GUIDELINES *for*

Developing Stand Density Management Regimes

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Preface

Stand density management is the process of controlling tree density within a stand to achieve desired objectives. This requires an understanding of the effects of density management practices on the structure and development of stands, and the combined effects of all treated stands on forest management objectives and future economics.

Stand density management practices include the espacement of planted trees, pre-commercial thinning (juvenile spacing) and commercial thinning. These practices can have a significant impact on the structure, health and pattern of stand development, which in turn influences stand composition and utility through time. Appropriate decisions may enhance future stand values, tree and wood properties, and habitat characteristics. Inappropriate decisions will at best fail to achieve management objectives, and may compromise future stand values, stand health, or both.

Prediction of future conditions incorporates a degree of risk, uncertainty and subjectivity. For instance, future value predictions depend largely on the expected future costs and values, and precise estimates of growth and yield are unlikely without extensive research and empirical observation. Nevertheless, a sound density management prescription must consider three elements of prediction:

1. biological responses of the stand to treatment
2. economic implications of the treatment
3. forest-level effects of the treatment.

This document provides essential information on each of these elements, and provides a structured decision process for making site-specific density management prescriptions. It intentionally avoids placing constraints on the prescriptive process, and therefore offers no regime, treatment method or density level recommendations. Rather, it encourages licensees, consultants and district foresters to develop density management plans using sound rationale and careful analysis.

The decision process requires a clear statement of objectives in TFL and TSA management plans. I therefore encourage both industry and government representatives to engage in extensive, joint dialogue in order to establish management unit objectives, and plan silviculture programs to achieve them. The importance of providing extensive and on-going training in the use of the planning methods identified in these guidelines is fully recognized.

Guidelines for Developing Stand Density Management Regimes does not define a maximum stand density figure. Instead, silviculture practitioners should adopt the decision process it outlines in order to determine the need for stand density management activities. This process should be applied to all tree species and stand conditions, including repressed stands. Guidance on the application of the biological, economic and forest-level criteria is outlined in the section “A structured decision process.” No activity should be considered unless they are shown to be biologically feasible.

The administrative details of stand density management issues are not discussed in this document; they will be dealt with through policy.

I am convinced that the needs and interests of future generations of British Columbians are best served by a diversity of stand and forest conditions across the province. This document supports this philosophy and provides a model for future guidelines. It challenges professional foresters to make biologically sound, stand-specific, well-reasoned prescriptions which are considered within the context of forest-level objectives. I encourage you to embrace the opportunities this philosophy and decision process provides.

L. Ped

Larry Pedersen
Chief Forester
British Columbia Forest Service

Executive Summary

Stand density decision making requires a thorough understanding of the concepts of stand development, the rigorous application of appropriate economic and investment principles, and careful consideration of the objectives of the forest owner. These biological, economic and forest-level factors must be integrated by the prescription writer to determine the need and opportunity for density management, and the priority of stand-specific treatments. The resulting prescription is a co-ordinated, stand-level plan aimed at meeting specific forest management objectives.

This document advocates a knowledge-based, structured, decision-making approach. A decision framework is described which helps to organize the decision process for the prescription writer. The following concepts, principles and considerations are fundamental components of the decision framework. They provide information useful in all aspects of stand density management planning, and all practices including initial espacement, and pre-commercial and commercial thinning. *The principle focus of this guideline, however, is pre-commercial thinning within the context of timber production.*

Biological concepts of timber production

Professional experience, scientific data and mathematical models support the following general biological relationships between density management and timber production. A more detailed discussion of each relationship, and possible exceptions, are provided in the main body of the document.

1. Increasing establishment density elevates harvest volume and reduces biological rotations, but at a rapidly diminishing rate – particularly at high densities.
2. Repression of height and/or volume increment may occur in lodgepole pine stands established at high initial densities. The impact of repression on height and diameter increment is evident in stands with densities as low as 10 000–20 000 sph, beginning before trees reach 2 m in height.
3. Pre-commercial thinning may prevent repression and loss of volume production if carried out when trees are less than 2 m in height; repressed stands taller than this have been found to respond erratically to juvenile spacing.
4. Stands regenerated or spaced to relatively high densities (e.g., 1500–10 000 sph) have small differences in volume and diameter at harvest.
5. Stands regenerated or spaced to relatively low densities (e.g., 250–1000 sph) have, at harvest, larger piece sizes because more growing space is available to each tree, lower volumes per hectare because of slow site occupancy following treatment, and longer biological rotations. That is, there is a trade-off between tree diameter and stand volume which is most clearly reflected in stand and stock tables, as opposed to volume per hectare and average diameter. The diameter benefits of spacing diminish the longer treatment is delayed beyond crown closure.

6. Commercial thinning moves future yields forward in the harvesting sequence, but does not greatly affect the total (thinnings + final harvest) volume. In general, a sequence of frequent, light, low entries can increase total yield if merchantability limits are very low. Infrequent, heavy entries can decrease yield substantially, particularly if concentrated in the upper crown classes long before the final harvest.
7. Increasing stand density improves wood quality by influencing the development of smaller knots, narrower annual rings and greater lumber strength.
8. The yield of mixed-species stands is usually intermediate between pure species of the same density when trees of a second species are substituted for trees of the first species. Stand yields of mixed species may increase if trees of the second species are added to the stand, thereby increasing stand density, or if they exploit resources not utilized by the first species.
9. Density management practices influence other forest resource values (e.g., wildlife habitat, livestock and wildlife forage, visual quality, water) and may interact with natural stand processes, such as the susceptibility to pest damage.
10. Stand density decisions should incorporate predictions of stand response. Any growth and yield decision aids used in the analysis should be consistent with the biological concepts of timber production.

Economic principles

A stand-level economic analysis must be undertaken to determine the relative efficiency of proposed treatments or treatment regime options. Generally, unless the harvest ages are identical between treatments, the soil expectation value (SEV) should be calculated for each option. The option with the highest SEV at harvest should be selected.

Because of the usually lengthy time period between density management treatments and final harvest, current utilization limits, product values, timber market conditions and harvesting costs may not be useful. Key elements and variables in stand-level economic analyses include:

1. stand models and data sets that are consistent with the biological concepts of timber production
2. anticipated product (log, lumber or chip) values at the time of harvest, including any anticipated future real price increases (these values and prices should be based on estimates of future product markets)
3. harvest costs anticipated at the time of future harvest, 30 to 80 years hence
4. silviculture treatment costs, if comparing rotations of different length
5. selection of an appropriate social discount rate
6. a sensitivity analysis of silviculture options.

Forest planning considerations

All stand density decisions, whether for timber or non-timber objectives, should be consistent with forest-level objectives (such as those identified in TSA or TFL management plans). Without a forest-level context, local stand density management interventions may result in:

- costly silviculture investments with little or no forest-level benefits
- cumulative forest-level effects that exacerbate a forest management problem
- large opportunity costs if actual forest management problems are ignored.

It is recommended that identification of silvicultural opportunities that help meet forest-level objectives follow a two-step process:

1. obtain and assess existing forest-level analyses
2. conduct additional forest-level modelling analyses.

The first step is essential. Completion of the second step may not always be possible, nor is it always necessary.

The decision framework and process

A stand density management decision framework is described which consists of assessing management objectives and determining strategic opportunities and tactical options. These elements are interdependent and hierarchical. Management objectives represent the highest level decisions, upon which strategies and tactics depend.

Within this decision framework, a decision process is presented which defines the appropriate sequence of queries and analyses. This process will assist planners and silviculturists in identifying appropriate density management strategies, and biologically and economically feasible stand-level prescriptions.

Decision support tools

Three types of decision support tool are available to assist practitioners in the analysis of density management options:

1. A number of stand growth and yield models and decision aids are available that are based on the biological concepts of tree and stand production. These tools are useful for predicting the response of stands to density manipulation (espacement, juvenile spacing, and commercial thinning). Appendix 2 “Tactical analysis and design” provides an illustration of the benefit and use of a stand-level model (TIPSY) in evaluating the suitability of a particular density management action.
2. Various forest estate models may be used to estimate the flow of goods and services from managed forests. They may be used to compare the supply of timber and other commodities and amenities resulting from different stand management interventions.

3. Computer models, which incorporate accepted economic principles, simplify the procedures of financial and sensitivity analyses.

Users of decision support tools should always be familiar with the specific capabilities and limitations of the models they use. Of particular importance is an understanding of the quality and quantity of data used in the analysis.

The language of this document represents terminology from the disciplines of forest science, economics and planning. A glossary is provided to assist readers in understanding unfamiliar terms or usage.

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Introduction

Background

The Chief Forester formed a Stand Density Management Working Group (the Working Group) in February 1996. The mandate of the Working Group was to provide a decision framework to address some contentious issues surrounding the effects of stand density. The Working Group consisted of five members from industry (CFLA[1](2), NFPA,[2] ILMA[3] and CLMA[4]) and five from the Ministry of Forests.

Working Group deliberations considered the full range of stand density management practices, from initial espacement, through pre-commercial thinning (juvenile spacing) to commercial thinning. The main emphasis, however, was pre-commercial thinning practices. Conclusions and recommendations are based on a primary consideration of timber production, its implications on economics and forest-level planning.

A change in philosophy

The Working Group advocates a philosophical change in the approach to stand-level decision making. The group believes that selecting an option from a predetermined range of acceptable density regimes or treatments is not a responsible approach to making a management decision. Rather, technically sound, stand density management demands a structured process of thought and analysis based on knowledge from a number of disciplines.

This document provides a decision framework that supports this new philosophy. It is designed to organize and guide the prescriptive thought process, rather than specify appropriate density regimes or default density standards. It also incorporates up-to-date stand density management concepts and information essential to the decision process.

Although not addressed here, the process of forest-level goal-setting is an important prerequisite to stand-level decision making. Given clearly stated, higher level direction, practitioners will find the information (knowledge) and framework (structure) elements of this document helpful in developing and justifying stand-specific prescriptions.

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[1] Coast Forest and Lumber Association.
[2] Northern Forest Products Association.
[3] Interior Lumber Manufacturers Association.
[4] Cariboo Lumber Manufacturers Association.

Decision criteria

In order to make technically sound density management prescriptions, three categories of decision criteria must be considered:

1. Biological – the biological response of tree and stand characteristics to treatment.
2. Economic – the economic factors, assumptions and analytical procedures necessary to determine the relative value of a treatment.
3. Forest level – the forest estate objectives against which the stand-level treatments are evaluated.

These three criteria are the basic components of the decision framework. Economic and biological criteria address decisions involving stand-level planning. Forest-level criteria define the timber and non-timber production goals specified in higher level plans. The combined effects of all stand-level interventions must be evaluated in terms of their contribution to the achievement of forest-level goals.

All decision elements and criteria of the framework should be considered during the prescription development process. The decision-making process must be comprehensive and technically valid; the resulting decision and stand prescription must be able to stand up to professional scrutiny.

Biological Concepts of Timber Production

The biological *concepts* underlying the growth and yield of trees and stands are fundamental to an understanding of the relationships between density management and timber production. Consideration of other resources, such as water and wildlife, is also important in density management decisions, but are discussed only briefly here.

Stand density changes from establishment to maturity in response to natural processes and management interventions such as plantation espacement, precommercial thinning (juvenile spacing) and commercial thinning. These and all other silviculture treatments which affect tree spacing will influence the subsequent growth of the stand and the harvest yield.

Stand production potential

The production potential of a particular population of trees growing on a given site is a function of site and tree resources. The productivity of the site resource, for example, is determined by the inherent characteristics of the soil and climate. These characteristics are essentially fixed, although the effects of external factors (e.g., poor soil management, adverse climatic change, industrial pollutants) may temporarily or permanently impair site productivity. On the other hand, intensive forestry practices such as cultivation, irrigation, drainage and fertilization may increase the production potential. Large productivity gains are rarely practical, however, because production-limiting factors are costly to manipulate.

The productive capacity of a particular species or species mixture is governed by its ability to utilize the site resource. This is a function of the ecophysiological characteristics of the species, and is largely fixed. There are, however, notable exceptions:

- Selection for tree vigour during silviculture treatments can either increase or decrease the efficiency of production because of the wide variation in the productive potential of individual trees.
- Inadvertent use of unsuitable provenances in reforestation can lower species productivity.
- Genetic selection and use of improved growing stock in future managed stands can increase natural productivity through genetic gain.
- Repression, a biological phenomenon important in lodgepole pine, can substantially reduce the height growth and productivity of all trees in stands established at high densities, particularly on sites of average or low productivity.

Apart from these site and species exceptions, it is reasonable to assume that stand productivity potential is fixed.

Stand development

Stand development, or stand dynamics, is the process of structural change that occurs in stands over time. Stand development begins at the earliest point of stand establishment and influences the pattern of tree growth, stand structure and timber production throughout its life. The rate and tree-to-tree variability of height growth are the principal mechanisms driving the processes of stand development.

Genetic variation is very large within and among species for tree characteristics such as height growth, and processes such as photosynthesis. For example, the weakest trees in a monoculture typically increase in height at about one-half the rate of the strongest trees. This inherent variation is responsible for large differences in the productive potential of individual trees, with the exception of species like aspen, which form clonal stands. Microsite differences, pests, natural disturbances and management interventions further alter the inherent growth variation among trees.

The concept of *growing space* is helpful in explaining the stand development process. Trees in a stand occupy physical space, measured in terms of the crown dimensions above ground, and the root spread below ground. It is more difficult to measure an individual tree’s share of total site resources and the influence of neighbouring trees on its consumption of site resources. Neither factor can be completely described by physical space alone.

Growing space, therefore, refers to a tree’s share of total above-ground and below-ground site resources, not just the physical space. The relative importance of both components of growing space vary with species, site, and tree and stand developmental stage. A tree must continue to grow in size and acquire more space if it is to continue to thrive. Trees without adequate growing space grow poorly; those that fail to meet their minimum requirements for growth will die.

The relationship between tree growth and growing space is complex. In even-aged stands, trees are unrestrained by space from establishment until they begin to compete for the site resources. This phase of tree growth is referred to as the period of *free growth*. Stand volume production is proportional to the number of trees occupying the site during this period. The biology and dynamics of the stand (i.e., the change in stand development over time) are far more complex after the trees begin to compete for growing space.

Inter-tree competition is a growing space related factor central to the stand development process. Site resources constrain the growth of trees in the main canopy as soon as the crowns and root systems attempt to utilize the same elements. This leads to intense inter-tree competition. On dry sites, below-ground competition may limit growth to the point that crown closure does not occur. On moist to wet sites, crown competition for light is of primary importance.

The dynamics of crown competition in even-aged coniferous stands are reasonably well understood. During the period of free growth, height growth is unimpeded and the tree crown covers the entire stem in the absence of constraining factors such as brush and pests. This period ends when the branches of adjacent trees meet and interlock in an attempt to use the same resources. The upper point of inter-tree crown contact moves upward and shading of the lower branches intensifies as crown expansion continues. The lowermost branches eventually die and the bases of the crowns of adjacent trees begin to *lift* at the same rate.

When inter-tree crown contact occurs, the branches of the more vigorous trees gradually overstep the lateral edge of the crowns of weaker trees. At this point the survival of these trees of lower vigour is threatened because they cannot increase in height fast enough to stay ahead of the receding base of their crowns. Their crowns gradually decline in size to the point where they are unable to maintain their rate of height growth. As a result, weak trees are forced to relinquish growing space enabling stronger trees to increase their consumption of site resources, and continue to thrive.

Competition for growing space may result in three types of tree and stand responses: differentiation and stratification, mortality and repression.

Differentiation and stratification

Individual tree variation in growth promotes the differentiation of trees into stratified crown classes (i.e., dominant, codominant, intermediate and overtopped classes). Differentiation is expressed as differences in total height, crown size and stem diameter throughout the life of the stand. The process of differentiation is accentuated by tree-to-tree variations in vigour, microsite quality and the time of establishment relative to other trees. The rate of differentiation later accelerates with inter-tree competition.

As even-aged monocultures develop, the disadvantaged trees (due to factors such as vigour, microsite, age) drop from the upper to the lower crown positions, and eventually die. The diameter distribution (i.e., number of trees by diameter class) continues to widen as stands age, and may shift from being normally distributed to one that is skewed toward smaller diameters. In most species, however, the development of highly skewed diameter distributions are limited by the mortality of smaller trees. In stands with a clumped distribution of trees, crown differentiation and stratification begin at different times in different parts of the stand, adding to the variability in tree size and growth rate.

In stands of mixed species, the variation in tree size is even more pronounced because of the wider range of inherent rates of juvenile height growth. Species in stand mixtures tend to differentiate into distinct layers or strata when differences in height growth are large. This initial stratification can persist if the slower-growing species are shade tolerant, or if sufficient sunlight can pass through the foliage of trees in the upper stratum.

The initial stratification may change over time if the component species have different patterns of height growth. For example, the height growth of paper birch slows dramatically after about age 40. Other species in the stand may subsequently overtake and surpass the birch in height. The stratification can also be altered by insects and diseases, which may preferentially damage and weaken one species or stratum in the mixture.

Diameter distributions in mixed-species stands generally reflect the height stratification. The species in the upper and lower canopy occupy the larger and smaller diameter classes, respectively. If the slower-growing species are shade tolerant, diameter distributions are often skewed toward smaller sizes. Broadleaf species sometimes exhibit a different height–diameter ratio than conifers and consequently appear lower down in the diameter distribution than they are in the height distribution.

Canopy stratification patterns can be altered if the species with slower juvenile height growth have an advantage in early stand development. They may regenerate in advance of the faster-growing species, or density control measures may free them from competition during the juvenile phase of slow growth, thereby ensuring they do not lag far behind the faster-growing species at the time of stand canopy closure. Silviculture treatments undertaken at or shortly after establishment can create single-layered stands of species that would otherwise naturally form stratified canopies.

Mortality

Regular mortality occurs when competition for growing space reduces the size and productive capacity of the crown to the point where it cannot support the basic respiration needs of the tree (respiration > photosynthesis). That is, the site-limited resources are redirected from the overtopped and dying trees to the survivors. This process will be initiated simultaneously throughout the stand if tree spacing and other factors are relatively uniform. Otherwise, it may start in the denser sections and spread to areas of lower density. The onset of regular mortality signals *full site occupation* or utilization. *Irregular* mortality is caused by pests, wind and other factors, and may occur any time throughout the life of the stand.

Competition and the associated tree mortality in dense stands can leave a more productive stand at maturity than one established at a much lower density, if only the most vigorous trees survive.

Repression

Repression is a biological phenomenon whereby tree growth and stand development fail to exploit the potential productivity of the site. The impact is widespread in fire-origin stands of lodgepole pine (Goudie 1996) but not in other species.

Biology

Repression reduces height and volume increment in lodgepole pine shortly after the growing space is fully utilized in stands established at extreme densities. The process usually begins before trees reach a height of 2 m, although stands with 1 000 000 trees/ha may be affected when only 0.2 m tall (Mitchell and Goudie 1980).

Analysis of espacement trials (Carlson and Johnstone 1983) shows that the height growth of plantations with more than about 15 000 planted trees/ha are affected (Figure 1), and future measurements may indicate minor repression at lower densities. The pattern of growth and development of repressed stands resembles that of stands growing on sites of much lower productivity; consequently, merchantable yields will be achieved considerably later than had repression been avoided. Repression does not, however, cause stands to *stagnate* or cease development, as was once believed.

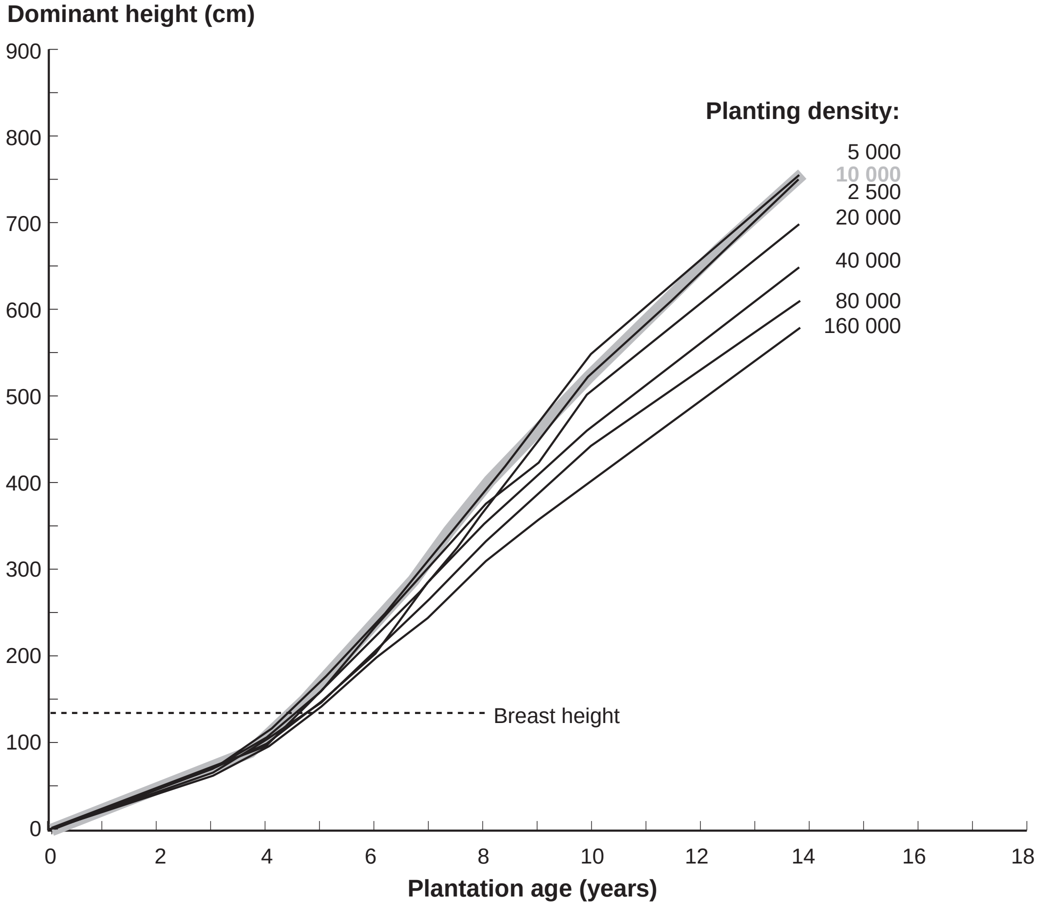


FIGURE 1. The height growth of lodgepole pine is reduced at high establishment densities.

Impact

Long-term growth losses are particularly dramatic in repressed fire-origin stands of lodgepole established with more than 50 000 trees/ha (Mitchell and Goudie 1980), particularly on sites of relatively low productivity. At extreme densities (500 000+ trees/ha), stand production may be reduced by as much as 60%.

Regeneration survey data indicate that repression is not likely to be a serious problem in stands that regenerate after logging because establishment densities are much lower, trees seed-in over five to 10 years (instead of two to three years), and clumped (less uniform) tree distributions are more common. The resultant lower densities and greater tree-size diversity of post-logging stands minimizes the risk of repression losses.

Repression is also unlikely in plantations, unless supplemented by concurrent, natural, in-fill regeneration. The impact of dense, but delayed, natural regeneration on planted lodgepole pine stands is not known.

Response to treatment

Stand density interventions are an effective means of preventing repression in lodgepole pine if treatment occurs before the onset of repression. Stands that are thinned after the onset of repression do not show a consistent height growth response to treatment (J.S. Thrower and Assoc. 1993). However, there is evidence of an independent response in diameter growth.

Until more is known about treatment response it is reasonable to assume that the early height growth of repressed stands is indicative of future productivity.

Stand production

Theoretically, near-maximum production in *monocultures* is realized when a stand fully occupies the site quickly, and performs to its potential throughout the rotation. Actual stand production is lower if crown closure and site occupancy are delayed by low establishment density. Similar yield reductions occur if portions of the site remain unoccupied because of factors such as inadequate stocking, brush competition and pests.

Full utilization of stem wood is achieved if all mortality is harvested as is illustrated by the *gross production* curve in Figure 2. The difference between *gross production* and *standing volume* represents the volume lost to *mortality*.

Maximum theoretical stand production must be tempered by consideration of economic merchantability. Merchantability standards, such as top diameter, stump height and minimum diameter at breast height (DBH) are economic constraints that reduce the yield of the stand, particularly when the trees are small. The difference between the curves for *standing volume* and *close utilization* (Figure 2) shows that tops, stumps and trees less than 12.5 cm reduce the volume by a fairly constant amount throughout the rotation.

Note that the impact of minimum DBH limits (*close, intermediate and rough utilization*) diminishes over time as an increasing proportion of the trees exceed a particular diameter. These limits also delay the culmination of mean annual increment (*maximum MAI*).

Relative to monocultures, the yield relationships of stand mixtures are less well defined because of the numerous possible combinations of constituent species and their relative proportions (Kelty *et al.* 1992). The yields from stand mixtures can be either greater than or less than the yield from corresponding single-species stands depending on the component species, stand density, height stratification patterns and site quality.

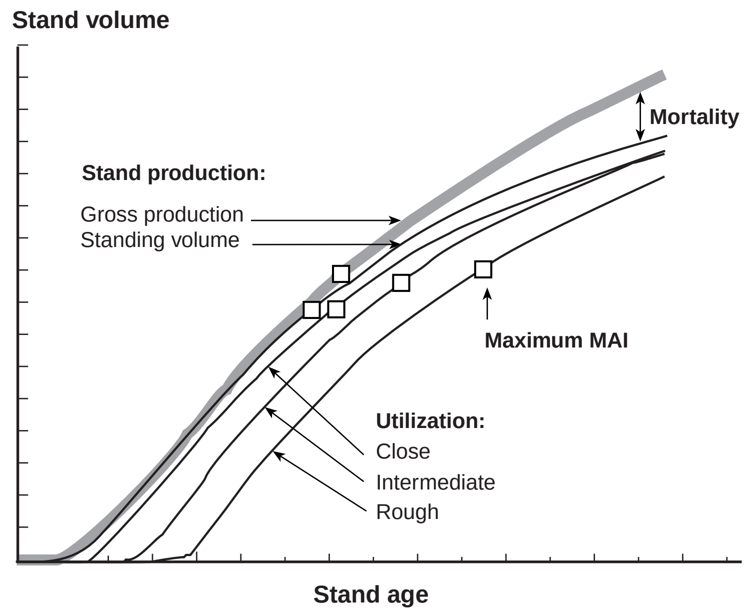


FIGURE 2. Harvest volume is affected by merchantability standards.

In order to better understand the complexity of mixtures and how they relate to monocultures, it is helpful to visualize mixed-species stands from the perspectives of substitution and addition. In the *substitution* perspective, a mixture is derived from a monoculture by substituting trees in the monoculture with trees of another species, keeping the total stand density constant.

In Figure 3, for example, the monoculture of species A (open circles in Figure 3a) at 600 trees/ha can be transformed into a mixture by substituting 300 trees of species B (shaded circles in Figure 3b). The yield of mixtures created by substitution are almost always intermediate between the yields of the two species in separate monocultures. Notable exceptions are combinations in which one species enhances the growth of another, such as some mixtures of Douglas-fir and red alder. Otherwise, the stand yield of the mixture is usually close to the average production of the component monocultures when weighted by the species proportions in the mixture.

In the *addition* perspective, a mixture is derived by adding to a monoculture some trees of a different species. From the monoculture of species A at 600 trees/ha (Figure 3a), we can create a mixture by adding another 600 trees/ha of species B (Figure 3c), bringing total stand density to 1200 trees/ha. Yields of mixtures created by addition can be greater than yields of the monoculture simply because there are more trees.

Yields will also increase if the competition between species is less intense than the competition within species. This will occur when the two species differ in important silvical traits like shade tolerance and rate of height growth. A common example is where a slower-growing, shade-tolerant species forms the lower stratum beneath a canopy of a faster-growing, shade-intolerant species.

If the lower canopy species takes advantage of resources unused by the overstorey trees, the yield of the lower stratum species may be completely additive to that of a monoculture of the overstorey species.

Where the demands of each species for site resources are not completely independent, the lower canopy species may reduce the growth of the overstorey somewhat through below-ground competition. Nevertheless, there is frequently a net additive effect where the production of the lower canopy species outweighs the reduction of the overstorey production.

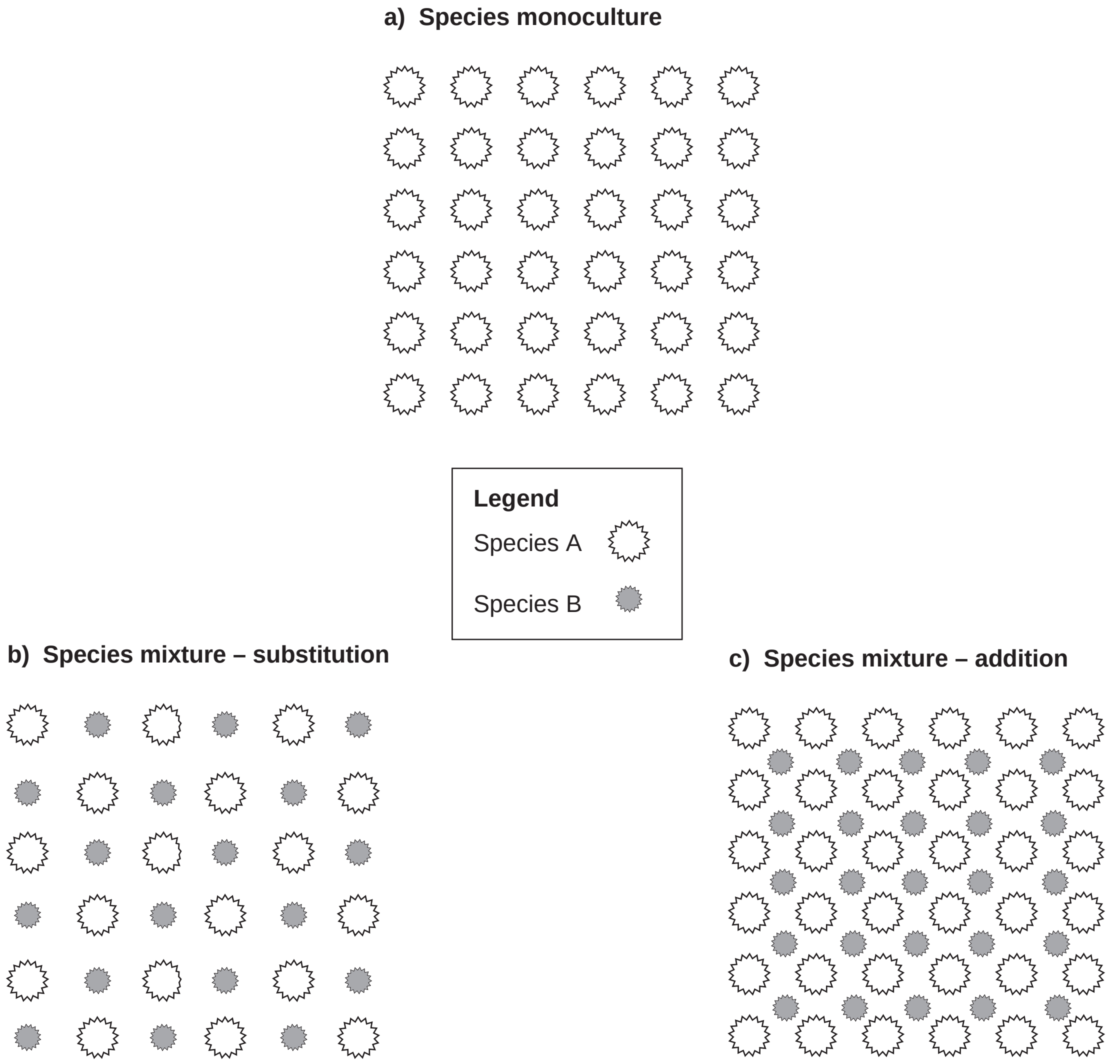


FIGURE 3. a) The density and productivity of a monoculture can be altered by b) substituting or c) adding trees of another species.

Density management practices

Density management techniques such as espacement and thinning manipulate the growing space and resources available to each tree. These silviculture treatments control crown and root development, the size and quality of each tree and the productivity of the stand. The following discussion focuses on the *concepts* underlying espacement and thinning (pre-commercial and commercial).

Espacement

Plantation espacement in BC since 1940 ranged from about 2 m (2500 trees/ha) to 4 m (625 trees/ha). Tree-to-tree spacing in natural stands covers a much wider range and is much less regular. Full site occupancy is achieved quickly if the establishment density is moderately high and the spatial distribution of trees is uniform. Uniformity increases in importance as establishment density decreases. Site occupation by tree crowns (Figure 4a) and merchantable volume (Figure 4b) decline in response to decreasing establishment density. Any clumping of the same number of stems will reduce the stand yield even further. Holes often reflect microsite limitations or brush competition.

Note that it is the unoccupied growing space or “holes” in the stand canopy that reduce timber yield—not the clumpiness itself. Low density stands produce less volume initially because there are too few trees to exploit the available growing space. The rate of stand growth improves after crown closure.

Theoretically, the growth rate of a low density stand could eventually surpass that of a dense stand, as predicted by yield projection models. This phenomenon, called *cross-over,* has not been observed in research plots in BC, which are still too young to confirm or reject the theory. Ministry data and models predict that cross-over is not likely to occur until well beyond rotation ages based on the culmination of MAI.

Pre-commercial thinning (juvenile spacing)

A specific target stand density can be achieved at an early age by means of initial espacement or pre-commercial thinning. The silvicultural benefits for both practices, in terms of average diameter growth, are due to the extended period of free growth before crown closure. High regeneration density followed by pre-commercial thinning provides unique silvicultural advantages over espacement because of the opportunity to select the best trees. For example, those left after spacing a stand from 5000 to 1000 trees, as opposed to planting 1000 trees, would likely to be:

- growing on better microsites
- growing faster because of the opportunity to upgrade the vigour of the stand
- healthier and of the most desirable species.

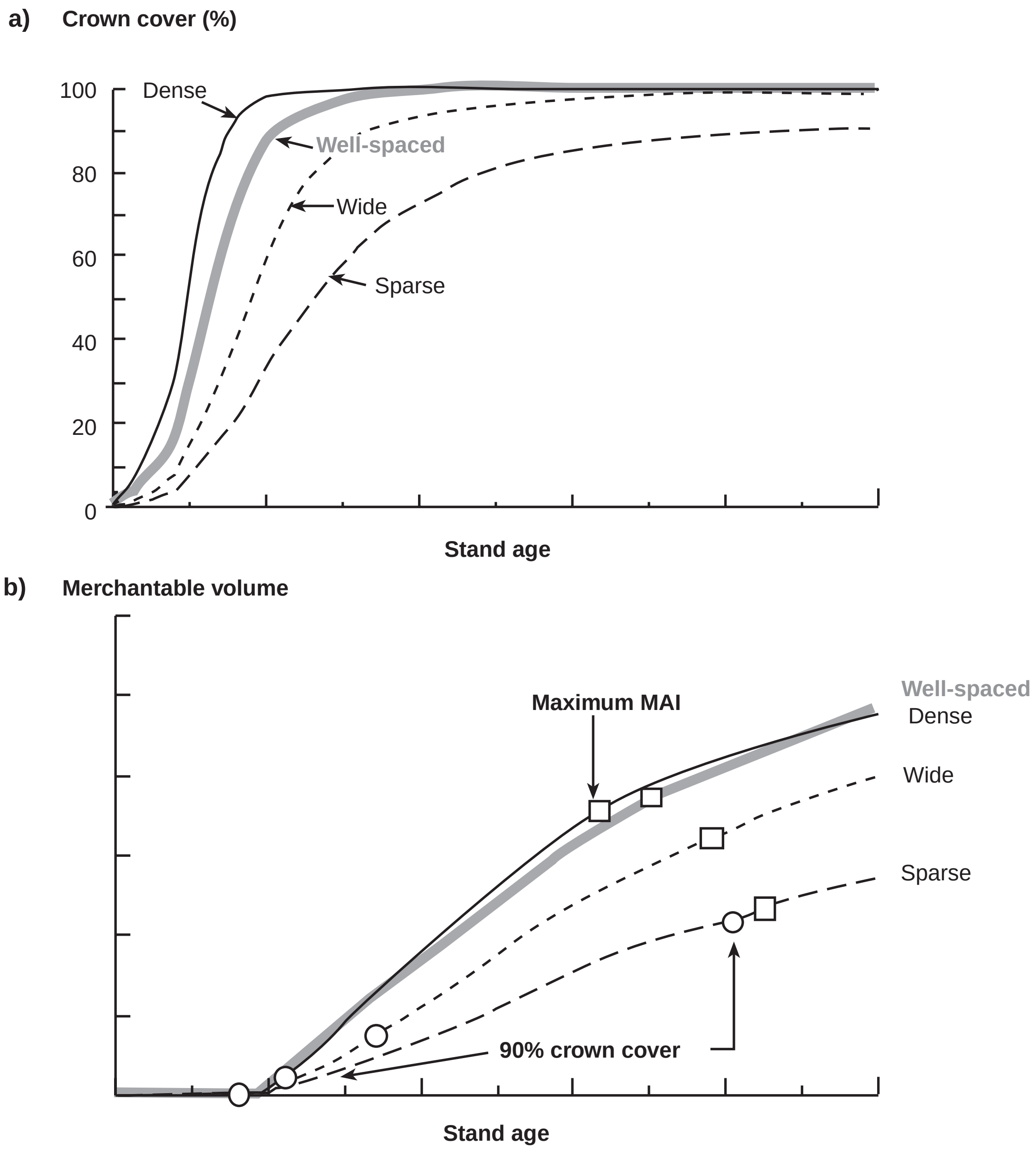


FIGURE 4. Espacement affects a) site utilization and b) volume production.

If the goal of forest management is to maximize stand volume production, crop tree selection criteria should focus on factors that reflect crop tree vigour, such as the rate of height growth, total tree height and diameter. The potential response of the residual stand to pre-commercial thinning will be compromised and could lead to the degradation of stand vigour and performance if:

- Crop trees of relatively low vigour are selected because:
  - uniformity of spacing takes precedence
  - height growth potential (i.e., tree vigour) is not obvious.
- Poor tree selection leaves large holes in the stand canopy, causing incomplete site utilization and reduced yield.

- Pre-commercial thinning of extremely dense stands of lodgepole pine is delayed until after the onset of height growth repression.
- Thinning practices in mixed-species stands reduce the potential for an *additive* increase in yield by removing a slower-growing, shade-tolerant species that could form a lower stratum in the stand canopy.

Pre-commercial thinning immediately reduces the number of trees, the occupancy of growing space and the *standing volume* per hectare. The magnitude of the reduction is related to the intensity of treatment. The subsequent development of the stand is more complex.

Crown cover normally increases at a diminishing rate until complete canopy closure occurs, and then levels off. The number of trees in the spaced stand remains fairly constant until the onset of crown closure, competition and mortality. *Volume increment/ha* is reduced until the vacant growing space created by spacing is fully utilized by the residual stand. The corresponding volume curves of the spaced and untreated stands will initially diverge and later parallel one another. Convergence of the curves usually starts shortly after mortality begins in the spaced stand. The duration of each phase depends on the intensity of pre-commercial thinning and the level of utilization.

If only overtopped trees are removed and 100% crown cover is maintained, convergence will begin immediately without any divergence. On the other hand, a very heavy spacing will initiate a lengthy phase of divergence that could extend until the stand is harvested. Since one phase tends to dominate, volume curves can be described in terms of *decreasing, constant* or *increasing* departure as illustrated in Figure 5.

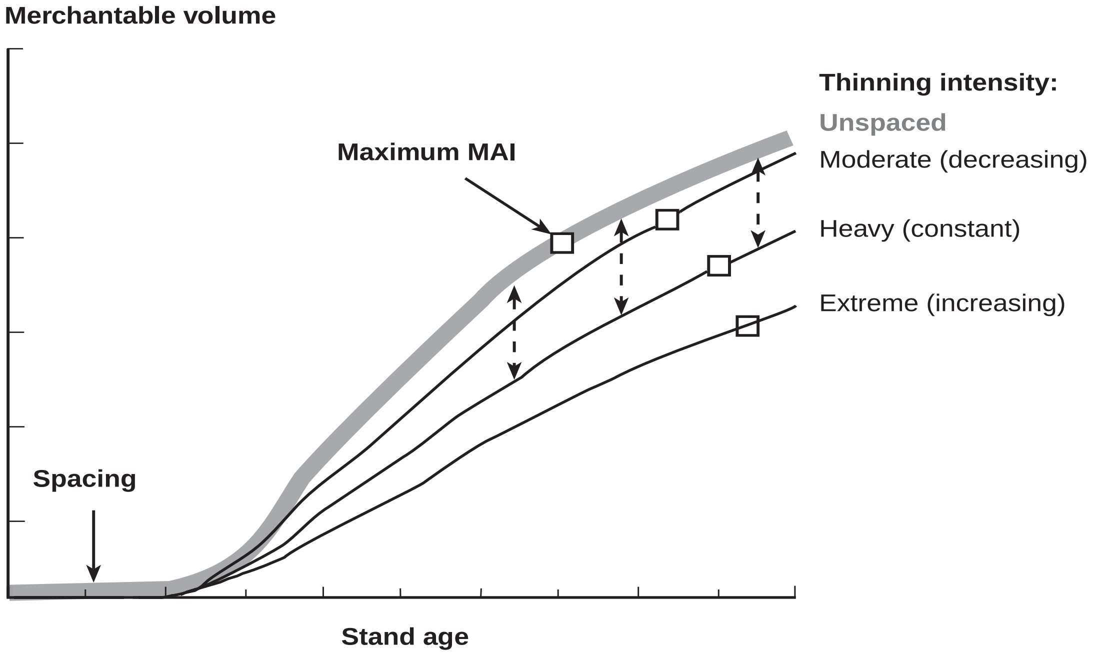


FIGURE 5. The intensity of pre-commercial thinning affects future volume.

The response of pre-commercial thinning is also affected by the product objectives and the stage at which the impact of treatment is assessed. An unspaced stand can produce more or less wood depending on the merchantability standard applied and when it is evaluated (Figure 6). A lower diameter limit (12.5 cm+) accounts for the many small trees in the untreated stand once they reach pole stage and attains greater volume per hectare than a spaced stand (Figure 6a). However, thinning provides more growing space for the leave trees, permitting greater diameter growth, allowing trees to cross diameter thresholds more quickly. The advantage is evident when the minimum diameter is increased to 17.5 cm (Figure 6b). Notice that the volume benefits of pre-commercial thinning diminish as an increasing proportion of the trees in the unspaced stand exceed the minimum diameter. Consequently, treatment response should not be assessed at an early age using a relatively large diameter limit. Methods of evaluating the effects of density management practices are discussed later.

Thinning and fertilization

In many cases the impacts of thinning (pre-commercial and commercial) on stand production can be modified by nitrogen fertilization. The nature of interactions between spacing and nutrition, and the tree- and stand-level biological responses are summarized in five steps:

1. Thinning reduces stand competition, crown cover and foliage volume, thereby increasing the availability of sunlight to the foliage of residual trees.
2. Nitrogen fertilizer elevates the foliar nitrogen concentration of residual trees, thereby increasing the photosynthetic efficiency of their crowns.
3. The improved photosynthetic efficiency and increased availability of nitrogen, sunlight and crown space results in the acceleration of residual tree growth.
4. The improved rate of tree growth results in greater crown expansion and foliage volume, thereby increasing the foliage interception of sunlight.
5. Increased light interception by residual trees increases their rate of photosynthesis, thereby increasing the volume increment of the stand.

Fertilization may compensate for the loss of stand volume increment caused by incomplete site occupancy immediately following thinning alone. However, due to the complexity of interactions between tree, stand and site factors, the actual response of combined thinning and fertilizer treatments can be quite variable.

For example, the timing of fertilization, relative to thinning, affects the efficiency of fertilizer uptake. Thinning usually leaves a large amount of fresh slash on the forest floor. During the first one to two years, the mineralization of this material can significantly improve the nutrient status of the forest floor. Elevated spacing slash can impede the penetration of fertilizer materials increasing nitrogen volatilization losses from the stand. Fertilization should therefore be delayed in most cases for one to two years following thinning in order to maximize the beneficial effects of treatment interaction. See the *Fertilization Guidebook* for more detailed recommendations.

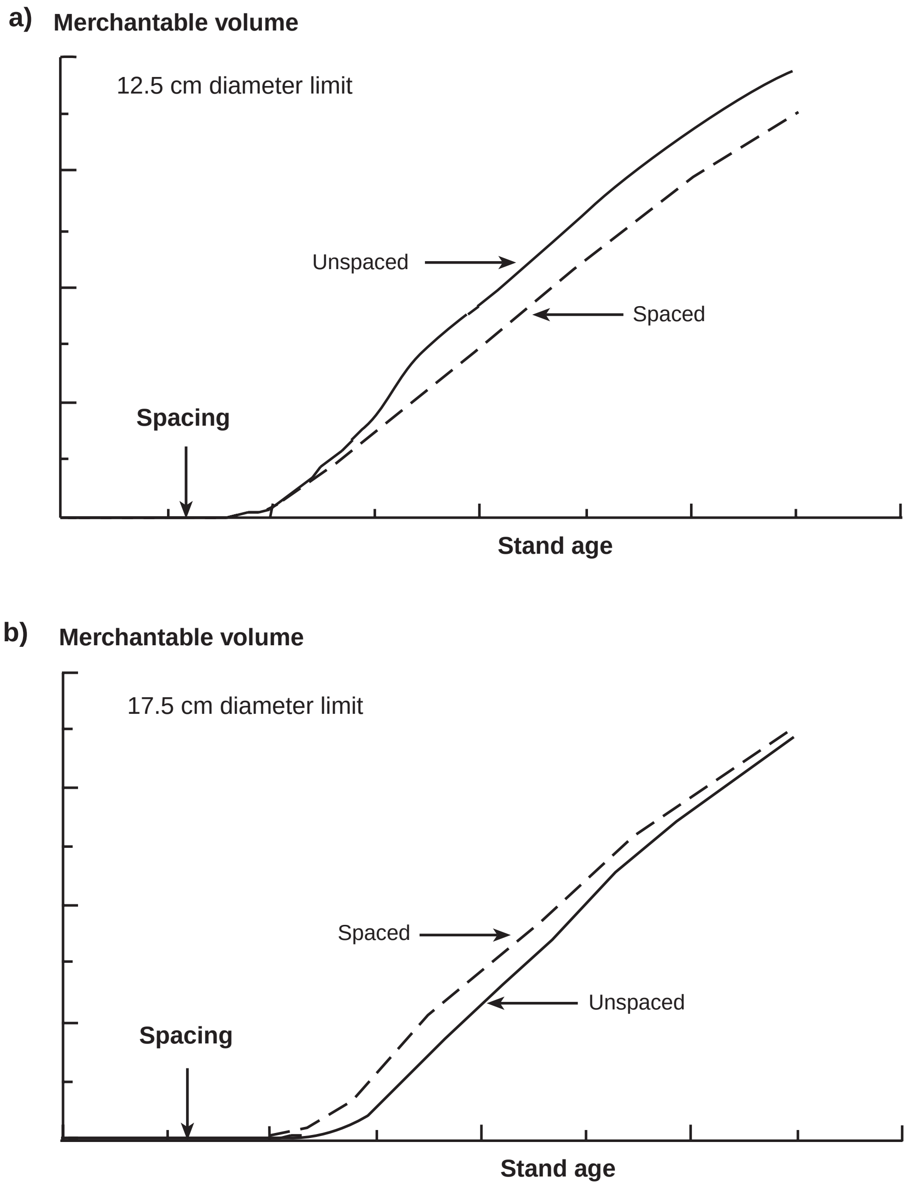


FIGURE 6. a) A minimum diameter limit of 12.5 cm gives unspaced stands a volume advantage, but b) increasing the limit to 17.5 cm gives an advantage to the thinned stands that diminishes over time.

Pre-commercial thinning and commercial thinning

Can pre-commercial thinning prepare a stand for a later commercial entry? Logging contractors report that access is improved considerably by the absence of many small trees that would have survived had they not been removed earlier. Long-term data from pre-commercial thinning trials suggest that operations which favour the removal of trees in the lower diameter classes also favour the growth of trees in the larger diameter classes. When pre-commercially thinned stands are ready for a second entry, the distribution of volume by diameter class tends to have shifted towards the larger diameters relative to stands that were not thinned earlier. The link between early and late treatment is illustrated in a later section concerning the use of stock tables to evaluate the effects of density management practices.

Commercial thinning

Commercial thinning occurs later than pre-commercial thinning when the trees are larger and less vigorous. Depending upon tree size and thinning intensity, it can create relatively large holes in the stand canopy that are reoccupied slowly by the crowns of leave trees.

When thinning commercially in BC today, it is common to carry out a single entry not long before the final harvest. This entry often removes a wide range of tree sizes, with most coming from the lower diameter classes. In Europe, it is common practice to conduct a series of frequent, light, low thinnings intended to capture wood that would be lost to mortality if untreated. One typically compares the harvest volume of the untreated stand with the total volume (final harvest plus all thinnings) taken from the treated stand. Lower utilization limits in Europe also increase the merchantable volume available from thinnings. A limit of 7 cm is common for both DBH and top diameter.

If we look at the mortality in an unthinned plot of Douglas-fir from BC we can see how much volume is potentially available from a series of frequent, light, low thinning entries. That is, we will assume we are able to harvest and utilize each overtopped tree just before it dies. In Figure 7, the uppermost *gross production* curve is what we get if all wood is salvaged by thinning without regard for merchantability limits. The middle *gross merchantable* curve shows what is left if tops (< 10 cm), stumps (< 30 cm), and small trees (< 12.5 cm) are not merchantable. The lowermost curve displays the *standing merchantable volume* if the stand was not thinned. If all merchantable mortality in Figure 7 is captured through repeated, light, low thinnings, it is possible to increase the harvest volume (12.5 cm+) by 20% at age 85 years. This increases to 30% with the harvest of all trees (0.0 cm+), tops and stumps. In this example, there is little doubt that mortality, merchantability standards and the number of stand entries affect the volume of wood available from commercial thinning, particularly beyond age 50.

A series of light entries increases the total harvest because the space vacated by small-crowned trees is small, and frequent entries maximizes the opportunity to salvage trees before they die. A single heavy entry, timed well before the final harvest, will likely decrease the total yield because tree removals create large openings, resulting in less than full site occupancy by the residual stand. Furthermore, only one opportunity to harvest impending mortality will result in lost volume between thinning and final harvest.

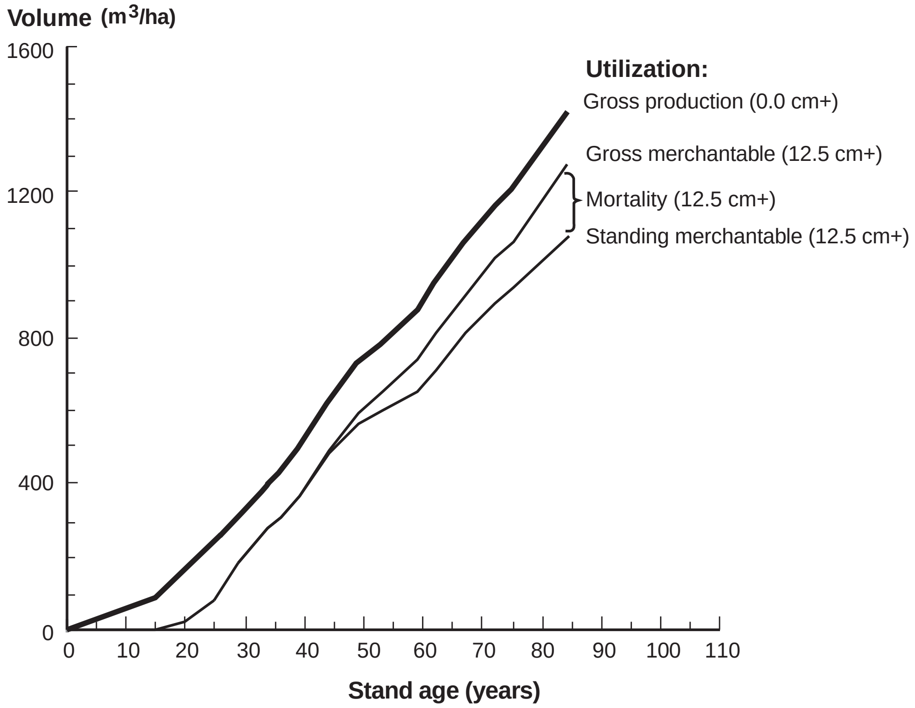


FIGURE 7. Utilization standards affect the yield from commercial thinning.

Figure 8 depicts research data from the control (T0) and three of four levels of thinning, most of which were quite light in terms of the volume removed (T1=14%, T2=21%, T3=29% and T4=41%) as reported by Omule (1988). Figure 8a shows how the standing volume of the untreated and thinned plots developed over time. Regime T2 is not displayed for reasons of clarity.

Figure 8b displays the total harvest volume (standing plus thinnings). The response to treatment was small in terms of merchantable volume (T1=5%, T2= 3%, T3=7%, T4= -6%), and the differences were not significant.

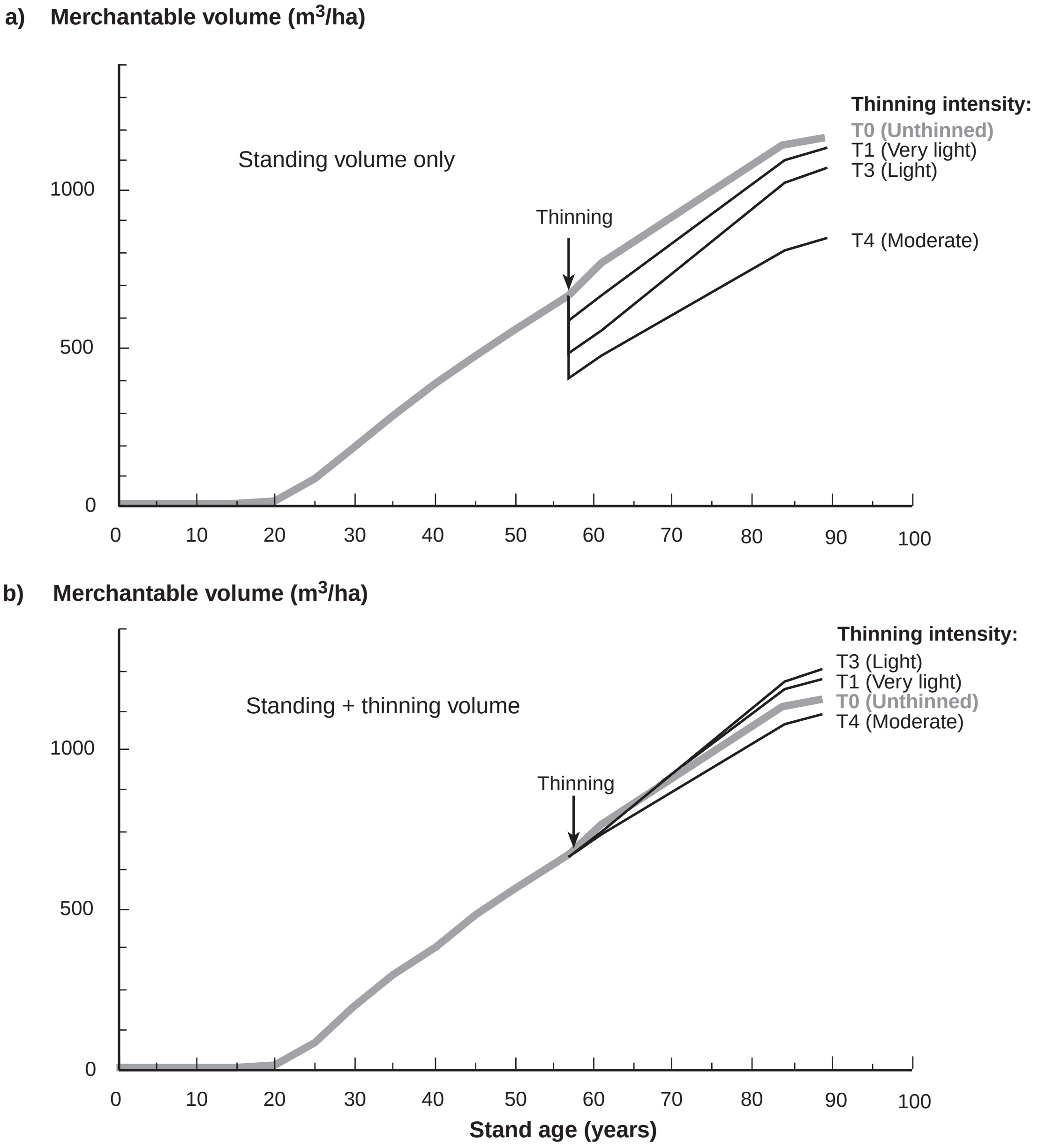


FIGURE 8. Light to moderate thinning regimes a) reduce standing volume but b) have little impact on total harvest volume.

Figure 9a, a hypothetical scenario that builds on the preceding example, displays the impact of removing 12, 38 and 62% of the stand volume as thinnings, with most coming from the lower crown classes.

The total harvest volume, including thinnings, of the very light entry surpasses that of the untreated plot in Figure 9b, while the heavy regime falls considerably below. The yield of the moderate thinning and the untreated control coincide.

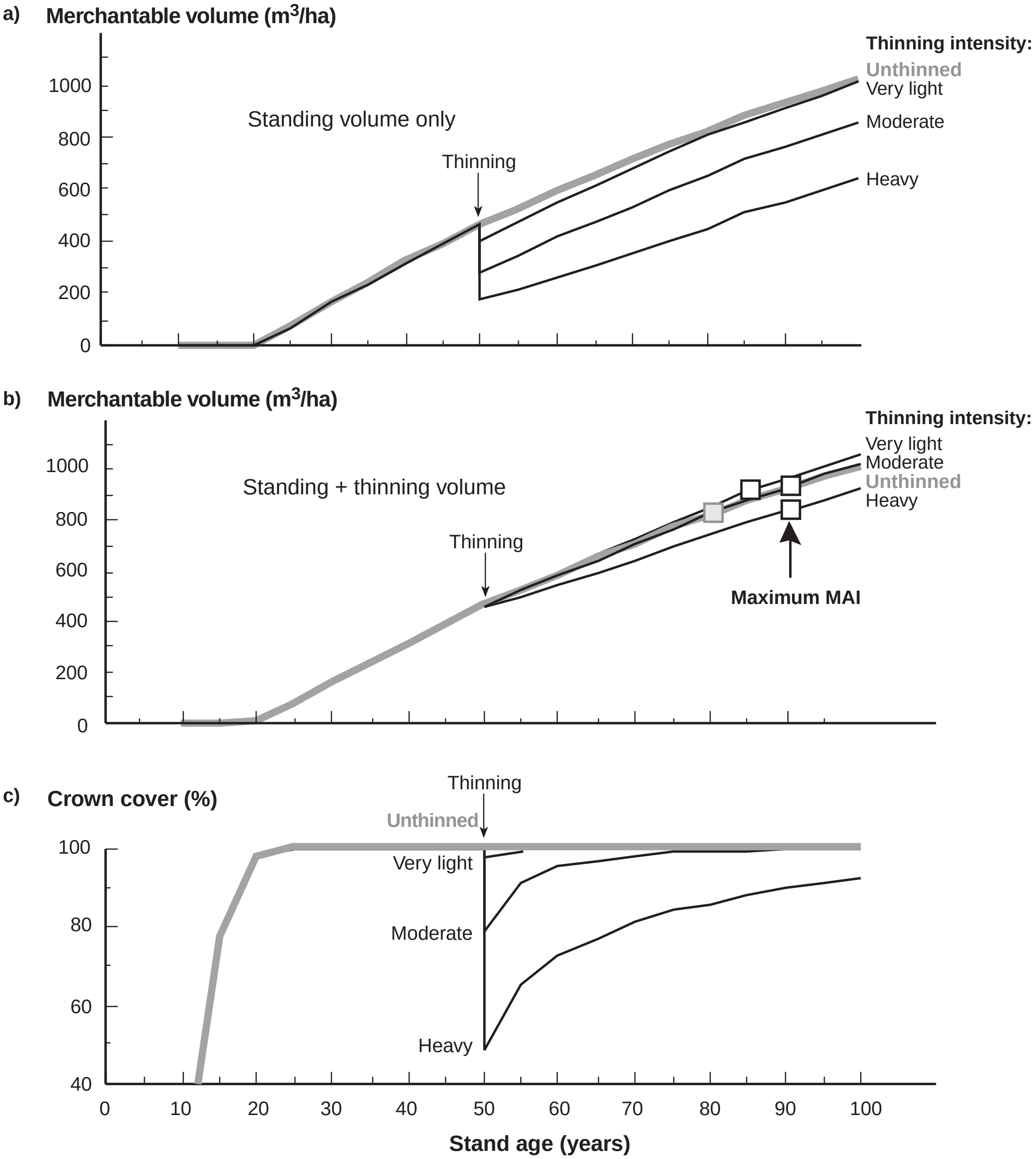


FIGURE 9. Heavy thinning regimes reduce a) standing volumes, b) total harvest volume and c) crown cover.

Also note that the MAI culminates later in the thinned stands. Figure 9c illustrates the rate at which crowns close following the very light, moderate and heavy commercial thinning regimes described above. Notice that the heaviest thinning regime is unable to reoccupy all of the available growing space, which accounts for its lower volume production.

Commercial thinning will not likely produce extra volume unless a regime of frequent, light, low entries is implemented. But it will provide an earlier, interim harvest by moving wood forward in the scheduling queue. It may also delay the final entry.

Evaluating the effects of density management practices

The effects of density management (espacement, pre-commercial and commercial thinning) on stand volume and tree diameter can be evaluated using four types of stand information: stand tables, stock tables, stand mean diameter and prime-tree mean diameter. Each is subsequently described and compared using an example based on data from a well-designed experiment of thinned and unthinned Douglas-fir research plots. In 1972, plots were established in a plantation which had been planted at a density of 3000 trees/ha. Note, however, that the treated stand was pre-commercially thinned from below to a residual density of 750 trees/ha when it was 16.6 m tall, which is very late by current standards.

Stand tables

Stand tables indicate the number of trees, by diameter class, at a particular stage of stand development. Stand tables of comparable thinned and unthinned research plots at heights of 16.6 m and 31.6 m are displayed in Figures 10a and b, respectively. In this example, Figure 10a indicates that the proportion of trees removed from five diameter classes ranged from 0 (25 cm class) to 100% (5 cm class), relative to the unthinned plot. Figure 10b illustrates that, as both stands matured (top height approached 32 m), the diameters of the largest trees in the thinned stand moved slightly ahead of the diameters of comparable trees in the unthinned stand.

Stock tables

A stock table displays volume, by diameter class, and enhances stand table data by identifying the diameter classes that contain the bulk of the volume. It is important to focus on the upper and middle diameter classes of each plot since they contain the largest trees. Figure 10c illustrates a stock table comparison of the thinned and unthinned plots at 31.6 m of top height. Note that the *extra wood* in the unthinned stand is concentrated in the smallest diameter classes.

Figure 10c also illustrates how stock tables can be used to evaluate the impact of pre-commercial thinning on future commercial thinning opportunities. In this example, considerably less wood will be available in the 15 to 30 cm diameter classes, but a little more can be removed from the larger classes. The benefits of early stocking control, in terms of later thinning opportunities, will depend on the diameter classes targeted and the volume to be removed.

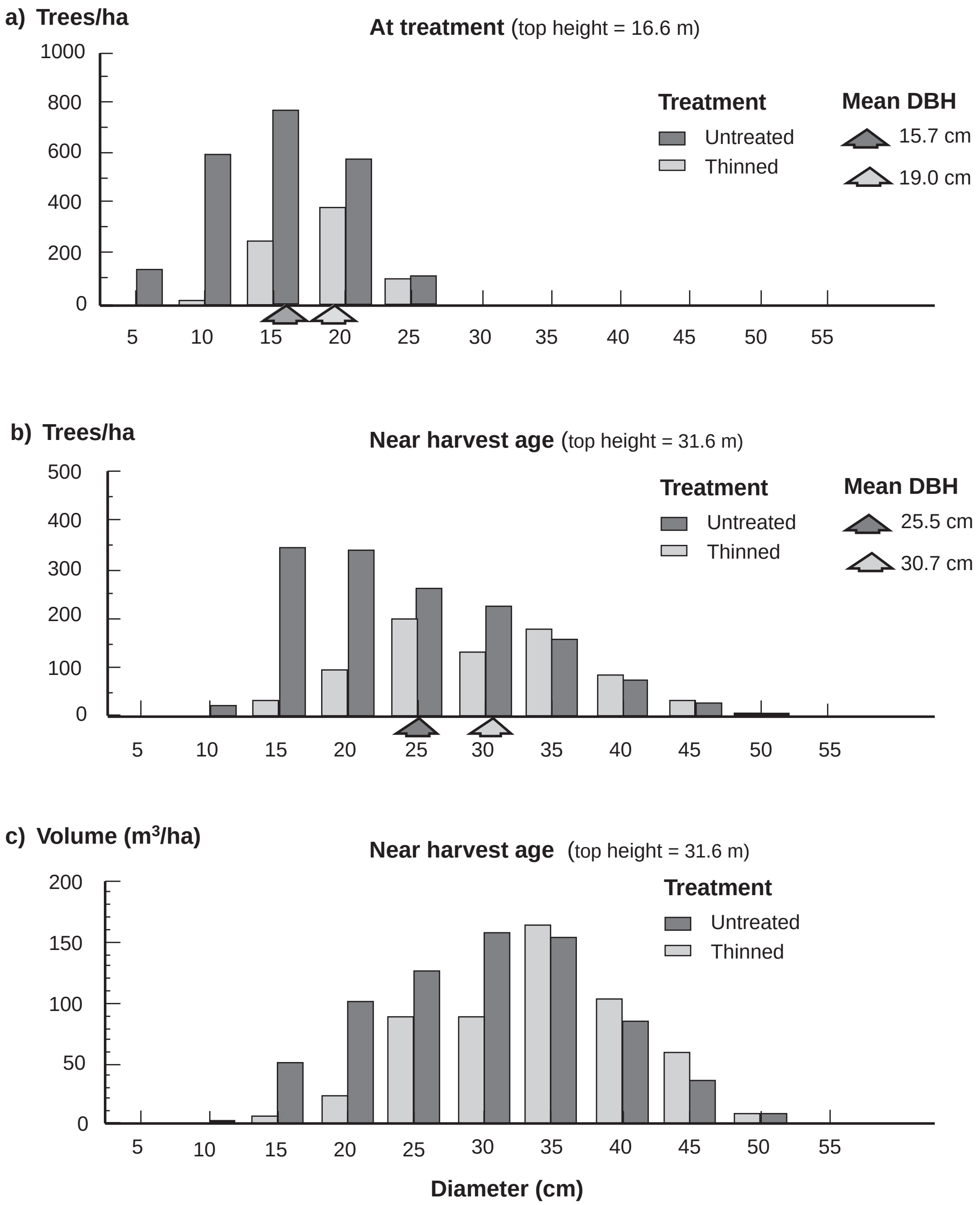


FIGURE 10. Thinning has the greatest impact on number and volume of small trees.

Stand average DBH or volume

The average diameter or volume of *all trees* in the stand provides a useful but narrow view of a stand, compared with a stand and stock table summary of stand structure. For example, in Figure 10a thinning from below instantly raises the average diameter of the plot (15.7 to 19.0 cm) in what is known as the *chainsaw effect*. This is caused by the removal of small trees during thinning inflating the arithmetic average diameter of the remaining trees.

Average diameter also fails to show the large spread in tree diameters in the thinned (15–50 cm) and unthinned (10–50 cm) stands in Figure 10b. Similarly, a heavily thinned stand has a larger stand average diameter than a lightly thinned stand, particularly during the sapling stage. Neither of these examples represents a *biological response* to thinning treatments, merely the presence or absence of many small trees that influences calculation of stand average diameter. These non-biological differences persist as the stands grow, although they tend to decrease towards maturity as competition and mortality eliminate the smaller trees from the unthinned stand. Since the average diameter of all trees does not adequately assess response to density management, analysts also look at other measures such as the average diameter of the larger and more valuable trees in a stand. These statistics include all trees above a particular diameter limit, or a fixed number of the largest trees. For example, one might trace the development of the average diameter of the largest 400 trees/ha if this is the cohort most likely to reach harvest age.

Prime tree average DBH

If there is a wide range of establishment densities, it is useful to compare the development of prime trees (largest 250 trees/ha) because these trees will likely survive to harvest in all stands. Furthermore, prime trees are independent of the chainsaw effect in stands thinned from below. For example, the average diameter of the prime trees in the thinned and unthinned stands is 38.3 and 37.5 cm, respectively, in Figure10b. The prime trees in the thinned stand outgrew those in the unthinned stand, but the difference is small because prime trees do not suffer from the same intensity of competition as smaller trees in the stand. Prime tree diameter is largely insensitive to stand density, unless the inter-tree distance is quite large. For example, the stand in Figure 10 was thinned late (16.6 m) to a residual density of 750 trees, which will only stimulate the growth of prime trees for a short period.

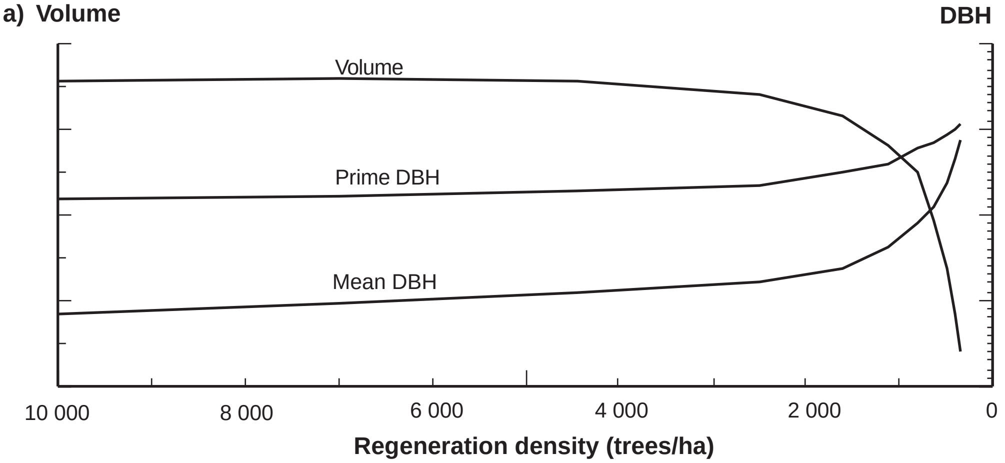
In summary, while average diameter of prime trees and stand average diameter are informative statistics, they must be used cautiously when assessing stand response to density management. Both statistics have shortcomings in portraying stand structure, and neither should be used in isolation of other relevant information (e.g., the range of tree diameters or volumes, the average diameter of non-prime trees, and stand and stock tables).

Volume-diameter trade-off

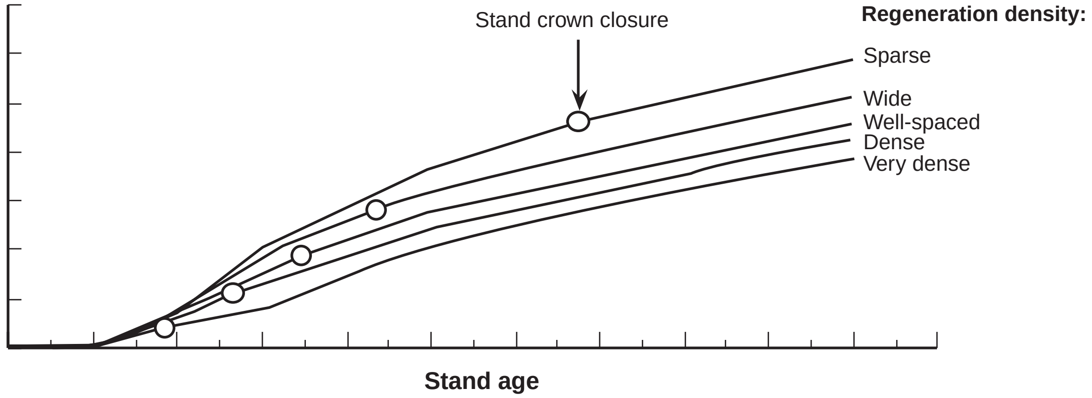
The trade-off between stand volume and piece size achieved through espacement, pre-commercial thinning and commercial thinning should be evaluated using stand and stock tables. However, in the interest of brevity, volume per hectare and average diameter (all trees and prime trees) will be used in the following example.

The simulated data in Figure 11a show that natural regeneration densities above about 1500 trees/ha cause only small changes in stand volume per hectare and average diameter at rotation age. Lower stocking regimes result in progressively larger trade-offs as establishment density declines below this threshold. That is, less volume is produced, but it is concentrated on fewer, larger trees. The volume-diameter threshold varies with species, regeneration method (natural regeneration or plantation), utilization standards, as well as other biological and ecological factors. Other information (e.g., economic analysis) is needed to determine the optimum regeneration density.

a) Volume



b) Mean DBH



c) Prime DBH

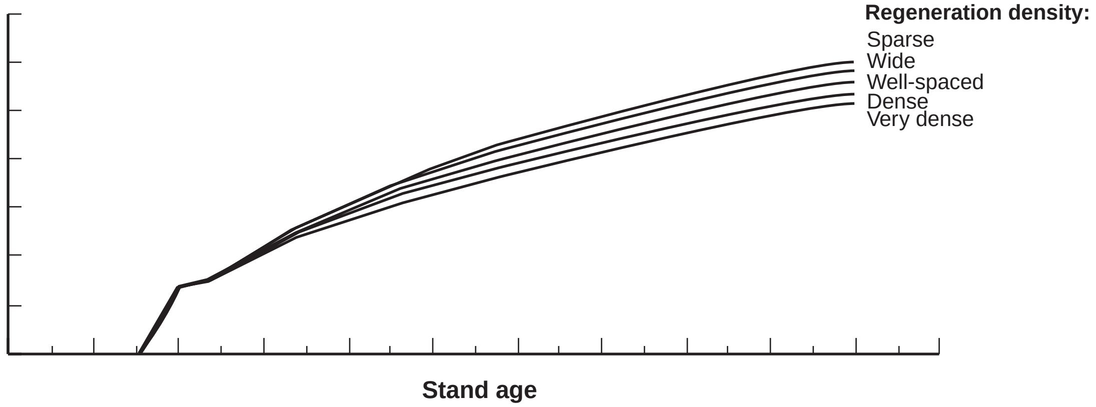


FIGURE 11. a) Harvest yield is much more sensitive to changes in regeneration density between 300 and 1500 sph than at higher densities. b) The trade-off between the mean diameter of all trees and stand volume occurs before crown closure. c) Prime tree average DBH is less sensitive to regeneration density than is stand average DBH.

The increase in average diameter resulting from wide inter-tree spacing occurs prior to stand crown closure [Figure 11b] with little or no increase thereafter attributable to establishment density. Since Figure 11 illustrates a stand espacement example, there is no artificial increase in diameter (i.e., chainsaw effect) immediately after treatment. The behaviour of prime trees in Figure 11c is similar, but much less dramatic.

Rotation ages in Figure 11a conform with the culmination of MAI. This ensures maximum sustained volume production. Planners may also use other criteria to determine the age of the final harvest. The attainment of a particular average diameter is a good example. However, they must be aware that technical rotations decrease the long-term stand volume production except in rare cases where the selected rotation age coincides with the culmination of MAI. At the forest level, planners have to consider trade-offs in terms of volume, diameter, rotation length and other relevant variables.

Other density management considerations

Wood quality

The interactions between basic tree and wood properties and species, seed source, geographic location, site conditions and management decisions are very complex. As a result, it is difficult to discuss these relationships in detail. However, an attempt is made in this section to outline the more important interactions in a general way so that foresters concerned with maximizing timber value are aware that silviculture decisions can affect both the tree volume and wood quality components of timber value. Tree and wood quality refers to specific characteristics that affect the value recovery chain from harvesting of trees to manufacturing and grade recovery of specific products (Zhang 1997).

Wood quality characteristics depend on the intended products and are usually defined by relative wood density, ring width, microfibril angle, fiber length, knot size and distribution, spiral grain angle and chemical composition (e.g., lignin-cellulose ratios and extractives). Their affect on product quality and value have been discussed in detail by Jozsa and Middleton (1994).

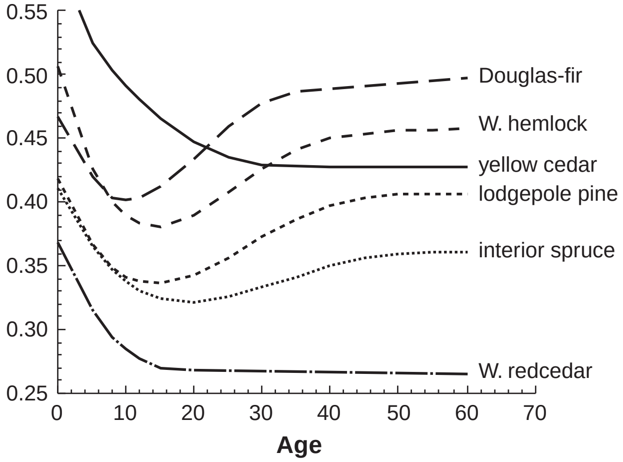
Although very dependent on species, the potentially larger proportion of juvenile wood (also called crown formed or core wood) added to regions of the bole covered by live crown is one of the greatest quality concerns in second-growth stands. The close proximity of growing shoots results in high growth hormone levels in the cambium leading to the production of wood with less desirable properties for most products. As the crowns close and lift, hormone levels below the live crown are reduced and the cambium gradually begins to produce mature wood (also called stem formed wood) of higher quality.

Early stand density affects wood quality largely through its effect on crown development and the subsequent production of wood of differing density and related characteristics. The variation in wood characteristics within a tree is largely associated with radial and, to a lesser degree, vertical position within the stem. The radial pattern of variation differs greatly between species. Figure 12a (after Jozsa and Middleton, 1994) shows the pith-to-bark trends of very rapidly grown trees of six species common to BC. The core wood of many species is lower in relative density than that of the outer shell, but this is not universally true. Wood closest to the pith of most conifers is of high density but this apparent advantage is offset by large fibril angle that contributes to low strength and stiffness and greater longitudinal shrinkage. According to DiLucca (1989), the wood of second-growth coastal Douglas-fir changes from juvenile to mature wood a few metres below the base of the live crown. Using this definition, Figure 12b illustrates how the juvenile wood content of simulated Douglas-fir changes with initial spacing and increasing stand age (after Mitchell *et al*. 1989). In the early years, all wood is juvenile because trees are open grown. Figure 12c illustrates how these initial spacings affect the proportion and distribution of juvenile wood in prime trees (tallest 250/ha) at harvest. In this example, very wide spacing has 55% juvenile wood relative to total tree volume while the narrow spacing has 45% due to the relatively rapid crown lift in dense stands. Commercial thinnings or late pre-commercial thinnings have less impact on wood quality because crowns usually have lifted.

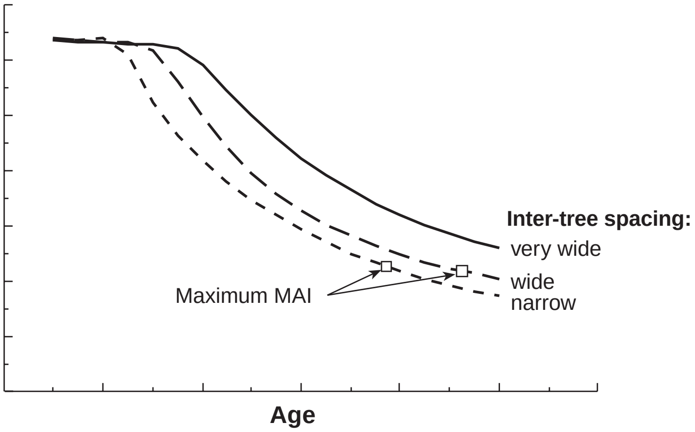
Tree quality is defined by characteristics such as log diameters, branch diameter and distribution, stem taper and straightness. For example, large tree and log size lowers logging and hauling costs and more lumber is recovered per cubic metre. However, increasing branch diameter for a given log diameter adversely affects structural lumber grade recovery. Silviculture decisions can strongly affect the characteristics defining tree quality. Managing for low stocking density through initial spacing or subsequent thinning operations may increase average piece size. For example, the mean DBH of the prime trees shown in Figure 12c is about 8 cm larger for the very wide as compared to narrow spacing. However, the resulting increase in crown length, particularly in the early years, will produce larger diameter branches and increase both bole taper and the proportion of juvenile wood.

Stand density management decisions affect various links in the value recovery chain, including both tree and wood quality, harvesting and milling costs, product value and financial return. The optimal combination of stocking density and harvest age for each species varies widely with end products produced. The forest manager needs to consider the impact of silviculture treatment on the volume, quality and value at harvest if they wish to maximize their return on investment. The reader is referred to Carter *et al*. (1986), Ellis (1998), Farr (1971), Kellogg (1989), Jozsa and Brix (1989), Jozsa and Middleton (1994), Jozsa *et al.* (1998), Middleton *et al*. (1995), Middleton *et al.* (1996) and Walker and Johnson (1975) for more in-depth discussions of tree and wood quality of BC species.

(a) Relative density



(b) Juvenile wood (%)



(c) Distribution of juvenile and mature wood

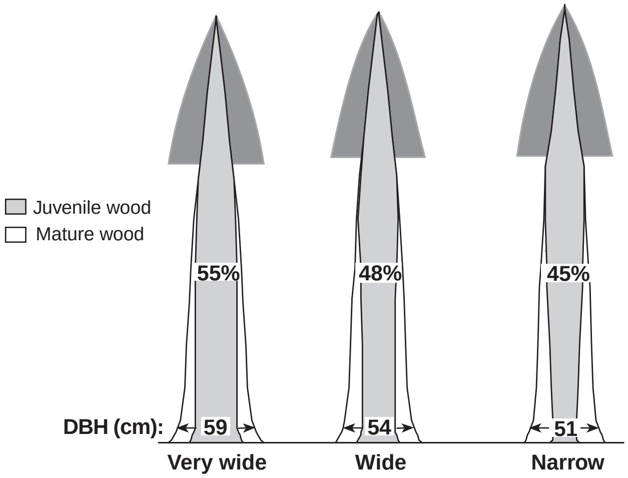


FIGURE 12. a) Average relative density trends from pith to bark in second-growth trees of several species (from Josza and Middleton 1994). b) The proportion of juvenile wood (Douglas-fir) increases with wide spacing. c) Distribution of juvenile wood and mature wood in Douglas-fir trees from stands established at different initial densities.

Waste and breakage

Managing for high density produces more small slender (larger height/diameter ratio) stems than would occur in stands of lower stocking. These trees have a greater risk of breakage during harvest, and windthrow if left exposed by commercial thinning or partial cutting. Consequently, some of the “extra” volume contained in the smaller diameter classes of the untreated stand in Figure 10c may be lost to breakage, or not utilized because of size, particularly if markets are poor. These losses may be offset by technological changes in the future.

Damaging agents

Damaging agents play a major role in the development of young stands, whether those agents are biotic, such as insects, diseases or undesirable vegetation, or abiotic agents, such as wind, snow or abnormal temperatures. For example, in a recent province-wide survey (Nevill 1996), more than 60 different insects and diseases were identified as having some effect on 217 of 234 assessed stands. Of those stands, 74 were experiencing significant damage and were likely to suffer long-term volume production losses. Some of this damage may be accounted for in yield forecasts, but the actual amount is not known. It is likely that damaging agents will prevent stands from achieving their potential production.

The provincial survey indicated the potential risk of damage at the landscape or forest level. However, the occurrence and the impact are highly variable in both time and space at the stand level. This is true whether or not stand density has been reduced. Because of this variability, little is known about the interactions among the occurrence and effect of damaging agents, stand density and density management. There are records of increases and decreases in damage with increasing density (Safranyik and Morrison 1998). Some damaging agents appear to be unaffected by stand density. There is also evidence that the occurrence and effect of some damaging agents are functions of the scale of silviculture treatment over the landscape.

Some types of stand damage, and the agents that cause them, are extremely difficult to detect and may require experts to adequately survey their incidence. This is especially true of many species of decay fungi, particularly in the early years of stand development. Many types of abiotic damage (wind and snow) may be periodic or random in occurrence, and difficult to predict in space and time. Given the complexity of the problem, great care should be taken to avoid creating stand conditions that increase the susceptibility to damaging agents. Resulting damage may partially offset or completely eliminate the intended benefits of stand density management treatments.

Information on specific damaging agents can be found in Forest Practices Code guidebooks.

Other resource values

Stand density affects a range of forest resource values apart from timber, including wildlife habitat quality, wildlife use, species diversity and water yield. These values are all influenced by stand characteristics such as structure (canopy coverage, tree size, species mixture), pattern of tree mortality (large and fine woody debris, standing snags), and understorey species composition (abundance and vigour), as well as rate and direction of change (dynamics). Stand density management practices may have a positive, negative or neutral effect on other resource values by modifying these stand characteristics.

Wildlife habitat

The report *Stand Tending Impacts on Environmental Indicators* (Greenough and Kurz 1996) identifies some of the effects that density management practices (pre-commercial and commercial thinning) may have on wildlife habitat, as measured by the following habitat indicators:

- per cent cover of understorey shrubs
- volume of shrubs and herbs
- number and size of snags
- volume and size of coarse woody debris
- functional maturity of stand.

Thinning practices decrease the overstorey crown coverage of a stand, and delay crown closure in proportion to the intensity of thinning. The production of understorey shrubs and herbs responds inversely to overstorey cover, and is proportional to the intensity of sunlight reaching the forest floor. The timing of thinning (stage of stand development) also influences the quality of the understorey forage production response. For example, properly timed thinning in coastal ecosystems may enhance berry production, whereas a delay of 10 or more years following stand crown closure often yields a poor response of berry-producing shrubs due to exhaustion of the understorey bud bank.

Coarse woody debris production within a stand is a prerequisite for many species of fungi, plants, insects and small animals. Stand density management practices affect the volume and size of coarse woody debris produced in a stand. Relative to unthinned stands, thinning tends to reduce the total volume, but increases the average size of coarse woody debris created over a managed rotation. The effect of thinning on debris-dependent habitats is further complicated by stand dynamics; for instance, reduced competition and mortality following thinning delays the production of large diameter, coarse woody debris.

A similar relationship exists between thinning and standing snags. Habitat values, which depend on the *functional maturity* of stands, are affected by changes in the size and frequency of standing snags, total volume and production rate of coarse woody debris, and the size distribution of large living trees. The effects of thinning on the quality of these habitats may be predicted by considering each factor and its response over time. However, the likelihood of co-ordinating factors to create favourable conditions presents a difficult prescriptive challenge. Some species of plants and animals are more critically dependent on stand age rather than functional structural characteristics.

Stands usually support a number of different species. Stand density management practices can be designed to immediately enhance habitat quality for one or several species. However, these changes may result in decreased habitat quality for other co-dependent species. Long-term thinned stand dynamics increase, reduce or reverse the initial relationship. No stand or density management treatment can possibly meet the needs of all wildlife species through all stages of stand development.

In addition to the *Biodiversity Guidebook*, the following reference guides discuss the relationship between density management regimes and critical habitat needs for various wildlife species:

Managing Identified Wildlife: Procedures and Measures[5]

- pre-commercial thinning and deer, mule deer and grizzly bear.

Guidelines for Integrating Grizzly Bear Habitat and Silviculture in Coastal British Columbia.[6]

Deer and Elk Habitats in Coastal Forests of Southern British Columbia (Nyberg and Janz 1990)

- pre-commercial thinning and screening
- regeneration densities
- snow interception
- crown closure and cover.

Handbook for Timber and Mule Deer Management Co-ordination on Winter Ranges in the Cariboo Region (Armleder *et al.* 1986)

- pre-commercial thinning.

Guidelines for Maintaining Biodiversity during Juvenile Spacing (Park and McCulloch 1993)

In order to balance a range of environmental, habitat, forage and timber requirements, a single, optimum density regime is neither feasible, nor desirable. Consequently, it is unwise to apply an economically optimum density management regime for timber production uniformly to all stands. Non-standard density regimes may be necessary to improve or maintain critical habitats under certain management scenarios.

A clear relationship does not exist between stand habitat quality, species utilization and population size. Factors other than local habitat quality affect the presence of a

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[5] Province of British Columbia. [In prep.] B.C. Min. Environ., Lands and Parks and B.C. Min. For., Victoria, BC.
[6] Province of British Columbia. [In prep.] B.C. Min. Environ., Lands and Parks and B.C. Min. For., Victoria, BC.

species in space and time. Wildlife habitat quality must be evaluated and planned at the landscape level, since the current and future distribution of different stand conditions, or the uniformity of stand conditions are important factors in assessing the habitat impacts of stand-level actions. Thinned and unthinned stand dynamics result in changes in the proportion, spatial distribution, linkage and fragmentation of habitats, all of which play a critical role in species distribution and biodiversity. Readers are encouraged to review *Conservation biology principles for forested landscapes* (Voller and Harrison 1998) for a better understanding of the effects of forest management disturbances in the landscape.

Hydrology

The effects of manipulating stand density on water quantity and quality are poorly understood. The current *Watershed Assessment Procedures* guidebooks compare unlogged forest conditions with newly logged areas to estimate the rate of recovery as the new stand regenerates and grows. These estimates are based on the assumption that, as the regenerated stand height increases, there is a proportionate decrease in snow accumulation and snowmelt rates. The effects of stand espacement and thinning intensity on the hydrological recovery rate is not known.

In a recent study in the Kamloops Forest Region, the snow accumulation and melt of a thinned and pruned, 6 to 8 m tall lodgepole pine stand was compared to a similar, but unthinned stand, and a recent clearcut. The study indicated similar values of snow water equivalent (SWE) for the three stand types at the onset of springtime snowmelt. All three stand types had considerably more snow water equivalent (SWE +40%) than an adjacent stand of mature Engelmann spruce, subalpine fir and lodgepole pine (SeBl[Pli]). The rate of snowmelt in the two young lodgepole pine stands and the clearcut was faster than in the mature stand. This study suggests that the hydrological recovery to old forest characteristics may be slower than indicated in the guidebook recovery curves. It does not, however, show any hydrological effect of thinning.

Associated biotic and abiotic effects

Many site and stand factors may be affected by stand density management practices; some may enhance the productive capacity of the stand, while others may introduce elements of uncertainty and risk. For instance:

- Higher levels of sunlight and warmer soil temperature may influence micro-organisms and the rate of nutrient cycling.
- Increased micro-organism activity may increase the decomposition rates of slash remaining after thinning, and eventually improve mineral nutrient availability for the remaining crop trees.
- Reduced uptake by the stand may influence the diurnal and seasonal availability of soil moisture, thereby influencing the pattern of stomatal activity, duration of photosynthesis, and the rate of biomass production in the standing crop.

- Increased sunlight, warmer air temperatures and increased air movement may increase the respiration rate of the standing crop, partially offsetting increased biomass production rates.
- Cutting activity associated with thinning may increase the concentration and spread of root decay inoculum within the stand, resulting in greater losses of usable timber from the stand.

The characteristics of the site and stand may indicate the potential significance of these biotic and abiotic responses to density management decision making.

Economic Principles of Timber Production

Introduction

These principles provide a production economics background for evaluating stand density management options. Production economics is the process of determining which, among all treatment options capable of meeting forest management objectives, will maximize the return on treatment investment for the forest estate owner. This approach is consistent with the philosophy that the purpose of stand density management is to achieve the timber and non-timber production objectives of a forest management plan.

These stand-level economics principles are not intended to address social welfare objectives such as income distribution or employment creation. In the following section, “Forest planning considerations,” economic issues are addressed at the forest level.

Density management activities as investments

Stands in BC exhibit great variability in growing conditions and capacity for timber production. This results in a wide range of economic conditions for making silviculture investment decisions. Assessing the economics of a proposed silviculture activity requires information about benefits and costs of the activity from the time of stand establishment to the time of expected harvest. Costs and benefits may be actual if they have occurred, or expected if they are anticipated in the future. Expected costs or benefits are estimates, and may differ from actual costs and benefits when they occur. Estimation therefore involves accounting for the uncertainty surrounding their actual values.

Information about the timing of stand activities is also required, since various costs and benefits usually occur during different time periods over the life of a stand. Economic analysis converts all costs and benefits to value in today’s dollars. This conversion process is referred to as discounting (see “Selecting a discount rate”). The net present value (NPV) is the sum of all discounted benefits of silviculture activity or regime, less discounted costs (see Stone 1992, 1996b for further discussion on NPV analysis and procedures).

Regeneration costs such as site preparation and planting are incurred within the first few years, whereas density management costs are incurred between stand age 10 and 30. Final stand net revenues (revenue less harvest cost) are obtained at the end of the expected rotation period. The procedure for calculating the NPV of a density management treatment in a single stand is straightforward; the NPV of a juvenile spaced stand is compared to that of the same stand without spacing.

In order to make economic comparisons between different stands or different treatments, however, NPV must be calculated over the same time period. That is, for each present value, the starting point must be the same for each stand or treatment, and the end point must be the same expected rotation length. Since the timing of different stand treatments and the rotation lengths of different stands are rarely the same, it is often impossible to compare treatments and stands in this manner. In these circumstances, the NPVs must be converted to a site value.

A site value is the present value of an infinite number of successive rotations on a site managed under the same regime. An economic comparison of two or more stand management regimes is made possible by calculating and comparing the site value of each, even though they may differ in the timing of stand treatments or expected final harvest.

Economic analysis provides a means of ranking the economic attractiveness of treatment options, thereby allowing appropriate allocation of silviculture expenditures. Ranking criteria may reflect either profit maximization or cost minimization objectives. Either single treatment or multiple treatment regime options may be analysed in this manner. A preferred treatment or regime selected in this manner may be applied to other similar stands (stand type/site quality) within the same management unit without the need for further, separate analyses.

From this brief overview of stand-level investment procedures, one can see that both the timing and relative value of treatment costs and benefits are important factors in the calculation of NPV and site value.

The link between pre-commercial thinning and commercial thinning is discussed by MacLeod (1997) and White (1997), and an economic analysis of spacing as it relates to commercial thinning is reported by Stone (1992, 1996b).

Revenue assumptions

Future forest product market conditions must be predicted in order to compare the economic efficiency of various silviculture investments. Because the timber production benefits of silviculture investments are usually not obtained for 40 to 80 years, estimating future forest product prices is fraught with uncertainty. The assumptions used to make them are key considerations in an economic analysis. Three factors influence revenue forecasts; valuation point, real price changes and the relationship between piece size (tree or log) and price.

Valuation point

For simplicity, the value of harvested timber can be derived from the selling price of manufactured end products. A common practice is to evaluate the timber as it moves up manufacturing stages to a point where a market price for a product can be determined. At that point any wood quality differences that affect the product are reflected in the price.

In the coastal region of BC the end-product values are derived from log transactions on the Vancouver Log Market (B.C. Ministry of Forests 1995b). In the interior, where log markets are uncommon, a market value is derived from processed lumber and residual wood chips (B.C. Ministry of Forests 1995a).

Real price changes

Since the effect of a silviculture treatment on stand revenue will not be realized for a considerable time, the potential for change in the real value of wood products, either upwards or downwards, should be considered (see Appendix 1). An important principle applies; time itself has no effect on prices. Rather, market supply and demand forces, which change over time, are the cause of price changes.

Simple price-trend models are sometimes used inappropriately to predict future prices. They assume the forces of supply and demand which caused past price changes are closely correlated with time, and will continue in the future. This assumption may not be valid, and caution is advised in using historical price trends to predict future product values.

Piece size and price

Currently, a large log commands a higher price per cubic metre than a small log, all other wood quality characteristics held constant. This price premium is due to the larger dimension and usually more highly valued products that can be manufactured from large logs, as well as the higher product recovery rates associated with a larger piece size. However, many other characteristics influence the price of a log. Stand density management treatments affect a number of log quality characteristics, such as log taper, knot size and distribution, number of growth rings per inch, and the proportion of lower strength juvenile wood (not always lower strength). These stand density-related characteristics may have important impacts on future stand values (Jozsa and Middleton 1994; Middleton *et al.* 1995).

Whether the price premiums associated with larger piece sizes will be maintained in the future depends on how future markets will value piece size and stand density-related wood quality characteristics. Changes in harvesting systems, manufacturing processes and wood products design will likely encourage better utilization of small dimension logs, higher recovery rates during manufacturing, and greater use of engineered wood products as substitutes for large dimension timber components.

The revenue assumptions used in an economic analysis must be clearly defined, and the analyst should provide evidence supporting all assumptions. Assumptions must also be consistently applied in comparisons of different density management options. For example, an assumption of increasing real prices for large logs made in an analysis of a juvenile spacing option must also be made for an analysis of a commercial thinning option. Different prices in a comparative analysis would allow no basis for comparison.

Harvesting costs

Harvesting costs can be categorized by harvesting phase, such as road and site development costs, tree-to-truck (felling and yarding) costs, log haul (loading, truck haul, towing or barging) costs and administration and overhead costs. The effects of density management on each cost phase must be accounted for in any analysis.

Development, overhead and administrative costs are fixed harvesting costs. Density management treatments which result in changes to the volume of timber produced by a stand will not affect total fixed harvesting costs, but will affect the average fixed costs per cubic metre of timber produced.

Density management treatments have a larger impact on certain components of tree-to-truck and log haul costs, called variable costs. For instance, log haul costs are influenced primarily by changes in loading time resulting from the number of logs required to complete a load. However, the cost of the loading component of log haul costs is relatively small. Density management practices have their greatest impact on tree-to-truck costs, particularly the yarding component.

For further information on more detailed aspects of harvesting costs, refer to the Ministry of Forests *Appraisal Manuals* (B.C. Ministry of Forests 1995a, b and Stone 1996a and Stone *et al.* 1996).

Milling costs

Milling costs need not be accounted for in economic analysis based on log values, since the log prices used in the analysis should already reflect differences in milling costs. However, when the analysis is based on lumber and wood chip end products, the effects of density management treatments on milling costs must be considered. Larger log sizes result in lower milling costs, although other factors, such as log taper, must also be considered. Stone (1996a) and Stone *et al.* (1996) illustrate a method for predicting changes in milling costs.

Silviculture treatment costs

The cost of stand density treatments is usually a function of site and stand conditions such as road access and travel distance, the average slope of the site, original stand density and the number of trees removed, and the average height and diameter of the trees removed. Local labour market conditions may also influence treatment prices. For instance, the number of silviculture operators available to bid on a project and the amount of work currently under contract may have a substantial effect on treatment prices. Local market treatment costs should be used to assess density management options. If this information is unavailable, regional average costs may be used.

Selecting a discount rate

Silviculture investments are characterized by treatment costs and benefits that occur in different time periods through the rotation. These costs and benefits must be converted to present values in order to assess investment efficiency. The purpose of a discount rate in an economic analysis is to reflect the preference that societies, organizations or individuals have for present versus future consumption.

Income received or costs incurred today are considered to be worth more than income or costs that occur in some future time period. The rate of discount is used to determine how much less future revenues or expenditures represent in today's dollars. Discounting permits a comparison of various flows of benefits and costs occurring over time in a consistent and logical manner.

Choice of a discount rate is influenced by markets for capital, opportunity costs of capital, risk and perceptions of risk, uncertainty, inflation expectations, differences in the rate of borrowing and lending, as well as other factors. Governments and private sectors are both influenced by these factors. However, private sectors of the economy are affected to a greater degree due to uncertainties in future product demand, natural resource conservation policies, and the wider range of alternative investment opportunities available.

Heaps and Pratt (1989), in *The Social Discount Rate for Silvicultural Investments*, estimated the discount rate using the social opportunity cost of capital for public sector investments in Canada, and found a range of between 3 and 7%, depending on how risk and uncertainty are accounted for. They argued that a risk-free rate should be used for silviculture investments, and recommended a discount rate of between 3 and 5%.

The Ministry of Forests uses a 4% real rate of discount for public sector forestry investment analysis. The discount rate, whether public or private, is a "real" discount rate. This means that it does not include any inflationary expectations. Inflation is "netted out" of a real discount rate since it is assumed to affect both costs and prices equally over time.

Whatever discount rate is selected, it must be used consistently for all silviculture treatments. For example, although a lower discount rate would "improve" the economics of juvenile spacing, it would also reduce the benefits derived from commercial thinning. The discount rate is clearly a two-edged sword.

The importance of sensitivity analysis

Sensitivity analysis is an important analytical method used to evaluate the effects of risk and uncertainty in economic analyses. Sensitivity analysis involves re-calculating the site value of a silviculture treatment using a range of values around key factor assumptions. Key factors in an economic analysis include future revenue, harvest cost, milling costs, silviculture costs (regeneration, tending, protection, administration), and investment period (rotation length).

For example, a sensitivity analysis of future harvesting cost would involve repeating the economic analysis using harvesting costs that are slightly higher and slightly lower than the expected value. The usual approach is to test values within plus and minus an arbitrary percentage (e.g., 10%) of the expected value. The sensitivity analysis is performed while keeping all other key factors constant.

The three site values from the sensitivity analysis are then compared; large differences indicate that site value is “sensitive” to small changes in harvesting cost. Sensitivity in one or more key factors suggests that the economic analysis is not robust, and may lead to errors of interpretation. The outcome of the sensitivity analysis will determine whether all input values and assumptions should be re-evaluated.

Forest Planning Considerations

Introduction

Silviculturists place great importance on practicing “good” silviculture by carefully selecting and prescribing appropriate interventions based on stand-specific considerations. Frequently, however, the connection between stand-level silviculture and forest management objectives is not made. The absence of this critical linkage means that stand-level interventions are undertaken with little appreciation of their effects on forest resource supply requirements (i.e., timber quality, size, harvest flow, location and species).

Stand-by-stand silviculture often assumes that a series of individual stand treatments results in an additive impact on resource supply at the forest level. Baskerville (in Kelty *et al.* 1992) warns that the effects of stand-level actions are usually not additive at the forest level. He suggests that stand-by-stand silviculture ignores the complex interaction of factors influencing resource supply, and reduces the likelihood of successfully controlling forest dynamics to achieve management objectives. For example, harvest flow considerations may force the advance or delay of harvests from the planned harvest ages that would have maximized the gain from a particular treatment. Thus the expected yields from stand-level planning may not be realized at the forest level.

A forest management strategy should be the guiding reference for stand-level silviculture (Reed and Baskerville 1990). The relative “goodness” of a silvicultural intervention is difficult to judge unless viewed within a strategic context. In this context, even basic silviculture expenditures are difficult to evaluate objectively, except in terms of discharging legally binding reforestation obligations.

A comprehensive forest management strategy is therefore necessary before rational choices of stand-level interventions can be made. For example, without a strategic context, local stand density management interventions may result in:

- inappropriate amounts or types of silviculture investments being implemented
- cumulative forest-level effects that exacerbate a forest management problem
- large opportunity costs if actual forest management problems are ignored.

The purpose of this section is to describe the forest-level context within which stand-level density management decisions are made. Specifically, this section examines the nature of forest-level objectives, their relationship to higher level plans, the strategies developed to meet those objectives, and how these strategies govern the selection of stand density management activities.

The next section describes a decision process for designing a forest management silviculture strategy. A thorough discussion of the theory and practice of forest management is beyond the scope of this document. Readers interested in the subject are encouraged to review the extensive literature available, a small sample of which is referenced here.

The following definitions may assist the reader in the ensuing discussion:

stand – A contiguous group of trees sufficiently uniform in species composition, arrangement of age classes, and condition to be a homogeneous and distinguishable unit.

forest estate – A collection of stands, of varying types, ages, etc., administered as an integrated unit and managed for some continuity or flow of harvest volume. For the purpose of this document, the forest estate is synonymous with the *sustained-yield unit* which includes timber supply areas, tree farm licences and woodlot licences.

forest-level objectives – Objectives established for the forest estate.

Linkages between levels of planning

Higher level planning, as used in forest management in BC today, refers to the hierarchical system of planning established under the *Forest Practices Code of British Columbia Act* (the Code). Under the Code, the following hierarchy has been established, where the highest level of plan is objectives for resource management zones, followed by objectives for landscape units, objectives for sensitive areas, and objectives for interpretive forest sites, recreation sites and recreation trails.

In a hierarchical planning process, higher level plans guide plans lower in the hierarchy. For example, objectives established for a landscape unit are guided by the objectives established for a resource management zone. The Code also stipulates that operational plans, such as stand management prescriptions (which may include density management activities), must be consistent with higher level plans.

At the same time, actual operational conditions provide guidance to the levels higher in the hierarchy. For example, planning delays or limits in budgets or other resources may result in amendments to plans higher in the hierarchy.

Forest-level objectives, which will guide stand-level activities, are embodied within resource management zone objectives and landscape unit objectives for all Crown land, and within management plans for TFLs and woodlots. For more information on higher level planning, refer to *Higher Level Plans: Policy and Procedures* (B.C. Min. For. 1996b) as well as *A Guide to Landscape Unit Planning*[7] and *A Guide to Writing Resource Objectives and Strategies* (B.C. Min. For. 1998).

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[7] Province of British Columbia. [In prep.] B.C. Min. For. and B.C. Min. Environ., Lands and Parks, Victoria, BC.

Forest-level objectives

For the purposes of this document, forest-level objectives can be classified as timber objectives, non-timber objectives and employment objectives. For each class of objectives, the forest-level planning process develops one or more strategies to attain the objectives. Both the objectives and their associated strategies are specified temporally (i.e., over the planning horizon) and geographically.

Timber objectives

Forest-level timber objectives may state the quantity, quality and timing of timber production from the forest estate. These objectives could be expressed as a schedule of harvests.

The strategy devised to achieve this schedule will specify timber management actions, including harvesting parameters (e.g., species mix, log size, log quality) and silvicultural parameters (e.g., management regime, including rotation length).

Ideally, timber management objectives are determined with the assistance of timber supply analysis. While this might occur as part of the timber supply review (TSR), it may not, because the TSR is focused on supporting allowable annual cut (AAC) determination. Nevertheless, the timber supply analyses supporting the TSR, and the associated AAC rationales, may be the best sources of information available for determining timber objectives at the sustained-yield unit level.

Non-timber objectives

A forest estate usually provides a large array of non-timber resource values.

Examples of non-timber values include stand and landscape features such as species occurrence, natural stand disturbance types, special wildlife habitat, riparian ecosystems, viewscapes, heritage artifacts and heritage opportunities, as well as amenities such as water production, food, shelter and recreational opportunities. Forest-level objectives describe how a resource or value will be managed (e.g., the desired future condition of each identified non-timber value).

The main strategies for realizing non-timber objectives are to wholly or partially preserve the pertinent area from timber harvesting, reduce harvesting intensity by distributing harvest areas throughout the landscape, lengthen rotations or specify an alternative harvesting method.

Other operational strategies may focus on post-harvesting treatments that control stocking, stand structure or composition.

Non-timber objectives are usually identified in higher level plans and are described in forest-level plans or TSR documents.

Employment objectives

Employment objectives may be a consideration in forest-level planning, especially in management units with forecast reductions in timber harvest.

Most stand-level silviculture treatments, including density management treatments, provide local employment opportunities that can help to sustain the forestry workforce within communities. Consequently, silviculture programs are often specified as a strategy to attain employment objectives.

Objectives for creating local employment may be specified in land and resource management plans and forest-level plans.

Objectives, opportunities and options

Stand density management is only one of a number of possible silviculture practices capable of influencing forest-level factors. Any stand treatment which contributes to the achievement of forest objectives is a silvicultural opportunity. The structure (e.g., species, age class distribution, density) and site quality of the forest estate and the complexity of management objectives are the major determinants of silvicultural opportunities.

These may require silviculturists to consider a wide variety of treatment or regime options to satisfy management objectives.

Once density management opportunities have been identified, and stand treatment options have been selected and implemented in the forest, the biological effects should be evaluated periodically and compared with expected responses. Actual departures from expected results may require reconsideration of the silviculture options, opportunities or both. This adaptive density management approach encourages continuous validation of assumptions, and incorporation of new information and experience.

The importance of forest-level plans

This section has emphasized that the stand-level density management decision should not be made without reference to forest-level objectives and the strategies designed to attain those objectives. The existence and quality of the forest-level plan(s) pertinent to a stand will determine the quality of the stand-level density management decision. However, higher level plans may not be in place for all of the land base and few forest-level analyses have been undertaken with the objective of determining strategic silvicultural opportunities. Useful information on forest-level objectives and strategies can be found in TSR documents, however, the forest estate modelling undertaken for the TSR is designed to quantify timber supply as a consideration in AAC determination. Stand-level decision making *may* benefit from additional forest-level modelling studies that have a focus on identifying strategic silvicultural opportunities, as part of the development of a strategic silviculture plan at the forest level.

Readers interested in more information about forest-level planning and timber supply analysis should review the literature presented in “References.”

Identifying strategic silvicultural opportunities that help meet forest-level objectives

Identifying silviculture activities which assist the meeting of forest-level objectives requires, at least, an assessment of existing information pertaining to the forest level. It may stop there. Forest-level modelling is neither necessary nor recommended if there are sufficient materials and expertise available to formulate silvicultural opportunities.

An understanding of forest-level concepts is important, and it is recommended that, where necessary, silviculture practitioners draw on the expertise and advice available within and outside the Forest Service.

It is recommended that the identification of silvicultural opportunities which help meet forest-level objectives follow a two-step process:

1. Obtain and assess existing forest-level analyses.
2. Conduct additional forest-level modelling analysis.

The first step is essential. Completion of the second step may not always be possible, nor is it always necessary.

For each, an understanding of forest-level concepts is important, and it is recommended that expertise in forest-level concepts or forest-level modelling be sought, where necessary.

Identifying silvicultural opportunities through the assessment of existing forest-level information

To better understand silvicultural opportunities for your forest estate, review all relevant existing materials. You can expect this review to provide useful insights and possibly sufficient information for identifying strategic silvicultural opportunities.

The results of the most recent TSR timber supply analyses and the AAC rationales provide a rich source of information on forest-level objectives, at least those perceived to impact timber supply.

An especially valuable section of the timber supply analysis document describes the sensitivity of the forecast harvest flow to changes in key variables, some of which might be affected by density management decisions. For example, the TSR timber supply analysis may note that short-term timber supply is increased substantially if the minimum harvest age is reduced by five years. This might be interpreted as an opportunity to use density management to decrease the age at which high value forest products (e.g., sawlogs) can be obtained from the stand.

In addition to reviewing documents, spreadsheet models that incorporate timber supply sensitivity analysis from the TSR can be useful for estimating the impact of stand density management activities on short- and long-term timber supply.

Forest-level modelling

Forest-level modelling is an analytical process that will assist the identification and quantification of strategic silvicultural opportunities.

A forest-level analysis may help determine a set of silvicultural regimes that best meets the combined objectives, subject to harvest flow requirements and forecast silviculture budgets. This set of regimes constitutes the strategic silvicultural opportunities for the forest.

Forest-level models can help determine the sensitivity of the forest-level objectives to each strategic silvicultural opportunity. This information may be used in the process of allocating funds to projects.

Any such modelling exercises undertaken should be integrated with other exercises such as those being conducted as part of formal planning processes.

Table 3 in “Density management planning tools” lists commonly available forest estate models. Often a considerable investment of time and resources is necessary before operators acquire the necessary experience to be able to use such models competently. An alternative is to make use of services available within and outside the Forest Service.

Three important considerations need to be made when conducting forest-level analyses for the purpose of assisting the determination of silvicultural regimes that are designed to impact the timber supply for the forest estate:

1. Assumptions should be consistent with, and follow from, those made in timber supply analyses supporting AAC determinations.
2. Forest-level analyses should consider the desired harvest flows for the entire forest estate or sustained yield unit, rather than for a sub-unit *only*.
3. Little is known about the future with certainty, and models provide imperfect views of reality. All results should therefore be treated with caution and be used only as an *aid* to decision making – not as the decision maker itself.

A Structured Decision Process

Introduction

Information pertinent to stand density management decisions has been introduced in preceding sections of this document. The knowledge required to make density management decisions is similar to that required for other silviculture decisions. For example, a silviculture planner must understand the requirements and objectives of the forest owner, the characteristics of the forest and the response potential of individual stands within the forest to specific management interventions

In this section, a framework for stand density management decision making is presented. The decision-making process links each component of the framework into a knowledge-based, structured approach to stand density management problem solving.

Decision framework

The decision framework consists of three major components.

Management objectives

Management objectives define the current and future quantity and quality of timber and non-timber resources desired from the forest. For instance, management objectives should specify the silvicultural system(s) to be employed, the periodic rate of timber harvest, the species to be managed, the standards defining current and future harvesting operability, and current and future product objectives.

Non-timber resource objectives require similar detail. For instance, biodiversity, habitat, recreation and visual management objectives should be defined in space and time parameters, including specified areas, specific locations, management periods and standards defining the kinds of management interventions permitted.

Defining management objectives for public forest resources is a complex process. Factors such as the nature and extent of the forest resources available, the goals of each resource user, and the resource management rules imposed by governments must be harmonized into a single, acceptable forest management plan. The process of defining forest management objectives is beyond the scope of this document. However, the importance of a forest management plan to the stand density management decision process is paramount. Forest management objectives must clearly state specific expectations of products, services and amenities to be provided by the forest.

Strategic practices

Management plan objectives and the structural and productivity characteristics of the forest estate will determine which silviculture strategy (forest practice) to pursue. The strategic value of reforestation, density management, fertilization and pest management can be determined through analysis, usually involving forest estate modelling (see “Density management planning tools”).

Pre-requisites for a forest-level strategic analysis are:

1. clear and specific forest management objectives
2. accurate information on the growing stock of the forest
3. knowledge of the potential benefits of a wide range of silviculture practices.

More than one strategy may be necessary to accomplish management objectives. A thorough analysis will indicate relative strategic values, (e.g., brushing vs thinning), as well as the scale of silviculture activity necessary.

Tactical prescriptions

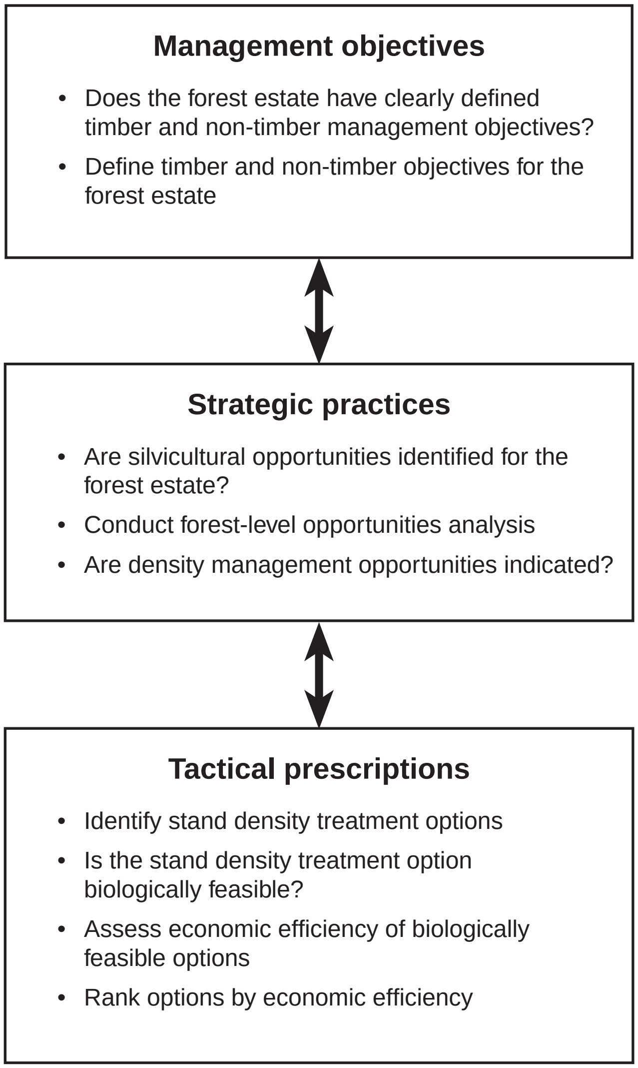
Stand-specific silviculture treatments are tactical decisions. Stand-level tactics (silviculture prescriptions) should support silviculture strategies. Prescription design and treatment effectiveness must be viewed within the context of the strategic plan.

The key point here is that stand density prescriptions must be made within the context of a broader silviculture regime, and a silvicultural regime must be guided by the strategic objectives for the mangement unit.

Decision support process

Objectives, strategies and tactics form an interdependent hierarchy. Within this framework a decision support process suitable for stand density management planning can be fitted. The process links the structural components with essential analyses and correctly sequenced queries. Figure 13 illustrates the resulting knowledge-based, structured decision support process. It is intended to assist forest planners and silviculturists identifying density management strategies, and in preparing biologically and economically feasible stand prescriptions.

The process begins with clearly defined management objectives, proceeds to the identification of strategic opportunities, and finally to the identification and evaluation of tactical options. The hierarchical structure of the process requires the satisfactory completion of higher level questions before proceeding to the strategic and tactical level. Strategy identification will result in the adoption or rejection of density management as a strategy depending on the results of forest-level analysis. Biological feasibility is the principle determinant of the tactical effectiveness of a density management option. Failing this test results in abandonment of the option, and reiteration of the tactic identification step.



Management objectives

- Does the forest estate have clearly defined timber and non-timber management objectives?
- Define timber and non-timber objectives for the forest estate

Strategic practices

- Are silvicultural opportunities identified for the forest estate?
- Conduct forest-level opportunities analysis
- Are density management opportunities indicated?

Tactical prescriptions

- Identify stand density treatment options
- Is the stand density treatment option biologically feasible?
- Assess economic efficiency of biologically feasible options
- Rank options by economic efficiency

FIGURE 13. An interdependant, hierarchical stand density management decision support process that links forest management objectives, silviculture strategies and stand treatment tactics in a structured, knowledge-based system.

Project planning

The stand density management decision support process should be the analytical prerequisite for biologically and economically feasible silviculture and stand management prescriptions. The matrix in Table 1 illustrates three possible decisions regarding the validity of individual stand density management projects. It indicates the expected outcomes of strategic and tactical analyses based on the "biological concepts," "economic principles," and "forest-level considerations" sections.

Three decision criteria must be considered: biological feasibility, economic feasibility and forest-level considerations. Biological and economic feasibility are based on a timber production perspective. Forest-level feasibility is a test of whether the treatment or project contributes to forest-level considerations, including both *timber* and *non-timber* objectives.

The test of biological feasibility is the most important of the three feasibility tests. Any treatment objective which is biologically infeasible for any reason must not be considered further. Forest resource stewardship also demands that silviculture practices should not compromise the structural integrity or long-term production potential of a stand.

TABLE 1. Examples of common decision outcomes and interpretations resulting from the evaluation of hypothetical stand density management projects

Decision criterion			**Expected outcome of forest and stand analyses**		
Biological feasibility[a]	positive	positive	positive	positive	positive
Economic feasibility[b]	positive	positive	positive	negative	negative
Forest-level feasibility[c]	negative	neutral	positive	positive	neutral
Stand-level treatment decision	unsuitable conflicts with management objectives	provisional rank options by maximum profitability	suitable rank options by maximum profitability	provisional rank options by least cost	unsuitable not justified economically

[a] Biological feasibility pertains to timber production only; criteria must be met or the activity is rejected from further consideration.

[b] Economic feasibility pertains to timber production only.

[c] Forest-level feasibility pertains to timber and non-timber considerations or objectives.

Suitable, *unsuitable* and *provisional* are relative measures of how closely a project meets the test of all three criteria. The last row in the matrix indicates the project suitability decision, and provides either a justification or recommends a subsequent procedure.

In the first decision scenario (column 2) the proposed density management project is expected to produce a positive biological response, generate a positive stand-level economic outcome, yet result in a negative forest-level effect. The appropriate decision in this case is that the project is **unsuitable** because it confounds achievement of forest-level objectives.

The second scenario (column 3) is similar to the first, except the expected impact of the project at the forest level is neutral, instead of negative. This changes the decision to **provisional**, and a recommendation to proceed with the project depends on the availability of silviculture funds and the inclination of those managing the forest estate.

The third scenario (column 4) represents the most favourable measure of project suitability. Positive results were measured for all criteria. The resulting decision makes the project **suitable** since it contributes positively to management objectives, and is biologically and economically feasible.

The positive (biological), negative (stand-level economic), and positive (forest level) combination in scenario four (column 5) results in a **provisional** decision, and a recommendation for minimum cost ranking. This means that the proposed project could be undertaken because of its capacity to yield a positive contribution to forest management objectives. However, there may be other projects also meeting objectives but capable of generating a more favourable (or less costly) economic outcome. Where funding is available, all stand density management activities would be ranked in order from least to most costly. Stand density management projects would be undertaken in this order to a point where total density management program costs equalled available funds.

In the fifth scenario (column 6) the density management project is expected to yield a positive biological response, a negative stand-level economic response, and a neutral forest-level response. The project in this instance is **unsuitable**. If a project has a positive biological impact, neither contributes to nor detracts from achievement of forest-level objectives, yet provides no net economic gain at the stand level, it would be difficult to justify the expenditure of silviculture funds. Practitioners should instead consider alternative projects or investments that provide greater returns and/or contribute more to achieving forest estate management objectives.

Adaptive management

The stand density management decision support process relies on up-to-date knowledge regarding the biology of timber production, and current information regarding the people, values and needs reflected in forest management plans. Scientific knowledge is continually updated through empirical observation and new discoveries. Forest management plans change with the participants, the economy and the times.

The availability and quality of data, information, assumptions and analytical techniques are continually changing. This means that the decisions reached today regarding objectives, strategies and tactics are very likely to change tomorrow due to new management direction and new empirical knowledge. The design of the decision support framework and process permits incorporation of improvements in knowledge and information as they become available.

The decision support process also facilitates timely revisions via the adaptive management principle. When management objectives are clearly stated, and strategic and tactical decisions are based on documented assumptions and predictions, periodic evaluation of actual stand responses to silvicultural interventions provides a valuable comparison of actual to expected results. This feedback process permits rapid adjustment of strategic plans and the selection of the most appropriate stand treatment options.

Density Management Planning Tools

Introduction

A number of different types of planning tools are available to assess stand density management options. These decision support tools range from simple “look-up” tables to sophisticated computer simulation and optimization models. Most models require a starting point or “seed” to define the initial conditions or state of the activities being modelled. In addition to a starting point, they may require an “end” point, or final condition that must be achieved at the end of the planning period.

The accuracy of all decision support tool predictions is determined largely by the quality of the information and data used in the analysis. Shortcomings are often caused by the limitations of each tool, lack of reliable information and inappropriate assumptions, and misuse or misunderstanding by the user. The following discussion describes the tools that are available, the type of analysis they perform, and the information each requires.

Growth and yield models

Growth and yield models provide stand age or height projections of stand growth parameters, such as height, average diameter, basal area, stocking density and timber volume. The most important model outputs, in terms of utility for stand density management decisions, are stand (tree size distribution) and stock (stand volume distribution) tables. These output tables are helpful for comparing the stand growth responses of several stand density treatment options.

Some of these models may allow the direct or indirect analysis of wildlife habitat as measured by environmental indicators.

Stocking guides

Stocking guides represent the generalized output of more sophisticated and detailed growth and yield models. They display information in the form of look-up tables, that allow the user to anticipate the effects of different treatments on stand characteristics. They do not, however, allow the user to modify the background data or model assumptions, or perform sensitivity analysis.

Stand density management diagrams

Stand density management diagrams display, on a single graph, the relationships between stand density, top height, quadratic mean diameter and mean tree volume. The data used in their construction are based on average values usually produced by growth and yield models. Users must estimate the relationship between the graphed variables and time using site index curves. A more complete description of stand density management diagrams, and their uses and limitations are available in Farnden (1996).

Stand density management diagrams have the same limitations as the models or data they are based on: they depict only single-species, single layer, even-aged stands, and provide stand average values rather than stand and stock tables.

Forest estate models

Forest estate models are useful for projecting the impacts of stand management activities on the forest inventory over time. They have evolved over the past 30 years in parallel with the evolution of computing technology. Modelling forest estates involves manipulating large amounts of data. The sophistication of the model reflects the detail that can be incorporated into the data set.

Two types of forest estate model are available: simulations models and mathematical programming models. Both are used to determine the impact of stand density management activities on the stock and flow of harvestable timber, and on the achievement of other non-timber objectives. The issues of data quality and reasonable assumptions are important considerations.

Simulation models

Simulation-based forest estate models operate on the principle of achieving pre-determined levels of outputs for flows and stocks of timber and non-timber resources. They can also incorporate risk in defining the success of outcomes of various activities being modelled. Unlike mathematical programming models, simulation models do not rely on a specific algorithm. Rather, they incorporate a wide variety of mathematical relationships, providing considerable flexibility of application.

Mathematical programming models

Mathematical programming models have their roots in the fields of engineering, operations research, medical research and defence. They are widely used to solve transportation network problems, warehouse and inventory control problems, product distribution and sales problems, and in a variety of military applications. Their use in forestry is a relatively small segment of their application throughout the world.

Linear programming is a method used to allocate limited resources to competing activities in an optimal manner. Although there are important assumptions regarding their use, linear programming offers considerable flexibility in applications such as forest management problems, harvest scheduling, silviculture planning and economic analysis.

Economic analysis tools

Economic analysis tools are simply computerized equations or calculation templates that incorporate economic principles for solving specific questions related to the worth of a silvicultural endeavour. Several of the models incorporate some of their capabilities to provide stand- or forest-level economic analysis.

For example, TIPSY allows the user to calculate the present value or site value of a juvenile spacing treatment. WOODSTOCK, a forest estate model, has the capability to account for production costs and the economic operability of any management activity. Most of the decision support models listed in Tables 2 and 3 can produce input to an economic analysis.

Stand- and forest-level analysis tools

Tables 2 and 3 provide a brief description of commonly available stand- and forest-level analysis tools that may be used to analyse the effects of stand density management treatments. The list is not exhaustive, and neither the Working Group nor the Ministry of Forests advocate using any particular system, listed or otherwise. However, planners and silviculturists are encouraged to use proven decision-making support tools in their work.

TABLE 2. A list of commonly available stand-level decision support models

Tool	Owner	Description	Comments
FINSIL3	MacMillan Bloedel Ltd. Vancouver (public domain)	Spreadsheet program for financial analysis of silviculture treatments.	Based on data obtained in mid-to-late 1980s, can easily be updated with new data.
Stand Density Management Diagrams	BCFS, CFS, UBC Vancouver and Victoria	A diagram that graphically displays the relations between (variously) volume, basal area, diameter, height, trees per hectare, per cent site occupancy, mortality, etc. Gingrich-style diagrams are one example.	Have been constructed in BC for lodgepole pine, white spruce, and interior Douglas-fir. Useful for illustrating relationships, however, similar and more information can be obtained from use of a growth and yield model.
PROGNOSIS	BCFS, Victoria	Stand Prognosis Model – growth and yield model for single and mixed species, even- and uneven-aged stands.	Part of a family of models that allows analysis of economics, pests, tree crowns and environmental indicators. Calibrated for 14 regions of the U.S. Being calibrated by BCFS for BC interior species, starting in the Nelson Forest Region.
PRUNSIM, **DF PRUNE**	Forest Resource Systems Institute, Florence, Alabama	Spreadsheet programs that estimates the financial return from pruning coastal Douglas-fir stands.	Helps determine how many and which trees in a stand should be pruned. Calibrated for southern Oregon.
SPS	Mason Bruce and Girard Ltd.	Stand Projection System – growth and yield model for single and mixed species, even- and uneven-aged stands.	Some calibration for BC.
FPS	J. Arney, Oregon, U.S.A.	Forest Projection System – growth and yield model for single and mixed species; even- and uneven-aged stands.	Some calibration for BC.
STIM **WINSTIM**	CFS, Victoria	Stand and Tree Integrated Model – growth and yield model.	Also projects the growth of spaced and thinned stands. Calibrated for hemlock in BC and Pacific Northwest.
TASS	BCFS, Research Branch	Tree and Stand Simulator – biologically based growth and yield model for even-aged pure-species stands. See TIPSY.	Calibrated for most even-aged stands of pure coniferous species of commercial importance in coastal and interior BC forests. Part of the SYLVER family of models.
XENO	MacMillan Bloedel Ltd., Nanaimo	A distance-dependent stand growth model capable of growing single or mixed species under both natural and managed regimes.	Model simulates development of Douglas-fir and western hemlock, also allows for economic analysis in consideration of wood quality attributes.
SYLVER	BCFS, Research Branch	A system of Silviculture practices models that evaluates the impact on Yield, Lumber Value and Economic Return.	Consists of models that grow stands, buck logs, saw lumber, grade boards and perform financial analyses (Kellogg 1989).
TIPSY	BCFS, Research Branch	Table Interpolation Program for Stand Yields – retrieves and interpolates stand yield information from a database generated by SYLVER.	Windows system that generates tables for standing yield (including stand and stock tables), mortality, snags, products (logs, lumber and chips) and economic return. Repression has recently been added for lodgepole pine.

TABLE 3. A list of commonly available forest estate models

Tool	Owner	Description	Comments
ATLAS	UBC, Vancouver	A Tactical Landscape Analysis System – multiple rotation, spatially explicit, block scheduling timber supply simulation model.	Also performs road network analysis.
CASH6 FM	Timberline Forest Inventory Consultants, Victoria	Critical Analysis of Schedules for Harvesting – spatial timber supply simulation model.	Operates in spatial or aspatial modes. Good for strategic-level or operational analysis.
FSSIM	BCFS, Timber Supply Branch	FS Simulator – timber supply simulation model.	Approximates spatial harvest restrictions. Good for strategic-level analysis; lacks economic analysis capability.
SIMFOR	UBC, Vancouver	Simulates the effects of forest management and stand development, predicts landscape composition, ecosystem pattern and habitat distributions for selected species.	Landscape size may vary from 5000 to 50 000 hectares.
TREEFARM	Stirling Wood Group, Victoria	Timber supply simulation model.	Approximates spatial harvest restrictions. Good for strategic-level analysis.
WOODLOT	BCFS, Resource Tenures & Engineering Branch	Simulation model that finds the maximum single even-flow harvest level for a planning period.	Used for AAC determination for woodlots in BC. Will receive yield projection output directly from TIPSY and VDYP stand yield models.
COMPLAN	Simons-Reid Collins, Vancouver	Forest estate simulation model for timber supply and forest estate activity planning.	Flexible data input structures, allows for explicit recognition of spatial constraints and objectives, also considers some economic issues.
OPTIONS	D.R. and Associates, Nanaimo	Forest estate simulation model for timber supply and forest estate activity planning.	
STANLEY	REMSOFT, Inc.,	Spatially explicit harvest scheduler.	Includes an automated block builder.
WOODSTOCK	REMSOFT, Inc., Fredericton	Flexible Forest Modelling System – timber supply model that allows the use of either simulation or linear programming.	Allows the analysis of random events (such as fire), and for economic analysis of forest-level outputs.

Glossary

addition A mixed-stand structural condition where trees of a secondary tree species occupy a separate stand niche or stratum, thereby adding to the timber production of the primary tree species of the stand (e.g., where regeneration of a complementary species becomes established and grows beneath the crown canopy of an existing species).

age class distribution A histogram of the area occupied by (timber volume represented by) distinct age classes (usually five or 10 year intervals) of growing stock within an area of forest land.

average diameter The arithmetic mean of all tree diameters measured outside the bark, at breast height (1.3 m).

biodiversity objective A type of management objective aimed at preserving or enhancing the presence and richness of species of plant, animal and other living organisms in all their forms and levels of organization (genes, species, communities), including the evolutionary and functional processes that link them.

biogeoclimatic subzone A geographic area having similar patterns of energy flow, vegetation and soils as a result of a broadly homogeneous macroclimate, as categorized by the Biogeoclimatic Ecosystem Classification System of British Columbia.

brush competition Non-commercially valued vegetation that impedes the survival, growth and production of commercially valuable tree species.

brushing A general term for a range of silviculture activities designed to eradicate or reduce the growth of non-commercially valued vegetation in order to reduce its interference with the survival, growth and production of commercially valuable tree species.

chainsaw effect 1) A reduction in the top height of a stand resulting from improper crop tree selection during juvenile spacing or commercial thinning; this effect lowers the vigour and timber production capacity of the residual stand. 2) An increase in average diameter caused by a low thinning (see definition for *low thinning*). This is an artifact of treatment, not a biological response to thinning.

close utilization Harvesting the maximum volume of timber from a stand, as measured by the minimum stump height, stump diameter and top diameter of each tree harvested.

clumping A spatial pattern of tree establishment where small groups, or clumps of trees are distributed throughout a stand, as opposed to random or even distribution of single trees.

commercial thinning A partial cut in stands where the timber removed is sold; conducted in even-aged stands, provides an interim timber harvest during a stand rotation.

community watershed A natural drainage area above the most downstream point of water diversion on a stream; water use is for human consumption and is licenced under the *Water Act* for either a waterworks or a domestic purpose if the licence is held by or is subject to the control of a water users' community incorporated under the *Water Act*; or an area designated as a community watershed under the *Water Act*.

crossover volume response A timber volume response to thinning (pre-commercial or commercial) that eventually exceeds the volume production of a similar, unthinned stand.

crown class A relative measure of the size and position of a tree's crown within the canopy of a stand; numerical or subjective categories of crown size and position have been defined (e.g., dominant, co-dominant, intermediate, overtopped).

crown closure The point during the growth of an even-aged stand when the branches of adjacent trees make physical contact; a continuous canopy of tree foliage.

crown competition The process of branch and foliage growth whereby trees compete for aerial growing space.

culmination of mean annual increment The mean annual increment (MAI) of a stand increases for many years, then declines. The maximum MAI and age at which it culminates may be used to assess productivity and set rotation lengths that maximize volume production in perpetuity.

decay inoculum The infectious spores, mycelia or mycorrhizae of decay-causing fungi.

diameter at breast height (DBH) The bole diameter of a tree measured outside the bark at a height of 1.3 m.

discount rate The rate of interest used to measure future expected costs and revenues in today's dollars; the rate of interest used for discounting is a function of social time preference, the opportunity cost of capital, and investment risk.

dominant A qualitative measure of the size and height and of a tree's crown; a tree whose crown is receiving full light from above and partly from the sides, is larger than the average size of crowns in the stand, is well developed, although somewhat crowded on the sides.

economic efficiency The level of production of economic goods and services with the lowest level of inputs (labour and capital) capable of producing only the amount of outputs demanded in the marketplace, at the highest attainable level of profit; a measure used to determine the optimum combination of inputs required to produce goods and services that meet both cost minimization and profit maximization objectives.

economic rotation age The point in time (stand age) during the growth of a stand when the rate of increase of the net value of the stand begins to decline; the economic rotation age generally occurs before the physical rotation age (culmination of mean annual increment).

espacement density The initial number of trees per unit area regenerated by planting, or by natural means after a reasonable seed-in period; often expressed as average inter-tree distance (i.e., distance between trees if square spacing is assumed).

establishment density A density similar to espacement density (see *espacement density* above) except it may exclude trees removed in an early spacing operation.

expected value A value that will be realized with some known level of probability in a future time period.

feasibility analysis A method used to determine the net benefits from a given set of management activities; the benefits may be measured in either volume and/or value terms and the activities may occur in present and/or future time periods.

fire-origin stand A stand which regenerates following a fire; usually consisting of tree species that rely on fire to regenerate.

forest estate A collection of stands, of varying types, ages, etc., administered as an integrated unit and managed for some continuity or flow of harvest volume. For the purpose of this document, the forest estate is synonymous with the *sustained-yield unit* which includes timber supply areas, tree farm licences and woodlot licences.

forest estate model A representation of the growth and natural dynamics of a pre-defined area of forest; used to simulate the effects of harvesting and silviculture on the long-term availability of timber supply from defined forest areas.

forest-level objectives All definable timber and non-timber goods and services, values and activities for a specific bounded area of forest land over a specified period of time.

free growing stand A stand of healthy trees of a commercially valuable species, the growth of which is not impeded by competition from plants, shrubs and other trees.

gross production The total yield of timber biomass contained in the stems of all trees (living and dead) as measured by volume per unit area at a given age.

growth and yield model One or more mathematical relationships which employ tree, stand and treatment (e.g., thinning) variables to project the growth and yield of stands.

harvest constraints Limits imposed on a condition or activity within a forest estate; defined as part of an overall forest estate model; are usually defined by forest-level objectives.

harvest scheduling flexibility The relative variability permitted in the order and timing of stand harvest activities in a forest estate model; defined by the interaction between forest-level objectives, harvest constraints, and the current and future conditions of the forest estate.

height–diameter ratio The diameter (DBH) of a tree relative to its total height at a given age; a measure of tree slenderness and susceptibility to wind and snow pressures.

height growth repression A condition that occurs in stands established at high density (usually greater than 10 000 trees/ha); results in a reduction in the rate of height growth of the stand compared to similar stands that are less dense; observed and documented in the species lodgepole pine.

hemlock square A characteristic lumber dimension sawn for the Japanese export market; variable in dimension from 3.5 × 3.5 inches to 15 × 15 inches; a common end product from coastal BC sawmill operations.

higher level plan Higher level plans establish the broader, strategic context for operational plans, providing objectives that determine the mix of forest resources to be managed in a given area.

income distribution The allocation and disposition of wealth among individuals, households and businesses in an economy; policies and laws governing taxation and the collection of resource rents are designed to address issues related to income distribution in an economy.

inflationary expectations The expected decline in the value of money over some future time period; determine the difference between the real rate of interest and the nominal (or money) rate of interest.

inter-generational equity The distribution of resources and wealth between current generations and future generations of individuals; use and consumption of resources and creation of wealth affects the ability of future generations to consume resources and create wealth.

intermediate A qualitative measure of the size and height of a tree's crown; a tree whose crown is shorter than trees in the stand classed as dominant or codominant, but extending into the crown cover formed by codominant and dominant trees; receiving a little direct light from above but none from the sides; usually with small crowns, and considerably crowded on the sides.

inventory projection A method for tracking the stock and state (timber volume and distribution of stand age classes) of an area of forest over time; forms the basis for virtually all forest estate models.

juvenile spacing (pre-commercial thinning) The removal of excess and undesirable trees from a stand before the thinnings have any commercial value.

juvenile wood In some species, wood formed in the vicinity of the crown has different characteristics than that formed in the stem below. In most species, this juvenile wood has properties (e.g., low density, short fibres, low strength) that limit its utility. Juvenile wood occupies the central core of stand grown trees because, as the crown lifts and hormone concentrations drop, the increment added below the crown changes to mature wood. Juvenile wood is also called crown-formed wood or core wood. (See definition of *mature wood*).

kerf The width of a saw blade used for cutting logs or cants into boards; displaces a certain amount of solid wood and thus affects the amount of solid wood produced in boards from a log or cant.

landscape unit objective A landscape unit is defined by the district manager. It is generally an area of land up to 100 000 hectares in size delineated according to topographic or geographic features such as a watershed or series of adjacent watersheds. The district manager must establish objectives for a landscape unit, and may vary or cancel an objective.

linear programming model A method for determining an optimal level of output from an activity – the optimal level of output is determined by the availability of conditions and inputs required to perform activities defined in the model; often used to define the timing and quantity of harvest levels that can be obtained from a forest estate while maintaining the forest in a condition that provides for all other defined forest values.

low thinning A thinning regime in which the smaller trees are favoured for removal. Also known as "thinning from below."

lumber recovery The ratio of the volume of sawn wood recovered from a log to the total volume of wood in the log.

machine stress rated lumber (MSR lumber) Lumber that is graded according to stiffness as measured by a machine that correlates lumber stiffness to measured modulus of elasticity.

management unit plans A forest management plan approved under a tree farm licence or a woodlot licence, usually in effect for a period of five years and specifies proposed management activities to establish, tend, protect and harvest timber resources, and to conserve other resource values.

mathematical programming model A model based on mathematical algorithms or sets of equations designed to solve a problem based on a pre-defined set of assumptions and starting conditions; a linear programming model is a type of mathematical programming model.

mature wood In some species, wood formed below the crown has superior cell structure than "juvenile wood" laid down in the vicinity of the crown. As the tree grows and the crown lifts, an outer sheath of mature wood of somewhat higher strength is formed. It extends from ground level to a point near the base of the crown. See definition of *juvenile wood.*

maximum density A Forest Practices Code requirement that silviculture prescriptions define the maximum density or upper limit of density for stands to be declared as free growing. Areas exceeding this density must be spaced as part of basic silviculture obligations.

mean annual increment (MAI) The arithmetic average annual change in the volume of a stand from establishment to a given point in time (MAI = volume/age).

merchantability standard The minimum top diameter, minimum diameter at breast height, and maximum stump height that defines a merchantable tree.

microsite The aerial, surface and underground environment in immediate proximity to a seedling or tree; includes the immediate climatic, sunlight, soil nutrition, soil moisture and surrounding vegetation conditions within a few metres of a tree.

monoculture A stand consisting predominantly of a single-tree species.

natural disturbance type An area whose soil and vegetation is influenced by a natural disturbance regime.

net present value (NPV) The sum of all discounted costs and revenues expected over the life of an investment; in forestry, the investment period is usually the rotation length.

non-timber values Dollar values and/or quantities of natural resources that are not priced or traded in markets, including wildlife, wilderness, scenic views and the utility derived from a wide variety of outdoor activities.

nutrient cycling The chemical, biological and climatic factors that cause various elements and chemical compounds to be transported through the atmosphere, soil, water, groundwater, dead and decaying matter, plants and animals.

oligopolistic A market behaviour characterized by a few large firms acting as sellers of goods or services; characterized by demand conditions being affected by each firm's output decisions, resulting in a conscious interaction among firms, leading to a variety of forms of strategic behaviour in production and output decisions.

opportunity cost of capital The amount a firm must pay to the owners of capital in order to attract the capital (or other factor of production) necessary to engage in the firm's business. The firm must pay the owners of the capital an amount sufficient to induce them to sacrifice the next best alternative use of the capital, which is generally the going market price of the capital, or other factor of production.

overtopped A qualitative measure of the size and height of a tree's crown; a tree whose crown is entirely below the general level of the canopy, receiving no direct light either from above or from the sides; also called "suppressed."

parallel volume response A thinned stand whose rate of volume increment continues to accrue at the same rate as a similar unthinned stand, but whose volume yield is reduced by the volume removed in the thinning.

pre-commercial thinning (juvenile spacing) The removal of excess and undesirable trees from a stand before the thinnings have any commercial value.

present value The value of some future expenditure, revenue or future series of expenditures and/or revenues discounted at some rate to the value of them in the present period.

prime trees The 250 trees of largest diameter in a stand at a particular age; the actual membership of trees classed as prime trees may change over time.

product values The market values of end products produced or expected to be produced after a stand is harvested.

production economics The theory of the behaviour and decisions of firms that produce goods and services demanded by consumers.

provenance The geographic source or race from which seed or other tree propagules were obtained.

real price change The per cent change in market price of goods or services over some time period over and above any change in its price due to inflation; is a reflection of the change in the scarcity of goods or services over time.

repressed stand A stand in which the height growth of all trees is impaired by high establishment density, and thereby fails to exploit the actual productivity potential of the site; has been documented in BC in dense stands of lodgepole pine greater than 10 000–15 000 trees/ha.

resource management objectives A statement of intent to ensure the maintenance or production of some level of timber and/or non-timber resources from the area of forest to which the resource management objective applies. The resource management objective may also be defined by a resource management zone, and the chief forester may designate a resource management objective and/or zone as a higher level plan.

riparian area Also known as a riparian management area; an area of a width determined in accordance with Part 10 of the *Operational Planning Regulation* of the *Forest Practices Code of British Columbia Act*, that is adjacent to a stream or wetland or a lake with a riparian class of L2, L3 or L4, and consists of a riparian management zone, and depending on the riparian class of the stream, wetland or lake, a riparian reserve zone.

rotation age The actual or expected age of a stand when it is harvested.

sensitivity analysis A method used to determine the relationships between measures and assumptions used in an analysis, and to determine the effects of changing the value of measures and assumptions on the results of an analysis; is usually conducted by recalculating an analysis a number of times each with a change in one measure or assumption at a time.

shade intolerance A characteristic of plants that describes their propensity to establish and grow in direct or full sunlight conditions.

shade tolerance A characteristic of plants that describes their propensity to establish and grow under indirect or reduced light conditions most often in the shade of other plants growing around or above them.

silviculture prescription (SP) A site-specific plan that describes the forest management objectives for an area; must be consistent with any higher level plan that encompasses the area to which the prescription applies; identifies the method for harvesting the existing forest stands and a series of silviculture treatments that will be carried out to establish a free growing crop of trees in a manner that accommodates other resource values as identified; subsequent documents, including cutting authorities and logging plans, must follow the intent and meet the standards specified in the silviculture prescription.

silviculture regime A series of carefully sequenced and implemented activities at specific time periods and intensities to achieve desired objectives.

simulation model An integrated set of equations and numerical techniques that mimic the relationships and development of actual systems (e.g., trees, stands, forests).

site occupancy The degree to which available growing space is utilized by trees.

site preparation An activity or set of activities which enables the regeneration of a new stand or enhances the survival and growth of regeneration.

site value (or soil expectation value) The sum of the discounted values of all costs and revenues over an infinite series of investment periods (rotations) of equal length.

slash The tree tops, branches and other coarse woody debris remaining on the ground after a logging or thinning activity.

social welfare objectives Government objectives that address the distribution of income or wealth in society; for silviculture in British Columbia, this has meant using silviculture activity as an economic development tool to provide employment in the forest; government can distribute income to silviculture contractors by providing funds for stand density management activities; in this context, it is important to distinguish between wealth generation and redistribution of wealth.

stand A contiguous group of trees sufficiently uniform in species composition, arrangement of age classes, and condition to be a homogeneous and distinguishable unit.

stand density management Silviculture activities that alter the quantity and distribution of trees in a stand including espacement, pre-commercial thinning (juvenile spacing) and commercial thinning.

stand density management diagram A graphical depiction of the relationships between stand density, top height, quadratic mean diameter and mean tree volume.

stand management prescription (SMP) A site-specific plan describing the nature and extent of silviculture activities planned for a free growing stand of trees to facilitate the achievement of specified or identified social, economic or environmental objectives.

stand table A tabular display of the number of trees in a stand by diameter class.

stock table The tabular counterpart to a stand table that displays stand volume by diameter class.

stocking guide Output from growth and yield projections in the form of a look-up table; displays average values of parameters such as tree volume, average diameter and average height.

stocking standard The recommended number of seedlings that should be planted per unit area; may also recommend the type of seedling or planting stock, when or how the planting should be conducted, and the types of sites suited to different stocking standards.

stump height The height above ground of the remaining portion of the stem of a tree after it has been harvested; stump heights are regulated as part of the utilization standard.

substitution A mixed-species stand resulting from a one-to-one substitution of trees of a monoculture with trees of another species so the total stand density remains constant.

sunk cost A cost that does not affect the decision to make a further or additional expenditure; an example of a sunk cost in forestry is the cost of planting in relation to a thinning investment; the planting cost does not affect the decision of whether or not to incur a thinning cost since the thinning cost is compared to a regime where no thinning takes place (in order to be comparable, both regimes must either assume a planting cost or no planting cost).

taper The rate at which the diameter of a tree changes relative to its height over the length of the stem. Taper is affected by the density of the stand; the less dense the stand, the greater the amount of taper.

tree vigour The general health of a tree; affected by genetic potential and natural growing conditions such as climate and soil, as well as by biotic factors such as competition for resources from other plants, and pathogens such as insects and diseases.

variable growth intercept method A technique for determining site index for a young stand from measurements of height growth above breast height; ideally suited to stands that are 2–3 m tall until they are about 30 years old; growth intercept models have been developed for western hemlock, interior spruce, lodgepole pine, Sitka spruce and Douglas-fir.

visual buffer An area of usually mature, undisturbed forest or a topographic feature such as a hill that masks harvesting disturbances such as recent clearcut areas.

visual quality objective (VQO) Defines a level of acceptable landscape alterations resulting from timber harvesting and other activities; visual quality classes have been defined in BC on the basis of the maximum amount of alteration permitted in a given area over a given period of time.

wildlife tree A tree or group of trees that are identified in an operational plan designated to provide present or future wildlife habitat.

wood quality A general term encompassing a wide range of physical wood properties and parameters that affect the end use and value of wood products; wood quality characteristics can be inherent to particular species, but are also influenced by tree growing conditions, and are also defined by end-use requirements; wood quality parameters include basic density, fibre length, juvenile wood content, fibril angle, compression wood, knot size, frequency and distribution, grain, ring width, and quantity and type of extractives.

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Appendix 1. Predicting future timber values

Introduction

Forecasts of future product market conditions are necessary in order to evaluate the economic efficiency of stand density management investments. Because the return on most investments will not be obtained for 40 to 100 years, these forecasts are fraught with uncertainty. A clear statement of the future price assumptions used is therefore necessary to allow for a critical review of the results of the analysis.

This section discusses the factors that may influence future real log and end-product prices, and provides a summary of research into the potential for real price increases. It concludes with recommendations on future price assumptions for stand density management investment analysis.

Timber price increases

Future timber prices depend on the answers to two fundamental questions:

1. Will the factors that led to recent price increases for old-growth timber also influence the future prices of second-growth timber?
2. Will stand density management practices in second-growth stands result in timber and wood characteristics similar the those of old-growth stands?

It is rather difficult to provide substantive answers to these questions. However, evidence suggests that the future will not be a reflection of the recent past.

Forecasts of future timber scarcity have led many observers to conclude that timber resources will experience real price increases with respect to other commodities over time. Changes in the real price of a commodity is an indicator of its relative scarcity. Increasing prices are associated with increasing scarcity and decreasing prices indicate decreasing scarcity.

The study of resource scarcity by Barnett and Morse (1963) examined prices and costs for the U.S. agriculture, minerals, forestry, fishing and total extractives sectors using data collected by Potter and Christy (1962) for the period 1870 to 1957. With the exception of the forestry sector, Barnett and Morse found that the real price of natural resources did not increase over the period examined.

Manthy (1978) updated the Potter and Christy data to the early 1970s and confirmed Barnett and Morse’s results. However, Manthy observed a significant change in the trend of forest product prices after 1950; from 1950 to 1970 real prices remained essentially stable.

Sedjo and Lyon (1990) examined price trends since 1970 and noted significant real increases in timber as well as most other natural resource prices during the 1970s. However, during the early 1980s real timber prices fell again to the levels of the 1950–70 period, and then remained stable. Sedjo and Lyon also concluded that the timber price trends of the post-1950 period were fundamentally different from earlier periods.

In the early 1990s sharp increases in timber prices were again experienced as North America recovered from an economic recession, and demand increased for timber products. At the same time, land-use decisions in the U.S. Pacific Northwest region resulted in the reservation of large areas of forest land for the protection of the northern spotted owl. Since 1990, timber prices have fluctuated wildly, a trend more characteristic of short-term adjustments in timber supply problems than of a return to rapid, long-term price increases.

Factors that tend to moderate timber scarcity include:

1. Technological changes that increase resource-use efficiency; for example, the development of saws with narrower kerfs and improved cutting patterns increased lumber recovery during the 1970s and 1980s.
2. Substitution of previously unused timber resources, compensating for shortages of conventional timber resources; for example, the substitution of hardwood chips and the production of wafer board for softwood veneer and plywood. Continued acceptance of substitute materials in products previously manufactured from old-growth timber will reduce the economic affect of old-growth timber scarcity.
3. Development of substitute products that replaces conventional timber products; for example, the manufacture of engineered construction products such as composite wood I-beams may replace much of the demand for large dimension, structural lumber (e.g., 2×10s and 2×12s) for certain applications.
4. Substitution of non-timber materials, replacing similar timber products; for example, the use of steel framing studs for light duty construction is becoming more common as the price of lumber increases relative to the price of steel.
5. Responses in timber supply to actual or threatened scarcity; for example, as the price of timber rises due to scarcity, manufacturers may increase the supply by a variety of means. First, improved milling utilization may decrease the marginal log size, thereby resulting in greater wood recovery from each stand. Second, improved logging utilization may result in the harvest of previously unprofitable stands, thereby expanding the operable harvest base. Third, increasing timber prices may make site productivity-enhancing silviculture treatments more attractive, thereby increasing the rate of production from a fixed land base.

It is unrealistic to expect any of these factors to completely offset future real price increases. For example, it is more likely that technological advancements will eventually experience diminishing marginal returns in the sawmill and woods sectors since there is only so much fibre contained within a log and only so much timber produced on a site. However, in view of the combined potential of all moderating factors, caution is advised in assuming rapid, sustained, long-term real price increases.

Projections of future timber price increases take some of these factors into account (Sedjo and Lyon 1990; Dykstra and Kallio 1987). Both studies are based on models of world timber supply and demand. Sedjo and Lyon (1990) predict in their base case scenario that the price of timber would increase over the period 1988–2000 at an annual rate of 0.2%. In a high industrial wood demand scenario, they projected an annual real price increase of 1.2%.

Dykstra and Kallio provide forecasts for different areas of the world and differentiate between the price for conifer and non-conifer species, and between the prices of sawlogs and pulp logs. They project an annual rate of real price increase of 0.3 to 5.9% for conifer sawlogs over the period 1980–2000, depending on the area of the world in which the timber is harvested.

In a study commissioned for Forestry Canada, H.A. Simons Strategic Services Division, and Cortex Consultants Inc. (1993) reviewed historical log, lumber and chip prices in British Columbia. Although only a small proportion of the total BC production of logs is valued on the Vancouver log market, they found that over the last two and a half decades, coastal log prices have increased on average by 0.3%/yr. However, the price increases varied considerably by period and by species. For example, real prices increased during the 1970s by as much as 3.9%/yr.

Vancouver log market prices, as well as those used to calculate provincial stumpage are still influenced significantly by international log and wood product prices. The authors (H.A. Simons and Cortex 1993) developed predictive equations to forecast log price increases for four coastal species groups. Table A1-1 presents species/price expectations for the period 1990–2040.

An analysis by Feltham and Messmer (1996) reviews a number of studies of historical sawn wood prices, projected future price changes, and the use of a time series to calculate historical real price changes and an index of wood quality change for BC and Canada. Their data represent total sawn wood timber volume and value, by species group, for BC and Canada from 1918 to 1990.

TABLE A1-1. Real price increase forecasts for logs from the coastal region[a]

	Tree species (% price increase/year)			
Forecast period	**Douglas-fir**	**Cedar**	**Hemlock**	**True firs**
1990–2000	1.4	3.8	0.2	0.8
2000–2010	0.1	-0.7	-0.6	-0.2
2010–2030	0.4	0.5	0.1	0.3
2020–2030	0.1	0.3	0.1	0.1

[a] These data are presented only as an example of forecasts typical of the range of values found from a number of recent analyses. They should not be considered the only, or the most accurate forecast of timber price increases available. See also Feltham and Messmer 1996.

Source: H.A. Simons Strategic Services Division and Cortex Consultants [1993].

Feltham and Messmer (1996) found the volume-weighted, average, real softwood prices in BC during the period 1926 to 1990 increased 0.53%/yr. Only two BC species experienced a decline in real price. In Canada, the average annual rate of increase was 0.24%; no species declined in real price over the period. The highest rate of price increase in Canada during this period was recorded for hemlock, which increased at an average rate of 1.56%/yr. The largest decline was recorded for Ponderosa pine, which changed in real terms at a rate of -0.32%/yr over the period.

The real price trends for the period 1965 to 1990 differ from those for the period 1926 to 1990. For example, the volume-weighted average of softwood species prices in BC for 1965 to 1990 was only 0.29%, with six BC tree species exhibiting declining prices. Canadian real prices declined by an average of 0.24% each year during this period, with five tree species showing an average annual decline. The highest annual rate of price increase in BC during this period was 2.2% for yellow-cypress, compared to the greatest decline of -1.14% for lodgepole pine. The highest Canadian real price rate increase was only 0.44%/yr for hemlock, compared with the greatest decline for lodgepole pine of -0.34%/yr.

Historical and projected price growth rates vary among studies. Variation may be attributed to the different periods over which the rates are calculated, as well as the different timber products and regions on which they are based. Despite this variation, however, Feltham and Messmer (1996) found consensus on expectations that future prices will increase at decreasing rates for timber supply regions in BC, the Pacific Northwest and the Southern U.S. for virtually all species and timber grades. There was no agreement among the studies on whether the prices of higher quality species and grades would change at a different rate (faster or slower) than prices for lower quality species and grades. The historical rates of price increase ranged from a high of 3.45%/yr for Douglas-fir Grade 1 logs from the 1930s to the 1990s, to a low of -1.6%/yr for hemlock lumber for the period 1965 to 1990.

A species effect on wood quality index was also calculated in the Feltham and Messmer analysis. From 1925 to 1990 the annual rate of decrease in wood quality attributable to the change in species composition averaged 0.14% for BC, and 0.12% for Canada. The Constantino and Haley study (1988), on which this index was based, used log data from the Vancouver Log Market and found an average annual decrease of 0.28%. The divergence between the two studies may be attributed to technological change and its role in dampening the transmission of species composition effects from the log market to the lumber market. Substitution between species may also account for some of the divergence.

End-product prices

The price of lumber is determined by the interaction of international lumber supply and demand forces. The market for lumber is relatively competitive and includes many buyers and sellers, with firms acting as price takers. The demand for lumber is considered a derived demand since the product is not directly consumed by households, but rather it is consumed indirectly in the production of housing and other products. Thus, the demand for lumber is derived from the demand for finished goods such as housing.

The U.S. is the major market for lumber in North America, so lumber prices are in U.S. dollars. The price Canadian producers receive is therefore determined by international market factors plus the current Canada/U.S. exchange rate. The difference in the exchange rate tends to amplify changes in U.S prices. For example,

Figure A1-1 illustrates the general trend for rising lumber prices over the period 1960 to 1995[8] relative to changes in the Canada/U.S. exchange rate.

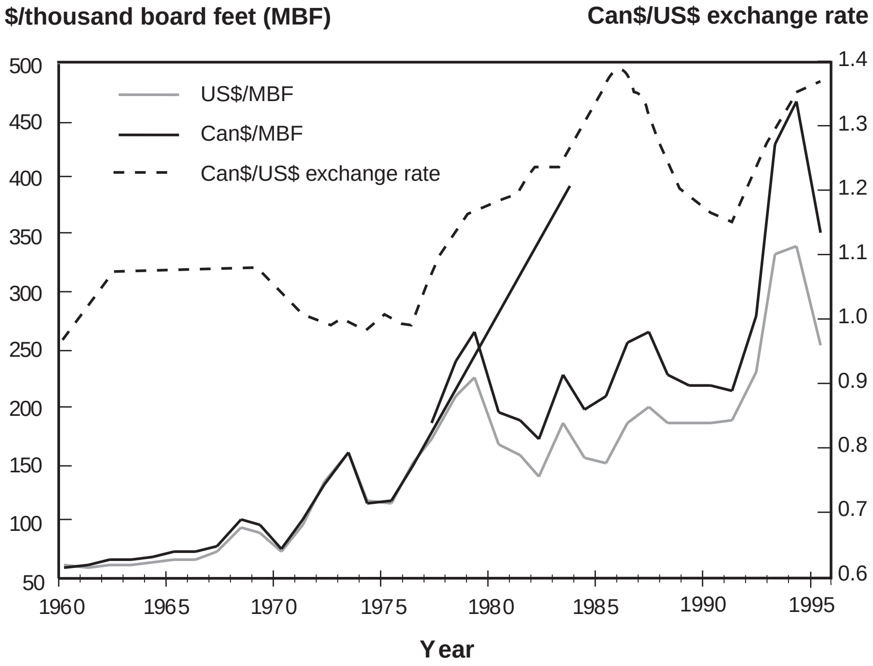

FIGURE A1-1. Trends in lumber prices (western spruce-pine-fir, kiln dried, standard and better, 2×4, random length lumber).

The effects of inflation must be removed in order to determine if a real price increase has occurred. This can be done by expressing real prices in constant dollars for a selected year (the base year), to which the prices in other years are adjusted using a suitable price index.

The prices in Figure A1-1 were therefore converted to Canadian $/thousand board feet (MBF), and adjusted using the consumer price index (CPI) for Canada to reflect constant 1995 dollars. The results of the conversion are shown in Figure A1-2. Note that real price fluctuated between $226–594/MBF with an average of $380/MBF over the period shown. No obvious trend is indicated by the diagram although it does show the extreme volatility of lumber prices over time. This volatility would be even greater if monthly prices were graphed. The lack of any trend in the graph indicates that although, on average over the period shown, the nominal prices have increased with inflation, there has been little or no change in real prices.

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[8] Based on average annual prices of kiln dried, standard and better western spruce-pine-fir 2×4 random length lumber (source: Random Lengths Publications Inc., various years).

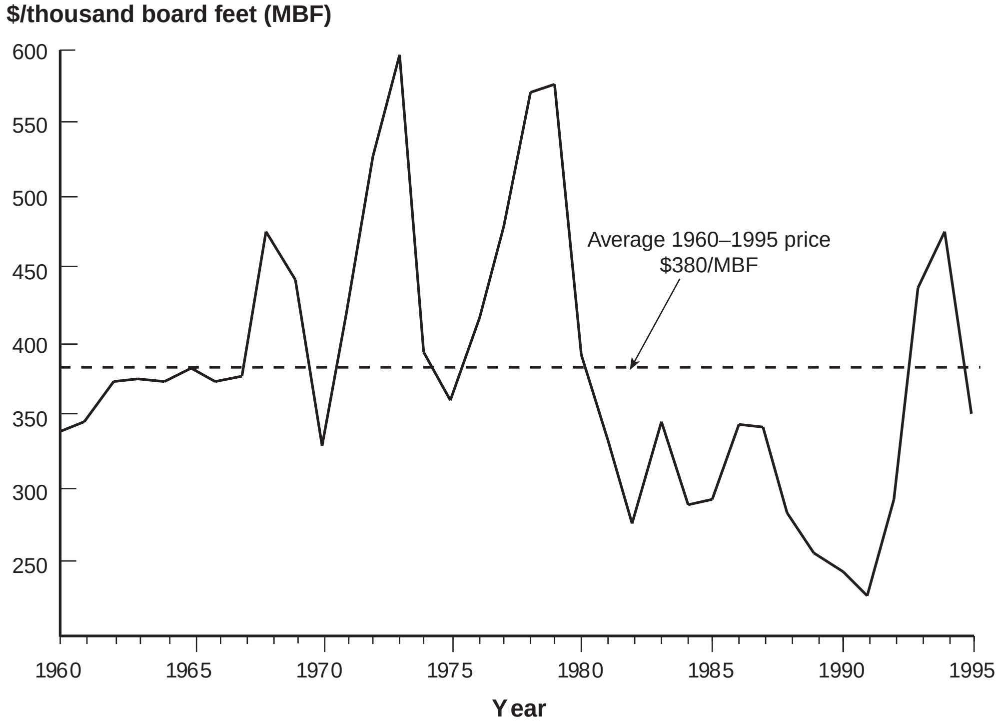

FIGURE A1-2. Trends in real lumber prices in constant 1995 Canadian dollars (western spruce-pine-fir, kiln dried, standard and better, 2×4, random length lumber).

Figure A1-3 shows the fluctuations in the price of structural dimension lumber in constant 1995 Canadian $/MBF for western spruce-pine-fir (SPF) kiln dried, standard and better, random lengths lumber. Not surprisingly, the price trend for each dimension tracks one another quite closely. This is more clearly demonstrated in Figure A1-4 which shows the variation in the ratio of the price of western spruce-pine-fir for each dimension relative to the price of 2×4s.

The ratio for 2×6 and 2×8 lumber fluctuated around 1.0 and averaged 0.97 and 0.99 respectively over the period shown. The ratio for 2×10 lumber varied between 1.1 and 1.3 with an average of 1.19 over the period shown.

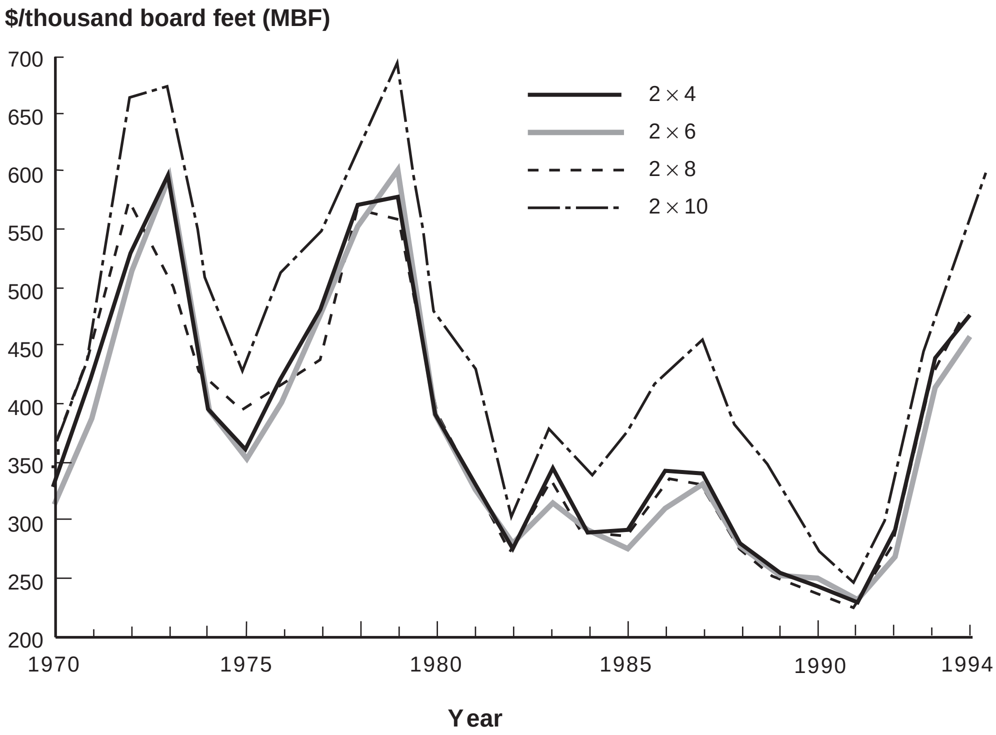

FIGURE A1-3. Trends in lumber prices by dimension (1995 Canadian $/MBF).

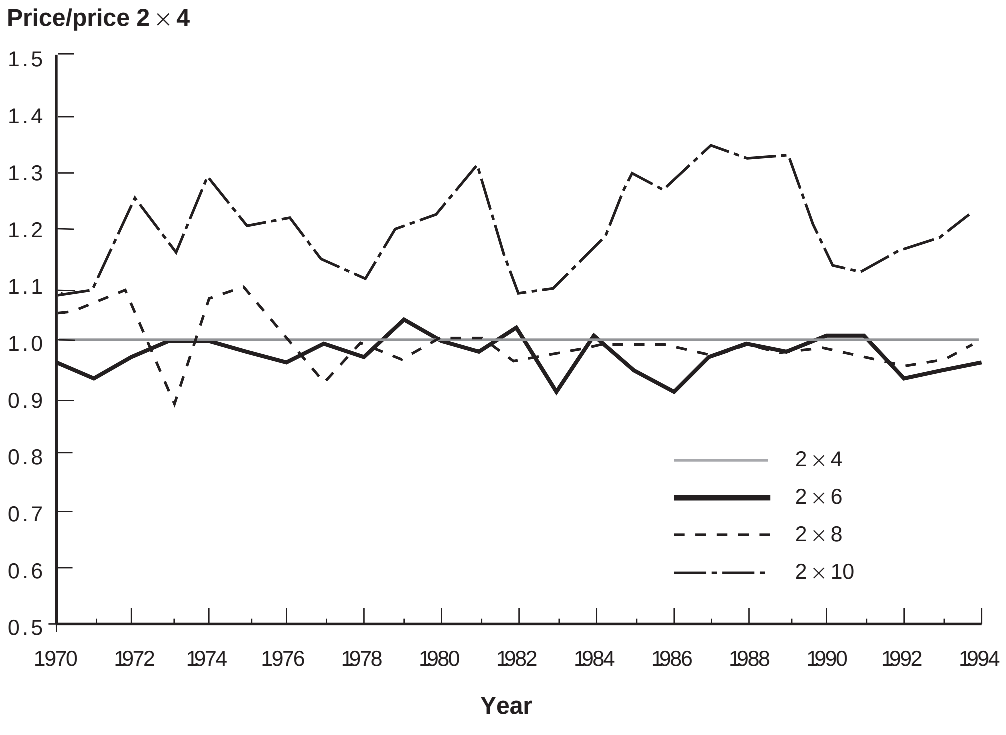

FIGURE A1-4. Ratio of price of western SPF kiln dried dimension lumber relative to the price of 2×4 lumber.

Wood chip prices

The Ministry of Forests Revenue Branch collects data on private sector sales of residual wood chips from sawmills to pulp mills in the interior of British Columbia.[9] The delivered chip prices in bone dry unit (BDU) are adjusted by the estimated freight haul cost to produce an estimate of the value of the material at the sawmill gate, for each appraisal point in the interior. These average market values are published quarterly and represent the average value over the preceding twelve-month period. Figure A1-5 shows the trend in whitewood chip average market values for the period January 1990 to June 1995.[10] Chip prices were quite stable until the end of 1994 when price began to increase sharply. These price increases may be attributable to a robust pulp market and the rapidly increasing price of market pulp, coupled with an increasing shortage of chip supplies in the interior regions. However, these large price increases are likely unsustainable in the long-run as there will be an eventual down-turn in the price of market pulp, and the probability of a chip supply response to the current high chip prices.

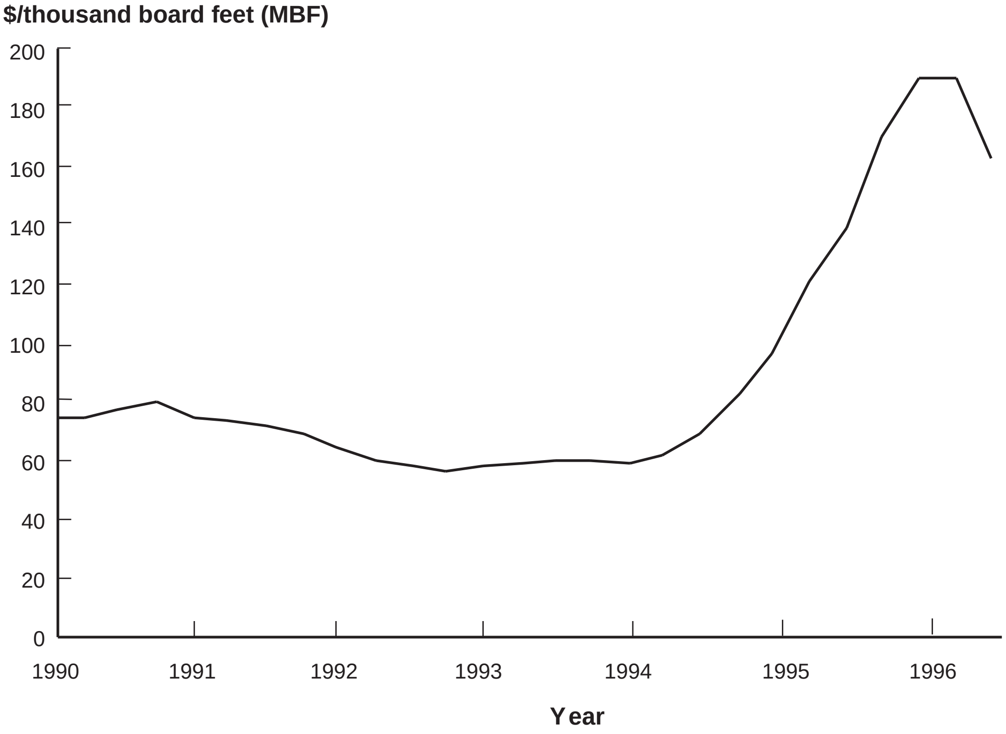

FIGURE A1-5. Interior average market values for whitewood chips 1990–1995 (constant 1995 $/BDU).

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[9] Thus they exclude intra-firm transfers of wood chips within vertically integrated firms.

[10] Prices graphed are the arithmetic average of all appraisal point average market values as published by the Revenue Branch after conversion to constant 1995 dollars. Whitewood refers to all conifer species except western redcedar.

The graph in Figure A1-5 indicates that the rapid increase in the average market value of chips had peaked at the beginning of 1996. On the other hand, prices may not return to the range experienced prior to 1995. Some studies have concluded that the market for residual wood chips in the interior has not produced competitive prices due to the potential oligopolistic power of pulp mills relative to sawmills (for example, see Nelson *et al.* 1994).

What means do we have then for estimating a long-run real wood chip price? Figure A1-6 illustrates the real price trends for North American wood chips over the period 1970–1995. The original data come from RISI (1994) and were expressed in nominal Canadian dollars per tonne for the Canadian markets, and in nominal U.S. dollars per short ton for the U.S. Pacific Northwest export market. Note the data for 1994 and 1995 are projections. These data were converted to dollars per BDU and then to constant 1995 Canadian dollars per BDU using the CPI and the Canada/U.S. exchange rate where appropriate.

The average price/BDU for wood chips over the period 1970 to 1995 was $104.76 for the BC coast, $73.21 for the BC interior, $122.02 for Ontario, $122.25, for Quebec, and $143.58 for the U.S. Pacific Northwest export market.[11] The price trends and averages for Ontario, Quebec and the U.S. Pacific Northwest are similar and could indicate that the world wood chip price level is currently between $110 and $130 per BDU (f.o.b. mill). Thus, the assumption of a long-run average price for whitewood pulp chips in BC of $110/BDU does not appear unreasonable.

The BC interior average market values of western redcedar wood chips has ranged from $10 to $19 per BDU and has not been affected by the upturn in pulp market prices. Cedar chips are viewed as an inferior product by pulp mills, so it is unlikely they will increase in real value in the foreseeable future. Thus, the assumed long-run price for cedar chips is $15/BDU.

Japanese lumber markets

While most of the lumber produced in the interior region of the province is exported to the U.S., lumber sales from the coast region are diversified to a much greater degree throughout the Pacific Rim countries, notably Japan. One of the major coastal timber products now sold there is hemlock squares (cants usually of 3-9/16" × 3-9/16" dimension). Figure A1-7 shows the real price of hemlock squares over the period January 1990 to April 1996.

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[11] Prices were f.o.b. mill for all regions except the U.S. PNW, which was f.a.s.

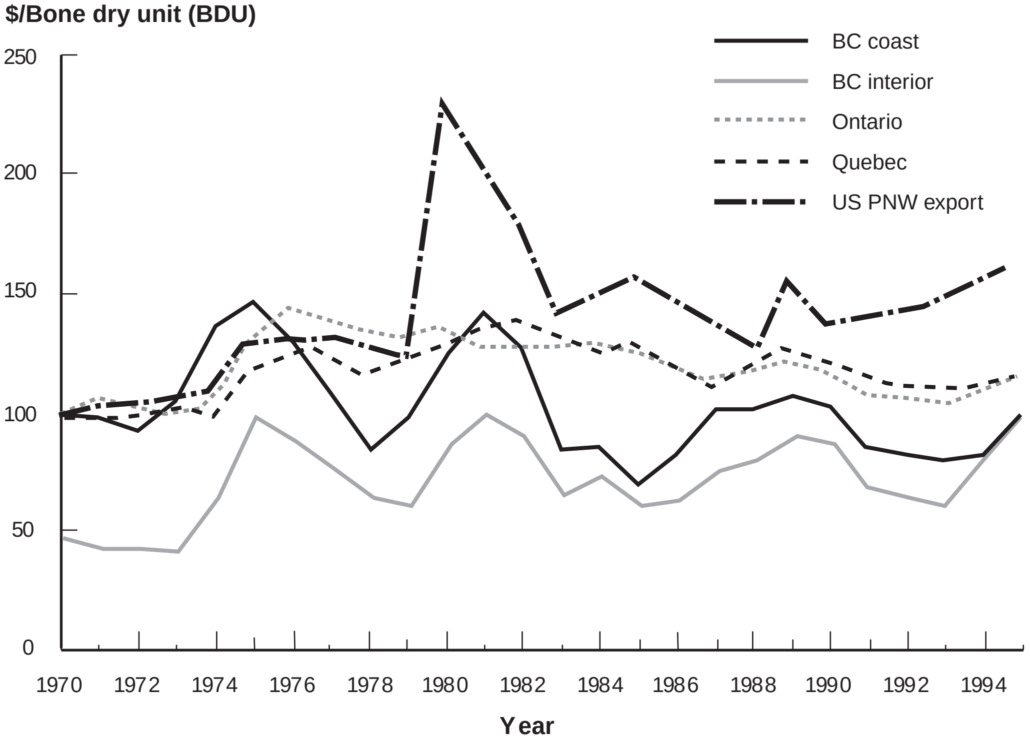

FIGURE A1-6. Trends in wood chip prices in North America (constant Canadian 1995 $/BDU).

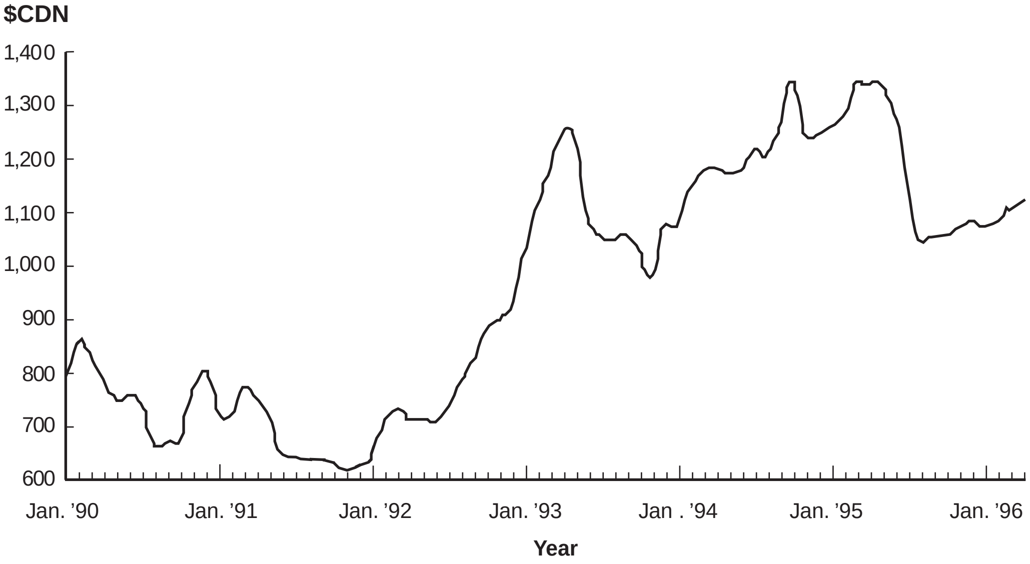

FIGURE A1-7. The real price of hemlock squares over the period January 1990 through April 1996 (delivered price/MBF).

Note the prices are delivered (c.i.f.) whereas the lumber prices reported in previous illustrations were f.o.b. sawmill prices. The graph indicates a substantial price increase starting around April of 1992. One of the reasons for this increase was a substantial rise in the value of the Japanese yen relative to the Canadian dollar. Figure A1-8 shows the Japanese/Canadian exchange rate over the same period. Note the value of the yen started to climb rapidly relative to the Canadian dollar starting about April 1992. The pattern over time for the price of hemlock squares shown in Figure A1-7 closely follows that of the exchange rate shown in Figure A1-8.

If one considers the price rise of April 1992 to be the result of changes in the exchange rate, it is reasonable to assume that future price may also be linked to future increases in the value of the yen relative to the Canadian dollar. However, it is extremely unlikely that the exchange rate will remain as high as the peak shown in Figure A1-8.

While many economic observers believed the yen was undervalued during the 1980s, few believe it is so today. The peak in the exchange rate shown in Figure A1-8 has been attributed by some to the sudden liquidation of foreign reserves by the Japanese government and industry in order to rebuild after the devastation of the 1995 earthquake.

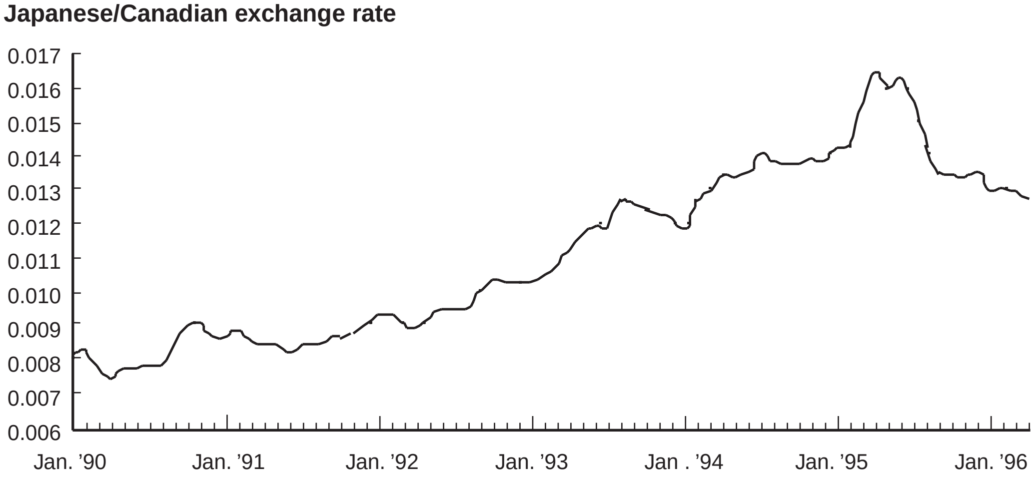

FIGURE A1-8. Japanese/Canadian exchange rate over the period January 1990 through April 1996 (based on the Japan noon spot rate; in Canadian dollars).

A final note concerns the cost of manufacturing hemlock squares, relative to that of dimension lumber. The lumber recovery factor (LRF) for logs sawn into squares is significantly lower than for the production of dimension lumber from the same logs. Thus, more raw material/MBF is required, resulting in a higher milling cost for producing squares.

Conclusions and recommendations

Time in and of itself has no effect on prices, and past prices do not dictate what future prices will be. Market supply and demand forces, which change over time, cause prices to change. Use of simple trend models to predict future prices assumes that forces of supply and demand which caused the past price changes are closely correlated with time and that this correlation will continue into the future. This assumption is simplistic, and warrants caution in the use of models based on similar logic.

Long-run real log price increases

Given the factors that mitigate against real price increases, it is appropriate to select a conservative estimate of future real price increases. The estimates presented in Table A1-1 are examples of those typical within the range of most estimates. They are not unreasonable, especially if limited to the 50 year period shown.

Long-run real lumber and chip prices

The real lumber and wood chip prices presented in Table A1-2 may provide reasonable long-run estimates (Stone *et al.* 1996). The long-run real price of 2×4 lumber for each species is the average for the periods studied, while the price for other dimensions is a function of the 2×4 price and the average price ratio of dimension lumber to 2×4 lumber.

TABLE A1-2. Default lumber and wood chip prices used in the TIPSY ECONOMIST (constant 1995 dollars)

	Lumber ($/MBF)				
Species	**2×4**	**2×6**	**2×8**	**2×10**	**Wood chips ($/BDU)**
Coastal Douglas-fir	455	460	455	560	110
Lodgepole pine	380	369	376	452	110
Western hemlock	406	406	414	491	110
Sitka spruce	380	369	376	452	110
Western redcedar	482	482	583	583	15
White spruce	380	369	376	452	110
Interior Douglas-fir	426	430	439	554	110

Source: Stone *et al.* 1996.

Real per annum price increases – a word of caution

Given the lack of any clear trend in past real lumber prices (as indicated in Figure A1-2), and the likelihood of only modest real price increases for logs in the future, caution is warranted in making future value assumptions when evaluating the economic efficiency of silviculture investments. For example, Figure A1-9 illustrates the cumulative effect of annual real price increases of 1%, 2%, 3% and 4%. If these annual price increases were compounded over a period of 75 years, as they might be in an analysis of juvenile spacing for instance, the resulting cumulative increase in timber value would be 111%, 342%, 818% and 1795%, respectively.

The significance of these extremely high future values is considerable in the calculation of NPV or site value of a stand density management investment analysis.

The compounding effect of an assumed annual price increase can be reduced by limiting the period during which the compounding takes place. For example, an assumption of a 1% per annum real price increase over the first 25 years with no real price increase thereafter results in a cumulative real price increase of only 28%.

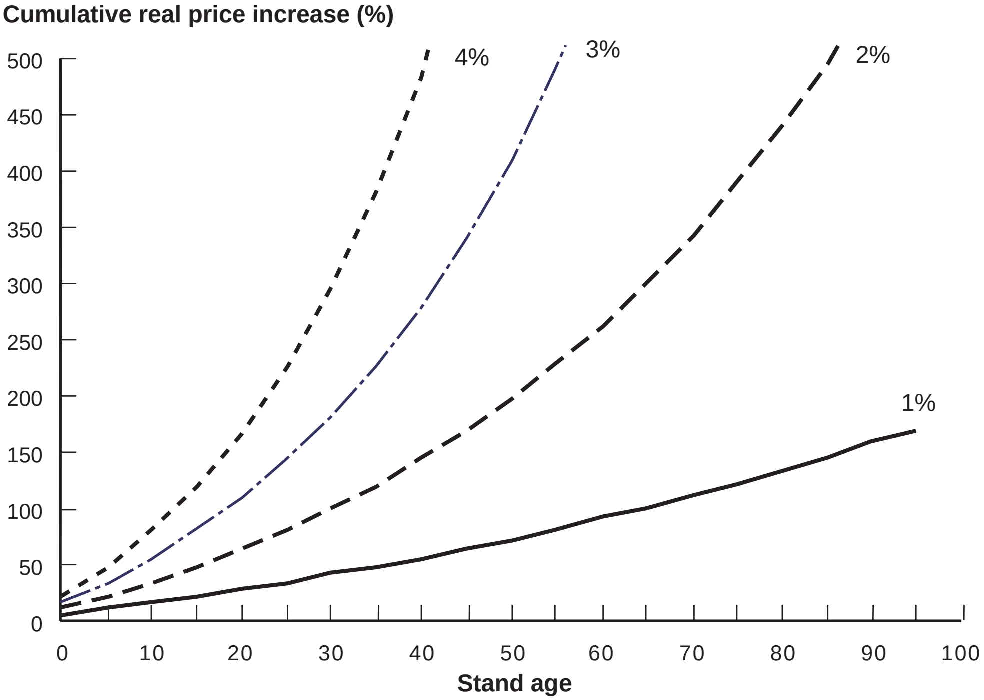

FIGURE A1-9. Cumulative real price increase resulting from 1%, 2%, 3% and 4% annual real price increases.

Appendix 2. Tactical analysis and design

Introduction

In previous sections, biological, economic and forest-level information essential to the density management decision process was organized into a decision-making framework. Density management decisions incorporate forest management objectives, strategic analysis and tactical design decisions (i.e., evaluating and ranking stand-level treatment options).

General approach

Supporting feasibility analyses question the suitability of a specific density management action in relation to management objectives and strategic needs. The following questions reflect the approach taken:

- What tactical options are feasible given budget, manpower, access and other constraints?
- Will required standards for the management unit be met?
- Will the option generate acceptable economic returns?
- What is the priority of the option relative to other feasible activities?

To analyse stand density management tactics, the silviculturist must understand the management objectives for the forest estate, the characteristics of the resource, the forest policy constraints under which the estate is managed and the intended silviculture strategy. In the examples provided, these higher levels of the decision process are omitted in order to focus at the tactical level. Forest management objectives and strategies have been assumed for the sake of brevity. Nevertheless, their influence on decision making is noted.

The analytical process underlying a tactical analysis is illustrated by means of pre-commercial thinning examples in stands of coastal hemlock and interior lodgepole pine.[12] Operationally, density management solutions require detailed forest-level planning and thorough strategic analyses. The assumptions in these examples have been simplified to illustrate the decision process.

The decision support model, TIPSY 2.1e, is used in these examples. Output includes conventional yield summaries, stand and stock tables, log and lumber data, mortality and snag summaries and economic information. The model is supported by the Ministry of Forests. Some limitations of TIPSY are of note:

- TIPSY must initiate stand growth projections at age 0 since data from existing stands cannot be entered. However, establishment parameters can be

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[12] Since the examples provided in this appendix were developed using TIPSY version 2.1e, we anticipate minor changes in some results, particularly for the pine example, as new versions of TIPSY are released.

manipulated to approximate an actual treated stand at a particular age. Other models accept stand data, but may have other limitations.

- Only one pre-commercial thinning entry is possible and it occurs when stands are 4 m (interior) or 6 m (coast) tall. The time and frequency of treatment are more flexible in other models.

Pre-commercial thinning options analysis

Stand descriptions and management assumptions for coastal and interior scenarios, as they apply to untreated stands, are specified in Table A2-1. For convenience, these examples are based on the default values in TIPSY. Only the bolded information must be entered by the user to replicate the results. Note that some defaults depend on the region and district selected. Since the user can change TIPSY defaults, confirm all input data for untreated stands with Table A2-1 when reproducing these examples. Refer to the TIPSY online manual for detailed information and operating instructions. Note that:

- all stands regenerate naturally with 10 000 sph
- operational factors lower potential yields (see OAF values)
- most yields are based on a minimum diameter of 12.5 cm
- no cost is incurred for site preparation
- results may vary slightly if the table range or step is changed.

Table A2-2 shows the pre-commercial thinning suite of runs that readers are encouraged to duplicate. After completing the untreated case (Table A2-1), select the thinning option in TIPSY, specify the post-treatment density given in Table A2-2, change the age range and steps temporarily and re-run the example. No other changes are needed until you generate the site values at the time of thinning (last row of Tables A2-3 and A2-4).[13] To do that, set the "Analysis Base Year" so that discounting stops "At PCT Age." Discount the untreated stands to age 17 or 16 for hemlock and pine, respectively. Note that some calculations (e.g., harvest costs) may change in thinned stands.

Management assumptions

The forest estate is managed under a silvicultural system that requires clearcutting at the physical rotation age (culmination of MAI). However, harvesting at the economic rotation age (culmination of site value) will be considered. The stand specifications are shown in the first section of Table A2-1. A minimum DBH of 12.5 cm is assumed for the future harvest. Note that the discount rate is 4%, and no increase in real – excluding inflation – product prices is expected. Costs are incurred for "Surveys" but not "Site Preparation." Pre-commercial thinning costs are given in Table A2-2. The future harvest is expected to use ground skidding equipment. Harvesting, hauling, milling and development costs, and product prices are given in Table A2-1.

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[13] Note that treatment costs are provided by the "Linear Equation" option.

Should stands be pre-commercially thinned – and, if so, to what density? Assume the silviculturist wants to compare the unthinned option with the three residual densities for hemlock or pine shown in Table A2-2.

TABLE A2-1. TIPSY input values for untreated stands of coastal hemlock and western interior lodgepole pine

	Coast	Interior		Coast	Interior
Title	**Untreated**[a]	**Untreated**	Harvest system	Gr. skid	Gr. skid
			Tree-to-truck equation:	17.10	16.10
Stand specs			Slope/100	4.24	4.24
			Stems/1000	0.70	0.70
Species	**W. Hem.**	**Pine**	Volume/stems	0.43	0.43
%	100	100	Volume/1000	5.41	5.41
Site index (m)	**27**	**21**	**(**Distance – 50)/100	0.67	0.67
Regeneration type	Natural	Natural	= $/m^{3} (@ age 80)	14.36	15.66
Density (sph)	10 000	10 000			
Regeneration delay (yr)	2	2	Haul distance (km)	100	
OAFs 1 & 2	**0.90 & 0.95**	**0.90 & 0.95**	Towing/barging ($/m^{3})	1.93	
Thin to density (sph)			Cycle time (hr)		3.0
Table range and step	**80/130/5**	**50/80/5**	Off highway?		no
In relation to	Age	Age	Total haul cost ($/m^{3})	12.40	6.18
Merch. limits (cm)	12.5+	12.5+			
			Milling cost eq'n	expo.	expo.
Region	**Vancouver**	**Pr. George**	Sawmill capital ($/MBF)	7.07	7.07
District	Campbell R.	**Pr. George**	Coastal additive ($/MBF)	75.00	
Biogeoclimatic zone	CWH	**SBS**	Total milling cost ($/MBF)	207	144
Average slope	10	10			
Distance to support (km)	100	100	Development costs ($/ha)	9 168	1 450
			Overhead costs ($/ha)	13 026	2 229
Economic[b] *specs*			Annual costs ($/ha)	0	0
			Other harvest ($/ha)	0	0
Discount rate (%)	4.0	4.0	Other treatment ($/ha)	0	0
Price increase					
– general (%)	0.0	0.0	Lumber/chip prices		
Cost increase (%)	0.0	0.0	2 × 4 ($/MBF)		387
– duration (yr)	25	25	2 × 6 ($/MBF)		379
Analysis base year	0	0	2 × 8 ($/MBF)		383
			2 × 10 ($/MBF)		464
Surveys ($/ha)	19	16	chips ($/BDU)		110
Site prep. ($/ha)	**0**	**0**	Log prices ($/m^{3})		
Brushing costs ($/ha)	0	0	Grade H	145	
			Grade I	114	
			Grade J	82	
			Grade U	67	
			Grade X	63	
			Grade Y	62	

[a] Entries shown in bold are not TIPSY defaults (i.e., user must change specifications on screen).

[b] All costs and prices are in constant 1996 Canadian dollars.

TABLE A2-2. Treatment options, spacing costs and stand characteristics for coastal western hemlock and interior lodgepole pine density management regimes

	Coastal western hemlock				Interior lodgepole pine			
Initial density (trees/ha)	10 000	10 000	10 000	10 000	10 000	10 000	10 000	10 000
Thin to: (trees/ha)	n/a	1 200	900	600	n/a	1 800	1 400	1 000
PCT costs ($/ha)	n/a	650	660	670	n/a	585	598	611
PCT age (yr)	n/a	17	17	17	n/a	16	16	16
Spaced at height (m)	n/a	6	6	6	n/a	4	4	4

Options analysis

Production comparisons

Tables A2-3 and A2-4 display some of the information generated by TIPSY for the coastal and interior scenarios, respectively. Yields are compared at a constant age which is close to the physical rotation ages given in the second section of the table. Economic analyses for coastal hemlock and interior pine are based on the log and lumber markets, respectively. To see a discussion of minor limitations regarding TIPSY's ability to differentiate between H- and I-grade logs, go to the online documentation, use the 'Search for Help On…' option and type in 'log grades.' The following summary applies to the pre-commercial thinning (PCT) of hemlock (*Hw*) or pine (*Pl*) or, if unspecified, both in these examples:

- Merchantable volume is insensitive to thinning in this range.
- Mean DBH increases with intensity of PCT.
- Merchantable volume and DBH of prime trees increase but the latter is less sensitive to thinning than is the mean DBH of the stand.
- *Hw*: The volume of I-grade logs increases but is offset by decreases in other grades. Harvest revenue improves somewhat.
- *Pl*: Total lumber output (mostly 4″ and 6″ widths) and harvest revenue are higher but decline as residual density decreases. Spacing also elevates lumber recovery and harvest revenue.
- *Hw*: Physical rotations increase; MAIs are stable; site values decline.
- *Pl*: Physical rotations and MAIs are stable; site values decline.
- *Hw*: Economic rotations are stable, but MAIs and site values decline.
- *Pl*: Economic rotations and MAIs are stable; site values decline.
- Ignoring the initial pre-treatment costs (discounting to age of PCT instead of 0) doubles the site value but does not alter the ranking of treatments.

TABLE A2-3. Tactical options analysis for four western hemlock stand density regimes

		Unthinned	PCT to 1200 sph	PCT to 900 sph	PCT to 600 sph
Yield comparison [12.5+]					
Age at comparison (yr)		100	100	100	100
Merch. volume (m^3/ha)		1 062	1 064	1 059	1 011
All trees [0.0+]:	mean DBH (cm)	33.7	38.5	40.5	44.9
	no. of trees	774	632	570	444
250 prime trees:	merch. vol. (m^3/ha)	758	804	823	874
	mean DBH (cm)	47.2	50.3	51.3	53.7
Logs (m^3/ha):	Grade H	50	33	19	5
	Grade I	262	366	413	499
	Grade J	661	597	568	462
	Grade U	65	53	46	35
	Grade X	13	12	12	10
	Grade Y	2	2	2	2
	total	1 053	1 063	1 060	1 013
Harvest revenue ($/ha)		96 582	99 841	100 293	98 526
Physical rotation [12.5+]					
Age of culmination of MAI (yr)		90	95	105	120
MAI [= max] (m^3/ha)		10.67	10.65	10.61	10.27
Site value [< max] ($/ha)		1 056	746	583	307
Economic rotation [12.5+]					
Age of culmination of site value (yr)		80	80	80	85
Site value [= max] ($/ha)		1 083	884	904	860
MAI [< max] (m^3/ha)		10.55	10.39	10.22	9.76
Site value @ age 17 (PCT) ($/ha)		2 147	1 778	1 816	1 730

In summary, the biological response of the stand to pre-commercial thinning slightly increased the harvest revenue. However, the economic analysis shows that the site value did not increase enough to cover treatment costs when all revenues and costs were discounted to a common point in time. This does not mean that spacing can not be undertaken to meet other management objectives (e.g., maintenance of wildlife habitat).

TABLE A2-4. Tactical options analysis for four lodgepole pine density regimes

		Unthinned	PCT to 1800 sph	PCT to 1400 sph	PCT to 1000 sph
Yield comparison [12.5+]					
Age at comparison (yr)		70	70	70	70
Merch. volume (m^3/ha)		349	366	357	335
All trees [0.0+]:	mean DBH (cm)	20.0	23.5	24.8	27.6
	no. of trees	1 404	1 093	962	741
250 prime trees:	merch. vol. (m^3/ha)	150	159	167	180
	mean DBH (cm)	28.9	30.8	31.9	33.9
Chips (BDU/ha)		61	63	61	57
Lumber vol. (bd ft/ha):	2 × 4	55 797	57 789	55 380	50 274
	2 × 6	17 000	20 041	20 164	20 007
	2 × 8	2 154	2 326	2 465	2 677
	2 × 10	2 645	3 659	4 933	7 378
	total	77 596	83 814	82 942	80 336
Lumber recovery (bd ft/m^3)		222.1	228.9	232.5	239.5
Harvest revenue		36 764	39 505	39 035	37 727
Physical rotation [12.5+]					
Age of culmination of MAI (yr)		70	70	70	75
MAI [= max] (m^3/ha)		4.99	5.23	5.10	4.81
Site value [< max] ($/ha)		940	719	708	595
Economic rotation [12.5+]					
Age of culmination of site value (yr)		60	60	60	60
Site value [= max] ($/ha)		1 048	848	831	785
MAI [< max] (m^3/ha)		4.92	5.18	5.01	4.64
Site value @ age 16 (PCT) ($/ha)		1 992	1 598	1 567	1 481

Rotation ages in Tables A2-3 and A2-4 vary widely depending on the regime and criteria selected. However, the relationships of MAI to age and treatment (Figures A2-1 and A2-2) show that volume production is quite insensitive to both in this range with the exception of the heaviest treatment. TIPSY can draw these figures if each regime file is run in steps of five years from 0 to 160 (Hw) or 120 (Pl) years prior to plotting “MAI (merch) 12.5+” over “Age.” Notice that thinning impairs volume production of coastal hemlock until the site is reoccupied, after which it catches up with the untreated stand. Recovery time is related to the intensity of thinning and site productivity. The situation with pine is more complex because utilization limits have a great impact on yield, particularly when the rotations are short.

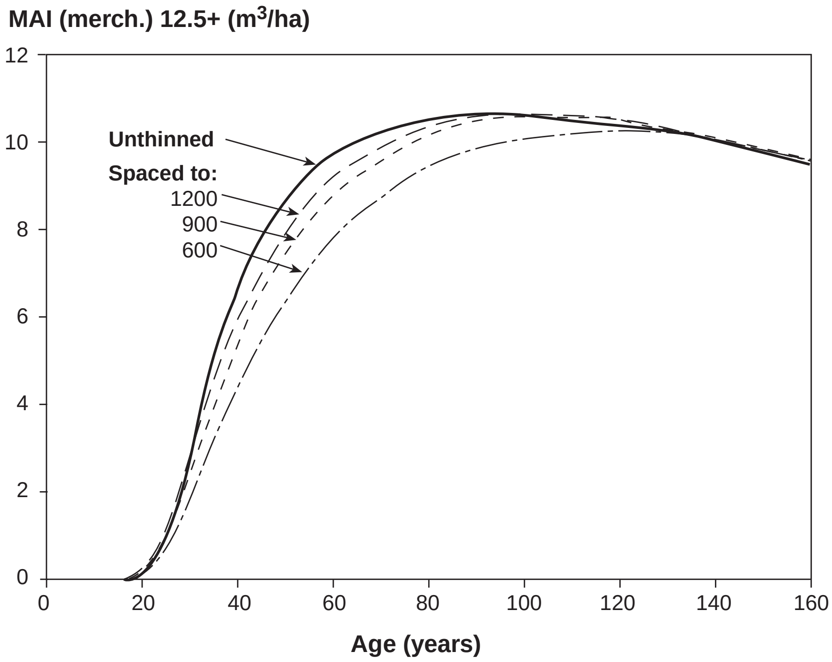

FIGURE A2-1. Mean annual increment over stand age for four coastal western hemlock density regimes.

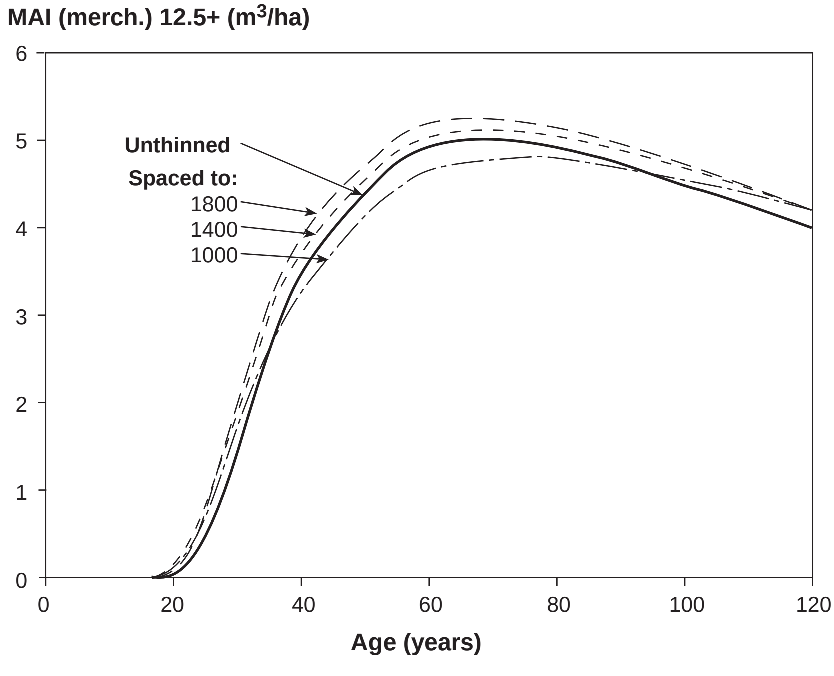

FIGURE A2-2. Mean annual increment over stand age for four interior lodgepole pine density regimes.

Similar insight into the dynamics of stand development can be achieved by plotting other variables over age (e.g., volume, diameter, number of trees and prime tree statistics). It is also informative to display number of trees (stand table) and volume (stock table) by diameter classes. TIPSY-generated stand tables at age 100 (Hw) and 70 (Pl) show that the unthinned stand has many more trees in the smaller diameter classes. The difference increases with the intensity of treatment. However, thinning produces slightly more trees in the largest diameter classes.

The corresponding stock tables for hemlock (Figure A2-3) and pine (Figure A2-4) are more meaningful than stand tables because they display volume, which is closely related to stand value. Notice that pre-commercial thinning shifts volume toward the larger diameter classes in both examples, which is the intent of this practice. A closer look at the untreated and thinned to 900 hemlock regimes (Figure A2-3) shows that 193 m^3 of small wood (mostly in the 20 to 35 cm classes) is replaced with 181 m^3 of large wood (mostly in the 50 to 65 cm classes). Spacing pine to 1400 trees/ha (Figure A2-4) converts 77 m^3, in the 15 to 20 cm classes into 83 m^3, most of which falls in the 30 to 35 cm classes.

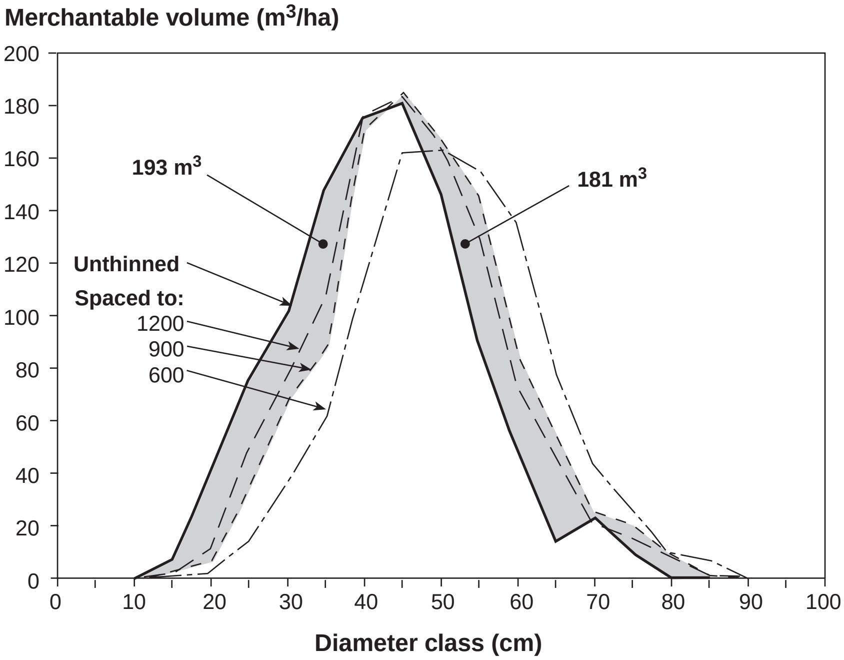

FIGURE A2-3. Distribution of volume by diameter class at age 100 for the coastal western hemlock density regimes.

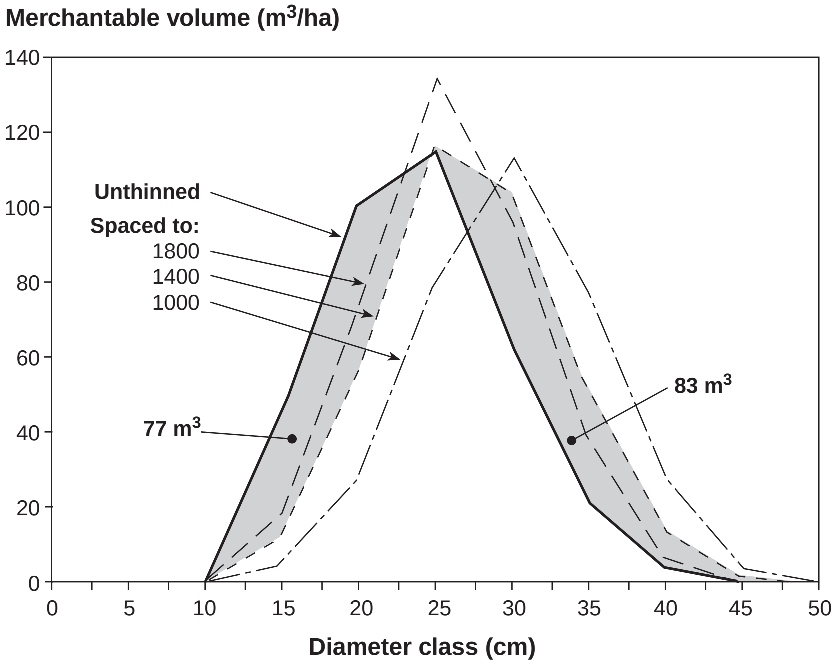

FIGURE A2-4. Distribution of volume by diameter class at age 70 for the interior lodgepole pine density regimes.

Investment decision

The site value of all density management regimes is positive over a wide range of ages for both hemlock (Figure A2-5) and lodgepole pine (Figure A2-6). This indicates that, in isolation, all regimes are economically efficient. However, all thinned stands have a lower site value than the comparable untreated regimes, indicating that the untreated regime is the most economically efficient choice in these examples.

The economic outlook for spacing will only be favourable if the increase in tree diameters increases log size and value sufficiently to offset thinning costs compounded to harvest. Notice that DBH distributions shift by about 5 cm in Figures A2-3 and A2-4. TIPSY addresses the premium for piece size through the effect treatment has on log and lumber yields by dimension and the associated prices.

The foregoing analysis indicates that alternative silviculture investment options, including treatments on other sites, should be investigated. Those options which yield higher net economic gains should be considered before investing in any of the thinning regimes in these examples.

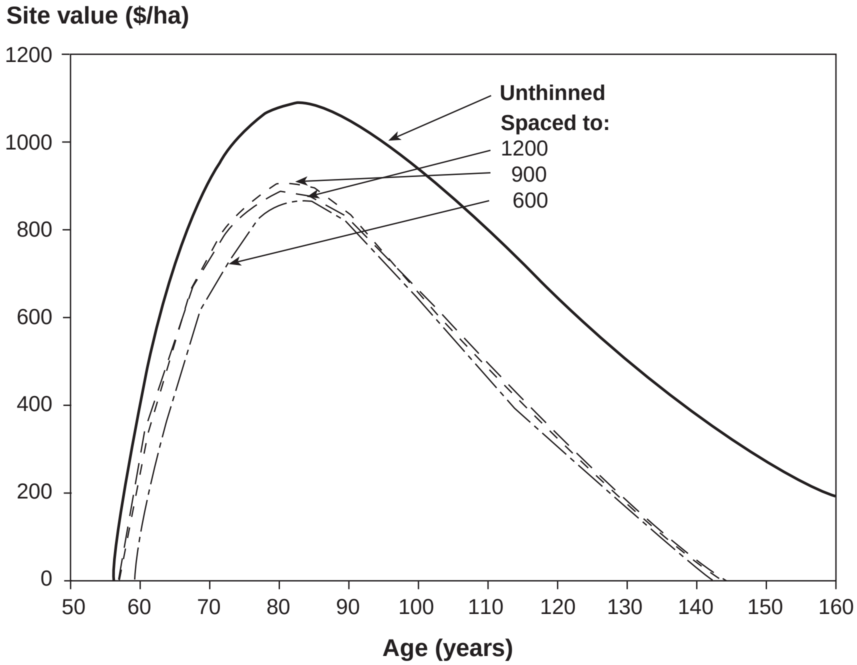

FIGURE A2-5. Site value over stand age (economic efficiency) for four coastal western hemlock density regimes.

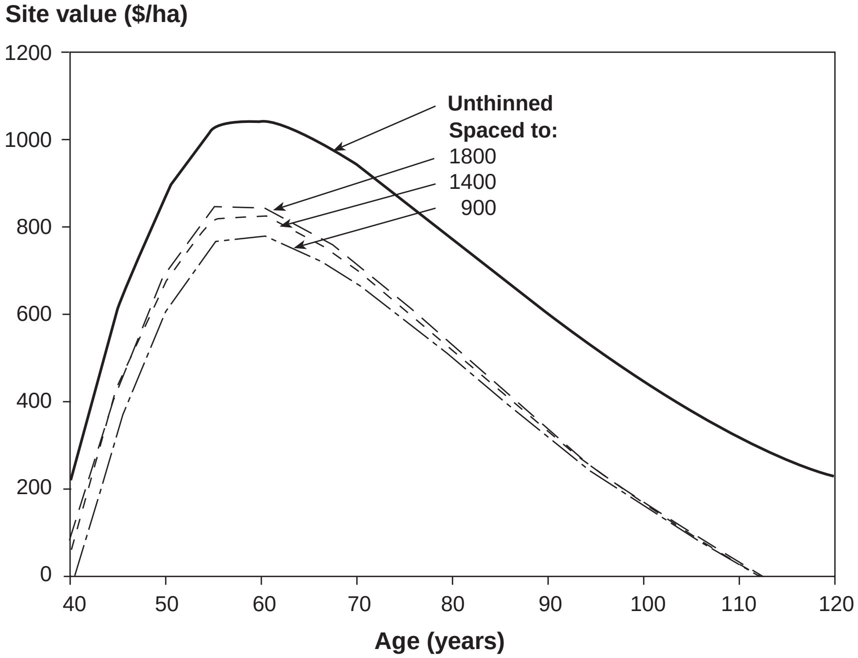

FIGURE A2-6. Site value over stand age (economic efficiency) for four interior lodgepole pine density regimes.

Other considerations

Figures A2-5 and A2-6 illustrate the effect of harvest timing on investment decisions. There is a 10 year plateau of economic advantage when the site value is at or near the optimum economic rotation age. Site value declines rapidly in later years due to the compounding effect of time on silviculture investments.

If, for reasons of resource management constraints (e.g., VQO, ungulate winter range, community watershed requirements), the rotation must be extended or deferred beyond the period of maximum site value, it would be unwise, from a timber optimization perspective, to invest silviculture capital in pre-commercial thinning. Silviculture investments made under these circumstances will likely yield low or negative returns. Similar economic impacts result from spacing stands of low productivity with lengthy investment periods.

Some assumptions used in the preceding analysis may not be based on the best available data for a specific site or area. Thinning costs, for example, were based on the “Linear Equation” option. Use of the “District Average” values raises the costs of thinning pine to 1400 trees by $154 and lowers the economic site value from $831 to $739. Managers should be aware of the relative sensitivity of the various assumptions in their analysis. Examples of sensitivity analysis follow.

Sensitivity analyses

Site quality

There is always uncertainty with assumptions. As discussed in “Economic principles of timber production,” sensitivity analysis is a useful procedure to deal with uncertainty. For instance, a site index of 27 m was used in the coastal hemlock example. Since the actual site index could range from 24 to 30 m, it is important to know if the investment decision would change within this range.

Sensitivity analyses measure the change in one or more variables required to change an investment decision. The partial analysis in Table A2-5 compares the thinned to 900 and untreated hemlock stands on sites 24, 27 and 30 m. Lodgepole pine thinned to 1400 is compared with its untreated counterpart on sites 18, 21 and 24 m in Table A2-6. In this simulated environment, it is evident that:

- increasing site productivity shortens the physical and economic rotations while increasing MAI and site value
- thinning is warranted on some sites (Hw 30, Pl 18–24) if it can be justified by a very small increase in MAI
- thinning will not improve the site value of any site in these examples if harvested at the economic rotation age.

TABLE A2-5. Sensitivity analysis of two hemlock density regimes to site quality

	Site					
	Unthinned			Thinned to 900		
	24	27	30	24	27	30
Physical rotation [12.5+]						
Age of culmination of MAI (yr)	100	90	85	110	105	100
MAI [= max] (m^3/ha)	8.79	10.67	12.66	8.66	10.61	12.75
Economic rotation [12.5+]						
Age of culmination of site value (yr)	95	80	80	90	80	80
Site value [= max] ($/ha)	561	1083	1834	332	904	1649

TABLE A2-6. Sensitivity analysis of two pine density regimes to site quality

	Site					
	Unthinned			Thinned to 1400		
	18	21	24	18	21	24
Physical rotation [12.5+]						
Age of culmination of MAI (yr)	80	70	60	80	70	60
MAI [= max] (m^3/ha)	3.78	4.99	6.34	3.85	5.10	6.50
Economic rotation [12.5+]						
Age of culmination of site value (yr)	70	60	55	70	60	50
Site value [= max] ($/ha)	530	1048	1770	288	831	1599

Future price increases

The preceding analyses are based on the assumption that real end-product prices remain constant over time. In other words, the future value of wood products will not change relative to the cost of production. Under this assumption, pre-commercial thinning examples show no net gain in value over and above the cost of thinning. This leads to the question, “How much of an increase in end-product price is required to cover spacing costs?”

Consider the untreated stand of pine on site 21 m and its counterpart which was thinned to 1400 trees. Assume the landowner expects that real end-product prices will rise steadily for the next 25 years and remain constant thereafter. What rate of increase is necessary to make the thinned stand as financially attractive as the untreated stand assuming all other costs and values are the same as in Tables A2-1 and A2-2.

A modified sensitivity analysis is used to determine the annual real price increase in products needed just to cover treatment costs. To calculate this “break-even” price increase, discount the cost of thinning ($598) from age 16 to zero at 4%. This amounts to $319, which is the net gain in site value at age zero needed to cover treatment costs. Set the cost of thinning to zero, and then elevate the “Real Price

Increase” in small steps for both stands until the site value of the thinned stand exceeds that of the untreated stand by $319 *at age 60*. Table A2-7 shows that an increase of just over 2.6% is needed to cover spacing costs. Note that a 90% total increase in price results from the 2.6% price increase over 25 years.

If the analysis is repeated using a physical rotation of 70 years, the break-even rate of price increase is 3.4%. Without the 25 year cap on the rate increase, the break-even point drops to about 1%, but the total increase at age 60 is 92%. Forecasting future prices is discussed in Appendix 1.

TABLE A2-7. Site values for pre-commercially thinned and unthinned lodgepole pine over a range of expected real price increase for 25 years

Real annual price increase (% per year over 25 years)	Total price increase (%)	Site value (SV) at 60 years ($/ha)*		
		PCT (1400 sph)	Base case (unthinned)	Difference in SV ($/ha)
0.0	0.0	1189	1048	141
1.0	28.2	2128	1931	197
2.0	64.1	3318	3052	266
2.5	85.4	4027	3719	308
2.6	90.0	4180	3862	318**

* Site values for PCT regimes exclude PCT costs in this example.

** Approximate PCT costs of $319 discounted to age 0.

Future harvest costs

There may be uncertainty about average harvest costs in thinned versus unthinned stands, and the manager may want to know how tree-to-truck harvest costs affect the analysis. For example, how much of a difference in tree-to-truck costs is required to equate the returns from the thinned and unthinned stands? Or, at what harvest cost does the net economic gain from thinning equal zero. And, how does it differ from the tree-to-truck costs used for the unthinned stand?

Consider two coastal hemlock stands at an economic rotation age of 80 years. One is unthinned and the other is thinned to 900 trees/ha. Thinning costs are $660 at age 17, which discounts to $339 at age zero. This is the amount by which the site value of the thinned regime must exceed that of the unthinned regime to offset the cost of treatment. The average default tree-to-truck costs in TIPSY are similar ($14.36/m^3 vs $14.43/m^3) for the two regimes.

Set the thinning costs to zero as in the preceding example and reduce the tree-to-truck costs of the thinned stand in small increments using the “Constant Cost” option until the difference in site values between the two regimes at age 80 matches the discounted spacing cost of $339.

Table A2-8 shows that treatment would have to reduce tree-to-truck costs from \$14.36 to \$9.90/m^3 for a savings of \$4.46. That is, it would be justified economically to thin the stand to 900 trees/ha if it reduced the average tree-to-truck costs by 31% relative to the unthinned stand.

TABLE A2-8. Site values for pre-commercially thinned and unthinned hemlock over a range of tree-to-truck costs

Average tree-to-truck cost (\$/m^3)		Site value (SV) at 80 years (\$/ha)*		
Unthinned	PCT 900 trees/ha	Unthinned	PCT 900 trees/ha	Difference in SV (\$/ha)
14.36	14.43	1083	1255	172
14.36	12.00	1083	1345	262
14.36	10.00	1083	1419	336
14.36	9.90	1083	1423	340**

* Site values for PCT regimes exclude PCT costs in this example.

** Approximate PCT cost of \$339 discounted to age 0.