

Stocking Standards for Uneven-aged Interior Douglas-fir

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INTRODUCTION

Interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) is a wide-ranging species with a very broad ecological amplitude. In the dry parts of its range, it grows in an uneven-aged fire-dominated subclimax. Historical fire frequency at Knife Creek in the Interior Douglas-fir Dry Cool (IDFdk3) biogeoclimatic zone is between 16 and 18 years (Daniels et al. 1995), and these frequent fires dominated the development of the natural stands. On the basis of this natural condition, the species is well suited to an uneven-aged management regime.

Large timber and proximity to highways and manufacturing plants make the Douglas-fir forests of the IDF highly desirable for timber harvesting. Their low elevation and limited snowpack makes the forests important winter habitat for mule deer (Armleder et al. 1986), and the forests are also used for cattle grazing. Their proximity to population centres makes dry-belt Douglas-fir forests important for public recreation. Such multiple demands on the land base impose complex forest management objectives, which in turn direct prescriptions for forest management.

Interior Douglas-fir tends to regenerate naturally in very dense thickets that establish in canopy gaps after disturbance. Thickets at very high densities tend to stagnate. The physiology of stagnation is poorly documented, but one possible explanation is that competition for soil moisture limits the trees' ability to take up water. Trees shed needles in response to the moisture stress, which in turn increases the light available in the stand. Relatively few trees die in this state, but net productivity is very low (J.P. Kimmins, University of British Columbia, Faculty of Forestry, pers. comm., 1996). Tree and stand vigour is reduced, growth declines, and risk of insect or disease attack increases. Management of stand density is therefore a critical activity in uneven-aged Douglas-fir forests.

Little guidance is available to silviculturists in the selection of appropriate residual stand density in this forest type. Complex stand structures influence carrying capacity, and effective ways to allocate growing space to structural components occupy much of the current literature (Hann and Bare 1979; Guldin 1991; Fiedler 1995; O'Hara and Valappil 1995). Few authors, however, provide detailed guidance on setting residual growing stock. The relationships between growth and density are poorly described for interior Douglas-fir. Functional linkages exist between stand density, diameter growth, and basal area growth, which can be observed with relative ease through retrospective analysis of growth. Understanding these functional relationships is critical to setting appropriate stocking levels. Silviculturists are making deci-

sions on stocking levels daily without knowledge of appropriate stocking, and simple tools for decision making are urgently needed.

This paper describes a retrospective case study of basal area growth and density relationships from four stands in the Knife Creek block of the University of British Columbia's Alex Fraser Research Forest. The objectives of the case study were to examine the functional relationships affecting growth, and to describe appropriate stocking levels for uneven-aged Douglas-fir forests for Knife Creek. A simple tool to assess stocking is calibrated and tested.

Stocking versus
Density

To avoid confusion, it is necessary to distinguish between stocking and density. Density is the quantitative measure of the occupation of a site by trees, expressed either as an absolute measure (number of stems, basal area, or volume per unit area) or an expression of the number of trees and their size (Curtis relative density, stand density indices, or crown competition factor) (Ernst and Knapp 1985; Davis and Johnson 1987). Density is a fact that can be attributed to a stand (Davis and Johnson 1987).

Stocking is defined as the density of the subject stand relative to the density of a reference stand (Davis and Johnson 1987), or relative to the optimum condition (Ernst and Knapp 1985; Davis and Johnson 1987; Nyland 1996). Stocking is the description of a stand related to its management objectives.

Problem Statement

Selection management requires explicit description of the stand structural objectives. Although alternative approaches are available, this paper discusses stand structure regulation by BDq (Basal area, maximum Diameter, and diminution quotient) (Guldin 1991; Matthews 1991; Fiedler 1995).

The arrangement of stocking by diameter class (D and q) is essentially a design process that describes the physical qualities of the stand required to meet management objectives. The level to which the stand is stocked is, however, a biological or ecological interpretation. Regulating stand structure and controlling stocking ensures that stand growth is maintained and management objectives are met (Hann and Bare 1979).

Dry Douglas-fir forests of the Interior of British Columbia have had a history of high-grading. Harvesting did not seek to regulate stand structure; instead, harvesting simply removed timber. This high-grading was made possible by the abundance of advanced regeneration that allowed heavy cutting to leave a regenerated stand. High-grading entries are dysgenic (Howe 1995), and leave an inappropriate stand structure composed of low-vigour trees, which are susceptible to insect and disease attack. Such stands are not capable of growing at a rate that maximizes site productivity. Appropriate stand structure targets and stocking control ensure that harvesting will meet management objectives and maximize growth, and rigorous attention to stocking control is critical.

Failure to adequately address residual stocking puts management objectives at risk. Carrying too little stocking means lost timber production and reduced wood quality. Carrying too much stocking also means lost timber productivity because of stagnation and mortality. More importantly, stands grown under intense competition have reduced vigour and are therefore more susceptible to insect or disease attack (Boyce 1961; Furniss and Carolin 1980; Larsson et al. 1983; Carlson et al. 1985; Entry et al. 1991; McDonald 1991; Dolph et al. 1995). In addition, trees grown closely together are slender with

small crowns, and are at high risk of loss because of wind or heavy snow (Herman and Lavender 1990).

The maximum size/density relationship represents the absolute limit of density; it is a function of species, site quality, and stand structure (Sterba and Monserud 1993). Stand growth is maximized when a stand is fully stocked, but below the level where suppression and mortality commence. A range of stocking produces the maximum stand growth (Daniel et al. 1979; Lotan et al. 1988); optimum stocking is conveniently stated as a proportion of maximum carrying capacity. Growing a stand at the lowest stocking that still captures all the growing space (B-level Stocking) maximizes both stand growth and individual tree growth (Daniel et al. 1979; B.C. Ministry of Forests 1992). In the absence of good information, stocking guidance usually takes the form of “rules-of-thumb” (Marquis 1976; B.C. Ministry of Forests 1992).

Very broad-based rules do not provide sufficient guidance for the silviculturist who seeks to set residual stocking goals. Silviculturists need:

- an understanding of functional relationships that govern growth;
- stocking standards for timber management in uneven-aged Douglas-fir stands that reflect the biogeoclimatic conditions and species composition of the target stands; and
- simple tools by which stocking can be assessed and cutting plans developed.

METHODS

Four separate stands were sampled on the Knife Creek block of the UBC/Alex Fraser Research Forest near Williams Lake, B.C. The stands selected were relatively flat mesic areas in the IDFdk3. Two of the stands had been cut by diameter-limit methods more than 20 years before measurement, and two stands had no known harvest history. None of the stands have had any forest management disturbance in the past 20 years, except some salvage of bark beetle-caused mortality. The sites were selected for their topographic uniformity and treatment history, and were chosen to represent the range of conditions encountered on mesic sites within the IDFdk3 in the Knife Creek Block.

The stands were sampled systematically by fixed-area plots. Ten plots were established at 100 m intervals on a rectangular transect through each stand. One plot was discarded because it contained a large stump from a tree salvaged after bark beetle mortality.

Layer 1 (dbh \geq 12.5 cm) and layer 2 (dbh 7.5–12.4 cm) trees were measured on a plot of 7.98 m radius (200 m²). Each tree in layer 1 and 2 had dbh recorded to the nearest millimetre, 10-year radial increment recorded to the nearest half millimetre, and vigour class (good, medium, or poor) assessed by external criteria. Radial increment was measured by one increment core, taken from the north side of the tree at breast height. Relatively few plots were measured on each stand, and their size was relatively small because of the labour required for measuring radial increments on many trees. In total, 794 trees were measured on 39 plots. Field work was completed in November. The short days and dark conditions required that radial increments were tallied using flashlights and hand lenses.

Although layer 3 (height ≥ 1.3 m, dbh < 7.5 cm) and 4 (height < 1.3 m) trees were measured, they have been excluded from these analyses because large numbers of small trees have great influence on stem count but not basal area. Discussions of relative density, quadratic mean diameter, and basal area therefore require stipulation of minimum diameter. All analyses, results, and discussion in this report are limited to trees exceeding 7.4 cm dbh.

Growth was measured by the radial increment of trees alive on the plots in November 1996. Dead trees were not measured, and all discussion of growth therefore excludes mortality.

The small sample size and limited replication necessitate caution in interpreting the results of this retrospective case study. The results of the analyses should therefore not be extrapolated outside the Knife Creek Block without careful validation.

Data from the tally sheets were entered into a purpose-built spreadsheet (MS Excel 5.0) that calculated diameter classes, basal area, basal area increment, and other required data. All subsequent data analyses were carried out using the Excel spreadsheet program and its functions.

EXAMINING FUNCTIONAL RELATIONSHIPS

Understanding the links between stand density and growth is a core issue in determining appropriate stocking levels. It is widely accepted that stand density affects the diameter growth of a given tree, and therefore the basal area growth of the stand. The relationships between density and diameter growth must vary by species and site productivity.

Stand Structure

The four stands chosen for sampling exemplified two distinctly different stand structures. Although all four stands display the “inverse-j” diameter distribution, two of the stands had been harvested by diameter-limit cutting; all of their density is concentrated between the 10- and 35-cm classes. The other two stands have not had any harvesting disturbance. Stand tables for the four sites are presented graphically in Figure 1.

When radial growth was compared for all trees, it was apparent that stand structure has a significant effect on increment. Figure 2 shows the average radial increment of sampled trees by 1-cm diameter classes, for each of the four blocks sampled. The function for radial growth in the unlogged stands (BM + WR and Jones Creek on the legend) follows the form suggested by Schütz (1975) and Saraçoglu (1988)—generally increasing growth with increasing diameter. The two stands that have been logged show a much different functional form, with rapid rise and then decline in growth rates as diameter increases. This is probably attributed to the extreme crowding that the trees experience as diameter increases (i.e., approaching the maximum size/density relationship), but may also be related to dysgenic tree selection. The model “Prognosis” employs a functional form for diameter increment that is the same as that shown for the logged stands (H. Temesgen, University of British Columbia, Faculty of Forestry, pers. comm., May 1997).

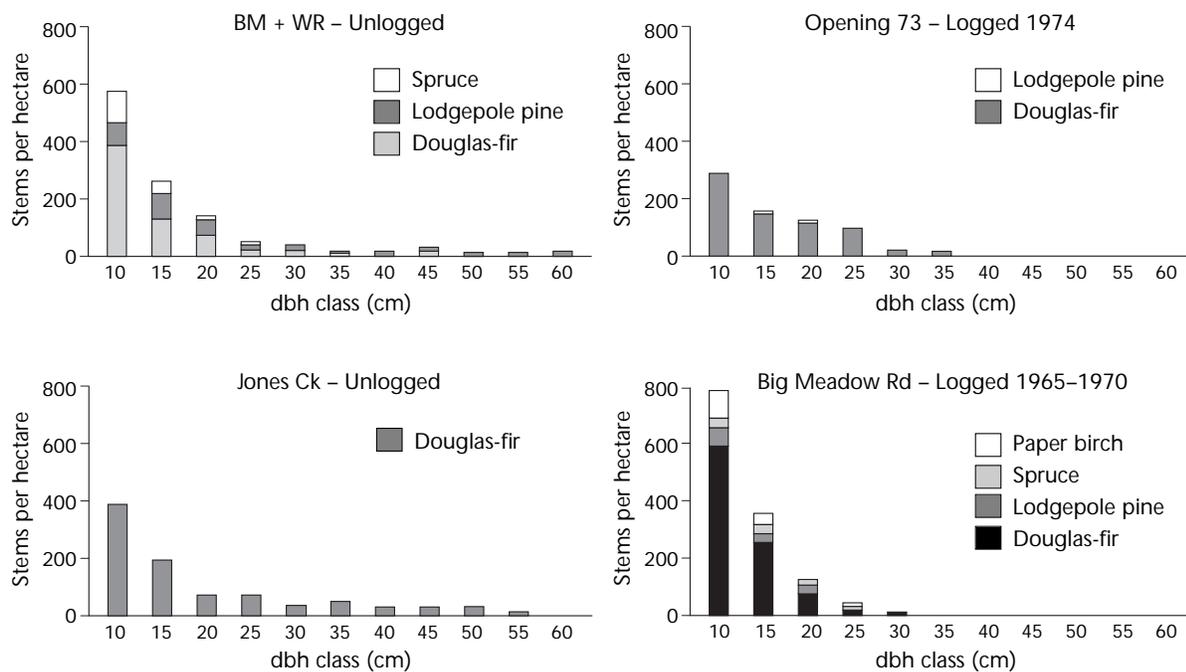


FIGURE 1 Stand density (stems per hectare) by species and dbh (stems > 7.4 cm dbh only).

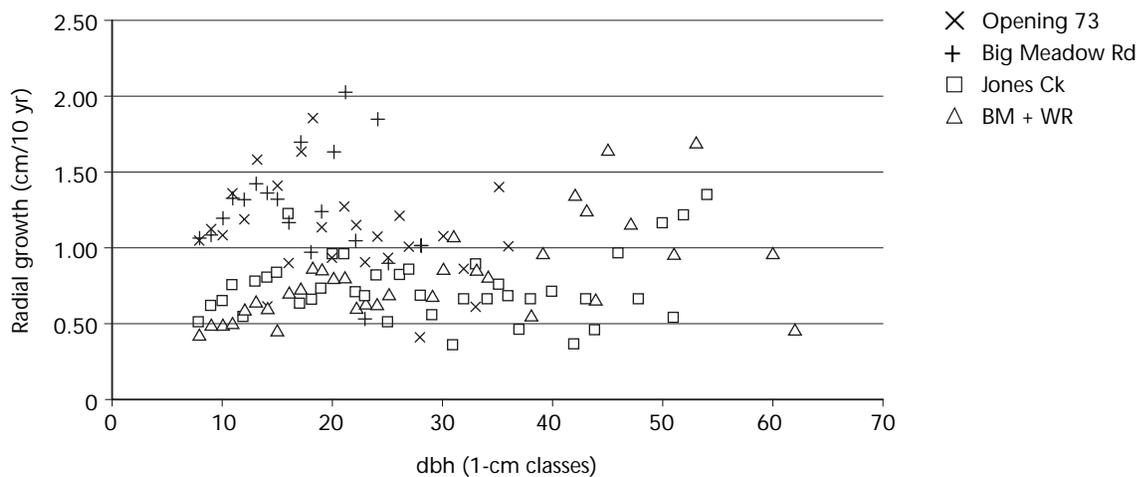


FIGURE 2 Radial growth as a function of diameter and stand structure.

Functional Relationships of Basal Area Growth

Tree diameter growth, and hence basal area growth, is a function of density and site quality. Determining the functional relationships that control basal area growth was a prime objective of this project. The data were summarized to examine growth as a function of density, quadratic mean diameter (D_q), and Curtis relative density (RD). Regression equations were attempted, but abandoned because of apparent autocorrelation. The ability to forecast basal area growth is critical to establishing appropriate re-entry periods for a given harvesting prescription. Descriptive statistics were compiled for basal area growth from the data, and are presented below in Table 1.

Empirical evidence indicates that growth will be higher after disturbance than the undisturbed stands examined; how much higher is unknown at this

TABLE 1 Descriptive statistics for blocks surveyed (all statistics include only stems > 7.4 cm dbh)

Site data	Unlogged		Diameter-limit cut		Total
	BM+WR	JonesCk	BMRd	Open73	
Average of stems per hectare	1138.56	874.75	1309.62	734.79	1011.25
StdDev of stems per hectare	560.96	517.99	560.00	310.87	528.43
Average of m ² /ha > 7.4	31.22	31.89	17.52	18.13	24.53
StdDev of m ² /ha > 7.4	6.58	10.64	6.58	8.62	10.60
Average of 10 yr growth m ² /ha > 7.4	3.82	3.50	5.63	3.80	4.20
StdDev of 10 yr growth m ² /ha > 7.4	1.08	1.55	1.90	1.24	1.67
Quadratic mean diameter	18.68	21.54	13.05	17.72	
Curtis relative density	7.22	6.87	4.84	4.30	

time. An estimate of growth based on the average of all stands examined should be a conservative estimate of periodic basal area increment, and will be useful until more precise estimates are available.

Relationship of Growth to Density

Within limits, height growth is a function of site quality, and diameter growth is a function of stand density. A range of appropriate density exists across which stand growth is maximized—this range of density is the management zone. Using basal area increment as a measure of growth, the relationship between density and growth was examined to describe Langsaeter’s relationship as discussed by Lotan (1988).

Langsaeter’s Curve

Langsaeter’s curve describes the relationship of current or periodic increment to total standing stock. The data acquired from the 39 plots in Knife Creek suggest a curve of a form similar to Langsaeter’s. Using multiple linear regression techniques, Langsaeter’s curve was estimated for the Knife Creek Block (Figure 3). Although the fit of the curve is poor ($R^2 = 0.113$, significance $P=0.115$), the functional form is appropriate. The logarithmic curve employed to describe the function does not provide a point of inflec-

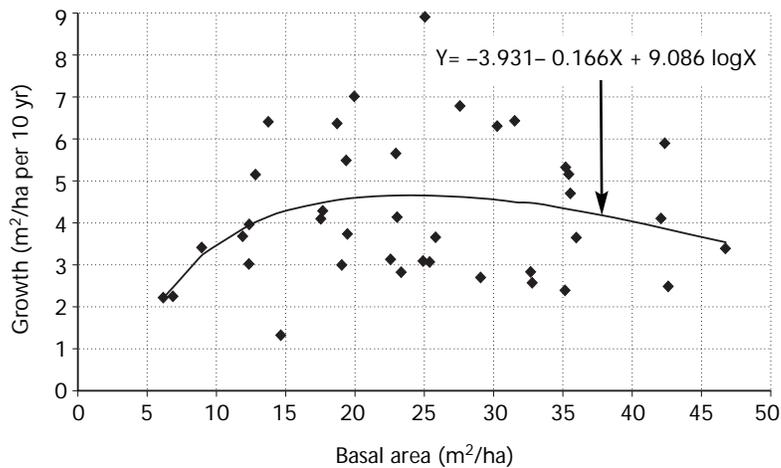


FIGURE 3 Langsaeter’s curve for the IDFdk3 at Knife Creek (multiple $R^2 = 0.113$).

tion, so B-level stocking (the lowest density that fully occupies a site) could not be calculated based on the regression curve.

To estimate B-level stocking for Knife Creek, the data were partitioned on the independent axis, and linear regressions performed on each part of the data (Figure 4). Moving the partition through the data, recalculating the regressions, and observing the residual sum of squares yielded the two regression equations with the lowest aggregate residual sum of squares. The point where these two equations intersect is used as an estimate of the point of inflection of Langsaeter’s curve. By this method, B-level stocking was estimated as 17.5 m²/ha.

CONSTRUCTION OF A GINGRICH STOCKING CHART

Stocking guides represent the biological potential of a site to support stand density. When the maximum density is shown, stocking can be described relative to that maximum value. A stocking chart developed by Gingrich [sic]¹ (1967) displays stand basal area and stems per hectare, and includes maximum density and suggested stocking levels. Ernst and Knapp (1985) set out a sequence of steps to develop a Gingrich chart, and those steps follow below.

Developing a
Reference Level

Reference levels are “the absolute stand density that we would normally expect . . . under some standard condition . . .” and are either a standard of maximum competition, or no competition (Ernst and Knapp 1985). It is with this reference level that relative density and residual stocking targets are described. Ernst and Knapp (1985) recommend that a standard of maximum competition is most useful.

The data collected at Knife Creek provided some very high densities across a wide range of quadratic mean diameters. When size/density data from the Knife Creek block were plotted on natural log axes, a reasonable re-

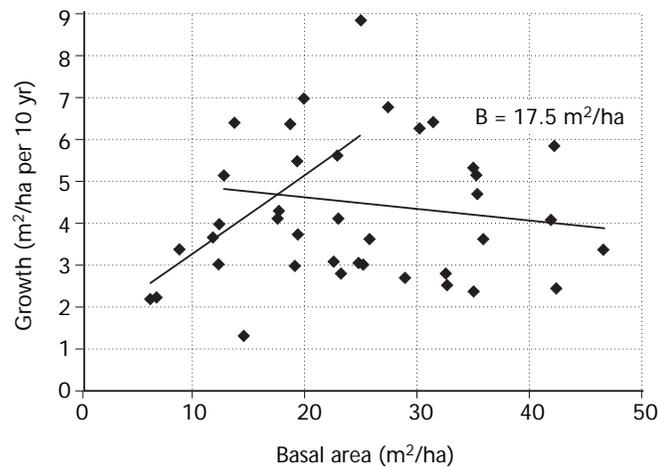


FIGURE 4 Calculation of B-level stocking by partitioned linear regressions.

¹ This first reference and the citation under “References” contain the unfortunate misspelling of Gingrich’s name in his article from 1967. All other references to this author contain the correct spelling of his name.

relationship of maximum size/density appeared to be present. The self-thinning rule (Long 1985) was employed because the slope of the self-thinning line (-3/2) seemed to fit the data well. A limiting size/density function was determined by:

- transforming the quadratic mean diameter (Dq) and density to natural logarithms;
- assuming the slope of the function to be -3/2; and
- moving the y-axis intercept until the function equalled the highest data point.

The simple function that results is the maximum size/density relationship for the Knife Creek Block, and is shown in Figure 5. The function was transformed to natural antilogs and manipulated to calculate the limit of density for a given quadratic mean diameter, according to Equation 1.

Using the values for stems per hectare that resulted from Equation 1, the basal area implied for each maximum density/ Dq combination was calculated according to Equation 2. The resulting data points were charted to create the reference level equivalent to the limiting size/density relationship for the stands sampled.

$$\text{Stems per hectare} = e^{11.718} \times Dq^{-1.5} \quad (1)$$

where: $Dq = 12 \rightarrow 30$ (increment = 2)

$$\text{Basal area per hectare} = \frac{\left(\frac{Dq}{2}\right)^2 \times \pi}{10\,000} \times \text{stems per hectare} \quad (2)$$

where: $Dq = 12 \rightarrow 30$ (increment = 2)

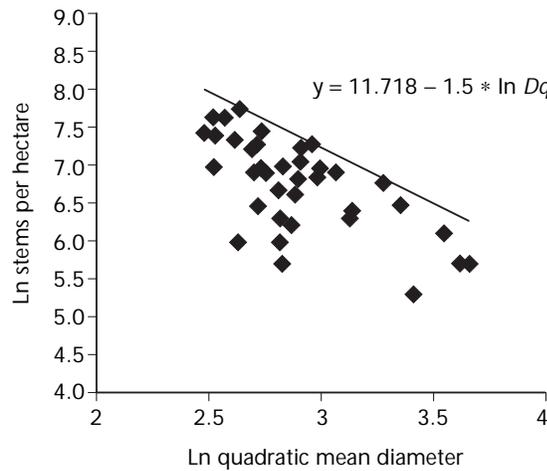


FIGURE 5 Maximum size/density relationship from the -3/2 power law for Knife Creek plots.

Stocking Levels

Stocking levels are a function of site quality, species, and management objectives, defined for an “ideal” stand (Gingrich 1967; Ernst and Knapp 1985; Davis and Johnson 1987; Purri et al. 1988; Nyland 1996). Stocking levels are shown on the stocking chart to depict a range of acceptable stocking—maximum and minimum stocking levels that delimit the management zone for a given objective. For a timber management objective, the lower limit should be the lowest stocking that represents full site occupancy, and the upper limit should equal the onset of competition-induced mortality.

Ernst and Knapp (1985) suggest that stocking limits should be based on experience and research in growth response to various levels of residual basal area. Other authors (Drew and Flewelling 1979; Long 1985; Lotan et al. 1988) suggest a different method of establishing stocking levels, in which proportional decreases of the reference level are used.

The stocking levels suggested by these authors are based on even-aged stands—I have assumed that the theory will extend to stocking levels for uneven-aged stands. On that basis, the stocking levels suggested by Long (1985) were used with the upper limit set at 60% and the lower limit set at 35%. The limits were drawn on the chart by proportionately reducing the maximum size/density line.

Creating a Gingrich Chart for Knife Creek

The background of the chart shows the isolines of quadratic mean diameter (Dq) that were calculated according to the formula shown at Equation 2 above.

1. Stems per hectare were varied between 100 and 3000 in increments of 10.
2. Basal area was calculated for each quadratic mean diameter and density.
3. Functions were graphed.
4. Maximum size/density function (Equation 1) was added to the chart.
5. Stocking levels were calculated for each Dq (as a percentage of the maximum size/density value) and added to the chart.

The Gingrich chart developed from the data collected at Knife Creek is shown at Figure 6.

Gingrich Chart Validation

The Gingrich chart was tested by observing the basal area growth for each plot, when classified by the stocking limits drawn on the chart as understocked, stocked, or overstocked (Figure 7). The mean volume growth for

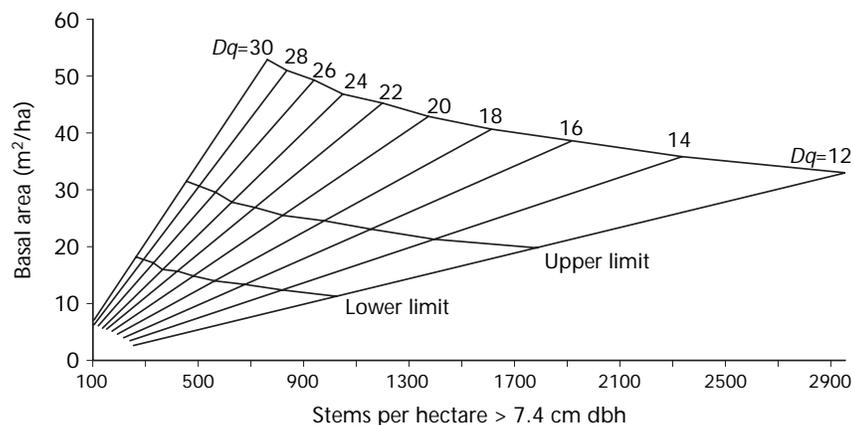


FIGURE 6 A Gingrich stocking chart for Knife Creek.

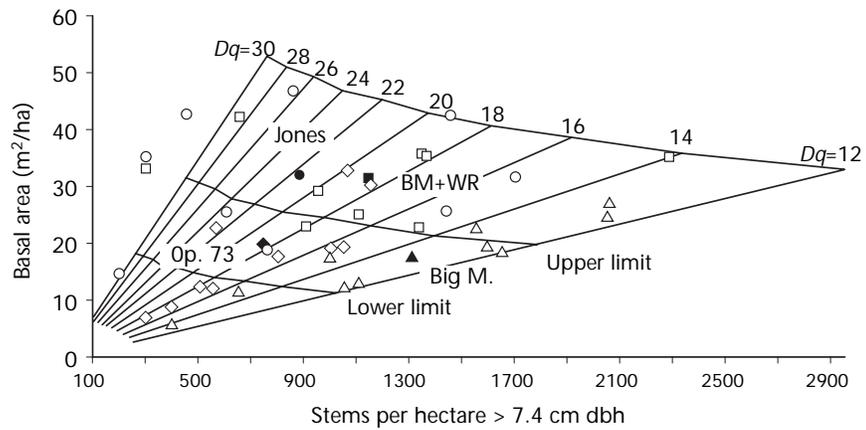


FIGURE 7 Plots (open symbols) and blocks (closed symbols) sampled at Knife Creek.

each stocking class was tested for differences by analysis of variance and least significant differences. These tests indicated that a significant difference ($p = 0.05$) existed between the understocked and the other conditions, but not between the stocked and overstocked conditions.

The data were compiled by blocks that were classified by stocking status (Figure 7) and the mean growth for each block was tested by analysis of variance and least significant difference. These tests showed that basal area at Big Meadow Road (stocked) grew significantly faster ($p = 0.05$) than all others. No significant differences could be clearly attributed to stocking status of the blocks because of the unexplained lack of significant difference in growth between Opening 73 (stocked) and the two undisturbed blocks (overstocked).

The stocking status of six permanent sample plots of Knife Creek (Marshall and Wang 1996) was classified by the Gingsrich chart and ranked in order of basal area growth. Apparently the three plots that appear to be most appropriately stocked show the best basal area growth. It is also important to note that all plots suffered some mortality during the remeasurement period, which indicates overstocking.

Data collected from 18 permanent sample plots at Knife Creek (Marshall 1996) were used to examine the changes in stocking status after three different pre-commercial thinning treatments. The treatment that leaves the lowest density appears to leave the stands appropriately stocked, while the other two treatments frequently leave the stand overstocked. Remeasurements are currently under way to determine periodic increment for each of the treatments. The results of these remeasurements will yield information to further validate the chart. Anecdotal comments from the field crew indicate that, on average, individual stem growth in the lowest-density treatment is better than diameter growth in the other two treatments.

Basal Area Growth

Basal area growth strongly depends on stand density. Therefore, the development of good relationships was expected, which could forecast growth based on the easily measured parameters of relative density, quadratic mean diameter, and density. The diameter growth and basal area growth relationships that were expected in the data were, however, obscured by plot variability. The stands studied are extremely heterogeneous, and the 10 relatively small plots did not characterize each stand precisely; that is, the area outside the plots influenced the measured values for growth within the plots to such an extent that relationships were not clear.

The data clearly show that diameter growth is a function of diameter. Further, the functional form of the relationship appears to vary by stand structure. This indicates that stand structure is important to maintain maximum basal area growth, and appropriate stand structures will enhance basal area growth.

Basal area growth does not equate to volume growth. Stands of low mean diameter may have very high basal area growth, but low volume growth because the basal area is distributed among many short stems. Conversely, stands with a large mean diameter may have low basal area growth, but high volume growth because the growth is accumulated on a few large trees with good height. This supports the general conclusion that uneven-aged stand structures should maintain most of the stocking in large-diameter classes.

On average, the stands studied grew at a rate of 4.2 m²/ha per decade. This average increment is useful as a preliminary guide to set re-entry periods, and allows a silviculturist to estimate that basal area harvested will be replaced at a rate of 0.42 m²/ha per year in the IDFDk3. This estimate is conservative because many of the plots are not stocked appropriately. Stocking control on all plots would presumably increase mean increment.

The lack of data on mortality is a concern. Including mortality in the growth projections would decrease the estimated increment. Marshall (1996) found mortality ranging between 0.08 and 0.59 m²/ha over a 4-year period (0.2–1.48 m²/ha per decade). However, appropriate timber marking will foresee mortality and harvest some of the trees that will not survive until the next re-entry (Day 1996).

Langsaeter's Curve

One method of determining an appropriate residual stocking level is to identify B-level stocking on Langsaeter's curve—the level of stocking below which current annual increment (CAI) is reduced, and above which CAI is maintained. This classical approach fails to recognize that B-level stocking should vary depending on mean diameter. To impose a uniform level of stocking to all cohorts regardless of their mean diameter will result in the overstocking of small-diameter cohorts and the understocking of large-diameter cohorts.

Using partitioned regressions, B-level stocking was estimated at 17.5 m²/ha for Langsaeter's curve. This stocking level falls into the lower limit of stocking developed with the Gingrich chart, for a quadratic mean diameter of approximately 26 cm. For any other mean diameter, however, this B-level stocking is not ideal.

Maximum Size/Density

Maximum size/density relationships are described by the widely accepted self-thinning rule (Yoda et al. 1963, referenced in Long 1985) and the stand density indices derived from that rule (Long 1985). This concept implies that, at the upper limit of stocking, some trees must die to provide space for others to grow. The relationship is very predictable (Long 1985), and is also referred to as the “ $-3/2$ power law” (Drew and Flewelling 1979). Some authors (Curtis 1982; Ziede 1987) suggest that the slope of the self-thinning function is variable, and depends on species (Curtis 1982) or stand structure and age (Ziede 1987).

In most cases, stand density indices that are derived from the $-3/2$ power law are used to describe even-aged stands (Drew and Flewelling 1979; Curtis 1982; Long 1985). Sterba and Monserud (1993), however, state that the concept of self-thinning applies to uneven-aged stands, although the slope of the self-thinning line is flatter in complex stand structures. Figure 5 clearly shows, however, that a slope of $-3/2$ fits the Knife Creek data well.

Gingrich Stocking Chart for Knife Creek

Gingrich stocking charts are a simple tool to describe the density of a stand by its basal area and numbers of stems. Although Gingrich (1967) intended the charts for use with even-aged hardwood stands, he states that “. . . stand structure has little effect on stocking percent . . .” and suggests that the charts could be used for “irregular” stands. Ernst and Knapp (1985) seem ambiguous—while stating that Gingrich charts can be developed and used for any tree species and forest type, they specify that reference stocking levels must be developed from even-aged stands. Purri et al. (1988) and Nyland (1996) discuss Gingrich charts for even-aged stocking only. Marquis (1976) states that Gingrich charts are equally useful for uneven-aged stands, and advocates their use.

Gingrich charts generally show maximum density and describe a management zone within which stand management objectives can be met. In the Knife Creek chart (Figure 6), the management zone is delimited with the proportion of maximum density taken from the literature. A minimum basal area for a given mean diameter is shown. For a given cohort in a multi-aged stand, this could be developed into residual density recommendations. In this way, adjustments to the residual basal area within the stand would recognize the mean diameter at the given location. This approach will help to avoid overstocking of small-diameter cohorts and understocking of large-diameter cohorts during stand marking.

Validation tests of the Gingrich chart are not conclusive because of the small plot area and the variable nature of the stands sampled. The tests showed, however, that a significant difference exists in basal area growth between understocked plots (according to the chart) and appropriately stocked or overstocked plots. When all plots were summarized by block, a significantly better basal area growth was evident on the appropriately stocked block compared to the other three blocks.

In comparing the chart to external data:

- the permanent sample plots with the best basal area growth rate were closest to appropriately stocking levels; and
- the spaced plots, with the best growth (anecdotal) were appropriately stocked according to the stocking chart.

There is, therefore, reason to cautiously employ the stocking chart on the Knife Creek block of the research forest, and to further investigate the applicability of the chart. Stocking limits should be revised as additional information becomes available.

CONCLUSIONS

Silviculturists should set uneven-aged stand structure goals on the basis of management objectives and site productivity. One of the most critical factors for silviculturists to control is stand density because the allocation of growing space is critical to attain stand structural goals. Little guidance on residual growing stock has been available, and silviculturists have, by necessity, used “rules-of-thumb.”

This paper discusses the functional relationships between stand density, stocking, and stand growth, but does not describe mathematical relationships between growth and density. A periodic basal area growth rate of 4.2 m²/ha per decade was calculated as an average for Knife Creek. This is considered a conservative estimate of potential growth given active management.

The use of Gingrich charts is proposed as a simple tool to guide decisions for residual growing stock. While it is not conclusive whether the chart drawn for Knife Creek has predictive value, it holds out some potential, and further validation work is required. Gingrich charts are easy to use, simple to calibrate, and can be used to describe the intended progression towards the stand structural goal.

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