stage, A.R. 1959. Site index curves for grand fir in the Inland Empire. USDA, For. Serv., Intermtn. For. and Range Exp. Stn., Res. Note No. 71. 4pp, illus.

Tappeiner, J.C., J.F. Bell, and J.D. Brodie. 1982. Response of young Douglas-fir to 16 years of intensive thinning. Ore. State Univ., Sch. For., For. Res. Lab, Res. Bull 38, Corvallis. 17pp, illus.

Van der Kamp, B.J. and F.G. Hawksworth. 1985. Damage and control of the major diseases of lodgepole pine. **In**: Lodgepole Pine: The Species and Its Management (Symposium Proceedings), Wash. State Univ., Cooperative Extension, Pullman. pp 125-131.

Van Sickle, F.G. 1959. The effect of understory competition on the growth rate of ponderosa pine in north central Oregon. Jour. For. 57:852-853.

Volland, L.A. 1985. Plant associations of the central Oregon pumice zone. USDA, For. Serv., Pac. N.W. Region, R-6 Ecol 104-1985. Portland, OR. 138pp, illus.

Waring, R.H. and W.H. Schlesinger. 1985. Forest ecosystems: Concepts and management. Academic Press, Orlando, FL 340pp, illus.

Watson, R. 1917. Site determination, classification, and application. Jour. For. 15:553-565.

Wheetman, G.F., R.C. Yang, and I.E. Bellal. 1985. Nutrition and fertilization of lodgepole pine. **In**: Lodgepole Pine: The Species and Its Management (Symposium Proceedings), Wash. State Univ., Cooperative Extension, Pullman. pp 225-232.

Wiley, K.N. and M.D. Murray. 1974. Ten-year growth and yield of Douglas-fir following stocking control. Weyerhaeuser Co., For. Res. Center, For. Pap. 14, Centralia, WA. 88pp.

Williams, C.B. 1967. Spruce budworm damage symptoms related to radial growth of gand fir, Douglas-fir, and Engelmann spruce. For. Sci. 13:274-285.

Williams, C.K. and T.R. Lillybridge. 1983. Forested plant associations of the Okanogan National Forest. USDA, For. Serv., Pac. N.W. Region, R-6 Ecol 132-1983. Portland, OR. 116pp, illus.

Williamson, R.L. 1976. Levels-of-growing stock cooperative study in Douglas-fir. Report No. 4--Rocky Brook, Stampede Creek, and Iron Creek. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Paper PNW-210, 37pp, illus.

Williamson, R.L. 1982. Response to commercial thinning in a 110-year-old Douglas-fir stand. USDA, For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-296. 16pp, illus.

Wykoff, W.R., N.L. Crookston and A.L. Stage. 1982. User's guide to the stand prognosis model. USDA, For. Serv., Intermtn. For. and Range Exp. Stn., Gen. Tech. Rep. INT-133. 112pp, illus.

Zimmermann, M.H. and C.L. Brown. 1971. Trees, structure and function. Springer-Verlag, N.Y. 336pp, illus.

Zon, R. 1913. Quality classes and forest types: Proc. Soc. Amer. For. 8:100-104.

APPENDIX 1

Scientific Plant Names

Balsam fir	Abies balsamea
Black spruce	Picea mariana
Douglas-fir	Pseudotsuga menziesii
Grand fir	Abies grandis
Incense-cedar	Calocedrus decurrens
Lodgepole pine	Pinus contorta
Norway spruce	Picea ebies (excelsa)
Ponderosa pine	Pinus ponderosa
Shasta red fir	Abies magnifica shastensis
Silver fir	Abies amabilis
Sitka spruce	Picea sitchensis
Western hemlock	Tsuga heterophylla
Western juniper	Juniperus occidentalis
Western larch	Larix occidentalis
White fir	Abies concolor
White pine	Pinus monticola
Englemann spruce	Picea engelmannii

GBA Slide Rule

The GBA slide rule has two sides: The front is used to determine and use GBA; the back contains instructions, a calculator, and measurement devices.

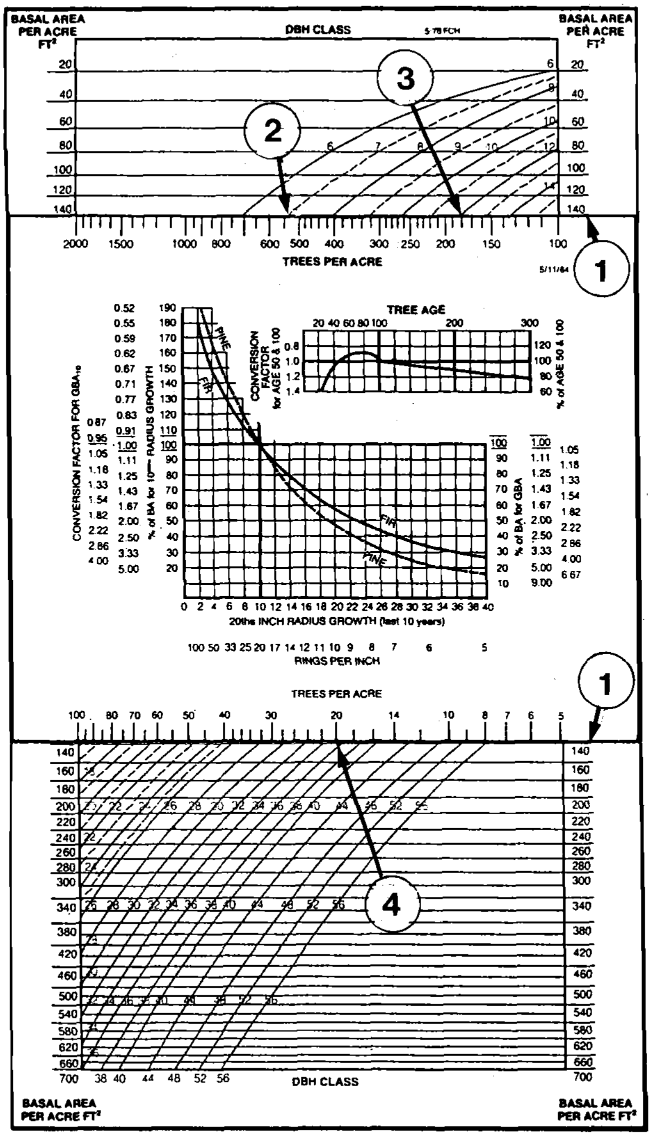


Figure 68. Front of the GBA slide rule. Three items are automatically calculated for any setting of the slide: TPA, BA/A, and Dq diameter. For example, (1) the slide is set at 140 ft^2 BA/A, which appears both above and below the slide. Read at (2) 530 TPA, 7 inches dbh, at (3) 180 TPA, 12 inches dbh, and at (4) 20 TPA, 36 inches dbh. The slide may be adjusted to read from 20 to 700 ft^2 BA/A.

Size/density relationships per acre (figure 68) are expressed as Dq diameter breast height (DBH Class), trees per acre (TPA), and basal area per acre (BA/A). All are automatically calculated for Dq's between 6 and 56 inches and 20 to 700 ft^2 BA/A.

Figure 69 is the slide containing pine and fir GBA curves and the age correction curve. The pine curve should be used with shade-intolerant species such as western larch, ponderosa, lodgepole, and white pine. The fir curve is used for more shade-tolerant trees such as Douglas-fir, incense-cedar, and true firs. Curves have not been developed for hemlocks, spruces, or hardwoods.

The GBA curves can be entered either at a rate of diameter growth or at a percent of GBA and Conversion Factor (CF). The CF is the reciprocal of percent GBA. Multiply the CF, determined by sample tree radius growth, times current stand BA/A to calculate GBA. The "% of BA for 10/20ths Radius Growth" is % GBA, the relationship between stand density and rate of diameter growth. GBA is set at 100% for 10/20ths radius growth (1.0 in/dec. diameter growth). Faster rates of diameter growth

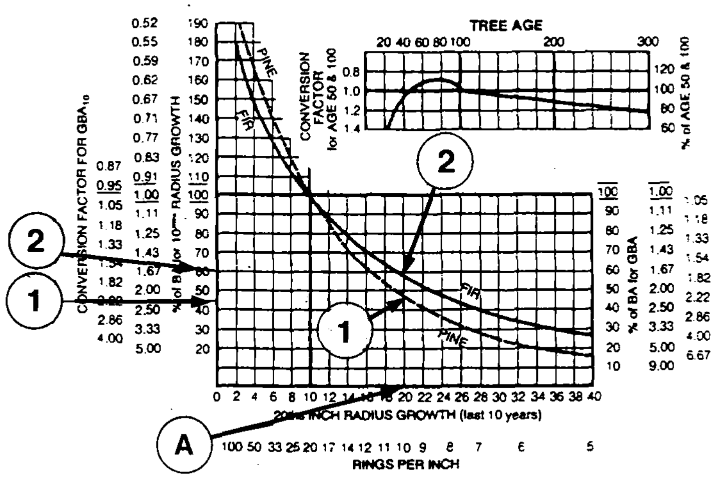


Figure 69. The slide of the GBA slide rule with GBA and age correction curves. The GBA curves may be entered either at a rate of diameter growth or at a % GBA and conversion factor (CF). For example, (A) enter at 20/20ths (2.0 in/dec.): (1) read up to the pine curve and left for 45% GBA and a CF of 2.22; or (2) read up to the fir curve and left for 60% GBA and a CF of 1.67. The procedure may be reversed: (2) enter at 60% GBA, read over to the fir curve and (A) down to 20/20ths radius growth or 2.0 in/dec. diameter growth.

must have less BA/A, such as 60% for 20/20ths (2.0 in/dec.) for Douglas-fir. Slower diameter growth rates have more BA/A, such as 150% for 4/20ths (0.4 in/dec.). At the bottom of the GBA curve is a comparison between rings per inch growth and 20ths of an inch radius growth. Both systems have been used to index intertree competition so they are shown here for comparison.

Figure 70 shows how GBA changes with stand age. GBA seems to reach a maximum between 70 and 80 years, which closely approximates culmination of periodic annual increment. For consistency in site appraisal, GBA is indexed to the same tree age as site index: age 100 for ponderosa pine and Douglas-fir, age 50 for lodgepole pine and larch. The curve is used to adjust GBA to age 50 or 100. GBA calculated for an 80-year-old stand must be decreased by 0.9; for a 160-year-old stand, it must be increased by 1.05 to index GBA at age 100.

The back of the GBA slide rule is depicted in figure 71. It contains a summary of instructions, circular slide rule, ruler marked in 20ths of an inch, trees per acre/square spacing conversion table, and rings per inch radius growth.

Most of the slide rule is devoted to instructions (figure 71). "DBH, BA, and trees per acre" is the size/density relationship previously discussed in this appendix. "GROWTH BASAL AREA" determination was discussed in Chapter 3. The three uses of GBA below the circular slide rule were discussed in Chapter 4. "Site productivity INDEX" combining SI and GBA was discussed in Chapter 5. Note that the equation on the slide rule uses a K factor of 0.5.

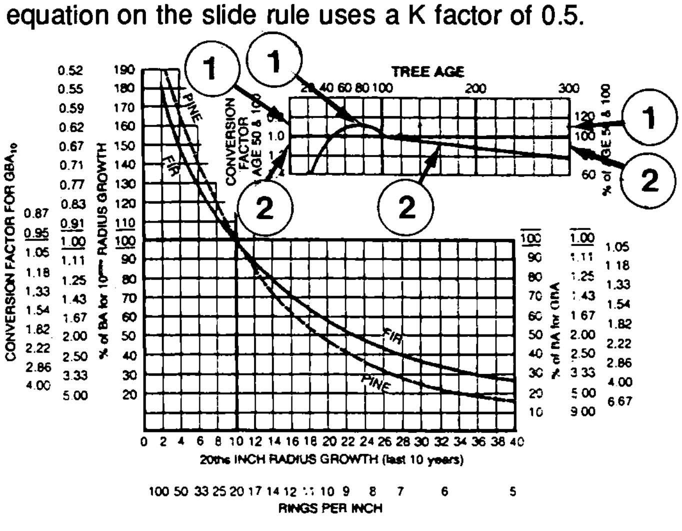


Figure 70. Age correction curve used to adjust GBA to age 50 or 100. Age 80 (1) reading right is about 110% of GBA at age 100 and reading left is a conversion factor (CF) of 0.9. This means that GBA at age 80 is higher than at age 50 or 100. A 160-year- old tree (2) has a GBA lower than at age 50 or 100 at about 95% and a CF of 1.05.

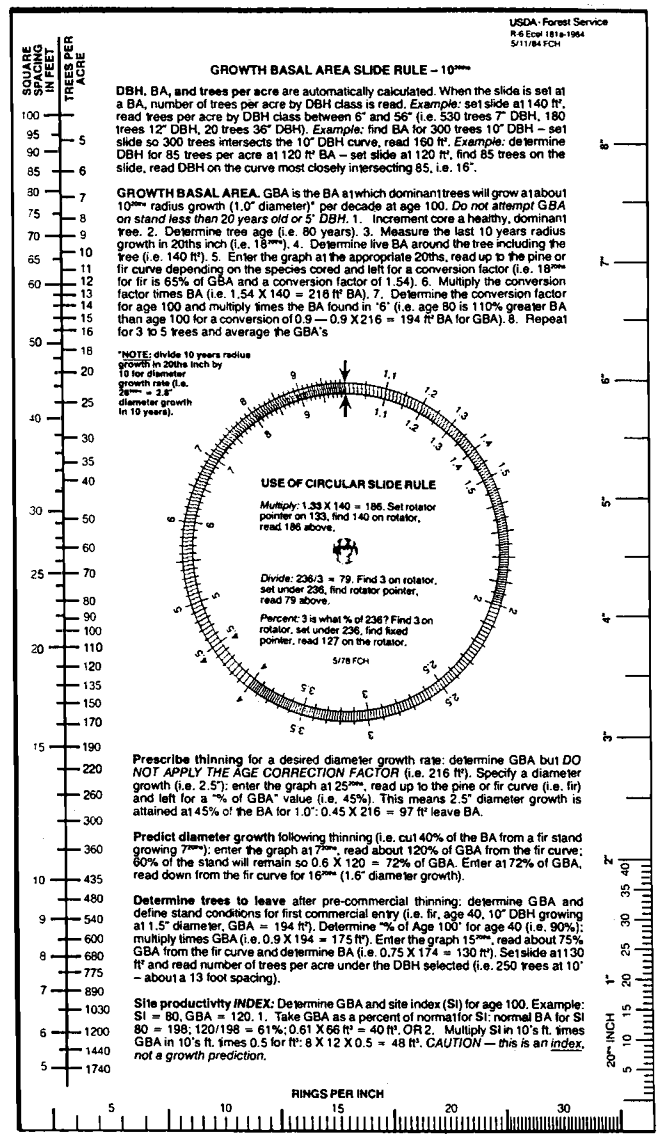


Figure 71. Back of the GBA slide rule.

This is incorrect. Use 0.44 for the K factor when SI is based on age 100 and 0.72 when it is based on age 50.

The circular slide rule provides a quick means of simple multiplication and division (figures 72 and 73).

Five rates of radius growth are depicted in rings per inch at the bottom of the slide rule. The primary function of these is to quickly estimate tree age as shown in figure 74. For example, the 20-rings-per-inch rate encompasses about 1/2 inch on the cross section, representing 10 years' growth. The rings per inch scales can be lined up with different rates on the increment core and added for quick estimates of tree age, a time-saving system for trees over 100 years old.

On the right side of the slide rule in figure 71 is an 8-inch ruler with the first 2 inches marked off in 20ths of an inch. These first two inches are used to measure the last 10 years' radius growth on an increment core. It is this rate of radius growth that is used to enter the set of GBA curves depicted in figure 69.

The left side of the slide rule in figure 71 is a conversion of TPA to square spacing in feet. Recall in figure 68, 180 TPA at 12 inches dbh amounts to 140 ft^2 BA/A. These trees will be spaced approximately 15 feet apart.

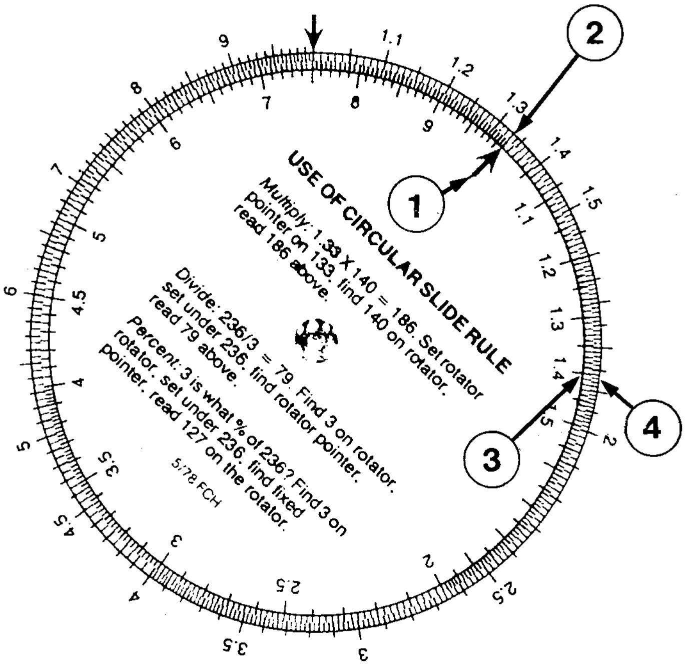


Figure 72. Multiplication on the circular slide rule. Multiply 1.33 times 140; (1) find the rotator pointer, (2) set this under 1.33, (3) on the rotator find 140, and (4) read the answer on the outside of 186.

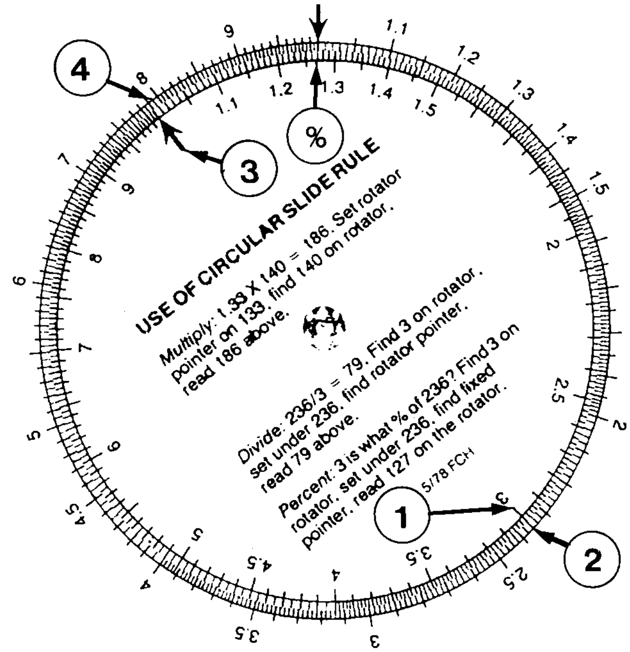


Figure 73. Division on the circular slide rule. Divide 236 by 3; (1) find 3 on the rotator, (2) set underneath 236, (3) find the rotator pointer, and (4) read 79 on the outside. This same operation can calculate percentage: e.g., 3 is what percent of 236? Use the first two steps, then find the pointer on the outside scale and read 1.27% on the rotator (%).

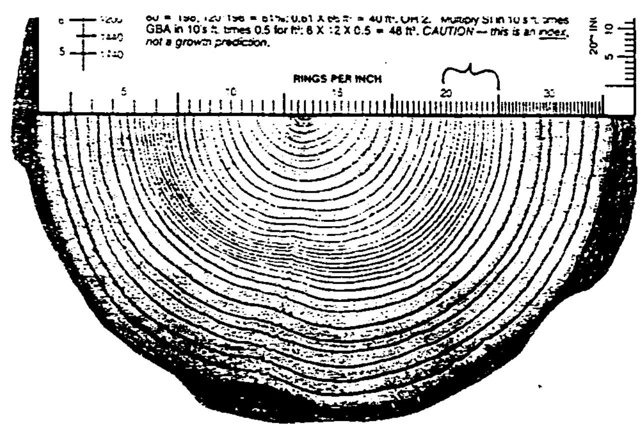


Figure 74. The rings per inch (rpi) scale can be used to quickly estimate age of a tree. The 20 rpi scale covers 1/2 inch and 10 years growth.

GBA Curves By Species

Curves are hand-drawn through mean data points for 0.5, 0.7, 1.0, 1.3, 2.0, and 4.0 in/dec.

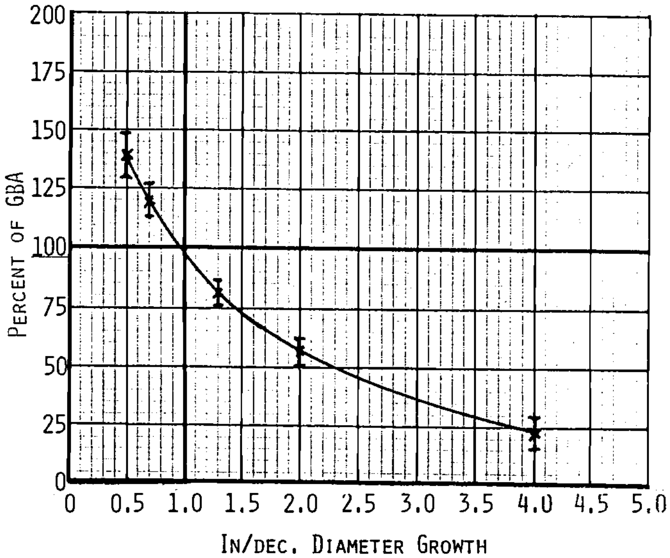


Figure 75. Composite GBA curve composed of ponderosa pine, lodgepole pine, and Douglas-fir data with confidence intervals (p = 0.01) (Hall 1983), n = 365.

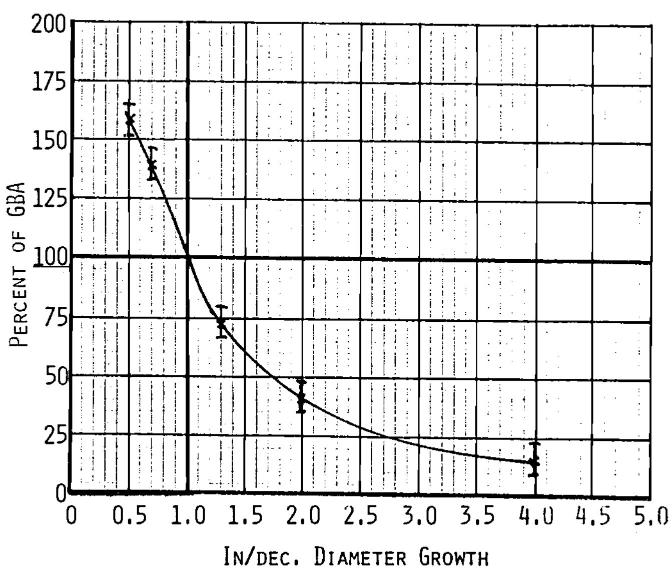


Figure 76. Ponderosa pine GBA curve with confidence intervals (p = 0.01) (Hopkins 1986), n = 246. This is the same curve as figure 14, repeated here for curve comparison.

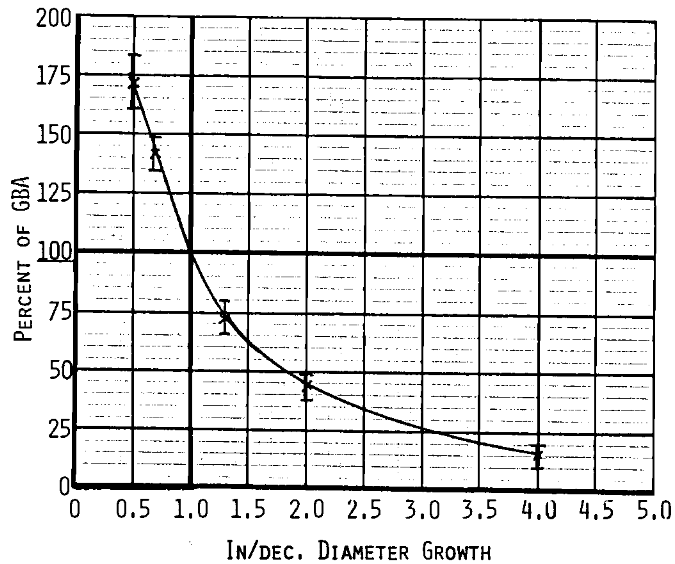


Figure 77. Lodgepole pine GBA curve with confidence intervals (p = 0.01) (Hopkins 1986), n = 138.

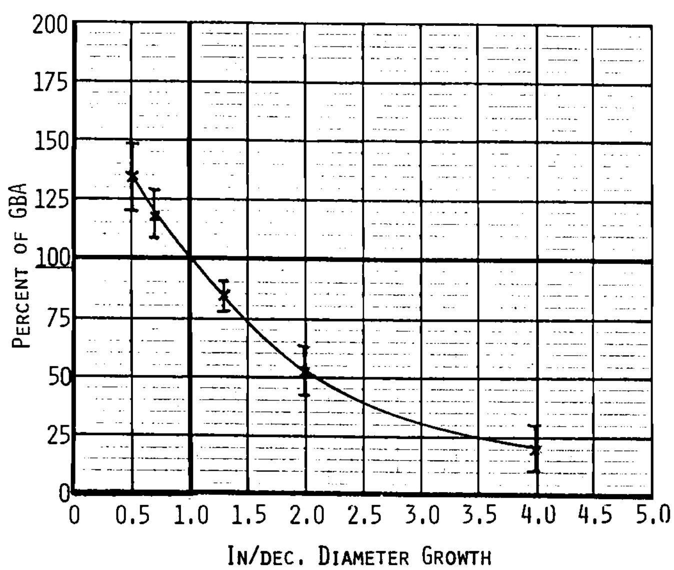


Figure 78. Douglas-fir GBA curve with confidence intervals (p = 0.01) (Hopkins 1986), n = 30.

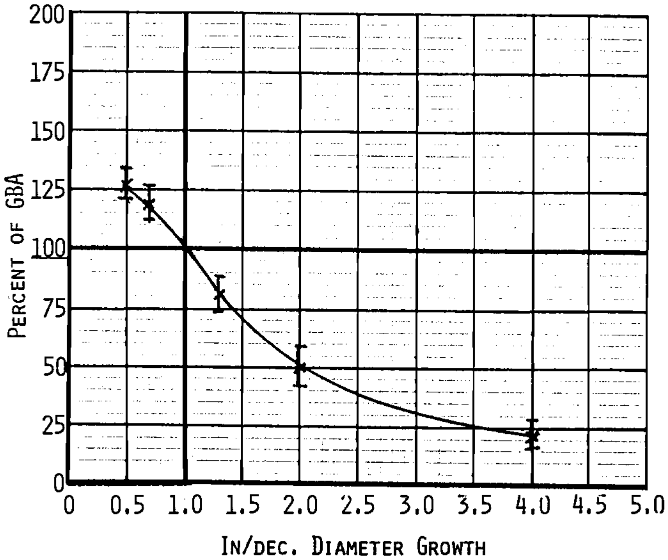


Figure 79. White fir GBA curve with confidence intervals (p = 0.01) (Hopkins 1986), n = 95.

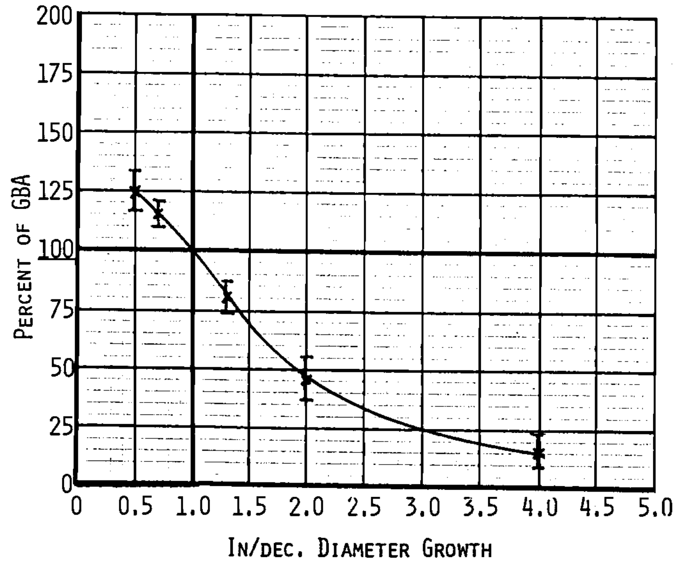


Figure 80. Shasta red fir GBA curve with confidence intervals (p = 0.01) (Hopkins 1986), n = 33.

Stand Density/Diameter Growth Curves

Figures 81 through 93 are measured plot data for basal area per acre/diameter growth relationships from stand growth and thinning studies. The appropriate pine or fir GBA curve is overlaid on the data to test the concept of predictable diameter growth response to change in stand basal area.

Figures 94 to 99 are predicted stand density/diameter growth data plotted from simulation models and compared with the pine or fir GBA curve. Most models appear to have a "GBA Curve" as part of the simulation.

GBA was determined by averaging the GBA calculated (Eq. 7) for each basal area/diameter growth data set. If Dq diameter growth was measured, it was adjusted by equation (9) to dominant-tree diameter growth. For each GBA, the number of samples (n), standard deviation (SD), confidence interval (p = 0.05) (CI), and percent the confidence interval is of the mean (%) are shown.

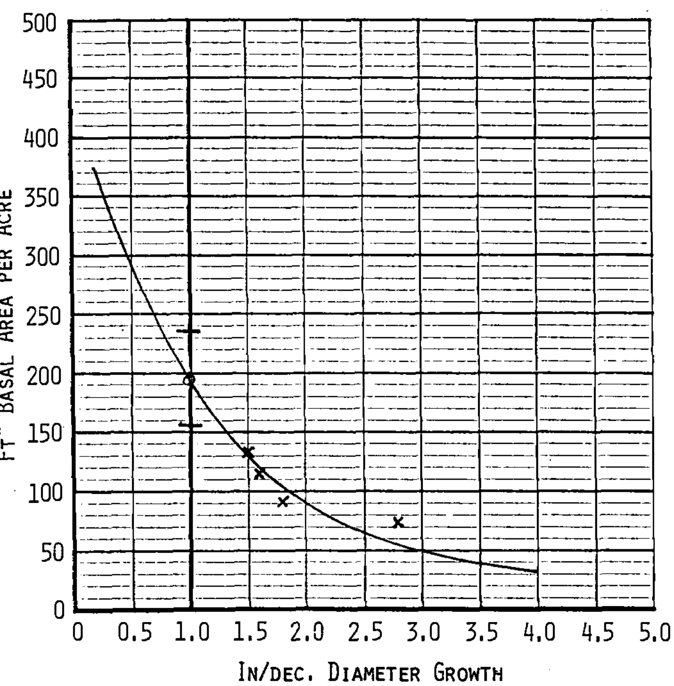


Figure 81. Ponderosa pine basal area/diameter growth data from Barrett (1972) with the pine GBA curve. Diameter growth was taken from crop trees. GBA averaged 196 ft^2, n = 4, SD = 30 ft^2, CI = 39 ft^2 at 20% of the mean, SI = 78 ft, PAI = 89 ft^3, and K = 0.0058.

Mean annual increment (MAI) or periodic annual increment (PAI) is taken from the cited study, as is the site index (SI) of the species evaluated. These, together with GBA, are used to calculate the constant (K) in the expression SI*GBA*K = ft^3/A/yr as an index of stand productivity. K is calculated as: K = MAI/SI*GBA.

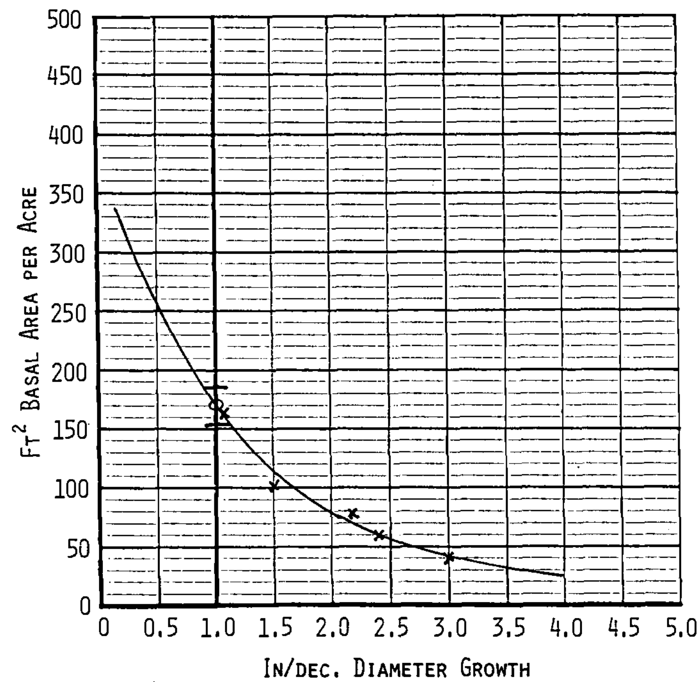


Figure 82. Ponderosa pine basal area/diameter growth data from Barrett (1981) with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). GBA averaged 169 ft^2, n = 5, SD = 14 ft^2, CI = 16 ft^2 at 9% of the mean, SI = 80 ft, PAI = 55 ft^3, and K = 0.0040.

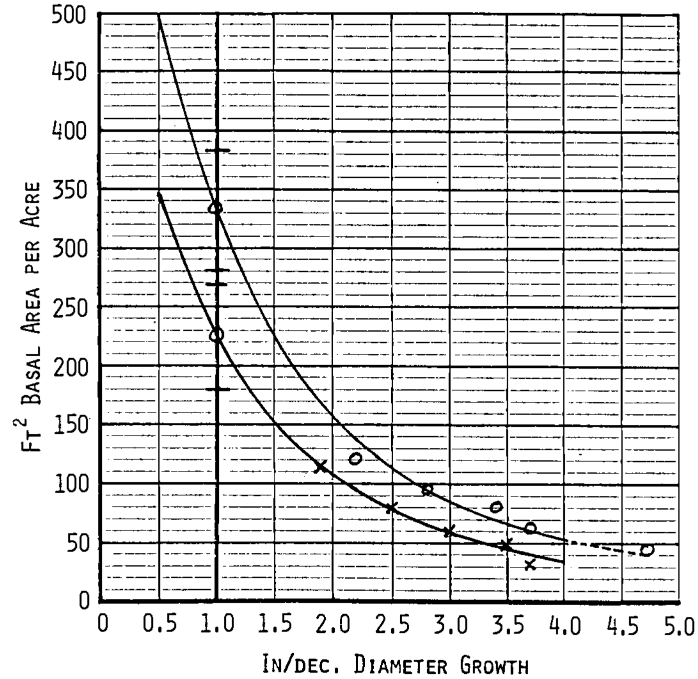


Figure 83. Ponderosa pine basal area/diameter growth data from Barrett (1982) with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). Vegetation eliminated is shown as (o), vegetation competing as (x). For vegetation eliminated: GBA averaged 333 ft^2, n = 5, SD = 43 ft^2, CI = 49 ft^2 at 15% of the mean, SI = 130 ft, PAI = 60 ft^3, and K = 0.0014. For vegetation competing: GBA averaged 225 ft^2, n = 5, SD = 38 ft^2, CI = 44 ft^2 at 19% of the mean, SI = 120 ft, PAI = 46 ft^3, and K = 0.0017. GBA was significantly different at p = 0.01.

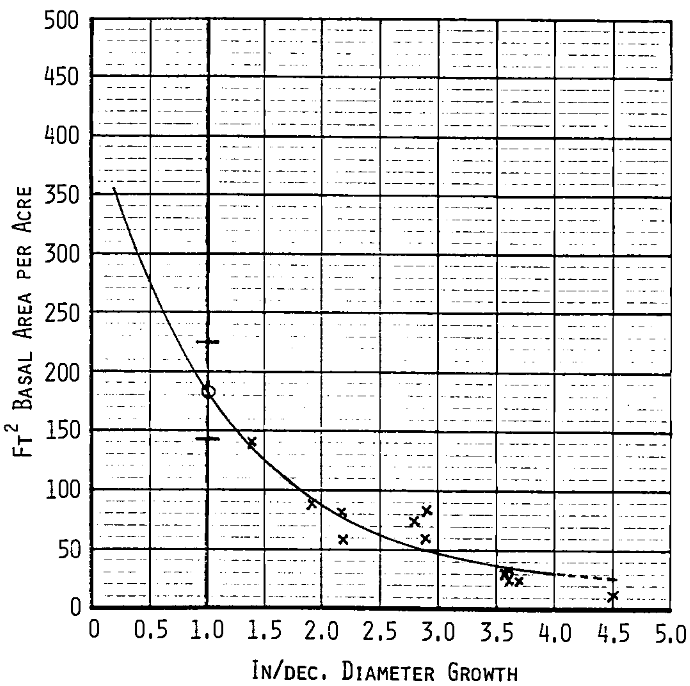


Figure 84. Ponderosa pine basal area/diameter growth data from Oliver (1972) with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). GBA averaged 189 ft^2, n = 12, SD = 63 ft^2, CI = 40 ft^2 at 21% of the mean, SI = 70 ft, PAI = 46 ft^3, and K = 0.0036.

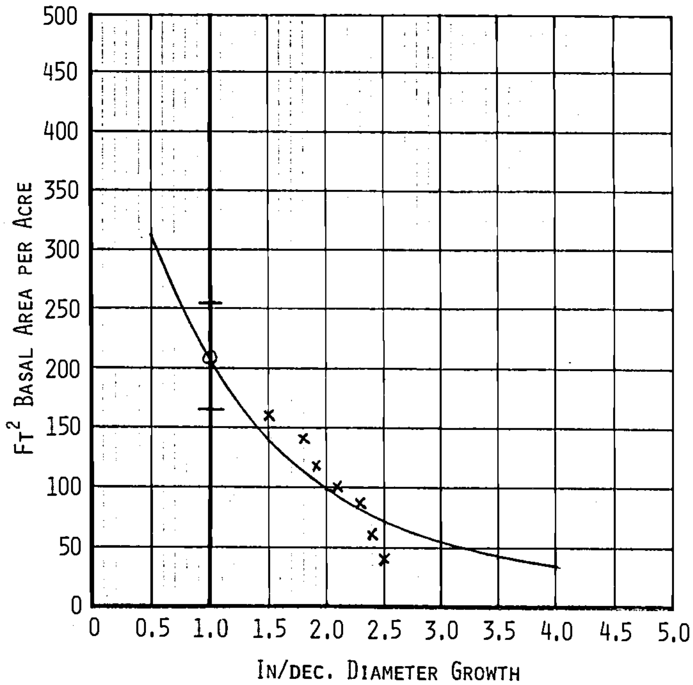


Figure 85. Ponderosa pine basal area/diameter growth data from Alexander and Edminster (1980) with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). GBA averaged 207 ft^2, n = 7, SD = 49 ft^2, CI = 44 ft^2 at 21% of the mean, SI = 70 ft, MAI = 64 ft^3, and K = 0.0043.

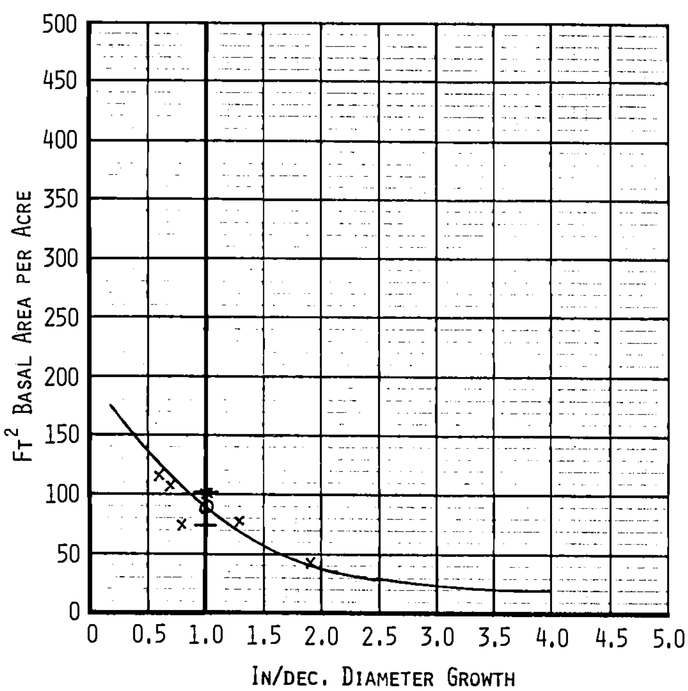


Figure 86. Lodgepole pine basal area/diameter growth data from Dahms (1971b) with the pine GBA curve. Diameter growth was taken from crop trees. GBA averaged 84 ft^2, n = 6, SD = 13 ft^2, CI = 13 ft^2 at 15% of the mean, SI = 88 ft (base age 100), MAI = 33 ft^3, and K = 0.0045.

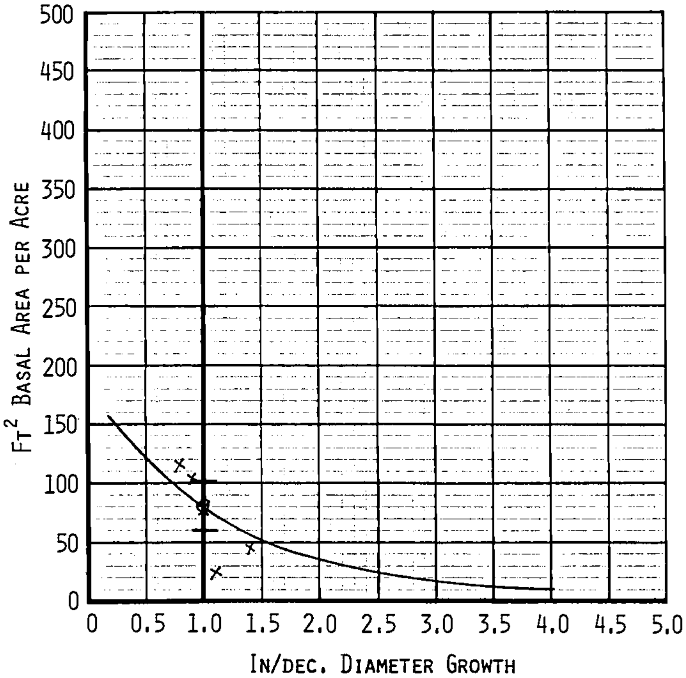


Figure 87. Lodgepole pine basal area/diameter growth data from Dahms (1973b) with the pine GBA curve. Diameter growth was taken from crop trees. GBA averaged 84 ft^2, n = 4, SD = 17 ft^2, CI = 22 ft^2 at 27% of the mean, SI = 80 ft (base age 100), MAI = 51 ft^3, and K = 0.0076.

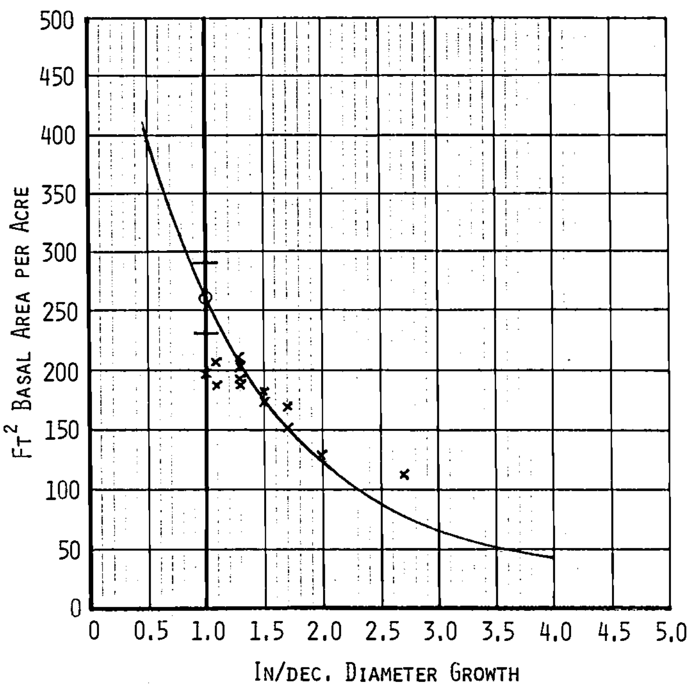


Figure 88. Lodgepole pine basal area/diameter growth data from Cole and Edminster (1985) with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). From table 4, GBA averaged 259 ft^2, n = 13, SD = 48 ft^2, CI = 29 ft^2 at 11% of the mean, SI = 80 ft (base age 100), MAI = 70 ft^3, and K = 0.0034.

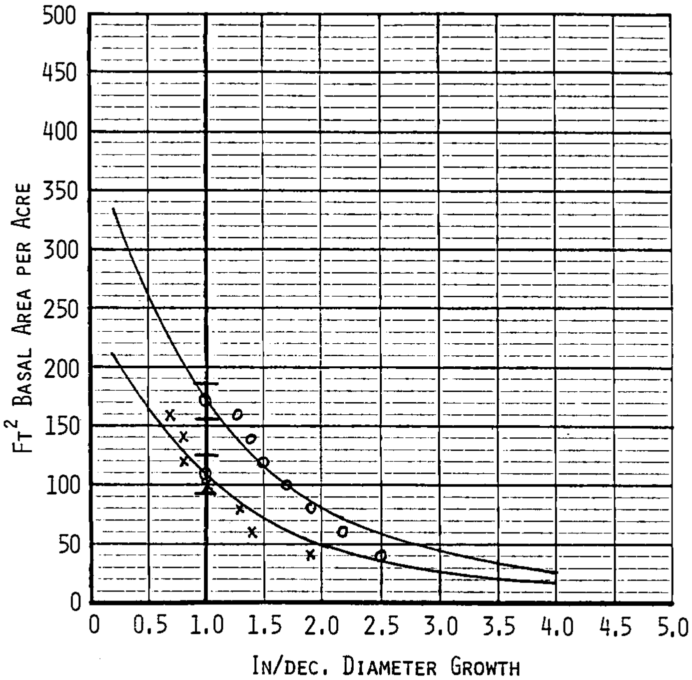


Figure 89. Lodgepole pine basal area/diameter growth data from Cole and Edminster (1985) with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). The north model is shown as (x) and the central model as (o). North model: GBA averaged 101 ft^2, n = 7, SD = 16 ft^2, CI = 15 ft^2 at 15% of the mean, SI = 80 ft, MAI = 71 ft^3, and K = 0.0088 (table 10). Central model: GBA averaged 167 ft^2, n = 7, SD = 30 ft^2, CI = 27 ft^2 at 16% of the mean, SI = 80 ft, MAI = 105 ft^3, and K = 0.0079 (table 12). GBA between the North and Central model is significantly different at p = 0.01 even though SI is the same at 80 feet (base age 100).

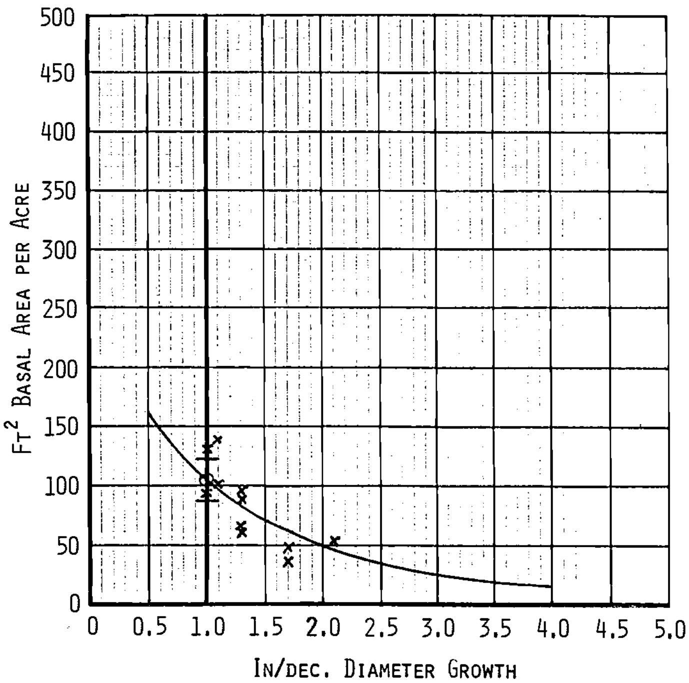


Figure 90. Western larch basal area/diameter growth data from Seidel (1980) with the pine GBA curve. Diameter growth was taken from crop trees for the thin-from-below treatment only. GBA averaged 106 ft^2, n = 11, SD = 26 ft^2, CI = 18 ft^2 at 16% of the mean, SI = 127 ft (base age 100), PAI = 85 ft^3, and K = 0.0063.

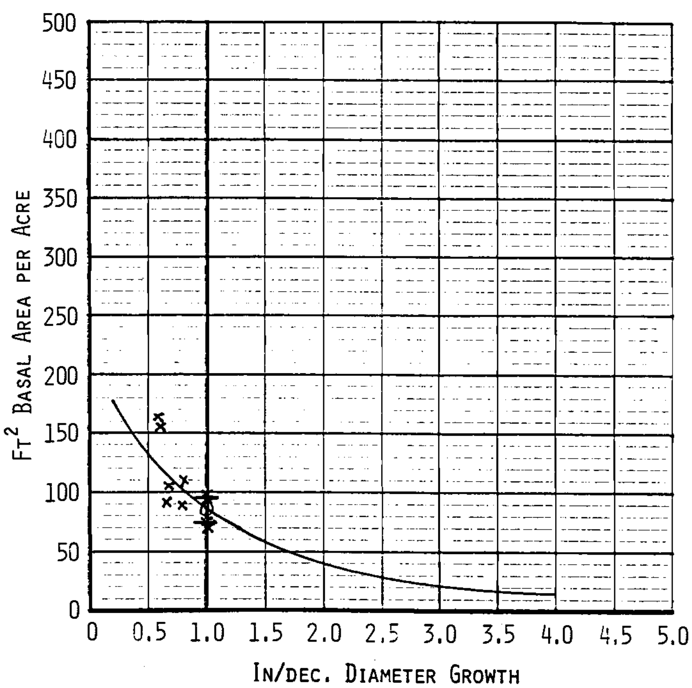


Figure 91. Western larch basal area/diameter growth data from Cole (1984) with the pine GBA curve. Diameter growth was taken from crop trees. GBA averaged 87 ft^2, n = 10, SD = 15 ft^2, CI = 10 ft^2 at 12% of the mean, SI = 84 ft (base age 100), PAI = 58 ft^3, and K = 0.0079.

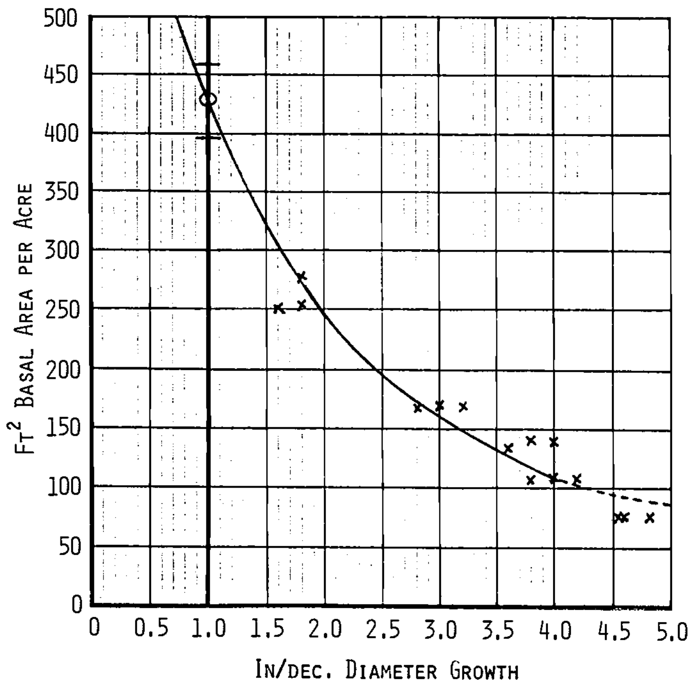


Figure 92. Douglas-fir basal area/diameter growth data from Berg and Bell (1979) with the fir GBA curve. Diameter growth was taken from crop trees. GBA averaged 430 ft^2, n = 15, SD = 55 ft^2, CI = 30 ft^2 at 7% of the mean, SI = 145 ft (base age 100), PAI = 418 ft^3, and K = 0.0067.

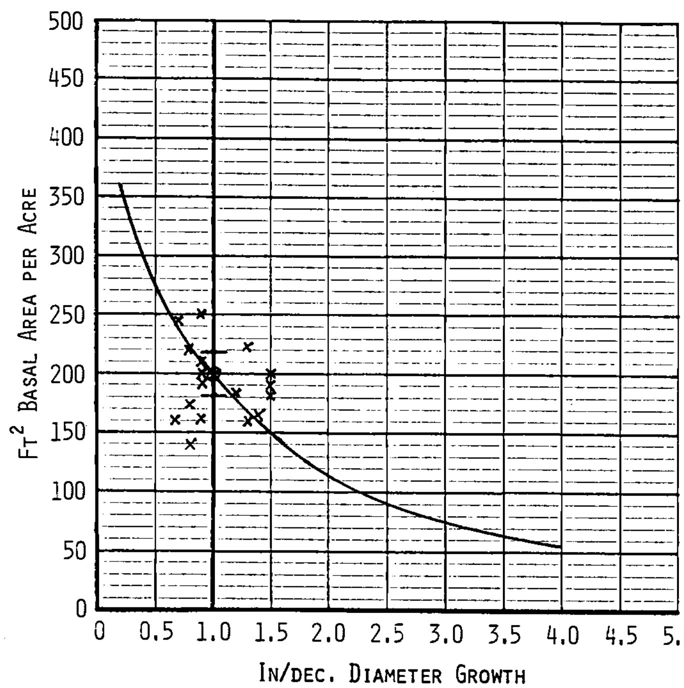


Figure 93. Douglas-fir basal area/diameter growth data from Reukema (1979) with the fir GBA curve. Diameter growth was taken from crop trees. GBA averaged 199 ft^2, n = 18, SD = 37 ft^2, CI = 18 ft^2 at 9% of the mean, SI = 97 ft (base age 100), MAI = 83 ft^3, and K = 0.0043.

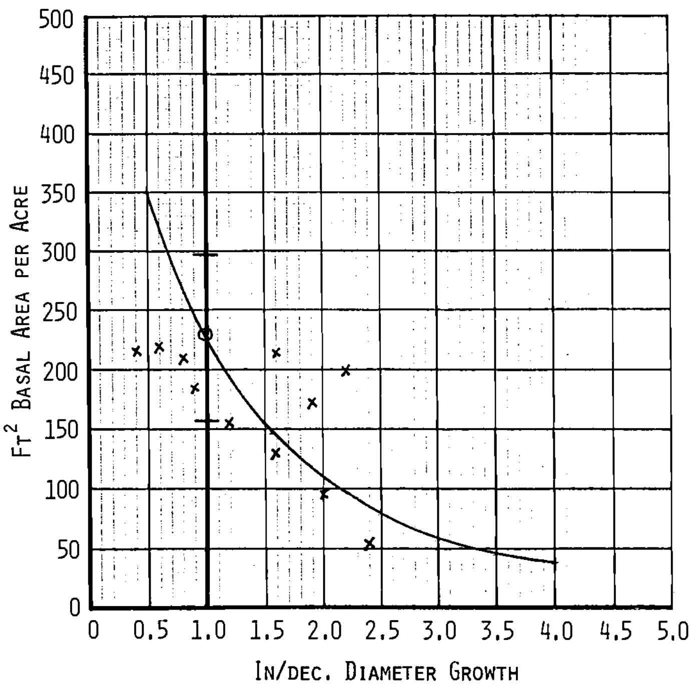


Figure 94. PROGNOSIS (Wykoff et al. 1982) derived basal area/diameter growth data for ponderosa pine with the pine GBA curve according to version 15. Diameter growth was taken from crop trees. GBA averaged 230 ft^2, n = 11, SD = 108 ft^2, CI = 72 ft^2 at 31% of the mean, SI = 128 ft, MAI = 77 ft^3, and K = 0.0026.

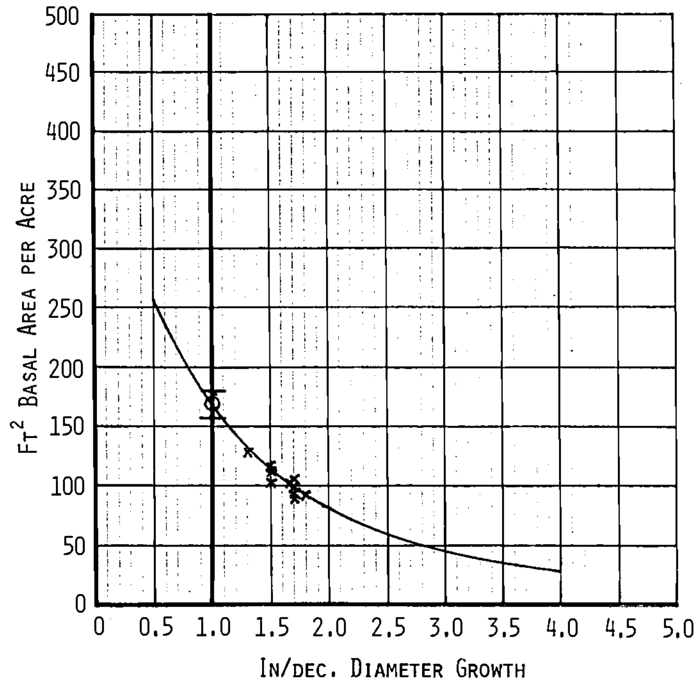


Figure 96. RMYLD (Edminster 1978) derived basal area/diameter growth data for lodgepole pine, GSL 120, with the pine GBA curve. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). GBA averaged 169 ft^2, n = 10, SD = 11 ft^2, CI = 8 ft^2 at 5% of the mean, SI = 70 ft (base age 100), MAI = 68 ft^3, and K = 0.0057.

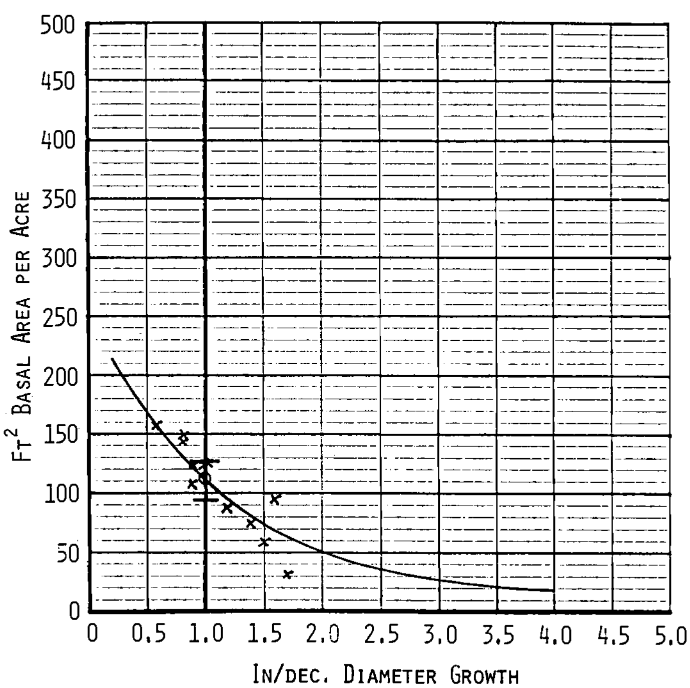


Figure 95. PROGNOSIS (Wykoff et al. 1982) derived basal area/diameter growth data for ponderosa pine with the pine GBA curve according to version 25. Diameter growth was taken from crop trees. GBA averaged 111 ft^2, n = 11, SD = 26 ft^2, CI = 17 ft^2 at 15% of the mean, SI = 81 ft, MAI = 22 ft^3 and K = 0.0025.

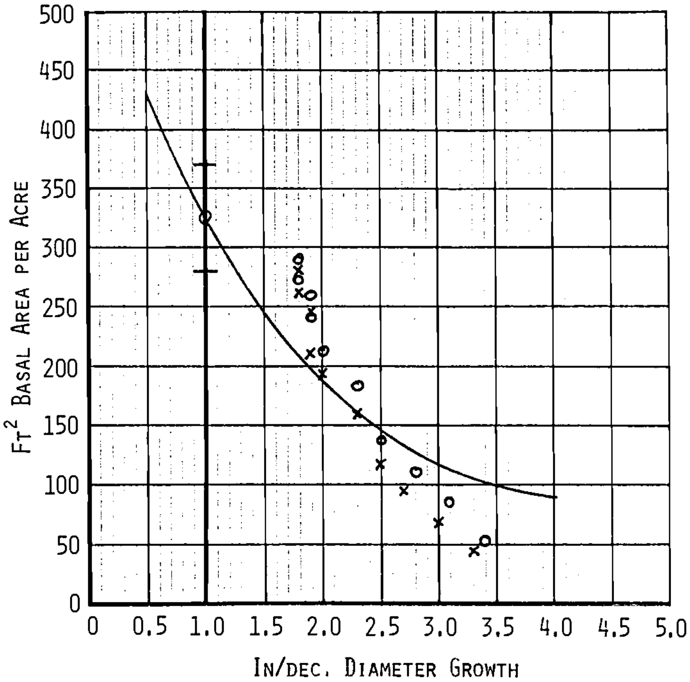


Figure 97. DFSIM (Curtis et al. 1982) derived basal area/diameter growth data for Douglas-fir with the fir GBA curve for SI = 113 (base age 100). Table 2A shown as (x) with no precommercial thinning and table 4A as (o) with precommercial thinning to 400 TPA at age 15. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). Table 2A: GBA averaged 318 ft^2, n = 10, SD = 99 ft^2, CI = 69 ft^2 at 22% of the mean, SI = 113 ft (base age 100), MAI = 105 ft^3, and K = 0.0029. Table 4A: GBA averaged 341 ft^2, n = 10, SD = 95 ft^2, CI = 67 ft^2 at 20% of the mean, SI = 113 ft (base age 100), MAI = 105 ft^3, and K = 0.0027. There was no significant difference (p = 0.01) between treatments. Data, when combined, were: GBA averaged 324 ft^2, n = 20, SD = 96 ft^2, CI = 45 ft^2 at 14% of the mean.

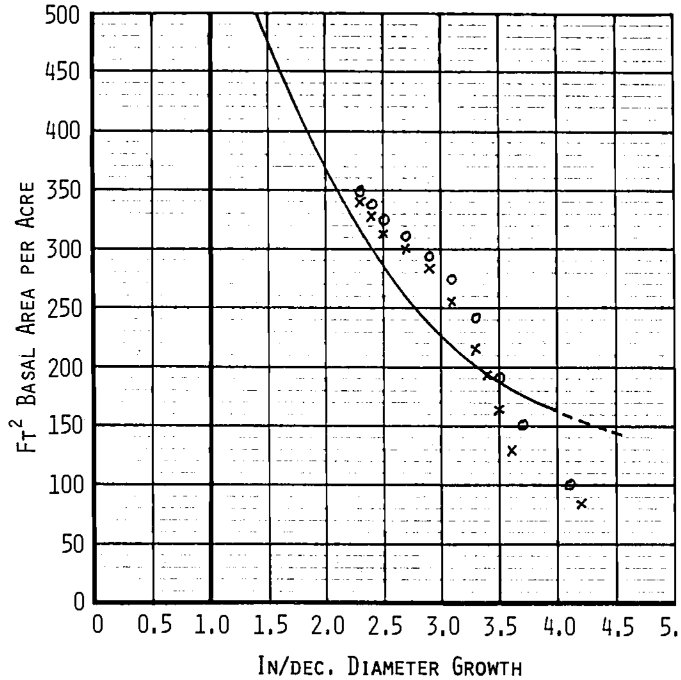


Figure 98. DFSIM (Curtis et al. 1982) derived basal area/diameter growth data for Douglas-fir with the fir GBA curve for SI = 196 (base age 100). Table 2D is shown as (x) with no precommercial thinning and table 4D as (o) with thinning to 400 TPA at age 15. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). Table 2D: GBA averaged 620 ft^2, n = 11, SD = 133 ft^2, CI = 89 ft^2 at 14% of the mean, SI = 196 ft, MAI = 257 ft^3, and K = 0.0021. Table 4D: GBA averaged 670 ft^2, n = 10, SD = 124 ft^2, CI = 87 ft^2 at 13% of the mean, SI = 196 ft, MAI = 257 ft^3, and K = 0.0020. There was no significant difference in GBA between treatments (p = 0.01). Data, when combined, were: GBA averaged 644 ft^2, n = 21, SD = 128 ft^2, CI = 58 ft^2 at 9% of the mean. In addition, there was no significant difference (p = 0.01) between these GBA data and those shown in figure 99 for the same SI.

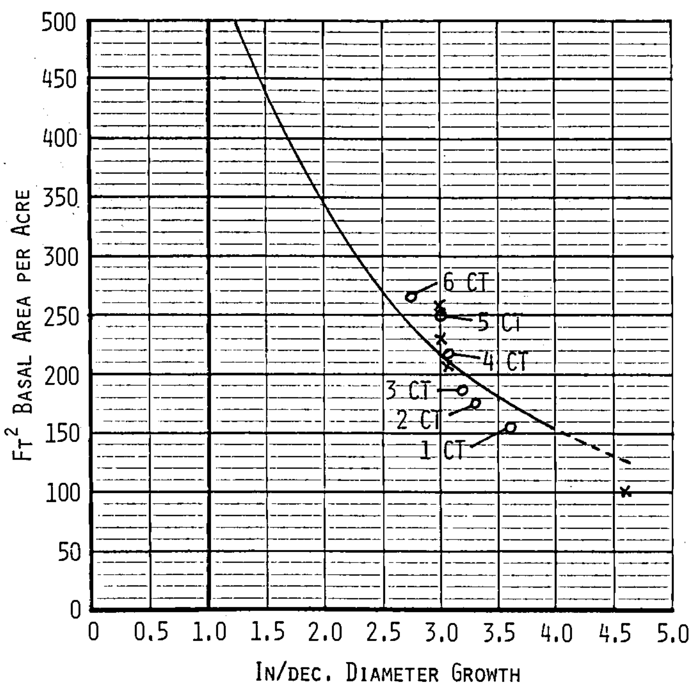


Figure 99. DFSIM (Curtis et al. 1982) derived basal area/diameter growth data for Douglas-fir with the fir GBA curve for SI = 196 (base age 100). Table 9D depicted precommercial thinning to 400 TPA at age 10 and then commercial thinning at ages 24, 31, 42, 57, 74, and 91. Dq diameter growth was adjusted to dominant-tree diameter growth by use of equation (9). GBA averaged 591 ft^2, n = 10, SD = 85 ft^2, CI = 60 ft^2 at 10% of the mean, SI = 196 ft, MAI = 281 ft^3, and K = 0.0024. There was no significant difference in GBA (p = 0.01) between these data and those in figure 98 for the same SI.

APPENDIX 5

SI-GBA RELATIONSHIPS

Site Index- Growth Basal Area (SI-GBA) relationships are given for seven tree species in eastern Oregon and Washington. Each dot on a graph represents average SI and GBA for that species in a plant association. Each plant association consists of five to thirty sample plots. From one to five individuals of the featured species are measured on each plot for SI and GBA. Thus each dot represents no less than five and usually more than ten trees.

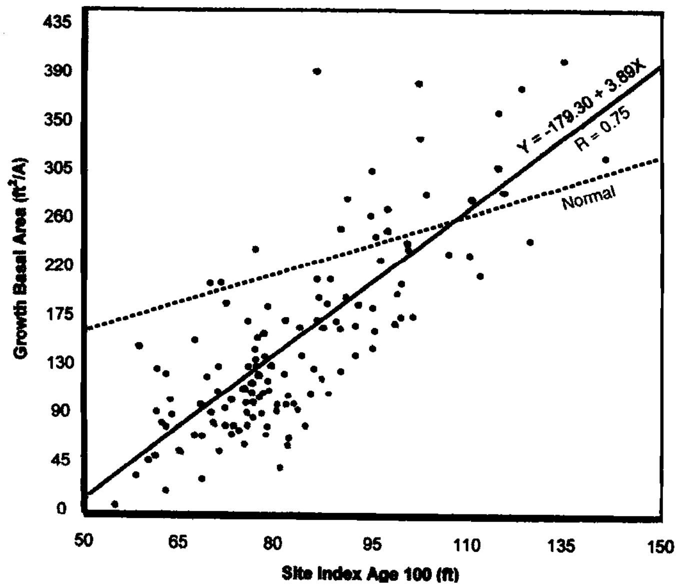


Figure 100. Relationship of ponderosa pine SI to GBA for 129 plant associations in Oregon and Washington. Normal ft^2/A is taken from Meyer (1938). SI accounts for 57% of the variability in GBA ($R = 0.75$, $R^2 = 0.57$); $F = 167.60$, $SE = 56.39$. Maximum variability in GBA for a SI class is 45 to 230 ft^2/A, a 510% difference in SI class 80..

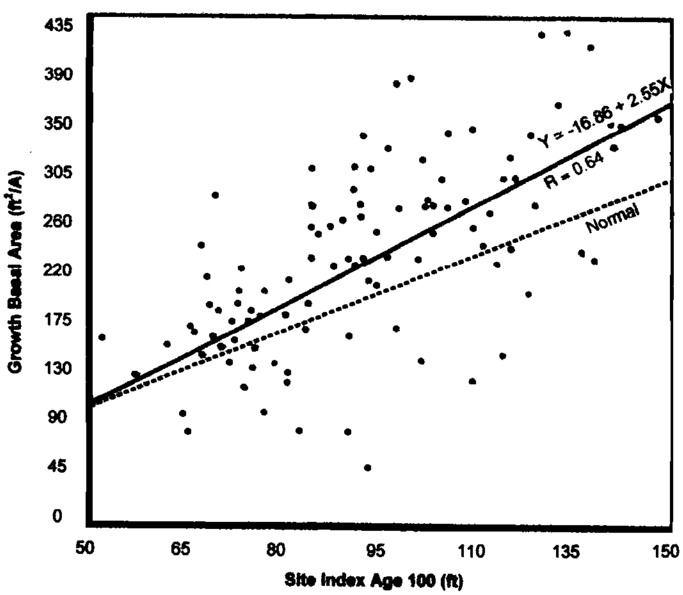


Figure 101. Relationship of Douglas-fir SI to GBA for 106 plant associations in Oregon and Washington. Normal ft^2/A is taken from Cochran (1979a). SI accounts for 41% of the variability in GBA ($R = 0.64$, $R^2 = 0.41$), $F = 77.20$, $SE = 58.64$. Maximum variability in GBA for a SI class is 45 to 340 ft^2/A in SI 95, a 750% difference.

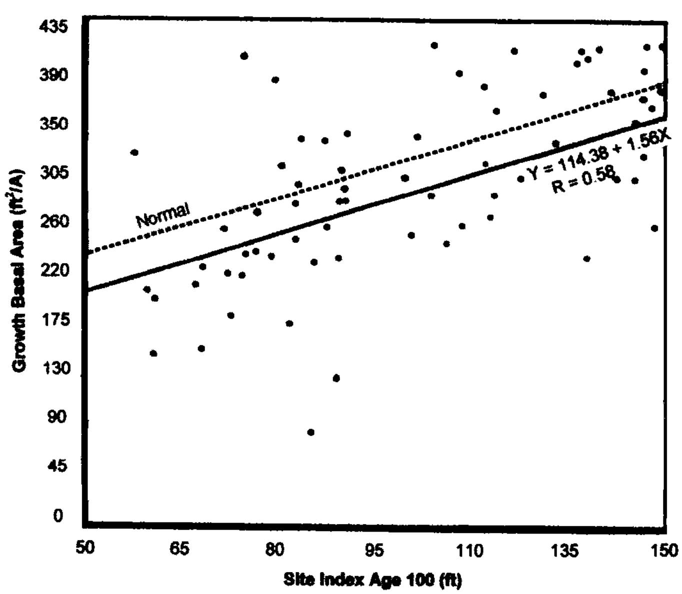


Figure 102. Relationship of grand or white fir SI to GBA for 75 plant associations in Oregon and Washington. Normal ft^2/A is taken from Cochran (1979a). SI accounts for 34% of the variability in GBA ($R = 0.58$, $R^2 = 0.34$), $F = 33.71$, $SE = 60.75$. Maximum variability in GBA for a SI class is 80 to 330 ft^2/A, a 410% difference in SI 85.

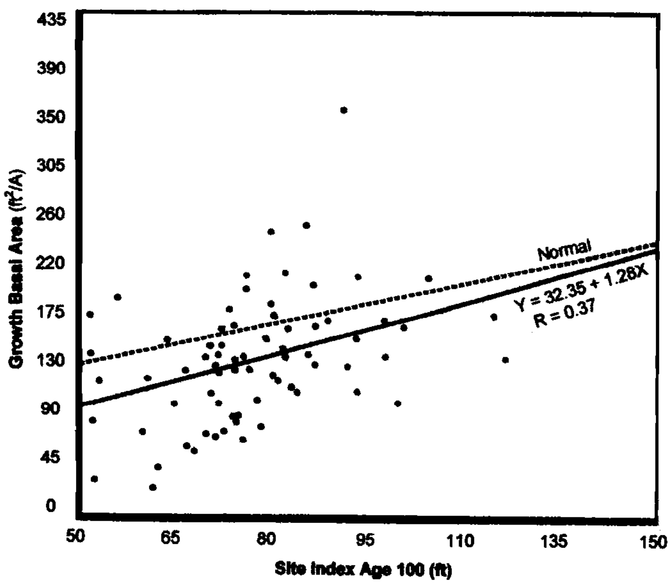


Figure 103. Relationship of lodgepole pine SI to GBA for 71 plant associations in Oregon and Washington. This is figure 65, repeated here for comparison with six other species. Normal ft²/A is taken from Dahms (1964). SI accounts for 13% of the variability in GBA (R = 0.37, R^2 = 0.13), F = 11.32, SE = 48.42. Maximum variability in GBA for a SI class is 60 to 250 ft²/A, a 420% difference in SI 80.

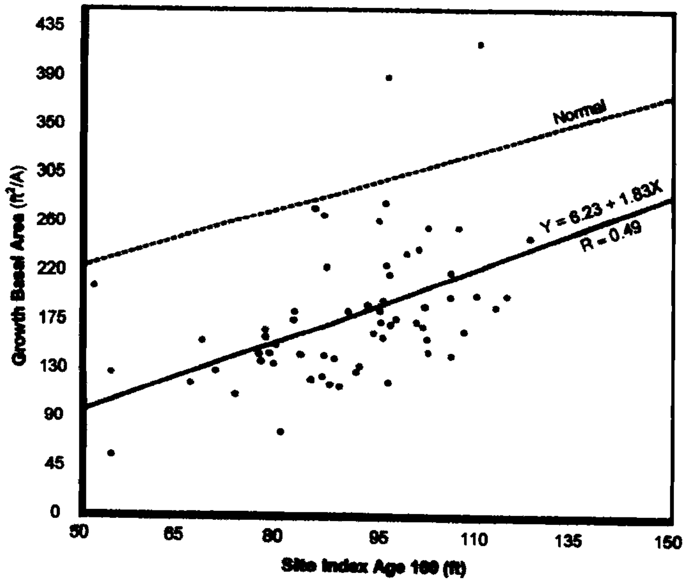


Figure 104. Relationship of western larch SI to GBA for 59 plant associations in Oregon and Washington. Normal ft²/A is taken from Schmidt et.al. (1976). SI accounts for 24% of the variability in GBA (R = 0.49, R^2 = 0.24), F = 17.02, SE = 51.61. Maximum variability in GBA for a SI class is 100 to 390 ft²/A, a 390% difference in SI 95. Note the discrepancy between normal and our regression line, about 110 ft²/A. Larch reaches the western limits of its range at the crest of the Cascade Mountains which may account for its limited stockability.

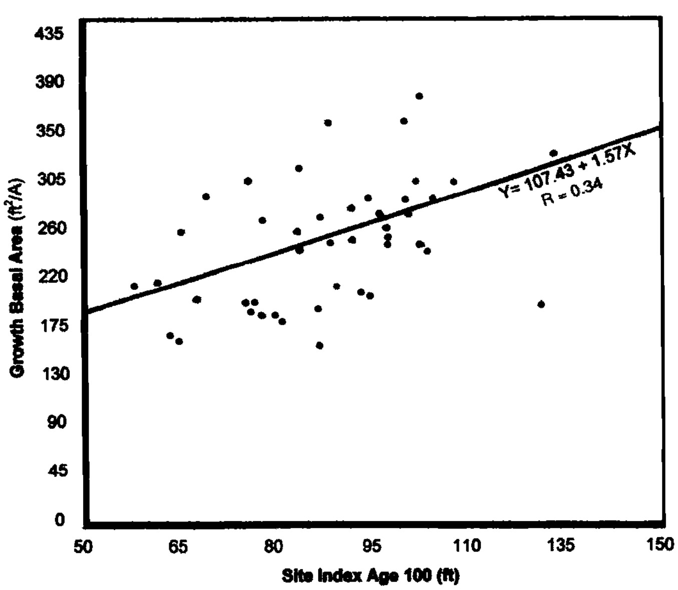


Figure 105. Relationship of Engelmann Spruce SI to GBA for 42 plant associations in Oregon and Washington. SI accounts for 12% of the variability in GBA (R = 0.34, R^2 = 0.12), F = 6.88, SE = 61.52. Maximum variability in GBA for a SI class is 140 to 360 ft²/A, a 260% difference in SI 90.

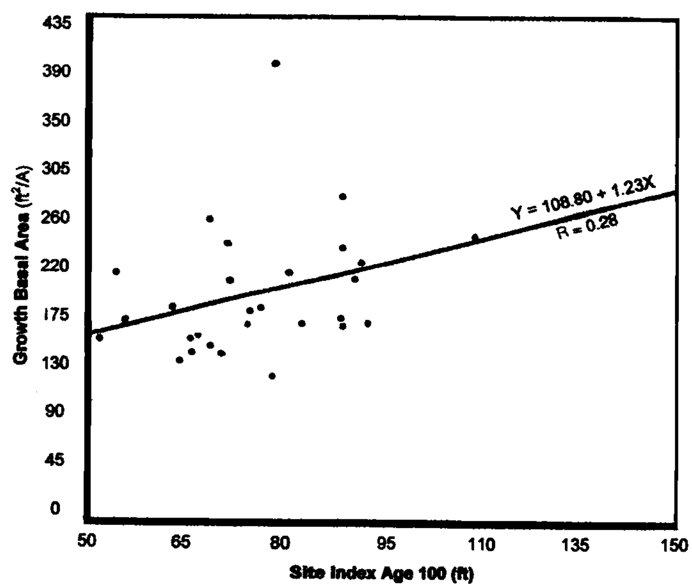


Figure 106. Relationship of subalpine fir SI to GBA for 28 plant associations in Oregon and Washington. SI accounts for 8% of the variability in GBA (R = 0.28, R^2 = 0.08), F = 2.80, SE = 52.25. Maximum variability in GBA for a SI class is 120 to 400 ft²/A, a 330% difference in SI 80.

APPENDIX 6

STOCKING CONSIDERATIONS IN UNEVEN-AGED MANAGEMENT

Uneven-aged stands are constrained by the same site potential limitations as even-aged stands. Chapter 2, pages 5 and 6 discusses leaf area and stockability which are illustrated in figures 2, 3, and 7.

Figure 107 depicts an uneven-aged stand with a Leaf Area Index (LAI) of 4 composed of the same three tree sizes shown in figure 7 (p. 7): 10 feet, 30 feet, and 60 feet tall. Number of trees per acre by size class is a fundamental characteristic of uneven-aged stands. Figure 107 depicts 1½ trees 60 feet tall, 2 trees 30 feet tall, and 5 trees 10 feet tall.

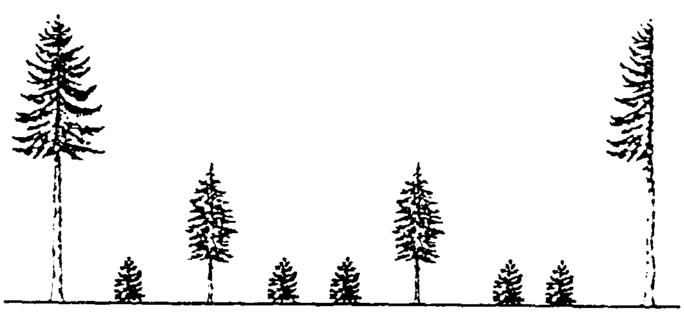


Figure 107. Uneven-aged stand of the same three tree sizes shown in figure 7, page 7. At an LAI of 4, the stand would be about 62 percent canopy cover.

Stagnation

However, stagnation is a common phenomenon on sites with limited LAIs for many species including ponderosa pine (Barrett 1981, 1982, LeBerron 1957, Lynch 1958, Morris and Mowat 1958, Sartwell 1979, Sassamen et.al. 1972, Weaver 1947, 1959, 1961) and Douglas-fir west of the Cascade Mountains (Curtis and Reukema 1970, Harrington and Reukema 1983, Reukema 1979).

Stagnation is a condition where trees are so dense that both height and diameter growth are severely retarded (figures 60 and 61, p. 38) yet mortality from suppression is almost nil (figure 9, p. 8). Lack of mortality refutes the concept of "normal stand development" based upon "suppression mortality". There is little effective "self thinning" on sites poorer than west-side Douglas-fir I and II.

Waring and Schlesinger (1985) devote three chapters in their text on forest ecosystems to discussion of tree physiology and competition. Changes in carbon allocation reflected by the growth efficiency index occur at increasing stand density. Under extreme stress, partitioning of carbon between maintenance and production functions becomes critical. Stagnation represents maximum allocation to maintenance thus tree and stand growth are minimal.

Stagnation is a critical concept in uneven-aged management because the small trees tend not to die. One common approach is to establish number of trees in various diameter classes according to a "Q" ratio. These ratios require increasingly more trees as tree size becomes smaller. For example, a "Q" of 1.2 means there should be 1.2 times more trees in an 16-inch dbh class then in a 20-inch class, 1.2 times more trees in a 12-inch class than in a 16-inch class, 1.2 times more 8-inch trees than 12-inch trees, etc. Plotting trees per acre results in a curve.

Figure 107 represents a "Q" factor of about

1.2. There are 1.3 times more 30 foot than 60 foot trees, 3.3 times more 10 foot than 60 foot trees and 2.5 more 10 foot than 30 foot tall trees.

If the theory of "normal stand development" were correct, most of these smaller trees would die from suppression as stands grow. But in the real world, they do not -- they stagnate. Thus higher "Q" values will require some extensive pre-commercial and commercial thinning if desired tree height and diameter growth are to be attained.

Site identification for Uneven-aged Management

Growth basal area, described in the text, is the best method for establishing stand density levels for uneven-aged management. It directly measures stockability of a site.

Site Index (SI) is a commonly used measure of site quality, purportedly little affected by stand density. And it usually has a single set of data characterizing stockability. Unfortunately, neither of these are correct.

Reduction in SI due to stand density can be dramatic enough to require adjustment of SI curves for lodgepole pine (Alexander 1966), ponderosa pine (Lynch 1958), and grand fir (Stage 1959). In even aged stands, height growth of ponderosa pine and Douglas-fir is reduced by increasing density as shown in Chapter 4, figures 60 and 61, p. 38.

Traditionally, a SI class had only one stocking level associated with it. However, this concept has proven to be inadequate (Chapter 5, pp.49-54; appendix 5). Multiple productivity levels due to inherent differences within a SI class have been well established (Assman 1970, Bradley et al. 1966, Carmean 1975, Cole and Edminster 1985, Curtis 1981, Dahms 1966, 1973, Hagglund 1981, Monserud 1984).

Figures 100 to 106 (pp. 77 and 78) illustrate SI and GBA relationships for seven species in Oregon and Washington. Within a SI class, GBA varies by a 3.6 to 7.5 fold difference. In Germany, Assman (1970) characterizes his "height site" classes by three productivity levels due to stockability differences.

SI should be used with caution when establishing stocking levels for uneven-aged stands. GBA, being a site specific indication of stockability, may be more useful.

Management Implications:

An example of stocking guides might be based on 80 ft^2 BA/A. A density of 80 ft^2 BA/A can mean many different things. For example:

1. At 150% of GBA it means 0.5 in/dec diameter growth of dominant trees and a GBA of 55 ft^2 BA/A. This 80 ft^2 represents maximum stand density for the site resulting in stand stagnation. Height (figures 60 and 61, p.38) and diameter growth (figure 25, p. 16) of younger trees would be seriously depressed.

2. At 100% of GBA it means 1.0 in/dec diameter growth of dominant trees (GBA of 80 ft^2) which is shown to retard height growth (figures 60 and 61, p.38) and diameter growth (figure 25, p. 16) in even aged stands.

3. At 35% GBA for pine it means 2.5 in/dec diameter growth of dominant trees (GBA of 230 ft^2) which is low enough stand density for good expression of height growth (figures 60 and 61, p.38) and smaller tree diameter growth (figure 25, p. 16) for even aged stands.

Uneven aged management must deal with height and diameter growth of the younger (smaller) half of the stand. Height growth concerns are illustrated in figure 108. Twenty ponderosa pine stands were sampled by all size classes providing 118 observations averaging about six tree sizes per stand.

Younger (smaller) trees were compared to the height and site index (SI) of the tallest (and oldest) trees on a 1/5 acre plot. If stand density or crown position of the smaller trees does not affect their height growth, they should average 100% of the SI of the tallest trees. Figure 108 clearly indicates that smaller trees do not average tallest tree SI; in fact, the smaller 20% of the stand averages only about 60% of the tallest tree SI.

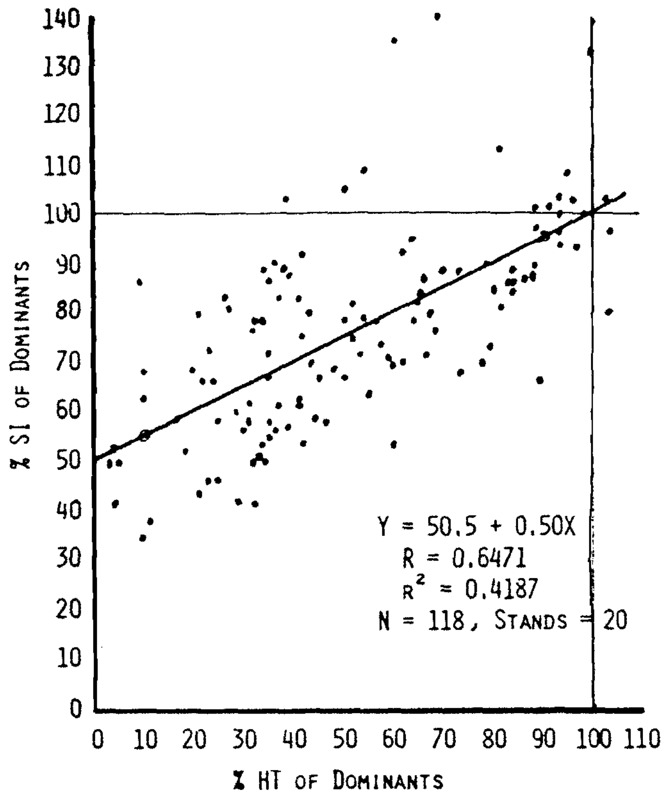


Figure 108. Relationship between site index (SI) of smaller trees and stand dominants in 20 uneven-aged stands. Dominant trees were growing faster than 2.0 in/dec. in diameter. Each smaller tree is shown by its percent of dominant tree height and by its percentage of dominant tree SI. If smaller trees are not affected by overstory, their SI should be the same as dominants. SI was calculated from data by Cochran (1978). Smaller trees are significantly lower in SI than dominants.

As a point of reference, Cochran (1978) presents equations for determining SI at various ages in even aged stands. For SI 80, trees 20 to 40 years old should average about 9 feet per decade (ft/dec) in height, 50 to 70 year old trees 6 ft/dec, 80 to 100 year old trees 4 ft/dec, and 110-130 year old trees 3 ft/dec. How well does the younger half of an uneven aged stand perform compared to these criteria? If height growth is slower, how long will it take for these trees to reach the desired future height?

Manipulation of stand density is an important tool for determining the rate of growth for this younger half so it will replace the older half of the stand at the time desired. Site potential for stockability (GBA) should be considered when evaluating treatment prescriptions.

Density Considerations

Several questions might be asked when considering various levels of stand density.

1. How well do simulation models predict height and diameter growth of the younger half of your stand for the site in question (i.e. GBA potential)? How well can different levels of stand density be evaluated with these models? Models may be appraised by sampling a stand by measuring trees at various ages, measuring height, diameter growth and dbh, and comparing to the model prediction. Does age correspond to dbh and SI class?

2. Is the younger half growing fast enough to replace the older half in the time desired? At the current rate of height and diameter growth, how many years will be required to reach target tree size? Can a change in current stocking affect this number of years?

3. How do resource objectives other than tree productivity affect growth of the younger half of the stand on the site in question? For example, stand density for wildlife habitat might require maintaining a minimum of 80 ft^2 BA/A. How will this density affect number of years to desired future condition for the

GBA potential of the site?

4. How does desired future condition for the site affect selection of a stand density that will attain that condition in the time desired? Or conversely, how is site potential for stockability (GBA) considered when establishing a desired future condition? For example, can the same stand structure (TPA by dbh class) be attained in 120 years on a site with a GBA 50 ft^2 compared to a site of GBA 200 ft^2? Considering site potential for stockability (i.e. GBA), does one adjust stand density (TPA by dbh class), or time to attain the desired future condition or both?

Trees in various age classes (dbh classes) in uneven-aged stands tend to grow differently than they would in even-aged stands of similar age or dbh. The slower rates of younger trees in uneven-aged stands should be expected and accounted for when selecting and programming treatment

Determination of Stockability

Growth Basal Area (GBA) was developed as an index of even-aged stand stockability thus its application to uneven-aged stands has not been clearly demonstrated. However, some means of estimating stockability seems highly desirable. There are two aspects to this evaluation: 1. a stocking index based on dominant trees and, 2. differences in stockability (GBA) between species in the stand.

For a stocking index of even-aged stands, one is asked to select the five largest diameter trees of the dominant species, increment core and take BA/A at each tree, calculate GBA for each tree, and average the results (Chapter 3, p. 27).

This approach was tested (figure 109) to evaluate the relationship between GBA of younger trees compared to dominant trees. Clearly, there is no relationship in the stands sampled which were at low to moderate stocking (i.e. dominants growing at 1.5 to 3.5 in/dec). This suggests that a change in determination of GBA is not warranted at this time.

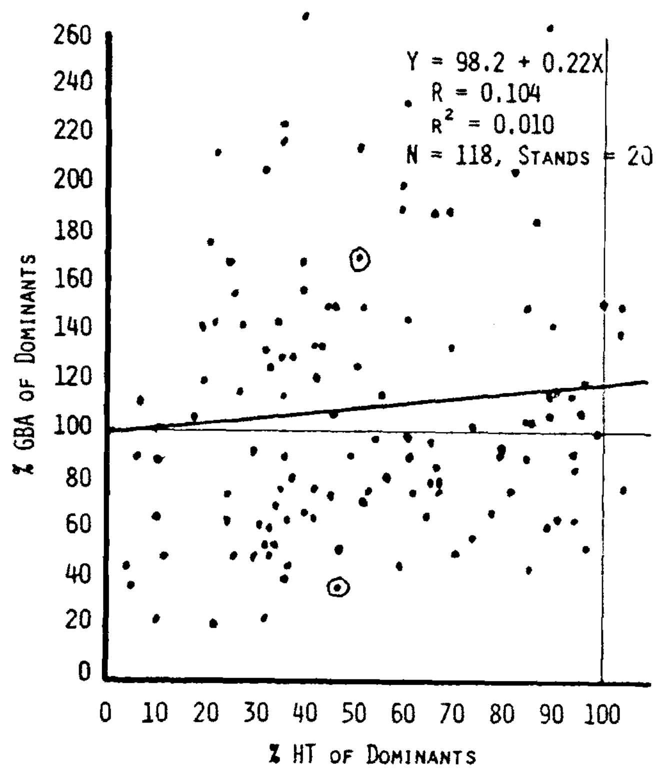


Figure 109. Relationship between tree size and Growth Basal Area (GBA) in uneven-aged stands of moderate to low density (25% to 80% of GBA). GBA was determined for each tree and that tree compared to GBA of stand dominants. For example, a tree half as tall (50%) as dominants had its GBA compared to the dominant tree GBA which might be 30% in one case (lower circled point) to 170% (upper circled point) in another.

However, observation does suggest slowing of diameter growth of smaller trees in uneven-aged stands at higher densities where dominant trees are growing less than 2.0 in/dec in diameter.

Differences in GBA between species often complicates uneven-aged stand management. Table 28 compares ponderosa pine and white fir growth when both are about equal in BA/A. SI is based on age 100 for both species.

Table 28. Differences between ponderosa pine (PP) and white fir (WF) for Site Index (SI) and Growth Basal Area (GBA) on two study sites. Both trees were about equally represented.

Tree	SI	In/dec	BA/A	GBA
North Plot				
PP	84	0.79	159	129
WF	125	1.92	155	254
South Plot				
PP	75	1.01	168	162
WF	117	2.30	180	331

White fir GBA and diameter growth are about double those of ponderosa pine. If one chooses ponderosa GBA as a stockability index, grand fir will reach desired sizes well ahead of ponderosa. If one chooses white fir stockability, ponderosa may take many years to reach desired sizes. The quandary here is difficult to resolve.

For example: average ponderosa pine GBA is 160 ft^2 BA/A. A manager decides that 1.5 in/dec diameter growth (67% of GBA, Table 13, p. 32) is the slowest growth desired. This would be a stand BA/A of 110 ft^2. and thus time to thin. Ponderosa pine would be growing at 1.5 in/dec.

White fir average GBA is 290 ft^2, but it would be growing at only 110 ft^2 BA/A (37% of GBA, Table 13, p. 32) so its diameter growth would be 2.9 in/dec -- nearly twice that of ponderosa pine. At this rate, by the time a 10 in. dbh pine attained 20 in., a white fir would attain 29 in. dbh

Choosing white fir GBA of 290 ft^2 BA/A would be as follows: 1.5 in/dec (67% of GBA) would be 195 ft^2 BA/A. For ponderosa pine, this is 122% of GBA for a diameter growth rate of 0.8 in/dec (Table 13, p. 32). By the time a 10 in. dbh white fir reached 20 in., a ponderosa pine would be only 15 in. dbh. Thus, ponderosa pine may take many years longer than white fir to reach desired sizes.

Establishing Stocking by Diameter Classes

The primary purpose for establishing stocking by various diameter classes is to control stocking and develop a desired distribution of size classes. Two approaches may be used to develop idealized models for uneven-aged stands: use a "Q"-factor approach or describe stand conditions desired in the future.

Desired future conditions emphasizing large trees is illustrated in Figure 110. Target size is 24 inches dbh where dominant trees are averaging 1.5 in/dec diameter growth. The 24 in. dbh size was selected as an average dbh of mature and old growth stands. GBA is 150 ft^2 BA/A.

Diameter growth of 1.5 in/dec was selected for several reasons. 1. It approximates the vigor level of ponderosa pine where it tends to become susceptible to bark beetles. 2. Entering the stand for thinning at 1.5 in/dec means trees are still fairly vigorous and will increase diameter growth promptly to 2.0 to 2.5 in/dec, and thus reach the target dbh of 24 inches in 110 to 130 years. 3. It will provide for a reasonable density of trees needed for a pleasing appearance. 4. And, growth of smaller trees should be acceptable.

Stand density in each dbh class was established to emphasize large trees -- not small trees -- and is based upon a 10% mortality concept: retain only those trees in each dbh class that will be needed in the next larger dbh class plus some for mortality. For example, 10 TPA in the 24 in/ dbh class is increased to 12 TPA in the 20 in. dbh class and they are increased to 14 TPA in the 16 in. dbh class. There is no reason to have a great number of smaller trees -- they contain crown volume that is desired on larger trees.

Stockability (GBA) for the tract is assumed to be 150 sq.ft. BA/A. But 1.5 in/dec is

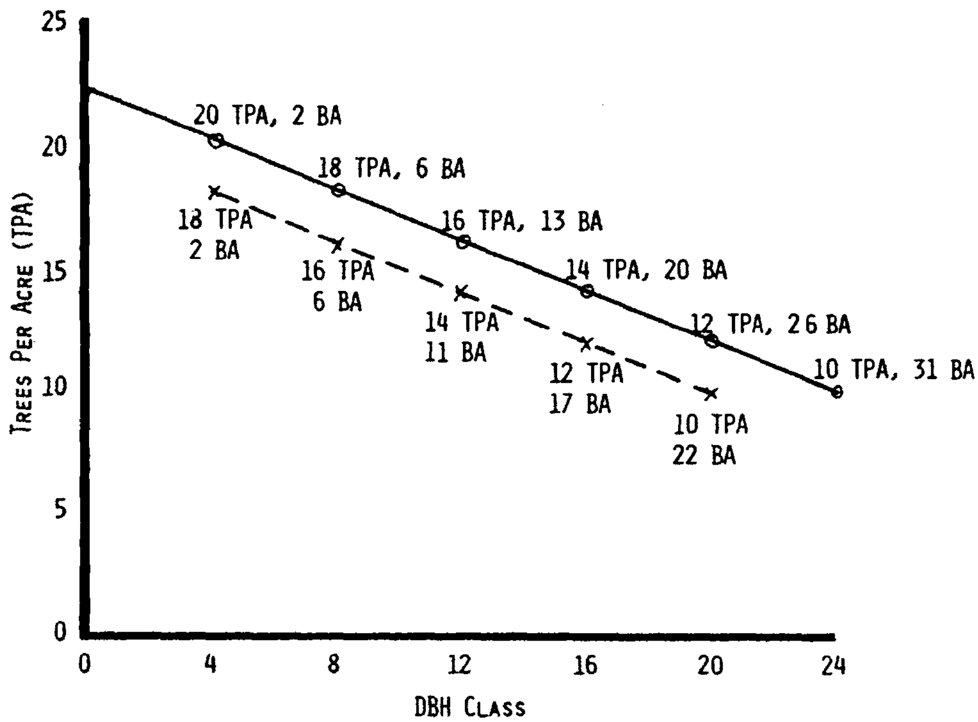


Figure 110. Use of GBA to establish stand densities and diameter growth performance in an uneven-aged situation dedicated to producing a maximum number of large trees. Assume GBA is 150 ft^2 BA/A and that 1.5 in/dec is set as the minimum rate of diameter growth: 1.5 in/dec is 67% of GBA (Table 13, p. 32) for 100 ft^2 BA/A. Distributing trees as shown on the solid line results in 98 ft^2 BA/A. At this time, the stand is entered and thinned to a new stand density shown by the dashed line resulting in 58 ft^2 BA/A. At this density, trees should average 2.3 in/dec diameter growth.

faster growth than that for GBA -- 67% of GBA (Table 13, p, 32) -- so the desired stand density is 100 ft^2 BA/A. At these conditions, the stand is entered and thinned in each diameter class to the TPA and BA/A shown on the dashed line.

NOTE that regeneration of only 22 TPA are required to fill the 0 - 8 dbh classes assuming 10% mortality. Only 18 TPA are wanted by the time trees are 8 in. dbh. These criteria set a desired stocking for regeneration to be established after a thinning entry -- only 22 trees per acre. After thinning, about 58 ft^2 BA/A would remain (39% of GBA, Table 13, p.32) so trees should grow at 2.3 in/dec. Averaging 1.5 and 2.3 in/dec suggests a mean diameter growth rate of 1.9 in/dec or about 126 years to attain 24 in. dbh trees -- **IF** all size trees in the stand grow at the same rate in diameter -- which they may not. The estimate of 126 years to a 24 in. dbh tree is most likely optimistic.

A "Q-factor" system is another approach shown in figure 111. Assume the same criteria as above: site potential is a GBA of 150 ft^2 BA/A, target tree size is 24 in. dbh growing at 1.5 in/dec at 100 ft^2 BA/A. Divide the 100 ft^2 BA/A into five dbh classes of 20 ft^2 BA/A each and calculate the TPA for each class.

Truncate the TPA curve to limit TPA in the 0

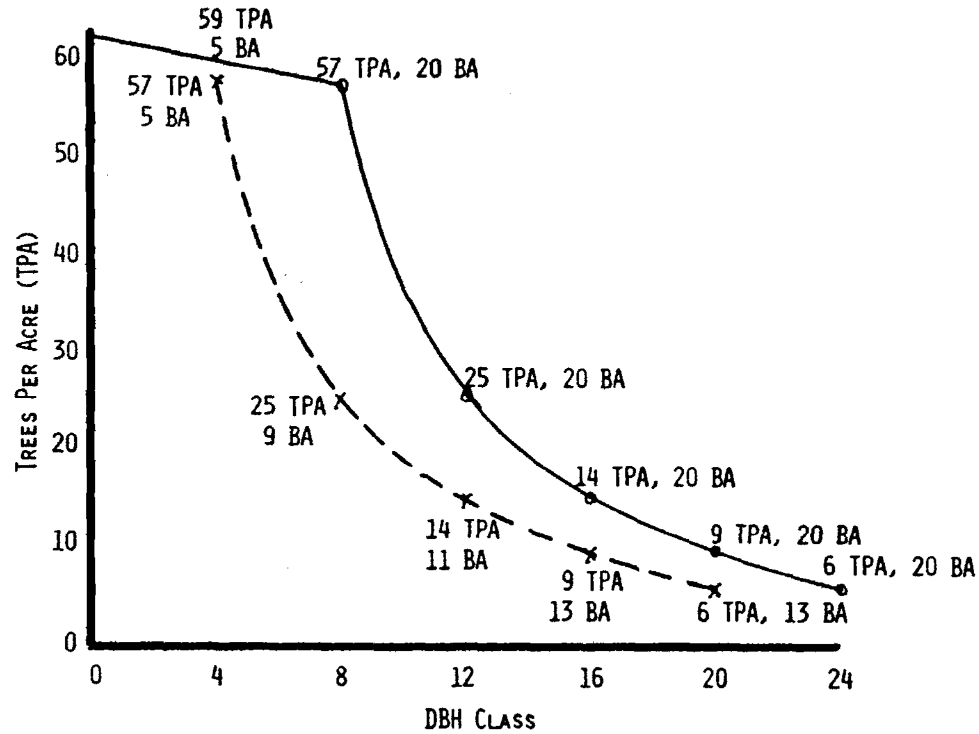


Figure 111. Use of GBA for establishing uneven-aged tree distribution with a "Q" factor concept. Assume GBA is 150 ft^2 BA/A and that 1.5 in/dec is set as the minimum diameter growth rate: 1.5 in/dec is 67% of GBA for 100 ft^2 BA/A. Apportion the 100 ft^2 BA/A evenly into five diameter classes of 20 ft^2 BA/A each and calculate the TPA for each. Truncate TPA by diameter class to provide only enough trees in the 0 and 4 in dbh classes to provide for the 57 TPA wanted in the 8 in. dbh class. The solid line shows stand condition when thinning should be planned. Thin down to the dashed line leaving about 51 ft^2 BA/A which is 34% of GBA for 2.5 in/dec. diameter growth.

and 4 in. dbh class. The assumption wa made that trees smaller than 6 in. dbh could not be sold commercially. Therefore, TPA in the 0 and 4 in. dbh classes are as signed according to the needed TPA in the 8 in. dbh class plus 10% mortality. Only 57 TPA are wanted in the 8 in. dbh class: 57 + 6 = 63 TPA at regeneration and 59 TPA in the 4 in. dbh class.

Thinning the stand is essential if stagnation of the smaller dbh classes is to be avoided. At 1.5 in/dec, a 4 in. dbh class would increase its BA/A by 1.8 times and an 8 in. dbh class by 1.4 times in a decade; at 2.5 in/dec, a 4 in. dbh class would increase by 2.25 times and an 8 in. dbh class by 1.56 times. Stagnation could occur within two decades.

Figures 110 and 111 demonstrate the great latitude a land manager has in designing stocking levels by size classes to meet desired future conditions. Large trees vary from 6 to 10 TPA at 24 in. dbh while 8 in. dbh trees vary from 18 to 57 -- all at a stand entry BA/A of 100 ft^2 and a dominant tree diameter growth of 1.5 in/dec for a GBA of 150.

Recall that GBA's vary from 25 to 400 ft^2 BA/A (appendix 5) and that diameter growth rates other than 1.5 in/dec may be chosen. The most important consideration is to define a desired future condition, appraise site stockability, and establish stocking levels to attain that condition in the time desired.

Summary

Successful application of uneven-aged management requires critical attention to site potentials for stockability and to distribution of stocking within stands. Important elements to consider are: 1. Most stands will stagnate instead of developing according to the concept of "normal stand development." 2. Stand density greatly influences height growth of trees; SI is affected by stand density. 3. A SI class can have several levels of productivity within it and thus several levels of stockability (indexed by GBA); SI may not be a reliable index for stockability. 4. Stocking in various dbh classes can be established to meet any desired future condition and need not be governed by arbitrary rules. 5. Interpreting how a stand has and is developing (reading the stand) and marking trees to take advantage of best tree characteristics are essential for successful application of uneven-aged management.

LITURATURE CITED

Alexander, R.R. 1966. Site indexes for lodgepole pine with corrections for stand density: instructions for field use. USDA For. Serv., Rocky Mtn. For. and Range Exp. Stn., Res. Pap. RM-24. 7 pp.

Assman, E. 1970. The principles of forest yield study. Studies in the organic production, structure, increment and yield of forest stands. Permagon Press, N.Y. 506 pp. illust.

Barrett, J.W. 1981. Twenty-year growth of thinned and unthinned ponderosa pine in the Methow Valley of northwestern Washington. USDA For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-286. 13 pp, illust.

__________ 1982. Twenty-year growth of ponderosa pine saplings thinned to five spacings in central Oregon. USDA For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-330. 15 pp, illust.

Bradley, R.T., J.M. Christie, and D.R. Johnson. 1966. Forest management tables, (British) Forest. Comm. Booklet 16. London. 212 pp.

Carmean, W.H. 1975. Forest site quality evaluation in the United States. Advances in Agron. 27:209-269.

Cochran, P.H. 1978. Height growth and site index curves for managed, even-aged stand of ponderosa pine in the Pacific Northwest. USDA, For. Ser., Pac. N.W. For. and Range. Exp. Stn., Res. Pap. PNW-232.

Cole, D.M. and C.B. Edminster. 1985. Growth and yield of lodgepole pine. In: Lodgepole pine: the Species and its Management (Symposium Proc.), Wash. State Univ., Cooperative Extension, Pullman, WA. pp. 263-290.

Curtis, R.O. 1981. Yield tables past and present. In: Forestry Predictive Models: Problems in Application, Wash. State. Univ., Cooperative Extension, Pullman. pp 1-8.

Curtis, R.O. and D.L. Reukema. 1970. Crown development and site estimates in a Douglas-fir plantation spacing test. For. Sci. 16:287-301.

Dahms, W.G. 1966. Relationship of lodgepole pine volume increment to crown competition factor, basal area and site index. For. Sci. 12:74-82.

__________ 1973. Gross yield of central Oregon lodgepole pine. In: Management of Lodgepole Pine Ecosystems (Symposium Proc). Wash. State. Univ., Cooperative Extension, Pullman. pp 208-232.

Hagglund, B. 1981. Evaluation of forest site productivity. For. Abstracts 42:515-527.

Harrington, C.A. and D.L.Reukema. 1983. Initial shock and long-term stand development following thinning in a Douglas-fir plantation. For. Sci. 29:33-46.

Lynch, D.W. 1958. Effects of stocking on site measurement and yield of second-growth ponderosa pine in the Inland Empire. USDA For. Serv., Intermountain For. and Range Exp. Stn., Res. Pap. INT-56. 36 pp, illust.

Monserud, R.A. 1984. Problems with site index: an opinionated view. In: Proceedings of the Symposium, Forest Land Classification: Experience, Problems, Perspectives. J.A. Backheim, Ed., Univ. Wisc., Wisc. Center, Madison. pp 167-180.

Morris, W.G. and E.L. Mowat. 1958. Some effects of thinning a ponderosa pine thicket with prescribed fire. Jour. For. 56:203-209.

Reukema, D.L. 1979. Fifty-year development of Douglas-fir stands planted at various spacings. USDA For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-253. 21 pp, illust.

Sartwell, C. 1971. Thinning ponderosa pine to prevent outbreaks of mountain pine beetle. In: Precommercial Thinning of Coastal and Intermountain Forests in the Pacific Northwest. Wash. State. Un., Cooperative Extension Serv., Pullman, WA.

Sassaman, R.W., J.W. Barrett, and J.G. Smith. 1972. Economics of thinning stagnated ponderosa pine sapling stands in the pine-grass areas of central Washington. USDA For. Serv., Pac. N.W. For. and Range Exp. Stn., Res. Pap. PNW-144. 17 pp, illust.

Stage, A.R. 1959. Site index curves for grand fir in the Inland Empire. USDA For. Serv., Intermountain For. and Range Exp. Stn., Res. Note No. 71. 4 pp, illust.

and grand fir zones, Mt. Hood National Forest. USDA, For. Ser., Pac. N.W. Region, R6 Ecol TP 004-88.

Waring, R.H. and W.H. Schlesinger. 1985. Forest ecosystems: concepts and management. Academic Press, Orlando, FL. 340 pp, illus.

Weaver, H. 1947. Management problems in the ponderosa pine region. N.W. Science 21:160-163.

_________ 1959 Ecological changes in the ponderosa pine forests of the Warm Springs Indian Reservation. Jour. For. 57:15-20.

_________ 1961. Ecological changes in the ponderosa pine forests of Cedar Valley in Southern Washington. Ecology 42:416-420.

APPENDIX 7

GBA Sampling Forms

Three kinds of forms are provided for reproduction:

1. A Field form as discussed in Chapter 3.

2. A form for determining a GBA curve based on percent of BA dib as depicted in figure 15.

3. A form for determining a GBA curve by horizontal stand sectioning.

1. Field form for determining stand GBA as discussed in Chapter 3.

SITE INDEX - GROWTH BASAL AREA

Plot No.______ **Prism Factor______**

SI	Species__________	% of Stand BA__________	Observer__________	BASAL AREA BY SPECIES		
Age ______	DBH______	20ths______	GBA now______		______@______	______@______
Ht.______	Sapwd______	TBA______	GBA100______		______@______	______@______
SI ______					______@______	______@______
Age ______	DBH______	20ths______	GBAnow______		______@______	______@______
Ht.______	Sapwd______	TBA______	GBA100______		______@______	______@______
SI ______					______@______	______@______
Age ______	DBH______	20ths______	GBAnow______		______@______	______@______
Ht.______	Sapwd______	TBA______	GBA100______		______@______	______@______
SI ______					______@______	______@______
Age ______	DBH______	20ths______	GBAnow______		______@______	______@______
Ht.______	Sapwd______	TBA______	GBA100______		______@______	______@______
SI ______					______@______	______@______
Age ______	DBH______	20ths______	GBAnow______		______@______	______@______
Ht.______	Sapwd______	TBA______	GBA100______		______@______	______@______
SI ______					______@______	______@______
SI ______	Prod*______	$\overline{\text{TBA}}$______	$\overline{\text{GBA100}}$______	Avg	______@______	______@______
					______@______	______@______
					______@______	______@______

*Prod (ft^3/A/Yr) = GBA*SI*0.0044 *(SI age 100)*
= GBA*SI*0.0072 *(SI age 50)*

SITE INDEX - GROWTH BASAL AREA

Plot No.______ **Prism Factor______**

SI	Species__________	% of Stand BA__________	Observer__________	BASAL AREA BY SPECIES		
Age ______	DBH______	20ths______	GBA now______		______@______	______@______
Ht.______	Sapwd______	TBA______	GBA100______		______@______	______@______
SI ______					______@______	______@______
Age ______	DBH______	20ths______	GBAnow______		______@______	______@______
Ht.______	Sapwd______	TBA______	GBA100______		______@______	______@______
SI ______					______@______	______@______
Age ______	DBH______	20ths______	GBAnow______		______@______	______@______
Ht.______	Sapwd______	TBA______	GBA100______		______@______	______@______
SI ______					______@______	______@______
Age ______	DBH______	20ths______	GBAnow______		______@______	______@______
Ht.______	Sapwd______	TBA______	GBA100______		______@______	______@______
SI ______					______@______	______@______
Age ______	DBH______	20ths______	GBAnow______		______@______	______@______
Ht.______	Sapwd______	TBA______	GBA100______		______@______	______@______
SI ______					______@______	______@______
SI ______	Prod*______	$\overline{\text{TBA}}$______	$\overline{\text{GBA100}}$______	Avg	______@______	______@______
					______@______	______@______
					______@______	______@______

*Prod (ft^3/A/Yr) = GBA*SI*0.0044 *(SI age 100)*
= GBA*SI*0.0072 *(SI age 50)*

2. A form for determining a GBA curve based on percent of BA dib as depicted in figure 15.

Increment-core a dominant tree according to the instructions in Chapter 2. Mark the core at the radius growth rates at the head of each column (i.e., 3, 5, 7/20ths). Many times all radius growth rates will not be available, particularly the very slow (3, 5, 7/20ths) or the very rapid (40, 45, 50/20ths). Note that ring widths for each radius growth rate are shown at the bottom of the form.

Measure the distance from the outside of the core to the growth rate and record in the appropriate column.

Determine dib at each growth rate.

Determine tree BA for each dib.

Determine the percent of BA at 10/20ths for each growth rate.

These are the observations used to determine a GBA curve. Two approaches may be used: Determine a mean and confidence interval for each diameter growth rate using at least 100 trees and no less than 20 observations for each radius growth rate. Hand-draw a curve through the average points (figures 75-80) or submit the data to regression analysis as discussed in Chapter 2. Draw the regression curve over the plotted data points to evaluate curve shape. The basal area/diameter growth relationship is **not** always a precise mathematical curve.

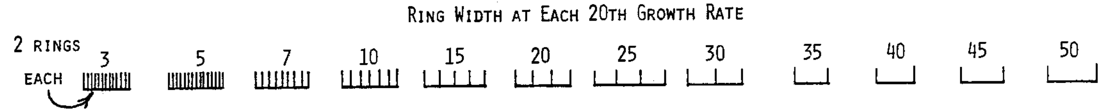
2/5/88
FCH

GBA Evaluation for % of 10^{20ths} DIB

Species__________ Date__________ Location____________________ Crew__________

		20ths												
		Now	3	5	7	10	15	20	25	30	35	40	45	50
dbh______	Inches dib in to rate	0												
Bark X2____	dib @ rate													
dib______	BA @ dib @ rate													
BA @ dib	% of BA @ 10^{20ths}													
dbh______	Inches dib in to rate	0												
Bark X2____	dib @ rate													
dib______	BA @ dib @ rate													
BA @ dib	% of BA @ 10^{20ths}													
dbh______	Inches dib in to rate	0												
Bark X2____	dib @ rate													
dib______	BA @ dib @ rate													
BA @ dib	% of BA @ 10^{20ths}													
dbh______	Inches dib in to rate	0												
Bark X2____	dib @ rate													
dib______	BA @ dib @ rate													
BA @ dib	% of BA @ 10^{20ths}													
dbh______	Inches dib in to rate	0												
Bark X2____	dib @ rate													
dib______	BA @ dib @ rate													
BA @ dib	% of BA @ 10^{20ths}													
dbh______	Inches dib in to rate	0												
Bark X2____	dib @ rate													
dib______	BA @ dib @ rate													
BA @ dib	% of BA @ 10^{20ths}													

RING WIDTH AT EACH 20TH GROWTH RATE



3. Form for determining a GBA curve by horizontal stand sectioning as briefly discussed in Chapter 2.

Establish fixed-area plots centered on suitable GBA trees. Trees and stands should be 50 to 150 years old, even-aged, and without mortality. Plot size is determined by size and number of trees that fall within the plot. More than 15 trees results in tedious sampling with little improvement in precision.

Measure the dbh, bark thickness (and double it), and increment-core each tree in the plot and record. Mark each core by tree dbh or tree number.

For the GBA tree: Mark the core where about three rings average the rates of radius growth listed for each column (3, 5, 7, 10/20ths, etc.). Note that ring width for each rate is shown at the bottom of the form. Count the number of years from present to the marked rates of growth rate and record in "Years before present."

Measure from the outer end of the core in to each growth rate and record in "Inches dib in to rate."

Determine diameter inside bark (dib) for each growth rate (double "Inches dib in to rate").

Determine BA at each dib.

Determine percent of the dib BA at 10/20ths for each radius growth rate. This is the same procedure described in the previous section (Appendix. 5, form #2). Compare these data with those determined at the bottom of the second page of the form for similarity in estimating percent GBA.

Determine dbh by adding "Bark X2" to each dib at each growth rate. When the doubled bark thickness of the current tree is too great for trees of smaller dbh, a dbh vs. bark thickness regression should be used to estimate bark thickness at small dbh's.

Determine tree BA for each dbh: (inches dbh)^2 X 0.005454.

For all other trees in the plot: Count the number of years from present in from the outer end of the core for each radius growth rate and mark the core. NOTE: Ring width on these cores is **not** used. The core is being dated for the time when the GBA tree was growing at the specific rates.

Measure in from the outer end of the core to each mark and record in the appropriate radius growth rate column at "Inches in to rate."

Determine dbh: Double "Inches in to rate" and add "Bark X2" or suitable value for smaller dbh trees.

Determine BA at each dbh and growth rate.

On the **second page of the form:** Determine total plot BA for each radius growth rate. This is the stand BA at which the GBA tree grew at the specified radius growth rates.

Take stand BA at each radius growth rate as a percentage of stand BA for 10/20ths. Compare these data with those derived by taking percent of BA at dib of 10/20ths.

Note the provision under the "now" column opposite "species", "dbh", and "dib" for recording current diameter growth rate for each tree. These data are used to develop a regression equation predicting diameter growth of co-dominant, intermediate, and suppressed trees based on GBA tree growth. When quadratic mean dbh is determined, these data may be used to refine equation (9).

BA Sectioning for GBA

2/6/88
FCH

Fixed Plot Size__________ Species__________ Date__________ Location______________________________ Crew__________

20ths

		Now	3	5	7	10	15	20	25	30	35	40	45	50
Species______	dbh______ dib______													
Bark X2______	Years before present	0												
	Inches dib into rate	0												
	dib @ rate													
	BA @ dib @ rate													
	dbh @ rate													
	BA @ dbh @ rate													
	% of BA @ 10 20ths													
Species______	dbh______ dib______													
Bark X2______	Inches in to rate													
	dbh @ rate													
	BA @ dbh @ rate													
Species______	dbh______ dib______													
Bark X2______	Inches in to rate													
	dbh @ rate													
	BA @ dbh @ rate													
Species______	dbh______ dib______													
Bark X2______	Inches in to rate													
	dbh @ rate													
	BA @ dbh @ rate													
Species______	dbh______ dib______													
Bark X2______	Inches in to rate													
	dbh @ rate													
	BA @ dbh @ rate													
Species______	dbh______ dib______													
Bark X2______	Inches in to rate													
	dbh @ rate													
	BA @ dbh @ rate													

	20ths												
	Now	3	5	7	10	15	20	25	30	35	40	45	50
Species______ dbh______ dib______													
Bark X2______ Inches in to rate													
dbh @ rate													
BA @ dbh @ rate													
Species______ dbh______ dib______													
Bark X2______ Inches in to rate													
dbh @ rate													
BA @ dbh @ rate													
Species______ dbh______ dib______													
Bark X2______ Inches in to rate													
dbh @ rate													
BA @ dbh @ rate													
Species______ dbh______ dib______													
Bark X2______ Inches in to rate													
dbh @ rate													
BA @ dbh @ rate													
Species______ dbh______ dib______													
Bark X2______ Inches in to rate													
dbh @ rate													
BA @ dbh @ rate													
Species______ dbh______ dib______													
Bark X2______ Inches in to rate													
dbh @ rate													
BA @ dbh @ rate													
TOTAL BASAL AREA BY RATE													
PERCENT OF BASAL AREA for 10^{20ths}													

RING WIDTH AT EACH 20TH GROWTH RATE