

Regeneration and Small Tree Height Increment in the Interior
Douglas-fir Zone of the Rocky Mountain Trench

by

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B.A., Simon Fraser University, 1994
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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES
THE FACULTY OF FORESTRY

Department of Forest Resources Management

We accept this thesis as conforming
to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

July 2003

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Date JULY 11, 2003

ACKNOWLEDGEMENTS

I consider myself very lucky to have ended up with Dr. Val LeMay as my supervisor; I can't even begin to list the reasons why. My sincere appreciation to my committee members for their valuable input and advice, and for valiantly wading through my "masterpiece": Drs. J. Daniel Lousier, Peter Marshall, and Steve Mitchell. Also thanks Drs. H. Temesgen and Abdel-Azim Zumrawi, for help with Prognosis^{BC} and other modelling questions that came up during the process.

Part of the graduate experience also includes interactions with other graduate students; I found their advice and support invaluable, and always enjoyable.

To my husband, Karl Froese, for unlimited support (often in the form of chocolate), and my brother, Dr. Robert Froese, for giving me more help and advice than he could probably spare at the time.

ABSTRACT

Data were collected in the Kootenay Dry Mild Interior Douglas-fir subzone variant (IDFdm2) of the Interior Douglas-fir biogeoclimatic ecological classification zone, Invermere Forest District. A total of 111 plots were sampled for plot-level data; 25 of these were subsampled for additional substrate information and spatially mapped. Objectives were to: 1) examine the explanatory ability of modelling techniques based on plot-level predictors and 2) examine the utility of spatial and substrate data for improving our knowledge of understory stand dynamics.

The utility of imputation techniques as a method of predicting regeneration abundance was examined using the full data set. Imputation techniques performed moderately well. Subsampled data were used to examine regeneration abundance relative to substrate availability and spatial and aspatial competition and release indices. Substrate abundance was demonstrated to vary by moisture condition, as did substrate suitability for regeneration. Spatial indices showed interesting patterns between germinants and competition indices, and established regeneration and release indices. The spatial relationship between localized aggregations of regeneration and overstory trees, examined using Ripley's $K(t)$ point pattern analysis, provided statistically significant results, but trends were generally inconsistent and could not be explained by available information.

The utility of regression-based modelling as a method of predicting small tree height increment was examined using the full data set. Height increment models performed reasonably well. Small sample sizes were a limitation for some species. Subsampled data were used to examine spatial competition and release indices for model improvement. Spatial indices showed little potential for improvements over aspatial, plot-level indices, but provided an indication of the type of competition affecting small tree height increment.

Both regeneration imputation and regression-based height increment modeling performed well, even with small data sets. Additional data for more sparsely sampled species are desirable. Further focus on substrate conditions and their effect on regeneration, within a multivariate context and for all species, is warranted. Subsurface properties are an unexplored avenue that merits investigation, since the analysis points to below-ground competition for resources. Finally, spatial tools may be more illustrative if data are gathered for both horizontal and vertical structures, or at larger scales.

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1. INTRODUCTION

Research in the Interior Douglas-fir (IDF) biogeoclimatic ecological classification (BEC) zone (Pojar and Meidinger 1991) of British Columbia (BC) has established that understory dynamics of these stands, particularly those that are uneven-aged and comprised of mixed species, are very complex (e.g., Johnstone 1985, Marshall and Wang 1996, Nienaber 1999). In southeastern BC, partial cutting has been commonly practiced for over 100 years (Przeczek 2001), yet there has been little research on regeneration and growth dynamics in these stands (Saceniaks and Thompson 2000). Encouraging natural regeneration and growth following silvicultural activities has been identified by many stakeholders as one of their most difficult challenges. Improving tools for predicting regeneration establishment and growth relies on increasing our understanding of understory dynamics.

The preponderance of literature pertaining to Interior Douglas-fir stands in BC relates to forests in the Kamloops and Cariboo regions (e.g., Johnstone 1985, Newsome *et al.* 1991, Marshall and Wang 1996, Nienaber 1999, Lencar 2002). Little research has been done in the IDF of the Rocky Mountain trench, Nelson Forest Region. The stands in the Rocky Mountain Trench are geographically separated from other areas of the IDF and are constrained between two mountain ranges; these stands are also distinguished by the presence of western larch, which is restricted to the southeastern portion of the IDF zone (Hope *et al.* 1991). These differences limit extrapolation between the two areas.

The natural dynamics of Interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca* (Mirb.) Franco) stands in the Rocky Mountain Trench are also difficult to establish, due to the history of human activities in the area. In addition to the history of harvesting of stands, active fire suppression began in 1947 (M. Houlind, pers. comm., in Saceniaks and Thompson 2000); this has led to encroachment of IDF forest onto previously fire-maintained grasslands, and the replacement of predominantly fire-adapted ponderosa pine (*Pinus ponderosa* Laws.) and western larch (*Larix occidentalis* Nutt.) by more shade tolerant Douglas-fir (Arno *et al.* 1997). Considering these changes to the landscape, it is not surprising that the dynamics in these stands are not well understood.

Past modelling efforts in the IDF produced moderately good results in terms of predicting small tree height growth; in general, however, predicting regeneration has been identified as the most problematic aspect of modelling (Lencar 2002). Given the seemingly irregular horizontal distribution of overstory trees and regeneration within many stands, combined with vertical differentiation, incorporating spatial attributes into modelling efforts may improve estimation and aid in understanding understory dynamics.

This thesis research was carried out in the Kootenay Dry Mild Interior Douglas-fir subzone variant (IDFdm2) of the Interior Douglas-fir BEC of the Invermere Forest District. The two broad objectives were:

- 1) to examine the ability of modelling techniques to predict understory attributes based on plot-level predictors; and
- 2) to examine the utility of spatial and substrate data for improving our knowledge of understory stand dynamics.

The two main understory attributes examined were regeneration abundance and small tree height increment. Chapter 2 provides general background information on the study area, the Prognosis^{BC} model, a tree growth model currently being used in southeastern BC for uneven-aged, mixed species stands, and characteristics of Interior Douglas-fir stands and species silvics, as they pertain to this thesis. The sampling design and data collection methods are summarized in Chapter 3.

Regeneration and small trees were examined separately. Chapter 4 discusses regeneration; the objectives of this chapter were:

- 1) to examine the potential of aspatial, plot-level variables to model regeneration abundance using imputation methods;
- 2) to explore the potential of subsampled information (substrate and spatial indices) as explanatory variables for predicting regeneration abundance; and
- 3) to examine the relationship between localized aggregations of regeneration (regeneration "clumps") and overstory trees.

Chapter 5 discusses small trees, focusing on small tree five-year height increment. The objectives of this chapter were:

- 1) to examine the potential use of aspatial, plot-level variables to model five-year height increment using regression techniques; and
- 2) to examine the potential of subsampled information for model improvement by assessing spatial indices based on plot-level spatial information.

This thesis has an applied and theoretical component. The applied component focuses on modelling regeneration abundance and small tree height increments for the Prognosis^{BC} model. The theoretical component focuses on examining whether spatial and substrate information can provide any improvement in understanding understory stand dynamics, and whether this can provide future direction for modelling efforts.

2. LITERATURE REVIEW

2.1 Interior Douglas-fir Stands of the Rocky Mountain Trench

The Interior Douglas-fir BEC zone occupies the rolling hills and valley terrain of the southern interior plateau of BC (Hope *et al.* 1991), accounting for approximately 5% of the BC landscape (BC Ministry of Forests 1995). Within the Nelson Forest Region¹, there are 500,000 ha of IDF forest, 324,000 ha of which is comprised of the Kootenay Dry Mild Interior Douglas-fir Variant (IDFdm2) (Saceniaks and Thompson 2000). The southeastern portion of the IDF in BC is distinguished by the presence of western larch (*Larix occidentalis* Nutt.) (Hope *et al.* 1991).

The IDFdm2 extends along the Rocky mountain trench from north of Golden south across the border with the United States (US) (Saceniaks and Thompson 2000), and in the valley bottoms of the major tributary rivers, such as the Findlay, Spillimacheen, and Kootenay (Braumandl *et al.* 1992). The IDFdm2 occurs in the Invermere Forest District² along with the IDFun (Undifferentiated Interior Douglas-fir (Windermere Lake) Unit), which occupies a small area that is mainly privately owned (Braumandl *et al.* 1992). The extent of the IDFdm2 within the Invermere Forest District is illustrated in Figure 1.

The IDFdm2 ranges in elevation from 800 to 1200 m on south aspects, and from 800 to 1100 m on north aspects. This is an important area for cattle grazing and wildlife. The IDFdm2 generally extends into the Dry Cool Montane Spruce (MSdk) at higher elevations and the Dry Hot Ponderosa Pine (PPdh) at lower elevations.

¹ As of April 2003, the Nelson Forest Region became part of the Southern Interior Forest Region, which is comprised of the original Nelson, Kamloops, and Cariboo Forest Regions, and the Robson Valley Forest District.

² As of April 2003, the Invermere Forest District became part of the Rocky Mountain Forest District, comprised of the original Invermere and Cranbrook Forest Districts.

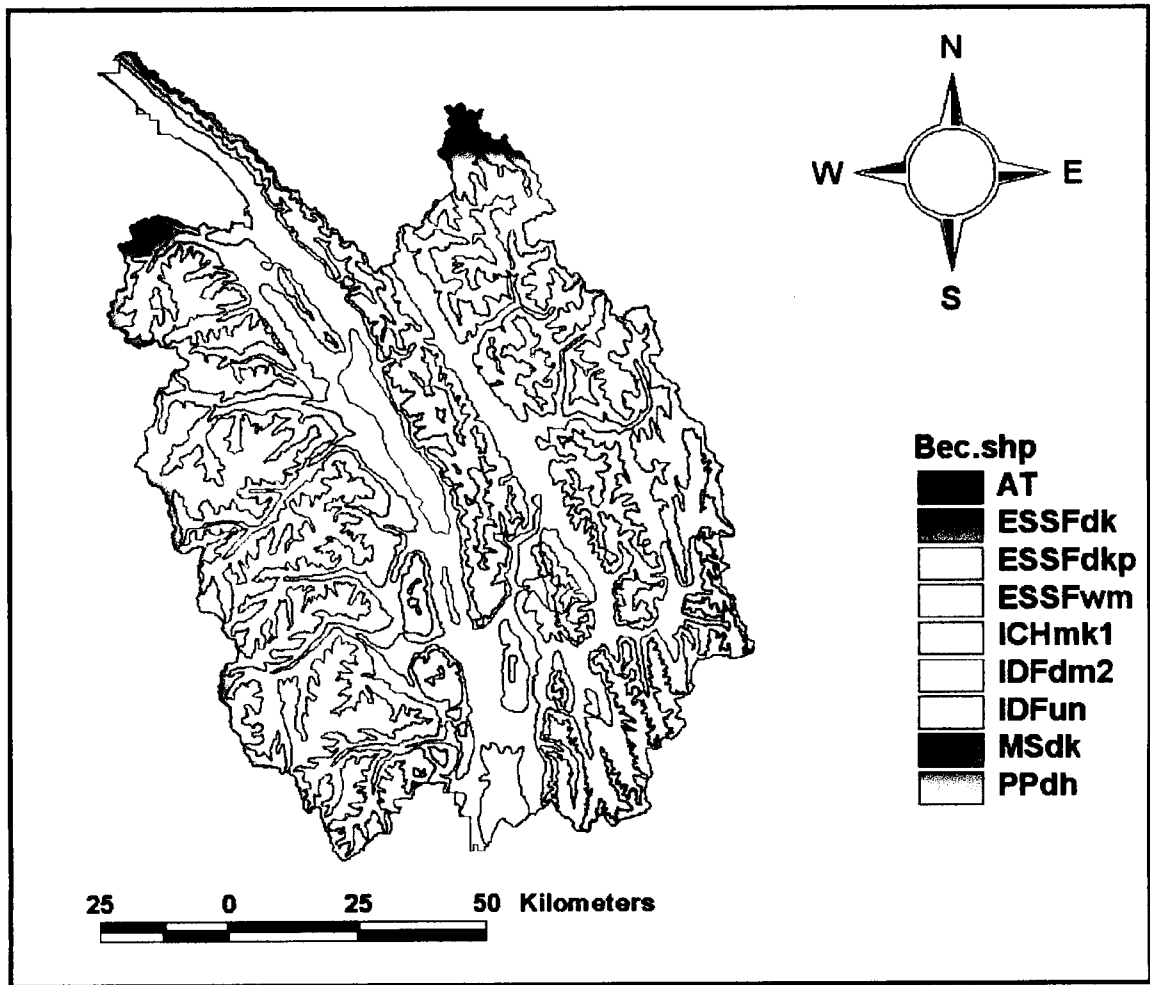


Figure 1. Location of biogeoclimatic variants within the Invermere Forest District. NOTES: AT = Alpine Tundra Zone; ESSFdk = Engelmann Spruce/Subalpine Fir Dry Cool Subzone; ESSFdkp = Engelmann Spruce/ Subalpine Fir Dry Cool Parkland Subzone; ESSFwm = Engelmann Spruce/Subalpine Fir Wet Mild Subzone; ICHmk1 = Kootenay Moist Cool Interior Cedar Hemlock Variant; IDFdm2 = Kootenay Dry Mild Interior Douglas Fir Variant; IDFun = Undifferentiated Interior Douglas Fir Unit; MSdk = Dry Cool Montane Spruce Subzone; PPdh= Kettle Dry Hot Ponderosa Pine Variant. (Source: BC Ministry of Forests, Invermere Forest District).

Summers are hot and dry and soils generally dry out for at least part of the late summer; winters are cool and snow packs usually last only briefly, allowing soils to freeze, at least to shallow depths (Saceniaks and Thompson 2000). The main limiting factors to tree growth in these areas include growing season frost and soil moisture deficits (Braumandl *et al.* 1992). Topographic factors are important to tree growth and often relate to soil moisture. For example, the hottest southern aspects are very difficult to regenerate (Saceniaks and

Thompson 2000). Rainshadow effects are another important climatic factor (Hope et al. 1991). Soils are often calcareous, which can limit both regeneration establishment and growth (Kishchuk et al. 1999, Kishchuk 2000).

Douglas-fir is the dominant species; however, ponderosa pine, lodgepole pine (*Pinus contorta* var. *latifolia* Dougl.), western larch and hybrid white spruce (*Picea glauca* x *engelmannii*) are also common. Deciduous species include trembling aspen (*Populus tremuloides* Michx.) and paper birch (*Betula papyrifera* Marsh.). Understories are generally dominated by pinegrass (*Calamagrostis rubescens* Buckl.) (Braumandl et al. 1992). Table 1 provides a complete list of tree species, scientific names, and species codes referred to in this thesis.

Table 1. Local name, scientific name, and species code for trees of the IDFdm2.

Local Name	Scientific Name	Code
Douglas-fir	<i>Pseudotsuga menziesii</i> var. <i>glauca</i> (Mirb.) Franco	Fd
Interior spruce	<i>Picea glauca</i> (Moench) Voss x <i>Engelmannii</i> Parry ex. Engelm.	Sxw
Lodgepole pine	<i>Pinus contorta</i> var. <i>latifolia</i> Dougl.	Pl
Paper birch	<i>Betula papyrifera</i> Marsh.	Ep
Ponderosa pine	<i>Pinus ponderosa</i> Laws.	Py
Subalpine fir	<i>Abies lasiocarpa</i> (Doug.) Lindl	Bl
Trembling aspen	<i>Populus tremuloides</i> Michx.	At
Western larch	<i>Larix occidentalis</i> Nutt.	Lw

Interior Douglas-fir stands are structurally complex, which is the result of a history of disturbances from partial cutting, insects, and fire (Marshall and Wang 1996), interacting with species-specific characteristics such as shade tolerance and bark thickness. In the absence of fire suppression, dry interior forests such as these are characterized by frequent low-severity stand-maintaining surface fires (Daigle 1996). The historic fire return interval has been estimated to range from 3-30 years (White 1997). In the absence of fire, ponderosa pine and western larch are generally seral species, eventually replaced by more shade tolerant species such as Douglas-fir (Arno et al. 1997). Historically, underburning from frequent fires prevented the establishment of a multilayered understory of more shade

tolerant competitors, allowing the persistence of these species (Arno *et al.* 1995). By 1950, the majority of stands in the area had been harvested, and active fire suppression had begun; these two factors led to an increased dominance of Douglas-fir (Saceniaks and Thompson 2000), and encroachment of forests onto grasslands (Taylor *et al.* 1998).

Currently, ponderosa pine and western larch make up only a small component of sites in the IDFm2 (Saceniaks and Thompson 2000). Ponderosa pine is seral or co-dominant in low elevation, dry stands, while lodgepole pine occupies a similar position in higher elevation or more northerly stands (Vyse *et al.* 1991). Ponderosa pine also occurs on hot dry aspects of moister zones (Hope *et al.* 1991). Climax Douglas-fir stands are often found on zonal sites, but mixed seral stands of Douglas-fir, lodgepole pine and western larch are also common (Saceniaks and Thompson 2000). In moist or subalpine habitats, Douglas-fir is often seral to more shade tolerant species (Arno 1991) such as interior spruce and subalpine fir (Hope *et al.* 1991).

2.2 Species Considerations

Understanding the silvics of component species in mixed-species stands is important for understanding regeneration establishment and early height growth dynamics. Knowing the environmental requirements (particularly the limitations) of each species allows the manager to make silvicultural decisions based on desired future stand conditions. Fiedler and Lloyd (1995) summarized the basic characteristics of conifers in the study area³:

- 1) Shade Tolerance: Lw<PI<Py<Fd<Sxw<BI
- 2) Frost Tolerance: Py<Lw<Fd<BI<Sxw<PI
- 3) Drought Tolerance: BI<Sxw<Lw<PI<Fd<Py
- 4) Fire Resistance: BI<Sxw<PI<Fd<Py<Lw
- 5) Excess Water Tolerance: Py<Fd<Lw<BI<Sxw<PI

³ Results from Fiedler and Lloyd are for Engelmann spruce (*Picea Engelmannii* Parry ex. Engelm.), not hybrid spruce, but the two are considered comparable for these purposes.

Douglas-fir is a moderately shade tolerant species which reproduces profusely following small-scale disturbance to the overstory (Vyse *et al.* 1991). Interior Douglas-fir occupies a broad geographic range as well as a wide elevational range, growing on all aspects and on virtually all geologic parent materials (Arno 1991). Main limitations include sites which are too hot or too dry, or near the high elevation timberline (Ferguson and Carlson 1991). It is a moderately drought tolerant species (Newsome *et al.* 1991) and intermediate in shade tolerance (Ferguson and Carlson 1991). Drought is a major contributor to seedling mortality, although in full sun situations, heat girdling may also be important (Haig 1936, cited in Ferguson and Carlson 1991). Douglas-fir is also one of the most sensitive of the Rocky Mountain conifers to variation in levels of soil organic matter, particularly in dry habitats, where it often occurs on soil humus or buried, decayed wood (Graham *et al.* 1991). Water deficit is likely the most frequent factor contributing to reduced growth in interior Douglas-fir (Lopushinski 1991).

Interior spruce is a shade tolerant hybrid of white spruce (*Picea glauca* (Moench) Voss) and Engelmann spruce (*Picea Engelmannii* Parry ex. Engelm.). White and Engelmann spruce both behave similarly with respect to response to light, growing well under canopy shade. In a study by Lieffers and Stadt (1994), height growth of white spruce under 40% shade was similar to that under 100% sun. As interior spruce ages, however, shade reduces potential growth rates (Coates *et al.* 1994). White spruce commonly colonizes burned sites, but less rapidly than intolerant species such as lodgepole pine and trembling aspen, and understory shrubs (Coates *et al.* 1994). In the IDF, interior spruce occurs on wetter sites and at higher elevations (Coates *et al.* 1994), generally requiring some shade for establishment on dry sites. Sensitivity to fire precludes its presence in areas with frequent fires, and partially explains its presence on wetter and higher elevation sites.

Lodgepole pine is a very generalized and adaptable species (Eis and Craigdallie 1983) that germinates quickly following disturbance and has rapid early height growth. Armit (1966) stated that physiography, climate, soil and ecological factors rarely limit its growth, except in extreme situations. Lodgepole pine is resistant to frost injury, able to grow in very nutrient poor sites and sites with extreme water conditions (Klinka *et al.* 1989), and is relatively insensitive to temperature extremes (Lotan and Critchfield 1990). The best germination of

lodgepole pine occurs in full sunlight on bare mineral soil or on disturbed forest floor that is free of competing vegetation (Lotan and Critchfield 1990). However, lodgepole pine is very intolerant of shade and competition (Armit 1966). Grasses can often be the most severe competitors of lodgepole pine. Only in drought conditions will shading contribute to lodgepole pine seedling survival (Lotan and Critchfield 1990).

Paper birch primarily regenerates from seed, although it does sprout from root collars following harvesting or fire; the resulting sprouts grow faster than seedlings (Massie *et al.* 1994). Paper birch is able to tolerate frosts and can tolerate high temperatures, provided that sufficient moisture is available (Simard 1996). The best seedbed for germination is mineral soil, and although it is a very shade intolerant tree, initial regeneration abundance is higher on shaded sites than full sun sites (Safford *et al.* 1990). Paper birch grows rapidly and is a short lived species (Simard 1996).

Ponderosa pine is a shade intolerant species; its distribution is mainly limited by soil moisture and it has a low tolerance for shorter growing seasons (Oliver and Ryker 1990). Regeneration is primarily affected by soil texture, plant competition (including grasses), and seedbed conditions. It is more tolerant of extreme temperatures than Douglas-fir, spruce and subalpine fir, and more able to exist in moisture stressed environments, primarily due to its ability to rapidly form a large taproot. Ponderosa pine is able to maintain its position as a dominant seral species in areas primarily due to its fire tolerance, which is greater than Douglas-fir (Oliver and Ryker 1990).

Subalpine fir grows on cool and wet sites, within a narrow range of mean temperatures; cool summers, cold winters and deep snowpacks are more important than total precipitation (Alexander *et al.* 1990). Regeneration of subalpine fir is best on mineral soil, but it does regenerate well on a number of substrate types, including organic soils (Eis and Craigdallie 1983). This species is very susceptible to high temperatures, heat girdling and drought. Subalpine fir is a slow growing species and is very shade tolerant. Shade is important to establishment and early survival, and this species does not compete well with spruce, lodgepole pine or Douglas-fir when light intensity exceeds 50% full shade (Alexander *et al.* 1990).

Trembling aspen regenerates primarily through a clonal root system (Peterson and Peterson 1995). High soil temperatures and both excess soil moisture and drought inhibit sucker production (Perala 1990). Trembling aspen is well adapted to fire (Massie *et al.* 1994). Low intensity fires thin aspen, while high intensity fires promote vigorous sprouting of suckers. While light is not an important factor in establishment of aspen clones, subsequent growth does depend on the presence of light, since trembling aspen is very intolerant of shade (Perala 1990). Early height growth is rapid for suckers, which grow much faster than infrequently-occurring seedlings (Massie *et al.* 1994).

Western larch is a deciduous conifer that is extremely intolerant of shade and, once established, is highly resistant to fire (Schmidt and Shearer 1995). Western larch does not occur on very warm or dry sites, nor on cold or wet ones; it is limited by drought at the lower end of its elevational range, and cold temperatures at higher elevations (Fiedler and Lloyd 1995). In drier areas, it is generally absent from hot, dry aspects (Schmidt and Shearer 1995). Western larch has the most demanding requirements for seedbed of any species in the area. It requires either mineral soil or burned seedbeds, and full or nearly full sunlight (Fiedler and Lloyd 1995). It is unable to compete with vigorous competition following disturbance (Thompson 1995), particularly grass and/or sedge cover (Fiedler 1995). The distribution of western larch within BC is associated with frequency of wildfire (Thompson 1995), which provides favourable seedbeds for natural regeneration (Schmidt and Shearer 1995). Western larch generally grows best on deep, well drained soils (Fiedler and Lloyd 1995). Western larch has very rapid early height growth, exceeded only by trembling aspen and paper birch (Thompson 1995).

2.3 Establishment, Survival and Growth

Seedling establishment, survival and growth reflect the interaction between the abundance of seed, a favourable substrate (LePage *et al.* 2000), and an appropriate microclimate. Microclimate, which is largely derived from macroclimate (the amount of solar radiation, precipitation, wind speed, temperature and humidity) interacting with stand factors and management activities, affects the levels of light, temperature and moisture that a seedling

receives (Spittlehouse and Stathers 1990). Seedling microclimate includes irradiance, precipitation, air humidity, wind, soil moisture and soil temperature (Stathers *et al.* 1990).

Once a seedling is established, growth patterns are less reliant on microclimatic factors. However, as with establishment patterns, height growth patterns are species-specific. The amount of height increment achieved by a seedling or tree is commonly thought to rely on a combination of the tree's growth potential and growth-limiting factors, which are primarily considered to be competition for access to resources. The rate of tree height increment is generally slow in the seedling stage, increases during the small tree or sapling stage, and then slows as the tree matures (Zedaker *et al.* 1987).

2.3.1 *The Importance of Stand Structure*

Describing stands based on species composition does not always provide a clear picture of the nature of a stand. Stands can develop in a variety of ways. The type, frequency and spatial patterning of disturbances, combined with species-specific responses to disturbance and succession, can result in very different final structures. Species, size distribution and ages can vary both vertically and horizontally. On dry sites in the IDF, Douglas-fir stands often have a complex, multi-layered structure with a mosaic of size and age classes; on moister sites, stands are generally even-aged with a greater mix of species (Vyse *et al.* 1991). On the driest and warmest sites, stands are relatively open, while on moister or cooler sites, canopy closure is increased (Steen 1987).

Post harvest stand structure can have very important ramifications for seedling establishment and growth across the range of silvicultural disturbances, from single tree selection (partial cutting) to full canopy removal. Puettman and Smidt (1997) suggested that knowing the degree of canopy stratification is critical to understanding understory and regeneration dynamics, especially where species vary in shade tolerance. The abundance, composition and patterning of stand elements can ameliorate microenvironmental effects such as thermal properties, available moisture, light availability, and nutrient status.

Overstory and understory cover can provide protection to seedlings in drier sites, or competition in wetter sites or for more shade intolerant species (Geier-Hayes 1991).

Overstories can reduce the amount of light that reaches the ground, providing protective cover for some species, and competition for others. The benefits of shade vary depending upon site type and species. Shade tolerant species can survive with suppressed growth under heavily shaded conditions, while intolerant species cannot survive long periods of suppression (Kobe and Coates 1997). Conversely, for species adapted to lower light levels under a canopy, very high light levels may in fact inhibit photosynthesis (Fowells and Means 1990).

Drier sites have been found to produce better Douglas-fir regeneration under partial shade rather than in clearcuts. However, on wetter sites, better regeneration occurred under seed tree systems (Steele and Geier-Hayes 1989). Aspect affects moisture status, and therefore the benefits of shade likely vary based on aspect as well (Ferguson and Carlson 1991). In a study in Idaho, Haig (1936, cited in Ferguson and Carlson 1991) found that heat girdling was the most important cause of Douglas-fir mortality in full sun, while it was only intermediate in partial shade, and not important in full shade.

Cover can be an important aspect of microclimates. In drier sites, cover can ameliorate negative site attributes such as temperature extremes and moisture conditions (Geier-Hayes 1991). For Douglas-fir, drought was an important factor in mortality in full shade and in full sun, but not in partial shade (Haig 1936, cited in Ferguson and Carlson 1991). On moister sites, where adequate moisture and more moderate temperatures may already exist, understory cover can have negative effects, by competing with seedlings for light.

Type of cover also matters. Geier-Hayes (1991) found that, in drier habitats, graminoids, forbs and late seral shrubs and trees did not provide good cover for Douglas-fir regeneration, while early seral species such as *Purshia tridentata* (Pursh.), trembling aspen and lodgepole pine were associated with abundant regeneration. Understory and midstory stand components, such as advance regeneration and saplings, were often found in

association with subsequent regeneration, and can provide shade for subsequent natural regeneration (McCaughey and Ferguson 1988).

The horizontal patterning of stand structural elements is also important. Uniform patterning results in uniform conditions for seedling growth, while gaps create a variety of microclimate conditions within a stand. In the US Pacific Northwest, Gray *et al.* (1997) found that as the size of openings increased, light and soil temperature increased; light and temperature also tended to be highest in northern portions of openings. Soil moisture was found to be higher in gaps than in closed canopy, with the wettest conditions occurring in medium size openings.

The effect of openings on microclimate conditions and seedling establishment and growth varies depending on opening size and type of microclimatic factor. Groot *et al.* (1997) concluded that smaller openings may have consistent soil moisture conditions, while light regimes may vary across the opening. Coates (2002) found that regeneration was similar in small gaps of less than 300 m², but in larger gaps, density of regeneration increased from north to south (sunny to shady) positions, regardless of shade tolerance ranking. Smaller openings may also provide higher nighttime temperatures (Groot *et al.* 1997). This is of particular interest for species that are susceptible to growing season frost, particularly Douglas-fir (Newsome *et al.* 1991). Clearcutting offers no environmental amelioration and can result in reduced soil moisture, increased soil temperatures, increased diurnal temperature fluctuations and increased light levels, relative to partially cut or natural stands.

Vertical structure affects and is affected by stand growth. Vertical stand differentiation accelerates competitive losses due to mortality. Well differentiating stands maintain higher levels of growth, vigour, and resistance to damaging agents than stands that differentiate poorly (O'Hara *et al.* 1995). The method of regeneration is also a factor; planted stands can have less variability and differentiate more slowly than naturally regenerated stands, due to reduced genetic diversity and age variability, more uniform spacing, and reduced microsite variability due to site preparation (O'Hara *et al.* 1995).

2.3.2 The Importance of Site

The combined attributes of a site describe the growing environment and competitive influences affecting tree growth. Interactions between stand structure and biotic and abiotic site factors create an array of growing conditions for seedlings.

Aspect influences how much sunlight a site receives. South and southwest facing (exposed) slopes receive more sunlight and are therefore warmer, while north and northeast (protected) slopes receive less sunlight and are therefore cooler (Kabrick and Larsen 1999). Aspect may also affect soil properties, how soon the snowpack melts from a given site, or how many growing degree days there are on the site. Slope and aspect, combined, have a major influence on the amount of solar radiation a site receives (Stathers *et al.* 1990). Slope can also affect soil precipitation runoff and infiltration, hence influencing soil moisture status and nutrient availability (Zedaker *et al.* 1987).

Elevation affects the number of growing degree days that are available to trees in a stand, frequency of late and early frosts, average temperatures, and is correlated with the amount of moisture a site receives. For a given location, the amount of moisture generally increases with increasing elevation (Stathers *et al.* 1990).

Moisture is an extremely important factor in the establishment and growth of seedlings. In general, moisture stress results in reduced tree growth. Lopushinski (1991) stated that the lack of soil moisture is a major factor in limiting transpiration in Interior Douglas-fir stands. Moisture and soil are intertwined; generally, moisture is absorbed into plants through the soil (Fowells and Means 1990). Therefore, properties of the soil such as moisture holding capacity and drainage are equally important as the amount of precipitation. The form of precipitation is also important, along with how much is intercepted by the canopy before it can enter the soil. Cover affects how much moisture is lost from the soil. Moisture availability may also interact with species genetics; for example, shade tolerance may be greater on drier sites (Williams *et al.* 1999).

Soil properties are important for other reasons. Low soil temperature, along with soil drought, is a major factor limiting water absorption in inland conifers (Lopushinski 1991). In southeastern BC, calcareous soils are a particular concern (Kishchuk *et al.* 1999, Kishchuk 2000). A study of stump uprooting in the Invermere area of BC found that seedlings planted in areas with turned-up calcareous materials exhibited decreased growth (Smith and Wass 1994), and a laboratory experiment on white spruce seedlings showed that carbonates decreased germination and survival (Maynard *et al.* 1997).

Interactions between these complex attributes must also be considered. The interaction between slope and aspect in regeneration prediction has been demonstrated (Ferguson 1997). The influence of exposed and protected sites may increase with increasing elevation. For example, Verbyla and Fisher (1989) found that mean site index of ponderosa pine was lower on north-facing slopes than on south-facing slopes at high elevations, but not significantly different at low elevations. Differences in elevation and latitude affect temperature and precipitation (Alexander *et al.* 1990).

2.3.3 *The Effects of Management*

The greatest effects on seedlings are caused by lasting changes in soil properties (Graham *et al.* 1991). Natural regeneration relies on the amount of seed and the availability of suitable microsites, which are affected by both harvesting activity and site preparation (Geier-Hayes 1991). Planted seedlings also require suitable planting locations. Harvesting affects residual stand structure, altering attributes such as access to light, protection by overstory, and levels of competing vegetation, and can have strong impacts upon soils and substrate affecting many other attributes of the growing space.

Success of seed tree silvicultural systems, where selected trees are left within a harvested area to provide a seed source for natural regeneration, is highly dependant on site preparation (Vyse *et al.* 1991). Site preparation can help alleviate frost and winter desiccation, cold soil temperatures, soil moisture, flooding, vegetative competition, animal damage, compacted soils and low aeration porosity (Eastham 1999). Froese and Marshall

(1996) found that site preparation can influence height increment of trees above breast height in certain circumstances, either by reducing vegetative competition, soil/forest floor layer modification, and/or altering soil productivity.

Growth is affected by the amount of organic material. For example, interior Douglas-fir is one of the conifers most sensitive to varying amounts of soil organic matter (Graham *et al.* 1991). Alteration in soil organic matter through harvesting activities or site preparation can, therefore, impact height growth of seedlings. How long this influence can last is unclear; Graham *et al.* (1991) and Froese and Marshall (1996) found evidence that the influence of site preparation on height growth lasted at least to the sapling stage.

Disturbance can alter the overstory stand composition, competitive relationships, and site productivity. Often, disturbance can result in “release” of understory trees from competitive restrictions, resulting in a change in their growth patterns. For Douglas-fir and lodgepole pine, Kneeshaw *et al.* (2002) found that there was a 2-3 year delay before leader height growth responded to release. Following release, growing space is made available for both advance and subsequent regeneration, but gradually new competitive restrictions are established.

2.4 Modelling Establishment and Growth

2.4.1 *Prognosis^{BC}: Model Architecture and Recent Development*

Predictive modelling often focuses on even-aged stands, which is generally not applicable to many of the stands found in the IDF. Predicting growth in mixed-species stands is complicated by the irregular dynamics of these stands. Growth patterns, shade tolerance, and response to site conditions all vary by species (Froese and Marshall 1996).

Prognosis^{BC} is a distance-independent tree growth model developed to predict the growth and yield of multi-species and multi-aged stands. Tree growth models project individual tree

growth on an annual or periodic basis, and then aggregate these attributes to a stand level (Dale *et al.* 1985). Prognosis^{BC} forecasts future stand conditions based upon expected growth and mortality of individual trees in a stand (diameter growth, height increment, crown development, and mortality of individual trees). The model can simulate harvesting and thinning, and has also been modified to simulate certain forest health events.

Prognosis^{BC} was adapted from the Forest Vegetation Simulator (FVS), originally called the Prognosis model, initiated by Stage (1973) in the US. FVS was selected for use by the BC Ministry of Forests (MOF) in the southeastern portion of British Columbia because of its ability to model multi-age, multi-species stands, similar to those commonly found in the area. Based on ecological similarities between northern Idaho and southeastern BC, the Northern Idaho (NI) variant of FVS was adapted to form the basis for Prognosis^{BC}. However, moving the model north required calibration of model components. The regeneration and small tree height growth components were of particular interest. Data were collected in several areas of southeastern BC for this purpose (e.g., Boisvenue 1999, Lencar and Marshall 2000, Froese *et al.* 2001, Hassani and Marshall 2001, Hassani *et al.* 2002b).

The Prognosis^{BC} model is based on a hierarchical series of steps, moving from one model component to the next. The regeneration component predicts the establishment of new trees for the Prognosis^{BC} model, taking the place of a regeneration inventory (Ferguson 1997). Over time, some of these trees graduate to the small tree status (minimum DBH of 2.0 cm), while others are lost to mortality. Small trees are grown using a small tree height increment model, until they reach a diameter of 7.5 cm, at which time they are graduated to the diameter-driven large tree model (or are lost due to mortality). As such, the ability to accurately predict regeneration establishment and small tree height growth is important to overall model performance.

The original regeneration model was regression-based and predicted the presence and number of regenerating stems by species, based on stand characteristics such as overstory conditions, years since disturbance, site preparation, slope position, slope, aspect and elevation. Robinson and Kurtz (1998) examined the performance of the original

regeneration component of the Prognosis^{BC} model. They found a consistent underprediction of both the number of regenerating species and the number of stems per hectare.

Boisvenue (1999) attempted to recalibrate the regeneration component of the Prognosis^{BC} model using data from the Columbia-Shuswap moist warm Interior Cedar-Hemlock variant of the Interior Cedar-Hemlock moist warm subzone (ICHmw2). She found that both the refitted equations and the equations using new variable selections outperformed the original Prognosis^{BC} (FVS NI) equation forms. However, because the data set was much smaller than the original data set used to create the regeneration equations, some categories had limited numbers of predictor variables.

Recent efforts have focused on employing imputation techniques as an alternative method for predicting regeneration. A major benefit of imputation is that predictions can be made using limited data, which can then be constantly updated as the database population increases, without requiring the time consuming recalibration of a regression-based model. To date, imputation models have been created for a variety of BEC subzone variants (e.g., Hassani and Marshall 2001, Hassani *et al.* 2002a and 2002b, Martin *et al.* 2002, Froese *et al.* 2003).

Initial examination of the five-year height increment of trees with a diameter outside bark at breast height (DBH; 1.3 m above the ground) of less than 7.5 cm showed that the small tree height increment model in the initial Prognosis^{BC} model (adopted from the FVS NI variant) overestimated growth in BC stands (Boisvenue 1999). Several research projects, including this one, were initiated to model small tree height increment in areas of BC (e.g., Boisvenue 1999, Lencar and Marshall 2000, Froese *et al.* 2002).

Boisvenue (1999) also calibrated the small tree height increment models for the ICHmw2. Because of sample size limitations, she grouped small trees by shade tolerance class prior to creating increment models. Models were calibrated using the same base variables as the FVS NI variant, then using the base plus additional variables. The addition of tree age and years since disturbance provided superior predictions over those that used the base variables, and all new equation forms outperformed the original FVS NI equations. Lencar

(2002) calibrated the small tree height increment models for the three variants of the interior Douglas-fir dry cool subzone (IDFdk) in the Cariboo Forest Region. The equation selected contained the same basic stand attributes used in original small tree height increment models; however, other density and structural indices were found to be significant. The data from all of these projects were combined to generate small tree height increment models fitted by biogeoclimatic zone, using the Prognosis^{BC} base variable set (Temesgen 2002).

2.4.2 Modelling Regeneration Abundance

Vanclay (1994) defined two basic model categories for predicting regeneration abundance:

- 1) Regeneration models, which predict the development of trees from seeds or seedlings; and
- 2) Recruitment models, which predict the number of stems reaching or exceeding a specified height.

The SORTIE model is a spatially explicit regeneration model that predicts the number and spatial locations of seedlings produced by an adult (maternal) tree as a function of the tree's size and location (Pacala *et al.* 1996). The model was calibrated for northwestern BC by LePage *et al.* (2000), based on methods outlined by Ribbens *et al.* (1994). The regeneration component of the model predicted the density (stems per m²) of germinants, R , based upon substrate availability and favourability, and parent seed source, using the equation:

$$R = STR \sum_{j=1}^S c_j f_j \sum_{k=1}^T \left(\frac{DBH_k}{30} \right)^2 \frac{1}{n} e^{-Dm_k^3}$$

where STR is the potential number of seedlings (between 1 and 3 years old) produced by a 30 cm DBH parent tree, c_j and f_j are the cover and favourability, respectively, of each

substrate type over the interval [0,1], S is the total number of substrates, T is the total number of potential parent trees, DBH_k is the DBH of each parent tree (cm), n is a normalizer used to scale STR into meaningful units, D is a species-specific dispersion parameter, and m_k is the distance to the k^{th} parent tree.

Recruitment models can be dynamic or static. Dynamic recruitment models predict recruitment as a function of site and stand condition (Vanclay 1994). The FVS model developed in the US is an empirically-based recruitment model, which models recruitment using a two-stage approach (Vanclay 1994). A two-stage approach first predicts the probability that recruitment will occur; the second stage predicts the abundance (stems per hectare) of regeneration. Probability of stocking was predicted using a logistic equation (Ferguson and Carlson 1993):

$$P = \left(1 + e^{-\left(\sum \beta_i X_i \right)} \right)^{-1}$$

where P is the probability of stocking over the interval [0.1], e is the base of the natural logarithm, β_i is the vector of regression coefficients, and X_i is the vector of predictor variables (including measures of site, silviculture interventions, pest history, habitat types, and distance to nearest US National forest).

The number of trees per stocked plot was then calculated using:

$$TPSP = B[-\ln(1 - X)]^{1/C} + 1$$

where

$$B = \text{EXP}(1.79862 + 0.64299 \times \text{COSASPECT} - 0.34931 \times \text{SINASPECT} - 2.18751 \times \text{SL}) \\ - 0.03815 \times \text{ELEV} + 0.27987 \times \text{SQREGT} + 0.15874 \times \text{SQBWAF} + \text{SERIES}$$

and

$$C = \text{EXP}(-0.33367 - 0.00751 \times \text{ELEV} + 0.07164 \times \text{SQREGT} + 0.06127 \times \text{SQBWAF})$$

and where *TPSP* is the number of trees per stocked plot (0.001346 ha), *X* is a pseudo-random number in the interval [0,1], *COSASPECT* is the cosine of aspect (in radians) multiplied by the slope ratio (slope percent/100), *SINASPECT* is the sine of aspect (in radians) multiplied by the slope ratio, *SL* is the slope ratio, *ELEV* is the elevation to the nearest hundred feet (ft/100), *SQREGT* is the sum of square roots for each year without budworm, *SQBWAF* is the sum of square roots of each year with budworm, and *SERIES* is a habitat series-specific parameter. Additional attributes of the stocked plots were then predicted, including the number of species, which species, the type of regeneration (advance, subsequent or excess), and the heights of regeneration. The probability of stocking was then used to scale attributes of stocked plots to a per-acre basis.

Static approaches to recruitment modelling assume that the amount of regeneration observed during data collection represents the long-term average (Vanclay 1994). These models may be appropriate for predicting recruitment where stands do not differ much from source stands. Imputation models are static approaches to recruitment modelling. Where regression-based approaches involve creating an equation that predicts the mean response of a variable of interest, based on specific predictor variables, imputation involves replacing missing observations with plausible and consistent replacement observations (McRoberts 2001) from another part of the population with similar characteristics (Ek et al. 1997).

Tabular imputation models are a form of post-stratification. Data are averaged and presented in sets of tables, based on specific predetermined classes. These tables are then used as "look-up" tables, where mean values from the appropriate reference table provide the predicted values for a given target unit. For regeneration, the tables contain predicted stems per hectare of regeneration by species, based on plot-level characteristics; plot-level characteristics from an area lacking regeneration information are then used to select the appropriate table of predicted regeneration.

The Most Similar Neighbour imputation (MSN) method developed by Moeur and Stage (1995) uses a Euclidean distance weighted by canonical correlations between the response variables and the predictor variables for a particular reference data set (Moeur 2000).

Greater weight is given to attributes in the response variables that are more strongly correlated with the predictor variable attributes. The reference unit with the shortest weighted Euclidean distance is the Most Similar Neighbour and is used to impute attributes onto the target unit. The Most Similar Neighbour method can be extended to the k-Most Similar Neighbour method (k-MSN), whereby the k most similar neighbours are averaged to provide values for the target unit (Crookston *et al.* 2002).

Moeur and Stage (1995) stated that imputation preserves the full range of natural resource variability and retains the original correlation structure among multivariate attributes. A major benefit of MSN imputation is that “impossible predictions” or predictions outside the bounds of biological reality cannot occur, since imputed values are taken from actual samples (Moeur and Stage 1995). Tabular and k-MSN imputations are based on averaging, and therefore mean responses are predicted.

2.4.3 Modelling Small Tree Height Increment

Ritchie and Hann (1986) stated that height increment prediction is often the “weak link” of stand growth simulators. Prediction of total height rather than height increment is more common; often models predict future height from current height, rather than height increment itself (e.g., Cieszewski and Bella 1993), subtracting to obtain height increment. Alternatively, height increment equations can be obtained by taking the first derivative of total height yield models. A number of height prediction model forms were summarized by Huang *et al.* (1992). Zeide (1993) provided a good summary of growth models in general.

Two approaches to modelling height increment were identified by Huang and Titus (1999):

- 1) the growth-potential dependant approach first identifies the potential height growth for trees with no competitive influences, then provides a “competitive adjustment factor” to reduce (adjust) this potential; whereas

- 2) the growth-potential independent approach focuses on height increment as a function of tree and stand characteristics, including competitiveness of the tree within the stand.

Growth-potential dependant models often predict potential growth as a function of site index and age (e.g., Monserud and Ek 1977, Hann and Ritchie 1988). Because site index is generally not a suitable measure of productivity for uneven-aged stands, these methods would need to be greatly altered for small tree height growth modelling in the IDFdm2. For example, the model developed by Huang and Titus (1999) used a site productivity index, determined by the height-diameter relationship between dominant and codominant trees. The model was based on the Box-Lucas function:

$$HI = \frac{\theta_1}{\theta_1 - \theta_2} (e^{-\theta_2 H} - e^{-\theta_1 H})$$

where HI is predicted height increment (m/year), H is total tree height (m), e is the base of the natural logarithm (2.7182818) and θ_1 and θ_2 are parameters to be estimated.

A number of growth-potential independent models have been developed. Wykoff (1990) referred to these as "composite models", whereby tree, stand and site characteristics are incorporated into a single equation.

In the US, the Northern Idaho variant of the FVS model is one such model. Height increment for small trees (those with a DBH less than 12.7 cm (5 inches) for lodgepole pine and less than 25.4 cm (10 inches) for all other species) was predicted according to the model (Wykoff 1986):

$$LNHTG = LOC + HAB + SPP + 0.22157 \times COSASPECT - 0.12432 \times SINASPECT \\ - 0.10987 \times SL + b_1 LNHT + b_2 CCF + b_3 BAL100$$

where $LNHTG$ is the predicted log of five-year height increment (ft), LOC is a location-dependant constant, HAB is a habitat type-dependant constant, SPP is a species specific

constant, *COSASPECT* is the cosine of stand aspect (in radians) x slope ratio (slope percent/100), *SINASPECT* is the sine of stand aspect (in radians) x slope ratio), *SL* is the slope ratio, *LNHT* is the natural logarithm of tree height (ln(ft)), *CCF* is the crown competition factor, *BAL100* is the basal area in larger trees/100 (ft²acre⁻¹/100), and *b*₁ to *b*₃ are regression parameters which vary by tree species.

For the Central Idaho variant of FVS, the height increment model for trees less than 12.7 cm (5 inches) DBH was (Dixon 2000, pers. comm., cited in Froese and Robinson 2000):

$$HTG = HAB + SPP + b_1(RELHT \times PTBA) + b_2PTBAL + b_3RELHT \\ + b_4CR + b_5CR^2 + b_6BA + b_7BAL100$$

where

$$RELHT = \frac{HT}{H40} \quad [0 \leq RELHT \leq 1.5]$$

and where *HTG* is the predicted five-year height increment (ft), *RELHT* is the height of the subject tree (HT) divided by the average height of the 40 largest trees per acre (H40), *PTBA* is the point basal area (ft²/acre), *PTBAL* is the point basal area in larger trees (ft²/acre), *CR* is the crown ratio, *CR*² is the squared crown ratio, *BA* is the basal area (ft²/acre), *b*₁ through *b*₇ are species-specific parameter estimates, and all other variables are as previously defined.

The BEC-level small tree height increment model used in Prognosis^{BC} (Temesgen 2002) is based on the FVS NI variant model. The equation form was:

$$HTG = EXP[b_0 + b_1COSASPECT + b_2SINASPECT + b_3SL + b_4HT + \\ b_5LNHT + b_6CCF + b_7BAL100]$$

where *HTG* is predicted five-year height increment (m), *COSASPECT* is the cosine of stand aspect (in radians) x slope ratio (slope percent/100), *SINASPECT* is the sine of stand aspect

(in radians) x slope (percent), SL is stand slope ratio (percent slope/100), HT is total tree height (m), $LNHT$ is the natural log of tree height ($\ln(m)$), CCF is crown competition factor, $BAL100$ is the basal area in larger trees/100 (dm^2/ha), EXP is the base of the natural logarithm (2.7182818) and b_0 to b_7 are regression parameters which vary by tree species.

This model form is similar to that recommended by Zeide (1993) as one of the most accurate basic model forms:

$$\ln(y') = k + p \ln(y) + qy$$

where y' is the growth rate of the variable of interest (some measure of tree size), y is the tree size variable, and k , p and q are parameters to be estimated.

2.5 Using Spatial Information to Characterize Understory Stand Dynamics

2.5.1 Spatial Relationships Within Forest Stands

In the past, management-oriented models often included plot-level measures of competition such as expressions of stand density, which assumed that competitive forces were applied equally throughout the stand (Moeur 1993). Aspatial methods of quantifying stand structure provide mean stand characteristics without reference to relative tree positions, spatial variation in tree size or species composition (Kint *et al.* 2003).

In uneven-aged stands, each tree has a unique position within the canopy and a unique relationship with neighbouring trees of varying sizes and species (Nienaber 1999). The spatial pattern of trees reflects the interaction between environment and stand history, including disturbance, initial establishment patterns, microenvironment differences, climate, light, competing vegetation and the chance success of different species over time depending on their individual life history characteristics (Moeur 1993). Therefore, attributes

such as size and spatial location of neighbouring trees have the potential to help explain the competitive effects experienced by a given subject tree and the conditions necessary for establishment.

Spatial data can be used to quantify stand structure either through the calculation of spatial indices or through the use of spatial statistical techniques (Kint *et al.* 2003). No single method of spatial analysis can reveal all of the important characteristics of spatial data, nor can different analyses be considered independent of each other (Dale *et al.* 2002). Two popular methods of incorporating spatial information from forest stands are through the use of competition indices and point pattern analysis. Competition indices are generally used to improve model performance, while point pattern analysis is used to examine the relationship between points in a stand, relative to some known point pattern process. Point pattern processes, once identified, can be used to predict point patterns.

Scale is an important factor in examining spatial relationships. Whether or not spatial information can improve estimates, and at what scale effects occur, depends on the response variable of interest. The response of established trees to their local environment occurs at a very different scale than that of seedling germination and establishment (Moeur 1991). Given that both microsite influences and gap dynamics are important to germination and seedling establishment, one might expect to see the influence of both small and large scale spatial effects, whereas with established trees, small scale effects may be less important.

2.5.2 Competition Indices

Competition theory is based on the concept that there is a theoretical maximum growth for a given plant, which is limited by competition with other plants for access to limited resource pools. Competition can reduce plant growth, and can result in plant mortality. Resource use by existing plants can also create environments which are unfavourable for germination and establishment of new plants.

Competition can be defined in a number of ways. Symmetric, or two-sided competition, has one of two interpretations (Thomas and Weiner 1989):

- 1) absolute symmetry, where resources are divided equally among competing individuals; or
- 2) relative symmetry, where neighbour influence is proportional to neighbour size.

Asymmetric or one-sided competition assumes that the effects of small plants on larger ones is discounted; completely one-sided competition assumes that smaller plants have no competitive effect on larger plants.

Resource depletion is a symmetrical relationship whereby individuals share limited resources in proportion to their sizes; resource pre-emption is an asymmetrical relationship in which larger individuals are able to obtain a disproportionate share of resources, at the expense of smaller individuals (Newton 1996). Resource depletion represents competition for below-ground resources, while resource pre-emption represents competition for above ground resources, mainly light (Nienaber 1999).

Measures of competition are often used to describe the influence of neighbouring trees, since trees utilize the same resources and therefore compete for access. Resources include light, moisture and nutrients, and, therefore, attributes such as shading and proximity to neighbouring trees are often used in calculating these measures of competition.

Competition indices are meant to reflect competition levels, either at a stand or individual tree level. However, both effect and response must occur for there to be biologically meaningful competition (Tremmel and Bazzaz 1993). The "true" competition index of a given tree is never observable (Monserud and Ek 1977). In addition, indices of competition are species and site specific (Burton 1993), so that the same value for an index of competition may have different meaning under different site conditions.

Indices are generally based upon hypotheses on the nature of competitive interactions, and each competition index reflects a different hypothesis about the nature of these competitive

interactions (Nienaber 1999). Stand or plot-level, aspatial indices assume that the competitive influence of the stand is diffuse, and therefore spatial location is irrelevant.

Vanclay (1994) identified four main categories of spatial competition indices:

- 1) zone of influence;
- 2) area potentially available;
- 3) size-distance (ratio); and
- 4) light interception and sky-view.

The zone of influence indices assume that each tree has a zone of competitive influence, which is somehow related to the size of the tree; zone of influence has been estimated using tree diameter and simple multipliers (e.g., Opie 1968) or related to species-specific crown widths (Bella 1971). Opie's Index assumes that the sum of the areas of overlap between a subject tree and its competitors represents the total competition experienced by that tree. Bella's Index is weighted by the relative sizes of subject and competitor trees, which can be multiplied by an exponent to explore hypothetical asymmetrical relationships.

Area potentially available represents the growing space available to a subject tree through a polygon around the tree, calculated by the spatial location of neighbouring trees (Moore *et al.* 1973). The assumption is that the amount of crown and root competition is based on the limits of the polygon. This approach has been identified as problematic in uneven-aged stands by Lorimer (1983), where small trees surrounding a large tree could result in an unrealistic definition of available growing space.

Size and size-distance indices assume that the sum of sizes of the competitors, often relative to the size of the subject tree, represents the total competition experienced by the subject tree, either summed over a specific search radius (semi-spatial) or weighted by the distance between trees (spatial). Replacing measures of size by their square has been suggested as a means of representing asymmetrical competitive effects (Nienaber 1999). Semi-spatial indices include total basal area of neighbours and the ratio of diameters

suggested by Lorimer (1983). A simple spatial index of competition, the ratio of diameters weighted by the subject-competitor distance, was introduced by Hegyi (1974).

Light interception and sky-view methods incorporate vertical structure into the process, including measures of tree crown. Sky view approaches examine the proportion of the sky "viewed" by the subject tree, potentially weighted by the part of the sky seen (e.g., horizon view or overhead view) (Vanclay 1994). Light interception attempts to calculate the amount of sunlight intercepted by the subject tree.

Aspatial plot-level competition indices used in the Prognosis^{BC} model include basal area per hectare (all trees), basal area per hectare in larger trees and crown competition factor. Crown competition factor is the aspatial partner to zone of influence indices (Vanclay 1994), while basal area is the aspatial relative of size and size-ratio indices. Both indices use all competitors in their calculations, which implies the assumption of a two-sided relationship. Basal area in larger trees is also related to size and size ratio indices, but competition is assumed to be one-sided by including only those competitors that are larger than the subject tree.

A number of studies have examined the performance of competition indices (e.g., Lorimer 1983, Weiner 1984, Daniels *et al.* 1986, Brand and Magnussen 1988, Newton 1996, Nienaber 1999, Kint *et al.* 2003). Studies such as Nienaber (1999) and Biging and Dobbertin (1995) examined the reduction in error of prediction of growth rate, relative to a base model with no competition index, to reflect the relative importance of various competition indices. Studies have also attempted to identify the primary resource limitation based upon which types of indices produced the best results (e.g., Nienaber 1999, Newton 1996). However, plants generally compete for aboveground and belowground resources simultaneously, confounding studies of competition (Thomas and Weiner 1989).

Some studies have found competition indices to be of little use in predictive modelling, particularly in even-aged, relatively homogeneous stands (e.g., Martin and Ek 1984). Other studies have found that the simpler indices have shown superior performance (e.g., Navratil and MacIsaac 1993, Nienaber 1999, Mailly *et al.* 2001). Results varied depending on the

response variable of interest, affecting the relative importance of competition indices. For example, Navratil and MacIsaac (1993) found that correlations between competition indices and measures of diameter were higher than between competition indices and measures of height.

Information on the effects of competition on the growth dynamics of Interior Douglas-fir stands is meager. Nienaber (1999) examined competition indices for stands in the IDF near Williams Lake, BC, and their effect on diameter increment. These stands were not representative of the area, since selection was towards those exhibiting uniformity (few openings), although an effort to represent the range of stand structures was made. From his results, Nienaber found evidence to support resource depletion as the primary motivating factor, since metrics based on squared diameters and/or those with exponents >1 performed poorly relative to the other indices. He did not feel that the evidence supported diffuse competitive effects, since plot-level indices did not perform as well as spatial indices. However, the effective distance of competitive effect was unclear, since results improved with increasing search radius (5, 7 and 9 m) for most distance dependant indices.

2.5.3 Point Pattern Analysis

The use of spatial point pattern analysis has become popular for examining stand structural dynamics, and has been used to examine within class and between class relationships (e.g., Kenkel 1988, Moeur 1991, Penttinen *et al.* 1992, Hanus *et al.* 1998, Nigh 1999). Generally, point pattern analysis has been used to test observed spatial patterns against the null hypothesis that there is an underlying Poisson (random) process (Ripley 1977). Deviations from a random pattern can give indications of stand dynamics and processes. Two opposing forces can affect the location of trees: competition between neighbours will result in thinning of close neighbours, resulting in a more regular or uniform pattern, while locally favourable (or unfavourable) conditions will result in clustering or attraction of trees. The problem arises when these two processes occur in conjunction, which can effectively "balance out" the forces and exhibit a random pattern (Upton and Fingleton 1985).

Spatial indices incorporate spatial positioning of trees, but provide a single value for the attribute and area of interest (Kint *et al.* 2003). Point pattern analysis examines the relative randomness of the location of points as a function of scale (generally, distance) (Moeur 1993). Ripley's $K(t)$ analysis examines the distribution of point-to point distances within a plane for all pairs of points (Moeur 1993). If the calculated value is greater than the expected value under a Poisson distribution, the spatial pattern is clustered (aggregated). If the opposite is true, then the spatial pattern is uniform or regular (inhibition, repulsion).

Marked point pattern analysis refines point pattern analysis by incorporating attributes of each point. Spatial patterns are examined based on specific characteristics ("marks"), conditional on the location (distances) of the points (Penttinen *et al.* 1992). An example would be looking at whether there is a spatial correlation for height of trees over a given area, or whether diameter sizes are clumped spatially or uniformly distributed within a stand.

While comparison against a hypothetical Poisson process allows determination of departures from randomness, another use of point pattern analysis as a function of scale is that it allows comparison against hypothetical point pattern generation processes (e.g., Moeur 1991, Hanus *et al.* 1998, Nigh 1999). Comparison of observed (measured) points against a specific point pattern process can determine whether such a process could be used to model spatial distribution of points. In theory, if spatial competition indices can improve prediction of variables of interest, and point pattern processes can be used to predict spatial pattern, then the spatial effects can be predicted without requiring measurements in the field.

Point pattern analysis has been used to examine a number of forest processes at a variety of scales. Kenkel (1988) studied patterns of self-thinning in Jack pine (*Pinus banksiana* Lamb.) stands, examining relationships between patterns of live and dead trees. Moeur (1993) studied gap-phase regeneration dynamics in old growth stands of western hemlock (*Tsuga heterophylla* Raf. Sarg) and western redcedar (*Thuja plicata* Donn ex. D. Don), examining the relationship between overstory trees and regeneration. Nigh (1999) examined the spatial patterning of lodgepole pine seedlings, based on initial pattern and

ingrowth. Penttinen *et al.* (1992) incorporated marked point processes, examining the spatial distribution of heights and diameters by species.

2.5.4 Edge Effects

Fixed area plots are problematic for calculating spatially dependant metrics because of the arbitrary boundary cutoff. Where the presumed zone of competitive effect extends outside of the plot boundary, the assumption is made that one or more competitors may lie outside of the plot (Martin and Ek 1977). Because competitors outside of the plot boundary are not observed, plot edge bias can result. The closer the subject tree is to the plot edge, the greater the potential bias (Martin 1982).

Ripley (1988) outlined two main methods for dealing with edge effects. This first is, simply, to remove edges. This can be done by creating a buffer zone or guard area in which size and location of potential competitors are measured (Upton and Fingleton 1985). The extra time and effort may not be feasible, in which case, for smaller plots, the loss of information can be considerable. Alternatively, an artificial buffer can be created by replicating the plot information. Reflecting (mirroring) the plot works for rectangular, hexagonal and triangular plots (Martin 1982). Toroidal corrections can be made to remove edges from circular plots (Upton and Fingleton 1985), whereby a circular torus is created by rotating a circle around a tangent, creating a donut-like three-dimensional object (Kühlmann-Berenzon 2002).

The second way of dealing with edge effect is by somehow calculating the magnitude of the edge effect, and rescaling the statistics accordingly (Ripley 1988). Isotropic correction gives weights to pairs of events that have been observed within the border, and estimates how many pairs of events were not recorded (Kühlmann-Berenzon 2002). Given a circle with a centre at subject *i* and whose radius is the distance from subject *i* to competitor *j*, the weight is the proportion of the length of the circumference that is inside the plot. The linear expansion method developed by Martin and Ek (1977) is similar. This method assumes that the distribution of angles to competitors is uniform, and that all competitors lie within a theoretical concentric zone of maximum competitive effect.

3. SAMPLING DESIGN

3.1 Sampling Frame and Site Selection

The sampling frame consisted of all areas within the IDFdm2 biogeoclimatic subzone of the Rocky Mountain Trench, Invermere Forest District, which had been disturbed (harvested) within the last 5-24 years, plus any undisturbed sites. Because of the long history of partial cutting in the area, undisturbed sites were rare. For the purposes of sampling, undisturbed sites were defined as those without evidence of harvesting within at least the last 25 years. Sampling effort was apportioned as follows: 80% partially cut (shelterwood, seed tree, and selection silviculture systems), 10% undisturbed (selected purposively based on similarities in site characteristics to those in partially cut stands) and 10% clearcut stands.

A sampling matrix was set up to help select disturbed stands. Openings were categorized by the number of years since disturbance, silvicultural system, site series, and elevation. There were 256 matrix categories (combinations of year since disturbance, silvicultural system, sites series and elevation) based upon these classification criteria (see Table 2). Data provided by the Ministry of Forests from their Integrated Silviculture Information System (ISIS) database were used to identify 333 candidate openings that were harvested within the last 5-25 years. Openings were removed from the candidate list if they were:

- 1) missing BEC site series, disturbance type, silvicultural system, or elevation data;
- 2) less than four ha in size; or
- 3) marked as "burned" or "wildfire".

The remaining 232 openings were classified as potential sites for data collection, and were categorized into the sampling matrix (Table 2). These openings covered a range of 75 matrix categories. In order to sample the full range of conditions within the cost and time limitations, a maximum of one opening per available matrix category was selected for sampling.

Table 2. Number of available openings in the IDFdm2, Invermere Forest District, by elevation, site series, and harvesting system.

SILVICULTURE SYSTEM																	
Years Since Dist. Site Series		Clearcut/Patch				Selection				Shelterwood				Seed Tree			
		0 to 900	901-1000	1001-1100	1101+	0 to 900	901-1000	1001-1100	1101+	0 to 900	901-1000	1001-1100	1101+	0 to 900	901-1000	1001-1100	1101+
5 to 10 (1991-1996)																	
02																	0
03			4									1					5
01		2	2	1		2	2	8	2	1	2	3		2		1	28
04				1			2				5				1		9
11 to 15 (1986-1990)																	
02																	0
03				1						1							2
01			1	5	2		8	4	6		2			2		5	42
04				1			2	2	1		1		1		1	1	8
16 to 20 (1981-1985)																	
02									1								1
03									1								1
01				6			10	12	11						3	4	54
04		1		1			2	3	3				1		2	3	15
21 to 25 (1976-1980)																	
02								1	2								3
03									3								3
01			2	2	1		3	7	17							1	38
04			1	6			1	5	5						1		23
Total		3	10	23	4	24	37	56	19	2	10	4	2	4	8	14	232

Because the IDFdm2 runs north to south along the Rocky Mountain trench, a geographic (north to south) trend was expected (e.g., moister, cooler to the north, and drier warmer to the south). In addition, the western side of the valley was generally on the lee (rainshadow) slopes of the mountain ranges, while the eastern side was generally on the windward slopes. Therefore, in addition to ensuring that the appropriate polygons were selected based upon the sampling matrix criteria, selection was directed towards obtaining a range of geographic locations.

Each selected opening was assessed in the field as to suitability. An opening was considered unsuitable if it appeared to be in disagreement with ISIS information such as years since harvest or method of harvesting, or if activities subsequent to harvesting (such as fire) made it unsuitable for sampling. Unsuitable openings were discarded and new openings were selected, and the sampling matrix was adjusted accordingly. In some cases, no suitable openings could be found within a given category.

Once an opening was selected, the number of polygons within the opening was determined by examining forest cover maps. Where a single polygon existed, that polygon was sampled. Where there was more than one polygon, the largest polygon was selected for sampling. Where no single polygon was of an acceptable size (one that would allow a minimum of two plots to be sampled at 100 m spacing, without being within 50 m of adjacent opening boundaries), an alternate opening was selected. Sampled openings are listed in Table 3.

Plots were established using systematic sampling with a random start. The number of plots was based upon the degree of variability present and the size of the polygon, with a minimum of two plots per polygon. More variable (heterogeneous) polygons were sampled more intensively. Plots were established at a minimum distance of 50 m from roads or other openings, in order to avoid the effects of edge, and 100 m apart within the polygon.

3.2 Data Collection

3.2.1 Data for Prognosis^{BC} Modelling

The sampling procedure for collecting data for the small tree and regeneration components of Prognosis^{BC} was initially designed by Boisvenue (1999), based upon sampling methods used for the FVS model (Ferguson and Crookston 1991). Field sampling completed in subsequent years in southeastern BC (Lencar and Marshall 2000, Hassani and Marshall 2001) incorporated refinements to the design. The sampling strategy for the 2001 field season incorporated further refinements based on results from this research, as well as an additional, exploratory component, which involved subsampling for spatial attributes and substrate information.

The location of each plot was recorded using a portable Geographic Position System (GPS) unit, and the following attributes were documented:

- 1) Mapsheet, opening number, polygon number, and plot number;
- 2) Universal Transverse Mercator (UTM) Grid Northing and Easting;
- 3) Aspect (degrees);
- 4) Slope angle (percent);
- 5) Slope position;
- 6) Elevation;
- 7) BEC site series and associated ecological factors (i.e., partial vegetation list);
- 8) Site preparation method (where identifiable);
- 9) Disturbance information (where available);
- 10) Disturbance year; and
- 11) Other information where deemed important (e.g., grazing intensity if cattle present).

Trees in each plot were categorized as large trees, small trees, or regeneration. Large trees were defined as having a DBH greater than 7.5 cm; small trees were defined as having a

DBH between 2.0 and 7.5 cm. Regeneration was defined using both DBH and height measures, where shade tolerant species were required to be at least 15 cm tall and less than 7.5 cm DBH, and shade intolerant species were required to be at least 50 cm tall and less than 7.5 cm DBH.

A series of nested plots was used for sampling (Figure 2). Large trees were measured within an 11.28 m radius plot (0.04 ha). Species and DBH were recorded for all large trees. This would allow identification of overstory species composition and calculation of plot-level measures of competition. Where numbers allowed, two trees from each species were randomly selected and measured for height. Tree health information (pests, pathogens, crooks, and so on) was recorded as necessary.

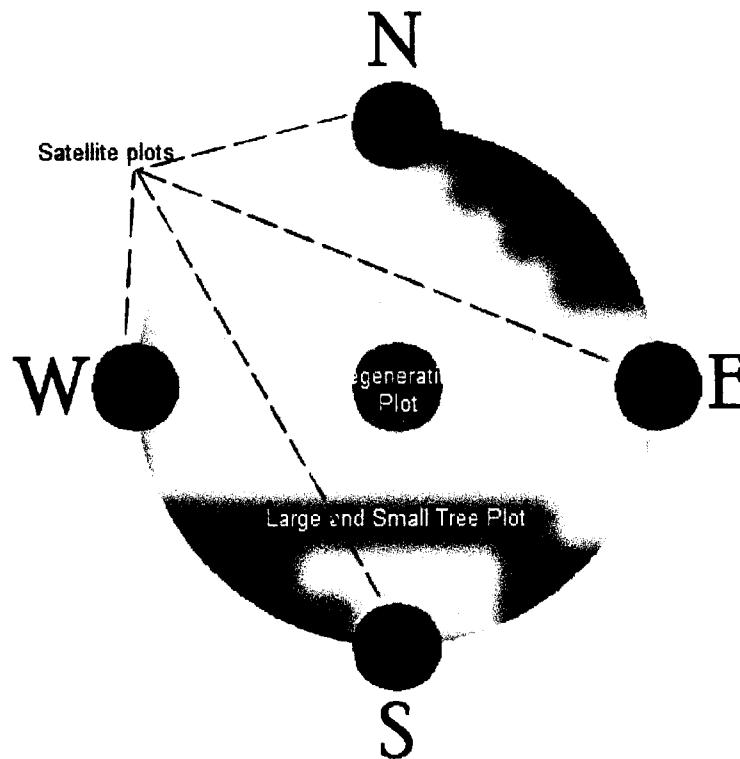


Figure 2. Layout of plots for field sampling.

Small trees were measured within the same 11.28 m radius plot, in order to maintain consistency with other Prognosis^{BC} research completed in the IDF (e.g., Lencar and Marshall 2000). Species and DBH were recorded for each tree. Where numbers allowed, five trees

of each species were subsampled for total height and five-year height increment. The five-year height increment was measured starting five years prior to the end of the previous growing season, so that the same period of growth (five full seasons) was measured for each tree. Where possible, whorls were used to determine five-year height growth. Where whorls could not be confidently counted (e.g., for non-determinant species and for some determinant trees), the trees were felled for measurement, and sectioned until the five-year increment was reached. Additional tree health information was again recorded as necessary.

Regeneration was sampled by placing a 2.07 m radius plot (0.00135 ha) at the center of the 11.28 m radius plot. All established and viable regeneration was counted and tallied into height classes as follows:

- 1) Class 1: 15.0-49.9 cm (shade tolerant species only);
- 2) Class 2: 50.0-99.9 cm;
- 3) Class 3: 100.0-129.9 cm; or
- 4) Class 4: greater than 129.9 cm and less than 7.5 cm DBH.

Regeneration was also marked as advance or subsequent (see Appendix A for the methods used to distinguish between these two types of regeneration). A subsample of exact height and total age was taken for both "best trees" and randomly selected regeneration within the plot. "Best trees" were defined by Ferguson and Carlson (1993) as:

- 1) the two tallest regeneration stems, regardless of species;
- 2) the one tallest regeneration stem of each additional species present; and
- 3) the tallest of the remaining regeneration stems until at least four were sampled.

Where numbers allowed, two regeneration stems of each species were randomly selected and sampled as "random trees". Again, where whorls could not be confidently counted, regeneration was destructively sampled. Health was noted as required.

Four additional 2.07 m radius regeneration plots (“satellite” plots) were established at 11.28 m from the plot center (along the large plot boundary), in the cardinal directions. Within each satellite plot, regeneration was tallied by species, height class, and regeneration type (advance or subsequent). Where the center (regeneration) plot was not stocked, one of the four satellite plots was selected randomly until a stocked satellite plot was located. This plot was then used for height and age sampling.

3.2.2 Data for Exploratory Analyses

One out of four plots sampled (generally, one plot for every one or two polygons) was selected for additional measurements of substrate and spatial attributes. The design for this component of the sampling strategy was loosely based upon LePage *et al.* (2000), and modified for use with circular plots. The goal of this addition was to explore whether spatial attributes or information on substrate type could aid in refining the understanding of understory dynamics in the IDFdm2.

Substrate Measures

In order to examine the relationship between substrate type and regeneration, regeneration was tallied by height class, species, and the substrate it occurred on, and classified as advance or subsequent regeneration. Germinants, for this study defined as regeneration less than 15 cm tall for shade tolerant species and less than 50 cm tall for shade intolerant species, were also tallied. Substrate measures were taken before any other measurements, to ensure that the substrates experienced minimal disturbance prior to sampling. The center regeneration plot was used regardless of whether it was “stocked” or not. This plot was divided into quadrants (using cardinal directions), and the percent cover by different substrates was estimated for each quadrat. Substrates were defined as follows:

- 1) Mineral soil – bare soil or soil with discontinuous litter cover <1 needle thick;
- 2) Litter – continuous litter cover >1 needle thick (needles, cones, etc.);
- 3) Kinnikinnick (*Arctostaphylos uva-ursi* (L.) Spreng.) – relatively continuous cover with/without needle litter;

- 4) Grass Discontinuous – discontinuous grass cover (“bunchy”/ scattered distribution);
- 5) Grass Continuous – continuous grass cover;
- 6) Moss – continuous moss cover;
- 7) Lichen crust – continuous lichen crust;
- 8) Slash – woody debris <17.5 cm;
- 9) CWD – woody debris >17.5 cm;
- 10) Shrub – occupied by shrubs (plus species and average height);
- 11) Rock – exposed rock;
- 12) Tree – existing stem (live or dead);
- 13) Organic – organic materials; and
- 14) FWD – decayed slash/coarse woody debris, which still retains some structure.

Spatial Measures

For spatial attributes, the goal was to obtain information necessary to examine the relationship between understory components and overstory conditions. Spatial mapping was sampled within the 11.28 m radius plot used for small and large tree sampling (Prognosis^{BC} calibration). Distance and bearing were taken for all large trees, to the front of each stem, at DBH using a Criterion laser. Distance to stem center was later calculated by adding the radius of the tree to the distance to the front of the stem.

A major constraint was the time limit for sampling, therefore regeneration stems were not individually mapped. Instead, the centre of regeneration “clumps” (localized aggregations of regeneration) was mapped. Individual regeneration stems not located within clumps were not mapped. Regeneration clumps were identified in the field using the following definition:

- 1) a minimum of three regeneration stems was required to be considered a clump (from regeneration Height Classes 1 to 4);
- 2) membership in a clump occurred if: for Height Classes 1-3, the stem was within 0.5 m of a stem belonging to the clump; for Height Class 4, the stem was within 1.0 m of a stem belonging to the clump; and

- 3) the shape of the clump was assumed to be ellipsoidal for the purposes of measurement and plotting.

The definition of small trees, as measured during the Prognosis^{BC} calibration sampling component, overlapped with that of regeneration. For the purposes of measuring the regeneration plot (2.07 m), a regeneration tree was defined as less than 7.5 cm DBH. For the purposes of measuring the small tree plot (11.28 m), a small tree was defined as a tree with DBH between 2.0 and 7.5 cm. When spatially mapping, small trees were technically regeneration as well. Since time was a limiting factor, small trees located within regeneration clumps were considered part of that clump. All other small trees were mapped individually in the same manner as large trees.

Distance and bearing to the center point of the clump were measured. The long and short axes were measured to obtain the length and width of the clump, and the bearing of the long axis was taken to establish the orientation of the clump. To be included in sampling, the center of the clump had to be within the 11.28 m radius; however, it was measured to its full extent, regardless of whether or not it extended beyond this boundary. Within each clump, regeneration was tallied by species and height class, and classified as subsequent or advance. Where a large clump visually appeared to be composed of two distinct clumps (e.g., a patch of class four regeneration plus a patch of class one regeneration), it was sampled as two separate clumps and noted as such.

Additional information was recorded for slash piles, large clumps of shrubs, windthrow, and stumps, where the center point (or point of germination) was within the 11.28 m plot. Large slash piles were recorded in a manner similar to regeneration clumps. Bearing and distance to the center of the pile were taken, and then width and length (based on an ellipsoidal shape) were measured, along with the orientation (bearing) of the pile itself. Large clumps of shrubs (generally, common juniper) were recorded in the same way. Windthrow was mapped if the point of germination fell within the 11.28 m radius, and its DBH was greater than or equal to 17.5 cm. For windthrow, bearing and distance were taken to the origin (point of germination) of the tree, and then DBH, length and bearing of tree axis were measured. Stumps (5 cm diameter or greater) were also mapped. Distance and bearing to

the center of the stump and diameter at 15 cm were recorded. The DBH of standing dead trees (DBH greater than or equal to 7.5 cm) was recorded and the location was mapped using distance and bearing to the front of the stem.

3.3 Data Description

Data collection commenced in May of 2001 in the Invermere Forest District. A total of 37 polygons were sampled between May 1 and August 31, 2001 – 32 from disturbed stands and 5 from undisturbed stands. A total of 111 plots were sampled for Prognosis^{BC} calibration. Figure 3 shows the location of the sampled polygons and Table 4 provides ranges for selected variables.

The target of 80 percent sampling effort in the partially cut areas was achieved; 89 partial cut plots out of 111 total plots were sampled. Roughly 1/3 of the plots were taken from each partial cutting type (selection, shelterwood, and seed tree systems). Slightly fewer shelterwood sites were selected due to poor availability of sites in older age classes. Clearcut and undisturbed stands each accounted for 10 percent of the total number of plots. Roughly 75% of the plots were comprised solely of natural regeneration, while the remaining 25% were comprised of mixed planted and natural regeneration.

Plots were predominantly mesic, with few very dry or very wet series. Sites that were classed by the ISIS database as less than or equal to 900 m in elevation were often slightly higher, resulting in few plots in that category. In the other three elevation classes, there was a good distribution of plots. There was also a good distribution of plots from north to south, by slope position, and by aspect. Slopes were generally low in most plots.

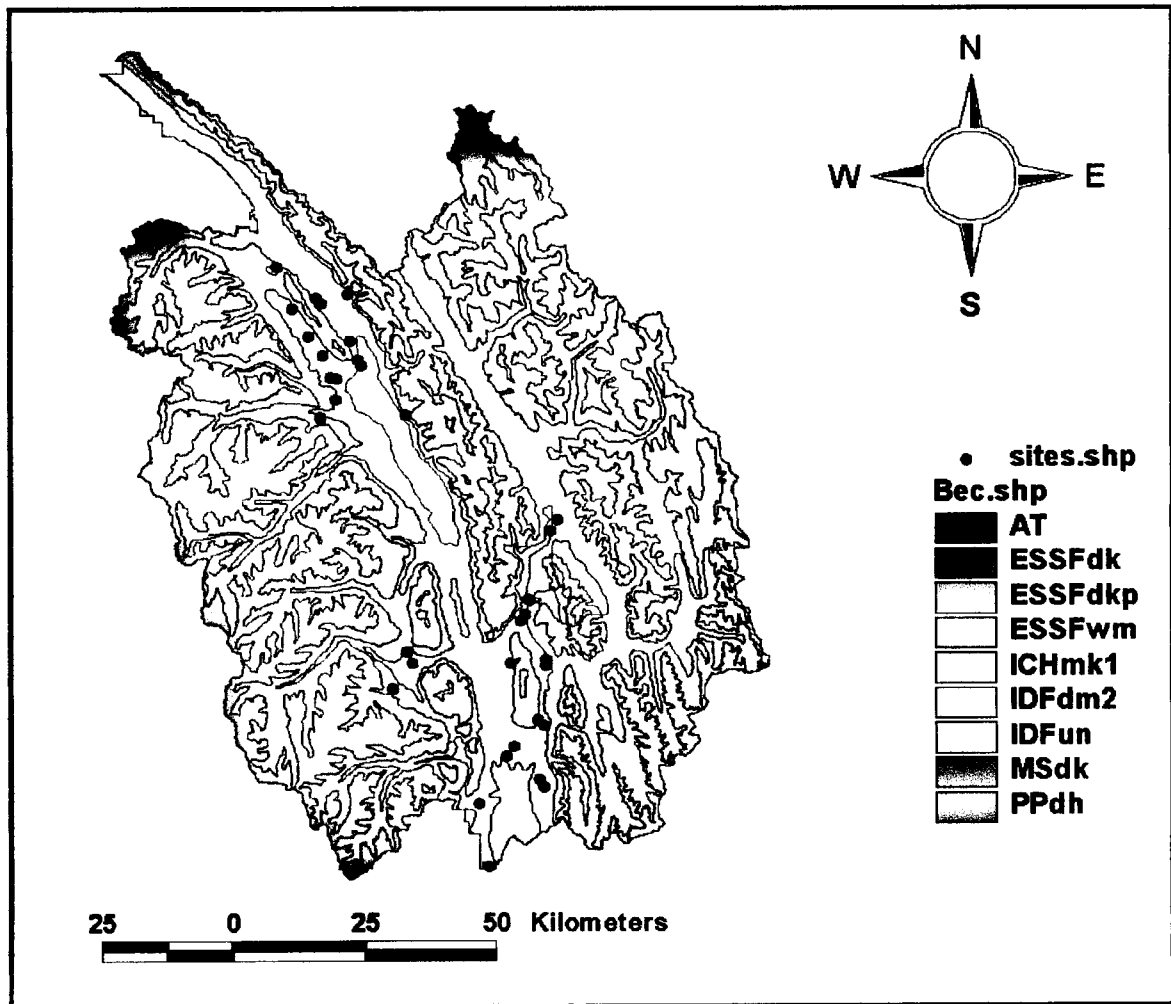


Figure 3. Location of polygons sampled in summer 2001. NOTES: AT = Alpine Tundra Zone; ESSFdk = Engelmann Spruce/Subalpine Fir Dry Cool Subzone; ESSFdkp = Engelmann Spruce/ Subalpine Fir Dry Cool Parkland Subzone; ESSFwm = Engelmann Spruce/Subalpine Fir Wet Mild Subzone; ICHmk1 = Kootenay Moist Cool Interior Cedar Hemlock Variant; IDFdm2 = Kootenay Dry Mild Interior Douglas Fir Variant; IDFun = Undifferentiated Interior Douglas Fir Unit; MSdk = Dry Cool Montane Spruce Subzone; PPdh= Kettle Dry Hot Ponderosa Pine Variant.

Table 4. Number of plots summarized by variable classes, all plots.

Plots By Site Series:		Plots By Silviculture System:	
02	0	Clearcut	11
03	5	Selection	38
03/01	10	Shelterwood	21
01/03	10	Seed Tree	30
01	40	Undisturbed	11
01/04	25		
04/01	6	Plots By Slope Position:	
04	13	Flat	20
04/05	2	Crest	14
		Upper	20
		Mid	29
Plots By Elevation (m):		Lower	19
0-900	4	Toe	3
901-1000	46	Depression	6
1001-1100	37		
1101+	24	Plots By Slope (Percent):	
		0 (variable)	11
Plots By Aspect:		0-10	45
None/Variable	27	11-20	35
N	11	21-30	10
NE	6	31-40	6
E	12	41+	4
SE	17		
S	6	Plots By Regeneration Method:	
SW	8	Natural	77
W	13	Planted & Natural	34
NW	11		

A total of 25 plots were subsampled for additional substrate and spatial information. The range of selected variables is presented in Table 5. A similar range of silvicultural systems, aspects, and slope positions were sampled. Roughly 75% of the plots were comprised solely of natural regeneration, with the remaining plots comprised of mixed planted and natural regeneration. The majority of plots were again mesic, with low to no slope, and located at generally low elevations, reflecting the preponderance of these site types in the IDFdm2.

Table 5. Number of plots summarized by variable classes, spatially sampled plots.

Plots By Site Series:		Plots By Silviculture System:	
02	0	Clearcut	2
03	1	Selection	7
03/01	3	Shelterwood	5
01/03	2	Seed Tree	8
01	10	Undisturbed	3
01/04	5		
04/01	1	Plots By Slope Position:	
04	3	Flat	3
04/05	0	Crest	6
		Upper	3
		Mid	6
		Lower	4
		Toe	3
		Depression	0
Plots By Elevation (m):		Plots By Slope (Percent):	
0-900	0	0 (variable)	1
901-1000	11	0-10	12
1001-1100	9	11-20	9
1101+	5	21-30	2
		31-40	1
Plots By Aspect:		Plots By Regeneration Method:	
None/Variable	7	Natural	18
N	1	Planted & Natural	7
NE	3		
E	3		
SE	2		
S	2		
SW	2		
W	1		
NW	4		

4. REGENERATION ABUNDANCE AND PATTERNING

4.1 Introduction

Regeneration is a particularly complex component of the stand understory. Where, when and why it occurs, and in what abundance, depends on the interactions of a number of factors, including factors which affect germination (such as seed source and periodicity, seed dispersal, availability of favourable substrate, and environmental conditions) as well as those that affect the long-term ability of regeneration to become established (such as competitive influences, growing season conditions, and the influence of pests and pathogens). Examining regeneration from a number of perspectives and at a variety of scales may aid in understanding the relative importance of some of these factors.

The objectives of the chapter were:

- 1) to examine the potential of aspatial, plot-level variables to model regeneration abundance using imputation methods;
- 2) to explore the potential of subsampled information (substrate and spatial indices) as explanatory variables for predicting regeneration abundance; and
- 3) to examine the relationship between localized aggregations of regeneration (regeneration "clumps") and overstory trees.

Regeneration abundance was modelled using imputation approaches to achieve two objectives: first, to provide useable models for Prognosis^{BC}, and secondly, to allow examination of the explanatory ability of models based on plot-level attributes. All additional analyses were completed using the exploratory data collected on a subset of plots. Data availability constrained the depth to which some of these analyses could be taken, since sample sizes, particularly for spatially mapped plots, tended to be small. These analyses were meant to provide a means for determining potential avenues for future investigation.

4.2 Methods

4.2.1 *Modelling Regeneration Abundance*

For each plot, the average of the five 2.07 m radius regeneration plots was obtained for use in the analysis. Data splitting was used to assess the performance of both the tabular and Most Similar Neighbour imputations. Data were split into a reference set (80%) and a target set (20%) of plot averages. Analyses were repeated six times, using the five different data splits plus the full data set, and assessed.

Tabular Imputation

Methods for tabular imputation followed work by Hassani (2002). Regenerated stems per hectare by species and height class, and total regenerated stems per hectare by height class, were the variables of interest to be imputed. For tabular imputation Model 1, tables were created based upon variable classes representing environment (BEC), competition (basal area in m^2/ha), and time (years since disturbance). Each table represented regenerated stems per hectare by species and height class, and total regenerated stems per hectare by height class.

To reduce the number of classes, BEC site series was transformed into moisture classes: dry (site series 03, 03/01), medium (site series 01/03, 01, and 01/04) and wet (site series 04/01, 04 and 04/05); basal area was converted into basal area classes based on balancing the distribution of plots within classes: open ($<20 \text{ m}^2/\text{ha}$) and dense ($\geq 20 \text{ m}^2/\text{ha}$); and years since disturbance was changed to years since disturbance classes: 5-9 years, 10-14 years, 15-19 years, 20-24 years, and undisturbed. For tabular imputation Model 2, the same classes were used, except that moisture class was omitted.

Model performance was assessed using the split data. Tables were created based upon the 80% reference data set. For each target plot, regenerated stems per hectare were predicted

by height class and species combinations, and for all species and heights combined. Test statistics were then calculated to assess performance. Where a target plot had no associated table, the plot was removed from the target set.

The final tabular imputation models were created based upon the full (100%) data set. Any categories that were based upon $n=1$ sample plots were deleted, since predictions would be unreliable. Because of the relatively small sample size, a number of tabular categories had either $n=1$ or $n=0$ plots, and therefore had no associated tables for prediction.

Most Similar Neighbour Imputation

Most Similar Neighbour imputation was completed using MSN 2.0 (Crookston *et al.* 2002). Most Similar Neighbour (MSN) and k-Most Similar Neighbour (k-MSN) imputation followed Hassani (2002). Regenerated stems per hectare by species and height class, and total regenerated stems per hectare by height class, were the variables of interest to be imputed (Y variables). The X variables used for imputation are listed in Table 6. To reduce the number of potential classes, BEC site series was again transformed into three moisture classes: dry (site series 03, 03/01), mesic (site series 01/03, 01, and 01/04) and wet (site series 04/01, 04 and 04/05). Aspect was transformed according to Stage (1976). Elevation squared was added to create a biologically logical function, as suggested by Crookston *et al.* (2002).

The reference (80%) set was used to impute Y values for the target set for all five data splits, using the Most Similar Neighbour method. MSN was also used on the full data set, where the imputed value was the second most similar neighbour (the most similar neighbour being itself). Imputation was then repeated using the k-Most Similar Neighbour method, where k was set to find the three most similar neighbours, and the imputed values were based on an average of the k-neighbours. Test statistics were then calculated to assess overall performance.

Table 6. Variables used in Most Similar Neighbour and k-Most Similar Neighbour imputation.

VARIABLE	DESCRIPTION
EASTING	UTM easting (m)
NORTHING	UTM northing (m)
COSASP	cosine of aspect(in radians) x percent slope
SINASP	sine of aspect(in radians) x percent slope
SLOPE	percent slope
ELEV	elevation (m)
ELEVSQ	elevation squared
MOIST	moisture class (dry, mesic, wet)
INT	intermediate entries such as thinning or pruning (Y/N)
OM	presence of organic material (Y/N)
PLANT	is site planted (Y/N)
PREP	site preparation following harvesting (Y/N)
TPH	trees per hectare
BAHA	basal area of stand (m ²)
CCF	crown competition factor
YRSINCE	number of years since harvest

Assessment of Results

For all analyses, mean absolute deviation (MAD), root mean square error (RMSE) and bias were calculated using the following formulae:

$$MAD = \frac{\sum_{i=1}^n |y_i - \hat{y}_i|}{n}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n}}$$

$$Bias = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)}{n}$$

where n = the number of target plots; y_i is the observed number of regenerated stems per hectare, and $\hat{y}_i$ is the predicted number of regenerated stems per hectare.

The accuracy of stocking prediction was assessed using three different metrics. Accurately predicting a stocked plot, that is, prediction of regeneration where regeneration was observed, is referred to as *Presence*. *Presence* was calculated by assigning a value of one to plots that were both stocked and predicted as such. Plots that were either unstocked but predicted as stocked, or vice versa, were given a value of zero. Plots that were both unstocked and predicted as such were not included. *Absence* is a measure of plots that were correctly predicted as unstocked, that is, predicted to have no regeneration and where no regeneration was observed. In this case, *Absence* was calculated by assigning a value of one to plots with were both unstocked and predicted as such. Plots that were either unstocked but predicted as stocked, or vice versa, were given a value of zero. Plots that were both stocked and predicted as such were not included. *Match* measures plots which were correctly identified as either stocked or unstocked, that is, there is a correct match between the observed and predicted, whether it is the *Absence* or *Presence* of regeneration. These matches were assigned a value of one, while plots that were incorrectly predicted were given a value of zero. For all three measures (*Presence*, *Absence*, and *Match*), an average value of 1.0 indicates 100% ("perfect") prediction accuracy, while a value of 0 indicates 0% prediction accuracy.

4.2.2. Substrate and Spatial Data

Substrate Relationships with Regeneration Abundance

Simple correlation analysis⁴ ($\alpha=0.05$) was used to assess whether plot-level variables were related to the relative abundance of substrate type. The effect of moisture class and other class variables was assessed using graphical methods.

⁴ All analyses were completed using SASTM, version 8.02 (SAS Institute Inc. 1999-2001), except where noted.

A Chi-squared test was used to assess whether the observed distribution of regeneration on available substrates was different from the expected distribution of regeneration ($\alpha=0.05$), based on relative abundance of substrate. Assuming that substrate has no effect, the expected number of regeneration stems is:

$$E_i = \text{total number of seedlings} * \frac{\text{area of substrate } i}{\text{total area}}$$

The statistic was calculated using:

$$\chi^2 = \sum_{i=1}^s \frac{(O_i - E_i)^2}{E_i}$$

and compared to

$$\chi^2_{s-1, 1-\alpha}$$

where O_i is the observed regeneration abundance, E_i is the expected regeneration abundance, and s is the number of substrate types present for each moisture class.

For each moisture class, relative efficiency of various substrates was calculated based on Geier-Hayes (1987) for each height class using:

$$\frac{\text{proportion of seedlings on substrate } i}{\text{proportion of substrate } i}$$

where a value of 1.0 indicates seedling abundance in proportion to substrate abundance (neutral seedbed); greater than 1.0 indicates overrepresentation of regeneration relative to substrate abundance (favourable seedbed); and less than 1.0 indicates underrepresentation of regeneration relative to substrate abundance (undesirable seedbed).

Calculation of Spatial Position

Distances to large trees were converted to distances to center points of large trees by adding $\frac{1}{2}$ DBH to each distance measurement. Angle and distance data were converted to Cartesian coordinates (Moeur 1993) using:

$$x = HD * \cos \theta$$

$$y = HD * \sin \theta$$

where x is the x coordinate relative to the plot centre, y is the y coordinate relative to the plot centre, and θ is the azimuth angle from north. To improve the ease of calculations, all x and y coordinates were then converted to positive values by adding 11.28 m (large and small tree plot size) to each x and y measurement, shifting the reference point to the southwest (Figure 4).

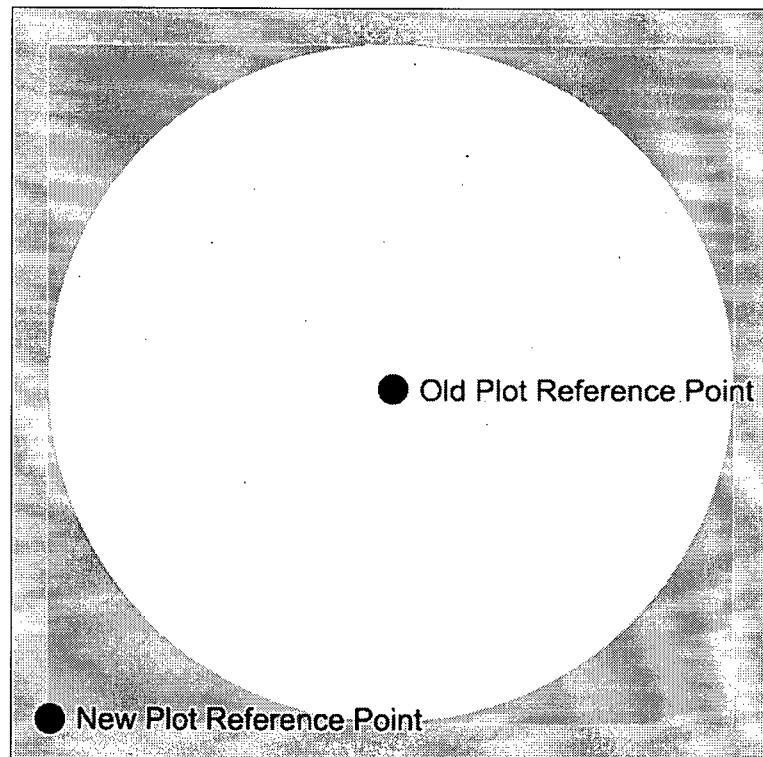


Figure 4. Plot reference points for spatial analyses.

Competition and Release Indices

Competition and release indices were calculated and compared relative to regeneration abundance (stems per hectare) in the centre (2.07 m) regeneration plot. Because of the sporadic nature of occurrence of some species, the species selected for analysis had to be reduced to those with sufficient abundance. Only Douglas-fir regeneration was present in sufficient abundance to proceed with further analysis.

Aspatial plot-level and spatial indices (zone of influence and size/ratio indices) were assessed. Light interception approaches were not possible without requiring a number of assumptions regarding crown form, since only DBH and selected height/height increment measurements were available for spatially mapped trees, and area potentially available approaches were not explored due to potential problems noted by Lorimer (1983) (see Section 2.5.2).

Three aspatial and four spatial indices and modifications thereof were selected for assessment (Table 7), based on results from Nienaber (1999), comparability to plot-level measures of competition used in Prognosis^{BC} modelling, and data availability. Using these formulae, competition indices were calculated using all live competitors (small and large trees), and release indices were calculated using the same formulae, based on dead trees (lost to harvesting or mortality). Neighbourhood basal area is a semi-spatial method because it sums basal area of trees within a specific distance of the subject tree, but does not require exact spatial locations for these trees. Indices were calculated for each height class and three search radii: 3 m, 7 m, and 11 m. Because regeneration had no definable basal area, formulae were modified as shown in Table 7.

Pearson's correlation coefficients ($\alpha=0.05$) were used to examine the relationship between indices and regenerated stems per hectare by height class for the three search radii. Graphical methods were used to assess the nature of identified relationships.

Table 7. Formulae for competition and release indices by variable of interest.

Name	Original Formula	Modified Formula	Description
Plot-Level Indices (Aspatial)			
BAHA	$\sum_{all\ trees} BA / area$	$\sum_{all\ trees} BA / area$	Basal area per hectare, all trees
CCF	$\sum_{all\ trees} MCA / area$	$\sum_{all\ trees} MCA / area$	Crown competition factor, all trees (Krajicek et al. 1961)
PCTBAREM	$\sum_{all\ trees} BA_{dead} / \sum_{all\ trees} BA_{total} \times 100$	$\sum_{all\ trees} BA_{dead} / \sum_{all\ trees} BA_{total} \times 100$	Percent basal area removed
Size and Size-Distance Indices (Spatial and Semi-Spatial)			
BAN	$\sum_{j=1}^k BA_j, u_{ij} \leq SR$	$\sum_{j=1}^k BA_j, u_{ij} \leq SR$	Neighbourhood basal area
Hegyi1	$\sum_{j=1}^k \frac{(DBH_j / DBH_i)}{u_{ij}}$	$\sum_{j=1}^k \frac{DBH_j}{u_{ij}}$	Distance weighted sum of diameters (Hegyi 1974, modified)
Hegyi2	$\sum_{j=1}^k \frac{(DBH_j^2 / DBH_i^2)}{u_{ij}}$	$\sum_{j=1}^k \frac{DBH_j^2}{u_{ij}}$	Distance weighted sum of diameters squared (Nienaber 1999, modified)
Zone of Influence Indices (Spatial)			
OpieA	$\sum_{j=1}^k \frac{A_{oij}}{A_i}, R = CW / 2$	$\sum_{j=1}^k \frac{A_{oij}}{A_i}, R = CW / 2$	Area of overlap of zones of influence (Opie 1968)
OpieB	$\sum_{j=1}^k \frac{A_{oij}}{A_i}, R = CW$	$\sum_{j=1}^k \frac{A_{oij}}{A_i}, R = CW$	Area of overlap of zones of influence
Bella1A	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) \left(\frac{DBH_j}{DBH_i} \right), R = CW / 2$	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) (DBH_j), R = CW / 2$	Size-weighted area of overlap (Bella 1971, modified)
Bella1B	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) \left(\frac{DBH_j}{DBH_i} \right), R = CW$	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) (DBH_j), R = CW$	Size-weighted area of overlap
Bella2A	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) \left(\frac{DBH_j}{DBH_i} \right)^2, R = CW / 2$	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) (DBH_j)^2, R = CW / 2$	Squared size-weighted area of overlap
Bella2B	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) \left(\frac{DBH_j}{DBH_i} \right)^2, R = CW$	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) (DBH_j)^2, R = CW$	Squared size-weighted area of overlap

NOTES: Spatial and semi-spatial indices were calculated separately for two index types (competing (live) trees and release (dead) trees) and three search radii (3, 7 and 11 m); BA_j is the basal area of competitor j (m^2), $area$ is the plot area (ha), DBH_j is the diameter at breast height of competitor j (cm), DBH_i is the diameter at breast height of subject i (cm), MCA is the maximum area that could be occupied by the crown of a tree of specified DBH , expressed in terms of percent area, u_{ij} is the distance between subject i and competitor j (m), SR is the search radius (m), A_i is the area of influence of subject tree i (m^2), A_j is the area of influence of subject tree j (m^2), A_{oij} is the area of overlap of A_i and A_j (m^2), R is the radius (m) used to calculate areas of influence A_i and A_j , and CW is mean crown width (m);

Point Pattern Analysis

Spatial data were mapped using the Stand Visualization System, Version 3.36 (McGaughey 1997). Regeneration clumps were mapped using small shrub forms with elliptical shapes; the midpoint of the tallest height class with a regeneration stem present was used as the height for each clump. The bearing of the long axes of each regeneration clump was converted to either north-south or east-west orientation due to graphical limitations within the program. Crown ratios for all trees were predicted using the crown prediction equations from the Prognosis^{BC} model (Temesgen 2001). Where missing, large tree heights were predicted using the total height prediction equations from Prognosis^{BC}. For small trees, height equations were not available, therefore linearized forms of the equation:

$$\hat{ht} = 1.3 + e^{(b_0 + b_1 DBH)}$$

were fit for each species, where b_0 and b_1 are coefficients to be estimated, DBH is diameter at breast height (cm), and e is the base of the natural logarithm. Equations performed reasonably for all species (no evidence of lack of fit, generally low RMSE and high R^2). For cut trees, stump diameters were converted to DBH using equations presented in Kozak and Omule (1992); where species was not available, the equation for Douglas-fir was used. These graphic images, along with plot photos, were used to visually assess spatial patterns.

Because all trees heights were not available, only horizontal spatial patterns could be examined. The Clark and Evans Positioning Index (Clark and Evans 1954) provides an indication of spatial patterning, but provides a single value for a defined area. Ripley's $K(t)$ statistic (Ripley 1977) examines spatial patterning as a function of distance, and could therefore provide additional information with the same data. Therefore, spatial relationships were assessed using Ripley's univariate and bivariate $K(t)$ statistics, following Nigh (1999). Univariate $K(t)$ statistics were used to examine the within-type patterning of overstory (>7.5 cm DBH) trees, to examine whether point patterns were indicative of clustering or uniformity. Three classes of overstory trees were examined: all trees (live + dead trees, which together represented initial overstory conditions), live trees (post-harvest or post-mortality conditions,

representing current competition by overstory for resources) and dead trees (representing release of resources via harvesting or mortality).

Bivariate $K(t)$ statistics were used to examine the relationship between the three overstory classes and the location of regeneration clumps. Patterns of overstory trees relative to regeneration clumps were used to examine whether clumps were aggregated towards, or repulsed by, attributes of the overstory. A causal relationship was assumed (i.e., that the overstory trees, live or dead or both, affected the location of regeneration clumps). Three classes of regeneration clumps were also examined: all clumps (regardless of whether initiation preceded overstory removal), clumps containing advance regeneration (representing clumps which originated prior to overstory removal), and clumps consisting of solely subsequent regeneration (representing clumps which originated following overstory removal).

When multiplied by the density (trees per unit area), Ripley's univariate $K(t)$ statistic is the expected value of the number of type β points within a distance t of an arbitrary type β point; Ripley's bivariate $K(t)$ statistic is the expected value of the number of type β points within a distance t of an arbitrary type α point (Nigh 1999). The $K(t)$ bivariate statistic was calculated for distances t of 0.5 m to 11 m at 0.5 m intervals using (Nigh 1999):

$$\tilde{K}_{\alpha\beta}(t) = \frac{|A|}{n_{\alpha}n_{\beta}} \sum_{i=1}^{n_{\alpha}} \sum_{j=1}^{n_{\beta}} \frac{I_t(u_{ij})}{w_{ij}}$$

where

$$I_t(u_{ij}) = \begin{cases} 1 & \text{if } u_{ij} \leq t \\ 0 & \text{if } u_{ij} > t \end{cases}$$

and

$$w_{ij} = \begin{cases} 1 & \text{if } u_{ij} \geq a - r \\ \left[1 - \arccos\left(\frac{a^2 - r^2 - u_{ij}^2}{2r \cdot u_{ij}}\right) / \pi \right] & \text{if } u_{ij} < a - r \end{cases}$$

and $|A|$ is the area of the study plot (m^2), n_α and n_β are the number of type α and β points in the plot, respectively, u_{ij} is the distance (m) between the i^{th} type α and j^{th} type β point, w_{ij} is the edge effect correction factor to account for unsampled competitors outside of the plot boundary, a is the radius (m) of the plot, and r = the distance (m) from plot centre to the i^{th} type α point.

Because $\tilde{K}_{\alpha\beta}(t) \neq \tilde{K}_{\beta\alpha}(t)$ due to edge effects, Nigh (1999) combined the two into a single estimator based on Lotwick and Silverman (1982) using:

$$\hat{K}_{\alpha\beta}(t) = \frac{n_\beta \cdot \tilde{K}_{\alpha\beta}(t) + n_\alpha \cdot \tilde{K}_{\beta\alpha}(t)}{n_\alpha + n_\beta}$$

Estimates of $K_{1,1}(t)$ and $K_{2,2}(t)$ provide univariate analyses of the patterning of the overstory trees and clumps, respectively (Nigh 1999), while the estimate of $K_{1,2}(t)$ provides a bivariate analysis of the pattern between the two.

In order to linearize $\hat{K}_{\alpha\beta}(t)$, stabilize its variance, and provide an expected value of approximately zero under a Poisson assumption (Besag, in the discussion in Ripley 1977), $\hat{K}_{\alpha\beta}(t)$ was transformed to $\bar{L}_{\alpha\beta}(t)$ using:

$$\bar{L}_{\alpha\beta}(t) = \sqrt{\frac{\hat{K}_{\alpha\beta}(t)}{\pi}} - t$$

The value of $\bar{L}_{\alpha\beta}(t)$ indicates the difference between the number of points found within the circle with a u_{ij} radius and the expected number of points based on a Poisson process (Hanus *et al.* 1998).

Monte Carlo techniques were used to generate 90% confidence envelopes for the estimates, for each plot and each type of analysis (Moeur 1993, Nigh 1999). A Monte Carlo confidence envelope was generated by calculating random coordinates for n trees, then

calculating $\hat{K}_{\alpha\beta}(t)$ using the random coordinates. This process was repeated 200 times. Then, at each value of t , the 200 values for $\hat{K}_{\alpha\beta}(t)$ were ordered, and the largest and smallest 5% were discarded. The remaining minimum and maximum values then defined the upper and lower limits of a two-sided 90% confidence envelope. For bivariate analyses, the locations of overstory trees were held constant, and regeneration clumps were randomly placed, to examine whether the location of existing overstory trees had an effect on the location of regeneration clumps. For the purposes of analysis, it was assumed that the center point of the regeneration clump represented its originating point.

These values, along with the empirically-derived $\hat{K}_{\alpha\beta}(t)$ values, were graphed for each plot. The hypothesis of a random distribution was rejected for those values of $\hat{K}_{\alpha\beta}(t)$ that fell outside of this confidence envelope. Those values which fell above the envelope were indicative of a clustered (aggregated or attracted) pattern, and those which fell below the envelope were considered to be indicative of a uniform (repulsed or inhibited) pattern.

4.3 Results

4.3.1 *Modelling Regeneration Abundance*

Table 8 presents the correlations between the predictor and response variables for the full data set, based on species. Statistically significant ($\alpha=0.05$) correlations are highlighted in bold. Correlations differed by species and height class. Trembling aspen was positively correlated with increasing northing and negatively correlated with increasing easting, for all height classes examined. Western larch and lodgepole pine had consistent positive correlations with elevation for all height classes. Lodgepole pine was also consistently negatively correlated with CCF and BAHA.

Table 8. Simple correlations between regeneration abundance and site variables, by species and height class.

Species	Height Class	EASTING	NORTHING	COSASPECT	SINASPECT	SL	ELEV	ELEV SQ	YRSINCE	TPH	CCF	BAHA
At	50-100cm	corr.	-0.27	0.27	0.09	0.07	-0.03	-0.06	-0.06	-0.09	-0.02	0.00
		prob.	<0.01	<0.01	0.33	0.45	0.75	0.55	0.40	0.33	0.80	1.00
	100-130cm	corr.	-0.24	0.24	0.11	0.01	-0.05	-0.04	-0.07	-0.03	-0.01	0.01
		prob.	0.01	0.01	0.27	0.96	0.61	0.65	0.44	0.78	0.92	0.92
	130+cm	corr.	-0.33	0.33	0.04	0.06	-0.14	-0.07	-0.08	-0.05	-0.04	-0.01
		prob.	<0.01	<0.01	0.65	0.55	0.15	0.46	0.40	0.64	0.71	0.92
Bl	15-50cm	corr.	-0.12	0.07	0.13	0.02	0.01	0.16	-0.02	0.11	0.09	0.05
		prob.	0.22	0.48	0.17	0.80	0.89	0.09	0.84	0.23	0.33	0.58
	50-100cm	corr.	-0.12	0.07	0.13	0.02	0.01	0.16	-0.02	0.11	0.09	0.05
		prob.	0.22	0.48	0.17	0.80	0.89	0.09	0.84	0.23	0.33	0.58
	100-130cm	corr.	-0.12	0.07	0.13	0.02	0.01	0.16	-0.02	0.11	0.09	0.05
		prob.	0.22	0.48	0.17	0.80	0.89	0.09	0.84	0.23	0.33	0.58
Ep	130+cm	corr.	0.00	0.00	-0.03	-0.03	0.06	0.23	0.19	0.34	0.14	0.06
		prob.	0.96	0.98	0.74	0.79	0.51	0.01	0.05	<0.01	0.15	0.53
	50-100cm	corr.	-0.08	0.12	0.02	0.04	-0.11	-0.03	-0.05	0.03	-0.14	-0.15
		prob.	0.40	0.20	0.84	0.68	0.26	0.74	0.59	0.78	0.15	0.11
	100-130cm	corr.	-0.18	0.19	0.05	0.05	-0.05	-0.04	-0.05	0.02	-0.13	-0.14
		prob.	0.06	0.04	0.59	0.62	0.58	0.69	0.61	0.82	0.19	0.15
Fd	130+cm	corr.	-0.24	0.24	0.14	0.10	0.01	-0.01	-0.06	0.00	-0.11	-0.11
		prob.	0.01	0.01	0.13	0.28	0.93	0.93	0.54	0.97	0.25	0.25
	15-50cm	corr.	0.15	-0.17	0.16	-0.04	0.11	-0.13	0.07	-0.21	0.11	0.20
		prob.	0.10	0.07	0.09	0.67	0.26	0.18	0.46	0.03	0.27	0.03
	50-100cm	corr.	0.24	-0.25	0.03	-0.06	0.08	-0.09	0.01	-0.11	0.02	0.08
		prob.	0.01	0.01	0.73	0.52	0.42	0.34	0.91	0.26	0.85	0.43
100-130cm	corr.		0.20	-0.18	-0.06	-0.01	0.14	-0.04	-0.05	-0.06	-0.03	-0.01
		prob.	0.04	0.05	0.50	0.89	0.15	0.69	0.58	0.54	0.77	0.92
	130+cm	corr.	0.15	-0.11	-0.09	-0.09	0.13	-0.08	-0.15	0.26	0.09	-0.01
		prob.	0.11	0.27	0.35	0.35	0.17	0.39	0.12	0.01	0.33	0.96

NOTES: corr. is the Pearson's correlation and prob. is the associated p value, under the hypothesis that the correlation is not significantly different from 0; bold indicates that the correlation is statistically different from zero at $\alpha=0.05$; EASTING is UTM easting (m), NORTHING is UTM northing (m), COSASPECT and SINASPECT are Stage's (1976) transformation of aspect, SL is slope ratio (slope percent/100), ELEV is elevation (m), ELEV SQ is elevation squared (m²), YRSINCE is the number of years since disturbance, TPH is the number of trees per hectare, CCF is the crown competition factor, and BAHA is total basal area per hectare (m²/ha).

Table 8. (cont'd). Simple correlations between regeneration abundance and site variables, by species and height class (n=111).

Species	Height Class	EASTING	NORTHING	COSASPECT	SINASPECT	SL	ELEV	ELEV SQ	YRSINCE	TPH	CCF	BAHA
Lw	50-100cm	corr.	0.09	-0.19	-0.06	-0.07	-0.11	0.28	0.31	-0.10	0.15	-0.16
		prob.	0.37	0.05	0.56	0.48	0.26	<0.01	<0.01	0.29	0.11	0.08
	100-130cm	corr.	0.11	-0.15	-0.05	-0.05	-0.08	0.37	0.39	-0.08	0.17	-0.15
		prob.	0.26	0.11	0.62	0.58	0.42	<0.01	<0.01	0.39	0.08	0.11
	130+cm	corr.	0.03	-0.15	-0.16	-0.05	0.03	0.40	0.42	-0.07	0.09	-0.17
		prob.	0.72	0.11	0.10	0.62	0.77	<0.01	<0.01	0.48	0.37	0.08
Pl	50-100cm	corr.	-0.16	-0.05	-0.07	0.00	-0.19	0.24	0.26	-0.15	0.16	-0.29
		prob.	0.10	0.57	0.45	0.97	0.04	0.01	0.01	0.12	0.10	<0.01
	100-130cm	corr.	-0.15	-0.01	0.02	-0.02	-0.16	0.32	0.34	-0.13	0.16	-0.29
		prob.	0.11	0.89	0.85	0.81	0.08	<0.01	<0.01	0.18	0.10	<0.01
	130+cm	corr.	0.01	-0.12	0.02	-0.05	-0.12	0.33	0.33	-0.12	0.59	-0.24
		prob.	0.93	0.23	0.85	0.59	0.23	<0.01	<0.01	0.22	<0.01	0.01
Py	50-100cm	corr.	0.09	-0.26	-0.03	0.05	-0.08	-0.19	-0.18	-0.04	0.01	0.02
		prob.	0.36	0.01	0.72	0.63	0.40	0.05	0.07	0.66	0.95	0.84
	100-130cm	corr.	0.07	-0.11	0.00	-0.01	-0.10	-0.07	-0.07	-0.04	-0.05	0.04
		prob.	0.47	0.25	1.00	0.93	0.31	0.47	0.48	0.70	0.61	0.71
	130+cm	corr.	0.12	-0.19	-0.07	-0.08	-0.10	-0.06	-0.06	-0.06	-0.02	-0.04
		prob.	0.21	0.05	0.44	0.41	0.29	0.51	0.52	0.53	0.85	0.67
Sxw	15-50cm	corr.	0.13	0.02	0.07	-0.02	-0.12	0.01	0.00	-0.08	-0.11	0.01
		prob.	0.18	0.80	0.47	0.88	0.21	0.94	0.98	0.40	0.25	0.95
	50-100cm	corr.	-0.11	0.07	0.11	0.04	-0.16	0.04	0.03	-0.10	-0.15	-0.11
		prob.	0.25	0.48	0.25	0.70	0.09	0.67	0.72	0.31	0.11	0.27
	100-130cm	corr.	-0.15	0.19	0.04	0.02	-0.15	-0.10	-0.10	-0.08	-0.08	-0.09
		prob.	0.13	0.05	0.68	0.87	0.13	0.30	0.29	0.41	0.39	0.36
130+cm	corr.	0.13	-0.06	0.00	0.02	-0.15	0.00	0.00	-0.01	-0.06	0.03	0.04
	prob.	0.16	0.54	0.97	0.81	0.13	0.97	0.92	0.92	0.50	0.75	0.69

NOTES: corr. is the Pearson's correlation and prob. is the associated p value, under the hypothesis that the correlation is not significantly different from 0; bold indicates that the correlation is statistically different from zero at $\alpha=0.05$; EASTING is UTM easting (m), NORTHING is UTM northing (m), COSASPECT and SINASPECT are Stage's (1976) transformation of aspect, SL is slope ratio (slope percent/100), ELEV is elevation (m), ELEV SQ is elevation squared (m²), YRSINCE is the number of years since disturbance, TPH is the number of trees per hectare, CCF is the crown competition factor, and BAHA is total basal area per hectare (m²/ha).

Tabular Imputation

Regeneration tables for Model 1 were based on years since disturbance class, moisture class, basal area class, and whether the site has been planted. Moisture class was omitted in Model 2, creating a simpler version for developing regeneration tables. Table 9 summarizes the number of plots per category for Model 1. Because a number of categories had only one plot, these plots were discarded, removing ten of 111 plots for tabular analysis. A total of 25 categories has no associated tables ($n=0$ or $n=1$). Table 10 summarizes the number of plots per category for Model 2. By removing moisture class, only two categories did not have the minimum two plots; both are from the undisturbed year class with less than 20 m²/ha in basal area, which is a rare site type. There were no categories with a single plot; therefore, all 111 plots were used in developing these tables. Tabular imputation tables for Model 1 are presented in Appendix B; tables for Model 2 are presented in Appendix C.

Table 9. Number of plots by years since disturbance, basal area, and moisture classes, planted and unplanted sites, Model 1.

Years Since Disturbance	Moisture Class	Basal Area Class		
		<20m ² /ha		>20m ² /ha
		unplanted	planted	unplanted
5-9 years	dry	0	0	0
	mesic	7	3	5
	wet	0	0	0
10-14 years	dry	6	0	0
	mesic	14	7	3
	wet	0	6	0
15-19 years	dry	2	0	0
	mesic	12	11	0
	wet	3	0	2
20-24 years	dry	2	0	0
	mesic	2	2	0
	wet	2	2	0
undisturbed	dry	0	0	0
	mesic	0	0	7
	wet	0	0	3

Table 10. Number of plots by years since disturbance and basal area classes, planted and unplanted sites, Model 2.

Years Since Disturbance	Basal Area Class		
	<20m ² /ha		>20m ² /ha
	unplanted	planted	unplanted
5-9 years	8	4	6
10-14 years	20	14	3
15-19 years	17	12	4
20-24 years	6	4	2
undisturbed	0	0	11

Fit statistics given in Table 11 were based on the prediction of the total regenerated stems per hectare for all species and heights combined using the reserved data sets (Runs 1 to 5) and all data (Full Data). Both models had high values for MAD, RMSE, and bias. Model 2 generally had a lower MAD and less bias. Model 2 had a lower RMSE for all five runs, but a slightly higher RMSE for fit statistics based on the full data set.

Table 11. MAD, RMSE and bias for total predicted regeneration stems/ha, five data splitting runs and final model fit using the full data set, Models 1 and 2.

	n	Model 1			n	Model 2		
		MAD	RMSE	Bias		MAD	RMSE	Bias
Run 1	18	3569	4860	-336	23	3591	4718	303
Run 2	24	4553	5565	-719	24	4490	5426	-681
Run 3	21	3318	4275	1213	22	2756	4073	847
Run 4	17	3936	5300	739	19	3846	5044	454
Run 5	19	2834	3465	-285	23	2242	2779	-412
Full Data	101	2942	3918	0	111	2903	3977	0

NOTE: n=number of plots

Appendix D provides fit statistics by species and by height class for Model 1 for each analysis run. Douglas-fir consistently had the highest values for MAD, RMSE and bias. Lodgepole pine, the second most abundant species, had lower values of MAD, RMSE, and bias. All other species, found infrequently on regeneration plots, had overall lower MAD, RMSE and bias. However, for species that frequently had zero regenerated stems per hectare, the predicted regenerated stems per hectare were also often zero, resulting in deceptively low statistics. For example, subalpine fir, a sporadically occurring species, had

MADs ranging from 4 to 27, RMSEs ranging from 9 to 103, and biases of -4 to 27 regenerated stems per hectare.

Appendix E provides fit statistics by species and by height class for Model 2 for each run. Douglas-fir again had the highest values for MAD, RMSE and bias for total regeneration stems per ha. Lodgepole pine again had lower values, and all other species generally had lower MAD, RMSE, and bias.

The accuracy of prediction of the *Presence* or *Absence* given in Table 12 was summarized over all species for each of the five data sets (Runs) and for all data combined. Results were similar for both models. Accuracy of predicting *Presence* or *Absence* of regeneration and overall matching success were all very high.

Table 12. Summary of model accuracy in prediction of *Presence* of regeneration, *Absence* of regeneration, and overall combined prediction for Model 1 and Model 2.

	n	Model 1			n	Model 2		
		Presence	Absence	Match		Presence	Absence	Match
Run 1	18	0.94	0.00	0.94	23	0.96	0.00	0.96
Run 2	24	1.00	-	1.00	24	1.00	-	1.00
Run 3	21	1.00	-	1.00	22	1.00	-	1.00
Run 4	17	0.94	0.00	0.94	19	0.95	0.00	0.95
Run 5	19	0.95	0.00	0.95	23	0.96	0.00	0.96
Full Data	101	0.97	0.00	0.97	111	0.97	0.00	0.97

NOTES: n=number of plots; entries with a "-" indicate a category where there were no observed instances of an absence of regeneration.

Accuracy of matching results by species and height class are presented in Appendices F and G for Model 1 (with moisture class) and Model 2 (without moisture class), respectively. These results were very different than those in Table 12. While the tabular models were successful in predicting whether a plot had regeneration or lacked regeneration overall, they were less successful in predicting the amount of regeneration for each species. The *Match* category, which combined accurate prediction of either *Presence* or *Absence*, masked these problems and generally resulted in high values for all species.

In general, species commonly found on most sites had very good prediction of *Presence*, and very poor prediction of *Absence*. Infrequently occurring species such as subalpine fir tended to have low accuracy in predicting *Presence*, and a high accuracy in predicting *Absence*. Species with moderate occurrence levels had moderate values for both *Presence* and *Absence*. Model 2 generally provided slightly poorer predictions.

Observed values of total regeneration stems/ha against predicted regeneration stems/ha for the entire dataset (Tabular Model 1) are presented in Figure 5. Because the tabular imputation tables are based on averages over a number of plots, predicted regenerated stems per hectare lack the variability that is found in the observed stems per hectare. Very low and very high regenerated stems per hectare were not predicted. These trends were similar across the different data splitting runs, and by height class.

Most Similar Neighbour and K-Most Similar Neighbour Imputation

Table 13 provides a summary of fit statistics for both Most Similar Neighbour and k-Most Similar Neighbour imputation. These fit statistics were based on the prediction of the total regenerated stems per hectare for all species. Both models had overall high values for MAD, RMSE, and bias. The k-MSN method had lower MAD and RMSE values for all runs, and generally had lower biases.

Table 13. MAD, RMSE and bias for total predicted regeneration sph, five data splitting runs and final model fit using the full data set, for Most Similar Neighbour and k-Most Similar Neighbour imputation.

	n	Most Similar Neighbour			n	k-Most Similar Neighbour		
		MAD	RMSE	Bias		MAD	RMSE	Bias
Run 1	23	5382	7349	-1919	23	4122	5442	-1116
Run 2	24	4025	5353	-1176	24	2543	3501	-165
Run 3	2	5397	6544	-1776	22	4181	5163	-1326
Run 4	19	5811	7548	899	19	3877	5545	1030
Run 5	23	4432	6233	1266	23	3976	5339	1559
Full Data	111	4399	5897	-541	111	3431	4521	-133

NOTES: n=number of plots.

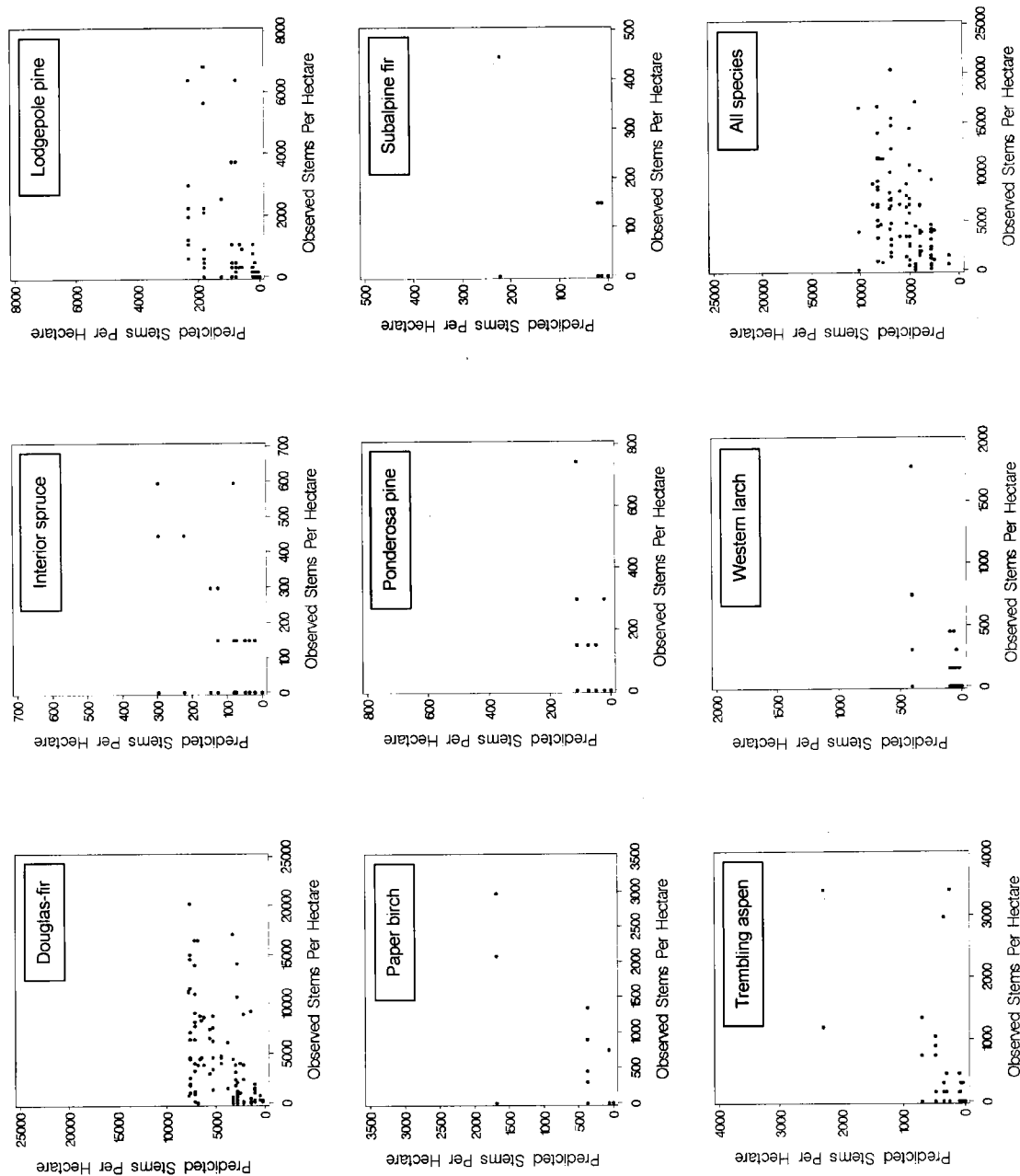


Figure 5. Predicted vs. observed regenerated stems per hectare by species and for all species combined, tabular imputation (n=111).

Appendix H presents fit statistics by species and by height class for the Most Similar Neighbour imputation. The most frequently occurring species (Douglas-fir) consistently had the highest MAD, RMSE and bias values. Sporadically occurring species had the lowest MAD, RMSE, and bias values. Species which occurred at moderate frequencies and abundances had intermediate values for all three fit statistics.

Appendix I presents fit statistics by species and by height class for the k-Most Similar Neighbour imputation. Douglas-fir again had the highest values for all three fit statistics. Species occurring at moderate frequencies and abundances had lower MAD, RMSE, and bias values, while sporadically occurring species had the lowest values.

Table 14 summarizes the accuracy of matching for both models. These results were based on the accuracy of prediction of the *Presence* or *Absence* for all species combined. The k-Most Similar Neighbour method generally had better results in accuracy of prediction of *Presence* and overall match. However, the Most Similar Neighbour method, was better in predicting *Absence*.

Table 14. Summary of model accuracy in prediction of *Presence* of regeneration, *Absence* of regeneration, and overall combined prediction for Most Similar Neighbour and k-Most Similar Neighbour imputation.

	Most Similar Neighbour					k-Most Similar Neighbour			
	n	Presence	Absence	Match		n	Presence	Absence	Match
Run 1	23	1.00	-	1.00	23	1.00	-	1.00	
Run 2	24	0.92	0.00	0.92	24	0.96	0.00	0.96	
Run 3	2	0.91	0.00	0.91	2	0.91	0.00	0.91	
Run 4	19	1.00	-	1.00	19	1.00	-	1.00	
Run 5	23	0.96	0.00	0.96	23	1.00	-	1.00	
Full Data	111	0.98	0.33	0.98	111	0.97	0.00	0.97	

NOTES: n=number of plots; entries with a "-" indicate a category where there were no instances of observed or predicted absence of regeneration.

Accuracy of matching results by species and height class are presented in Appendices J and K for Most Similar Neighbour and k-Most Similar Neighbour imputation, respectively. These results were very different than those in Table 14. *Match* values were high overall, but accuracy in predicting *Presence* and *Absence* varied by species. Accuracy was generally

similar for both approaches, but the Most Similar Neighbour approach was more accurate in predicting *Absence*.

Again, the most abundant species, Douglas-fir, had very good prediction of *Presence*, and very poor prediction of *Absence*. MSN provided a better prediction of *Absence* than k-MSN for this species. Sporadically occurring species had good prediction of *Absence* and poor prediction of *Presence*. Species occurring at moderate frequencies and abundances had moderate levels of successful prediction of *Presence* and *Absence*. All species had moderate to high match results.

Using MSN and the full data set, the observed versus predicted regeneration per ha values show that the variability found in the observed regenerated stems per hectare is retained (Figure 6). Very low and very high regenerated stems per hectare are predicted, unlike the tabular approach which uses average values as estimates. However, the predictions often did not corresponding well with the observed values (e.g., subalpine fir). These trends were similar across the different data splitting runs, and by height class.

4.3.2 *Substrate and Spatial Data*

Substrate Relationships with Regeneration Abundance

Based on simple correlation analysis ($\alpha=0.05$) (Table 15), the abundance of substrate was not significantly affected by years since disturbance, nor by overstory stand characteristics, with a few notable exceptions. The abundance of fine woody debris had a strong negative correlation with the number of large trees per hectare. Abundance of kinnikinnick, moss and stump substrates were positively correlated with elevation. Other correlations occurred between certain substrates and aspect and easting.

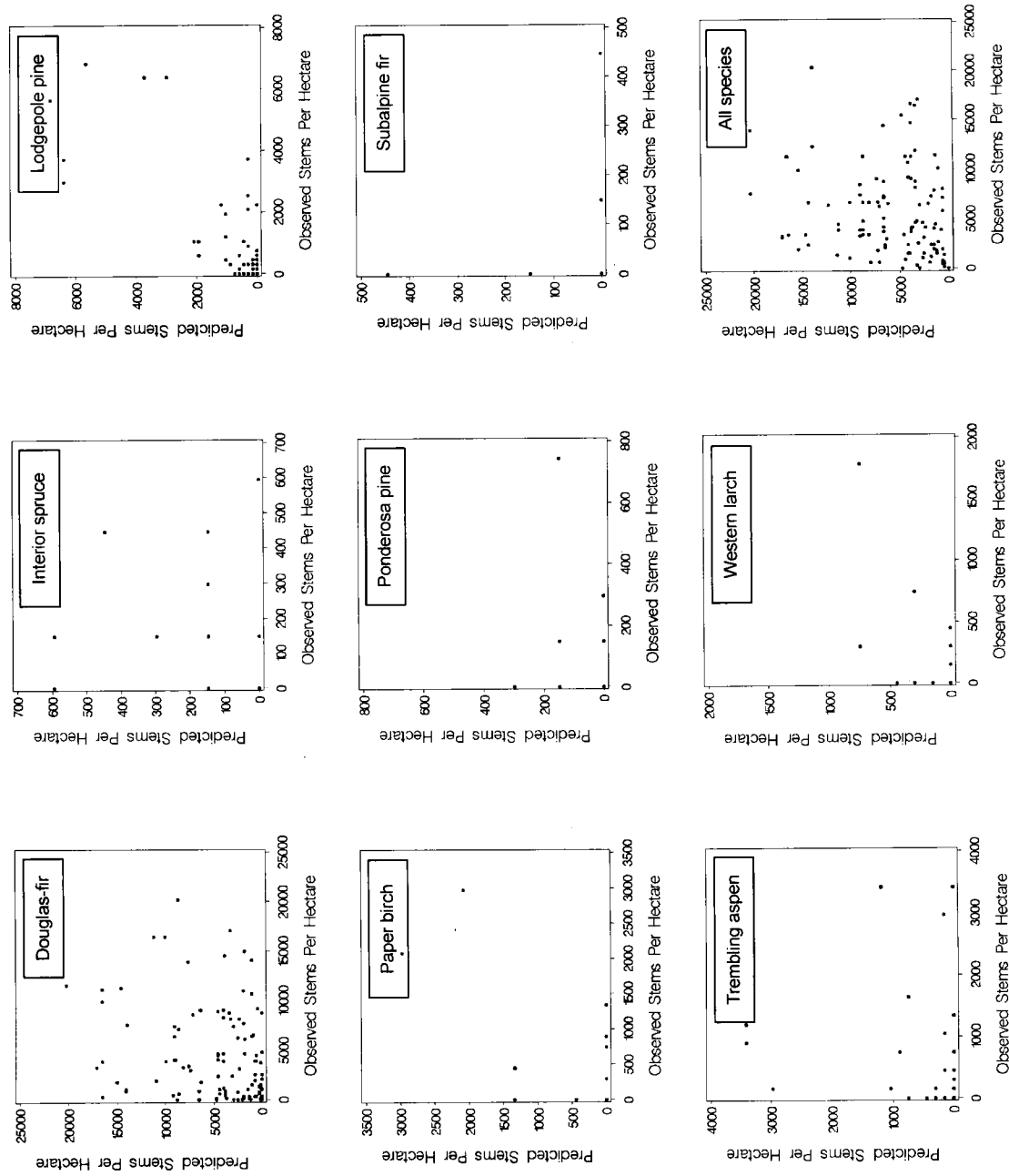


Figure 6. Predicted vs. observed regenerated stems per hectare by species and for all species combined, Most Similar Neighbour imputation (n=111).

Table 15. Simple correlations between percent substrate and stand variables (n=25 plots).

Substrate	EASTING	NORTHING	COSASPECT	SINASPECT	SL	ELEV	ELEV SQ	YRSINCE	TPH	CCF	BAHA
Coarse Woody Debris	corr. 0.11	0.06	-0.11	-0.18	-0.70	-0.64	-0.62	0.07	0.31	-0.03	-0.12
	prob. 0.81	0.89	0.81	0.70	0.08	0.12	0.13	0.87	0.49	0.95	0.80
Fine Woody Debris	corr. 0.81	-0.75	0.47	-0.81	0.78	0.30	0.29	-0.59	-0.82	0.40	0.53
	prob. 0.05	0.09	0.35	0.05	0.07	0.57	0.57	0.22	0.04	0.43	0.28
Grass-Continuous	corr. -0.17	0.23	0.22	0.09	0.10	-0.19	-0.18	0.17	-0.22	0.38	0.37
	prob. 0.61	0.46	0.49	0.78	0.77	0.55	0.57	0.61	0.49	0.23	0.24
Grass-Discontinuous	corr. 0.02	0.10	0.49	0.34	-0.10	-0.33	-0.34	0.34	-0.07	-0.24	-0.22
	prob. 0.94	0.66	0.02	0.13	0.66	0.14	0.13	0.14	0.76	0.30	0.35
Kinnikinnick	corr. 0.01	-0.02	-0.28	0.11	0.01	0.67	0.67	0.20	0.43	-0.46	-0.53
	prob. 0.97	0.95	0.36	0.73	0.98	0.01	0.01	0.52	0.15	0.11	0.06
Lichen Crust	corr. -0.30	0.31	0.01	0.02	0.36	0.08	0.07	-0.06	0.58	-0.39	-0.51
	prob. 0.51	0.49	0.98	0.97	0.42	0.87	0.88	0.90	0.17	0.39	0.25
Litter	corr. 0.20	-0.30	-0.41	-0.18	-0.32	-0.12	-0.12	0.03	0.29	0.02	-0.04
	prob. 0.44	0.24	0.10	0.49	0.21	0.64	0.65	0.92	0.26	0.93	0.87
Mineral	corr. 0.28	-0.40	-0.24	-0.79	0.47	-0.44	-0.44	-0.10	-0.45	-0.15	-0.04
	prob. 0.44	0.25	0.50	0.01	0.17	0.20	0.21	0.78	0.20	0.68	0.90
Moss	corr. -0.62	0.54	-0.56	-0.19	0.32	0.85	0.84	-0.05	0.67	0.67	0.42
	prob. 0.19	0.27	0.25	0.71	0.53	0.03	0.04	0.93	0.14	0.14	0.40
Organic	corr. -0.61	0.34	-0.78	-0.52	0.43	-0.13	-0.11	-0.98	-0.12	0.57	0.66
	prob. 0.58	0.78	0.43	0.65	0.72	0.92	0.93	0.11	0.92	0.61	0.54
Shrub	corr. -0.45	0.35	-0.15	0.10	-0.37	-0.21	-0.22	-0.18	0.13	-0.24	-0.30
	prob. 0.09	0.20	0.61	0.71	0.18	0.46	0.44	0.53	0.64	0.38	0.29
Slash	corr. -0.10	0.04	-0.05	0.32	-0.01	0.21	0.22	-0.04	-0.02	-0.22	-0.25
	prob. 0.69	0.86	0.82	0.17	0.98	0.37	0.36	0.87	0.95	0.35	-0.28
Stump	corr. 0.23	-0.56	-0.65	0.18	0.73	0.89	0.89	0.48	0.62	0.39	0.37
	prob. 0.62	0.19	0.11	0.69	0.06	0.01	0.01	0.28	0.14	0.38	0.41
Unavailable	corr. -0.09	0.10	-0.14	-0.28	-0.18	-0.23	-0.23	0.13	0.21	0.23	0.30
	prob. 0.84	0.83	0.76	0.54	0.69	0.62	0.61	0.78	0.65	0.62	0.51

NOTES: corr. is the Pearson's correlation and prob. is the associated p value, under the hypothesis that the correlation is not significantly different from 0; bold indicates that the correlation is statistically different from zero at $\alpha=0.05$; EASTING is UTM easting (m), NORTHING is UTM northing (m); COSASPECT and SINASPECT are Stage's (1976) transformation of aspect, SL is slope ratio (slope percent/100), ELEV is elevation (m), ELEV SQ is elevation squared (m²), YRSINCE is the number of years since disturbance, TPH is the number of trees per hectare, CCF is the crown competition factor, and BAHA is total basal area per hectare (m²/ha).

Dry sites had a preponderance of litter, with moderate levels of discontinuous grass, bare mineral soil and slash cover (Figure 7). There were minor levels of coarse woody debris, kinnikinnick, lichen crust, and shrub cover. Wet sites were comprised of predominantly grass, both continuous and discontinuous, with moderate components of shrub and slash. Coarse and fine woody debris, kinnikinnick, litter, mineral soil and moss made up a small component of substrate. Mesic sites were also comprised of predominantly grass types, with an increased component of litter and similar slash loadings. Moss and kinnikinnick were also present in moderate levels, with all other substrate types present at low levels.

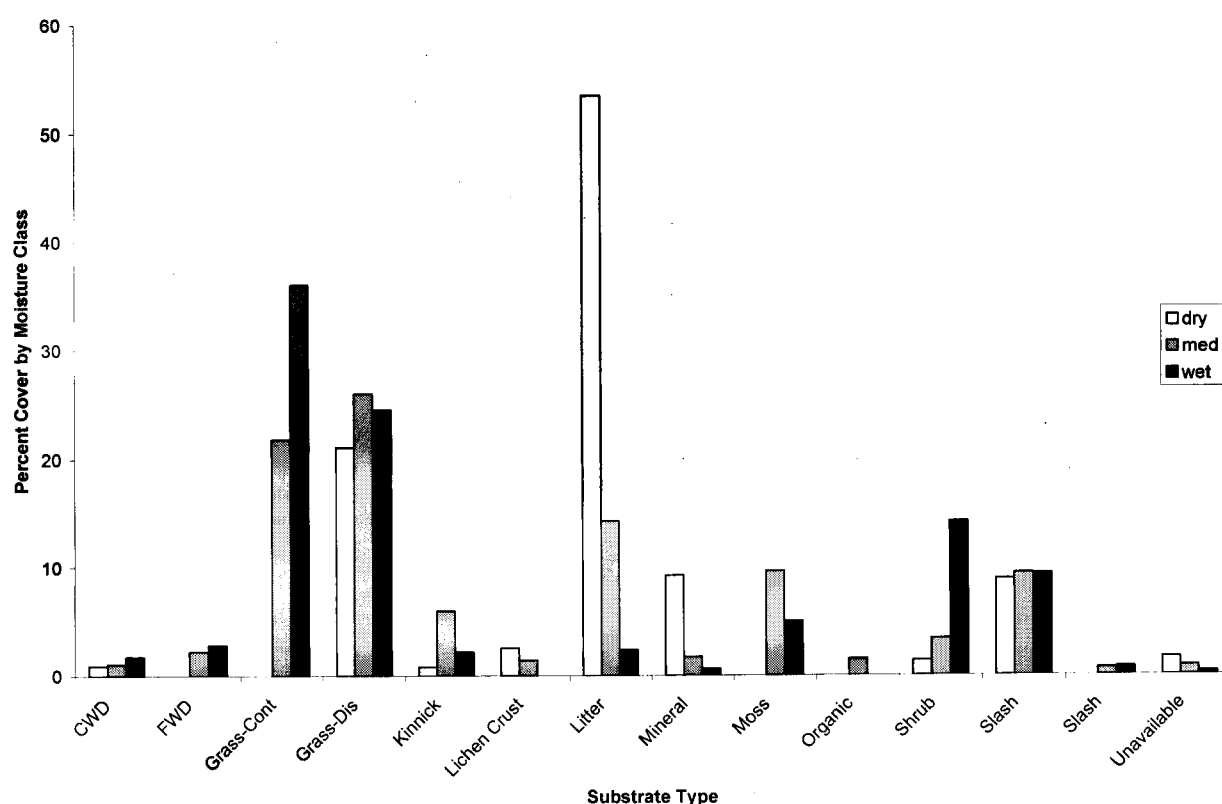


Figure 7. Percent substrate cover by moisture class. NOTES: CWD=woody debris >17.5 cm; FWD= decayed slash/coarse woody debris, which still retains some structure; Grass-Cont=continuous grass cover; Grass-Dis=discontinuous grass cover ("bunchy" or scattered distribution); Kinnick= relatively continuous Kinnikinnick cover with/without needle litter; Lichen Crust=continuous lichen crust; Litter=continuous cover >1 needle thick (needles, cones, etc.); Mineral=bare mineral soil or soil with discontinuous litter cover <1 needle thick; Moss=continuous moss cover; Organic=continuous organic materials; Shrub=shrub; Slash=woody debris <17.5 cm; Unavailable=unavailable for regeneration, e.g., exposed rock, preexisting trees.

A Chi-Square test (Table 16) indicated that the distribution of regeneration on available substrates was significantly affected by substrate type for some height classes and moisture classes. For dry sites, germinants (0-14.9 cm) and Height Class 3 (100-129.9 cm) regeneration were absent; abundance of both Height Class 1 (15-49.9 cm) and 2 (50-99.9 cm) seedlings was significantly affected by substrate, while Height Class 4 (>129.9 cm) was not. On mesic sites, only Height Class 1 regeneration was significantly affected by substrate. Despite the small number of plots on wet sites, the occurrence of germinant, Height Class 1 and Height Class 4 regeneration was significantly affected by substrate.

Table 16. One-tail probability that the observed seedling distribution does not differ from the expected seedling distribution, based on a Chi-Squared test.

Moisture Class	n	Height Class				
		0-15cm	15-50cm	50-100cm	100-130cm	130+cm
dry	9	-	<0.01	<0.01	-	0.91
mesic	14	0.35	0.01	0.81	0.46	0.96
wet	12	<0.01	<0.01	0.99	-	0.02

NOTES: n=number of substrate types; "-" indicates no observed regeneration stems; bold=significantly different at $\alpha=0.05$.

The incidence of germinants on substrates can be considered an indication of which substrate types are suitable for seedling germination. Relative to these levels of substrate, the incidence of germinants varied (Figure 8), where a value of one indicates that the number of regeneration stems was in proportion to substrate availability, less than one indicates regeneration was underrepresented relative to substrate availability, and greater than one indicates that regeneration was overrepresented relative to substrate availability.

There were no germinants tallied on dry sites. On mesic sites, germinants were slightly overrepresented (proportion >1.0) on discontinuous grass, kinnikinnick, lichen crust, litter, and mineral soil, indicating potentially favourable germination sites. Germinants were underrepresented but present on continuous grass, moss, and slash. All other substrates were present, but no regeneration was observed, indicating potentially unsuitable substrate types.

On wet sites, germinants were highly overrepresented on moss, indicating a very suitable site for germination. Continuous grass cover provided a relatively neutral to unfavourable

substrate. Lichen crust and exposed organic soils were not represented on wet sites. All other substrates had no observed germinants and are potentially unsuitable substrates for germination.

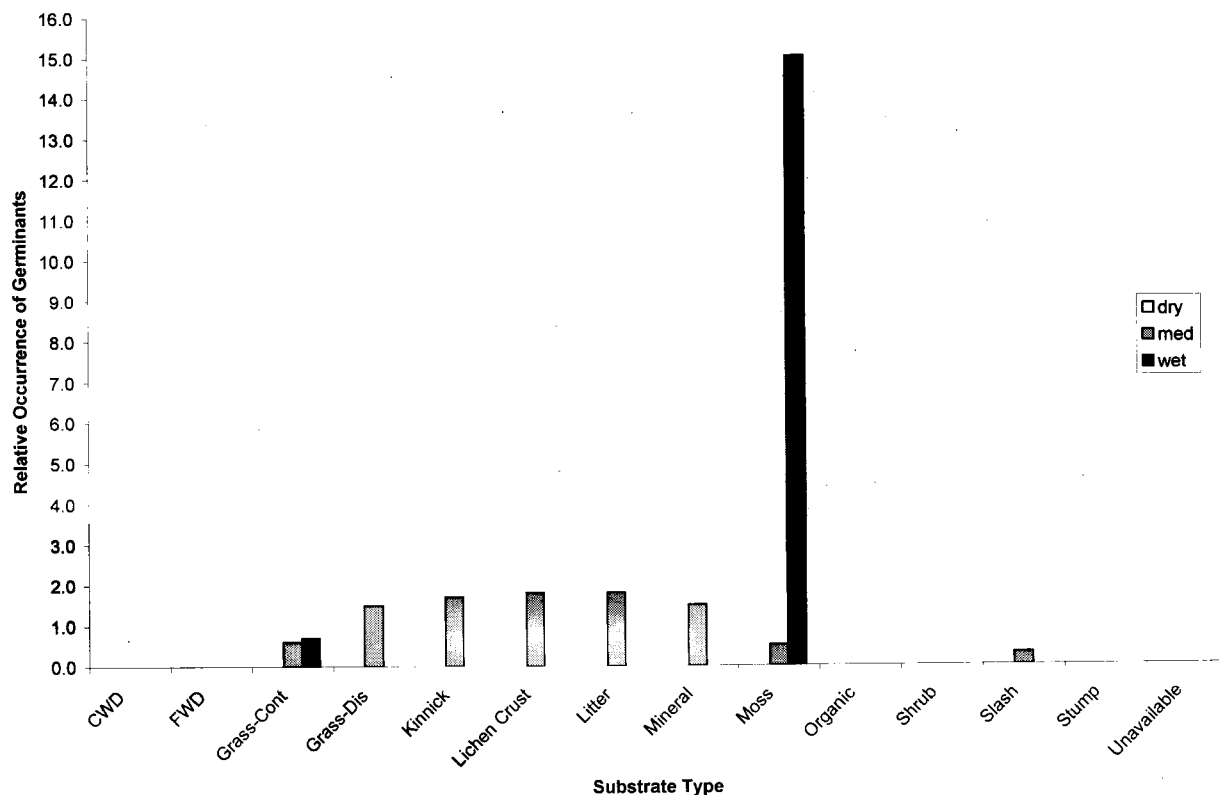


Figure 8. Relative occurrence of germinants by moisture class and substrate type. NOTES: CWD=woody debris >17.5 cm; FWD= decayed slash/coarse woody debris, which still retains some structure; Grass-Cont=continuous grass cover; Grass-Dis=discontinuous grass cover ("bunchy" or scattered distribution); Kinnick=relatively continuous Kinnikinnick cover with/without needle litter; Lichen Crust=continuous lichen crust; Litter=continuous cover >1 needle thick (needles, cones, etc.); Mineral=bare mineral soil or soil with discontinuous litter cover <1 needle thick; Moss=continuous moss cover; Organic=continuous organic materials; Shrub=shrub; Slash=woody debris <17.5 cm; Unavailable=unavailable for regeneration, e.g., exposed rock, preexisting trees.

The presence of small (Class 1) regeneration can provide an indication of which substrates are suitable for seedling establishment (Figure 9). The substrates deemed suitable for germination differed from those that supported established regeneration. Substrate preference was particularly evident for dry sites. Kinnikinnick and shrubs were highly overrepresented. Litter was slightly overrepresented. Discontinuous grass, which comprised 21% of observed substrates on dry sites, had no observed Class 1 regeneration,

indicating an unsuitable substrate under low moisture conditions. Grass, slash and shrub together comprised 84% of wet site substrates; however, the majority of regeneration was observed on moss and litter. For mesic sites, regeneration exhibited less clear preferences. Fine woody debris, continuous grass cover, lichen crust and mineral soil were all slightly overrepresented, indicating a slightly preferable substrate. All other substrates were slightly underrepresented.

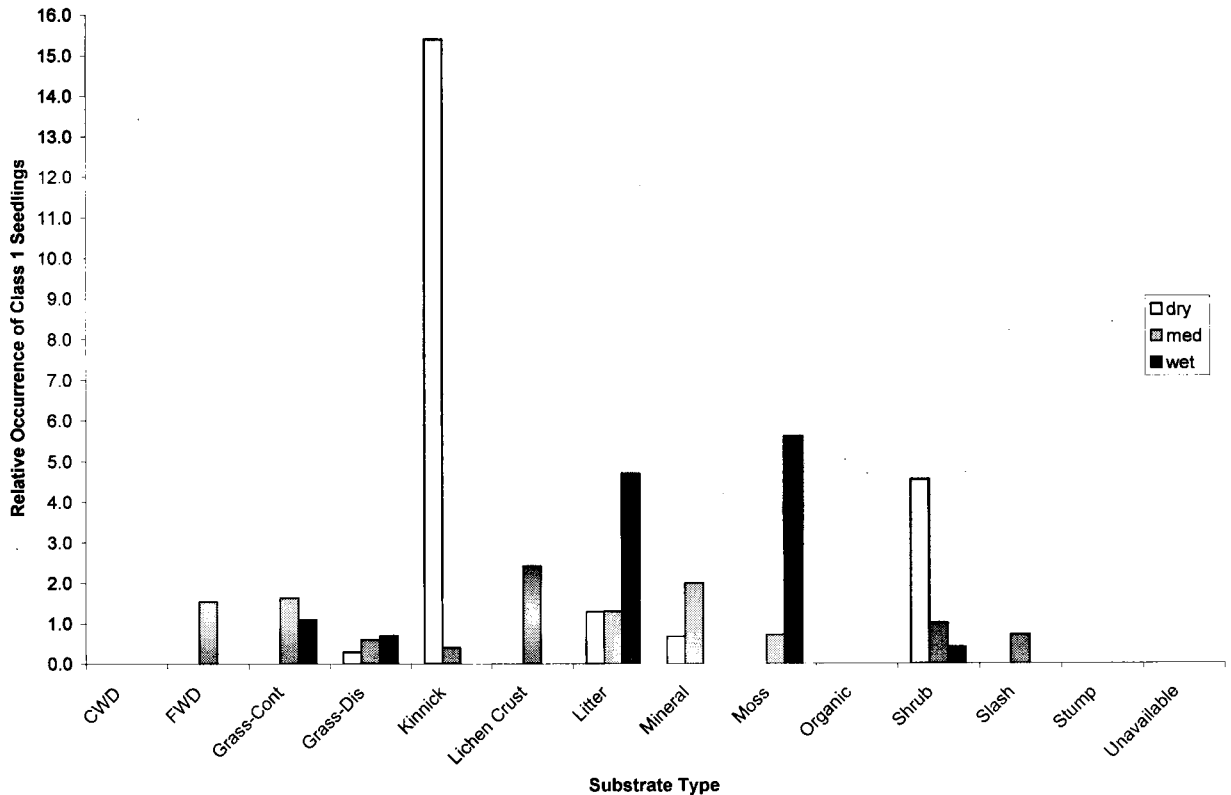


Figure 9. Relative occurrence of Class 1 regeneration by moisture class and substrate type. NOTES: CWD=woody debris >17.5 cm; FWD= decayed slash/coarse woody debris, which still retains some structure; Grass-Cont=continuous grass cover; Grass-Dis=discontinuous grass cover ("bunchy" or scattered distribution); Kinnick=relatively continuous Kinnikinnick cover with/without needle litter; Lichen Crust=continuous lichen crust; Litter=continuous cover >1 needle thick (needles, cones, etc.); Mineral=bare mineral soil or soil with discontinuous litter cover <1 needle thick; Moss=continuous moss cover; Organic=continuous organic materials; Shrub=shrub; Slash=woody debris <17.5 cm; Unavailable=unavailable for regeneration, e.g., exposed rock, preexisting trees.

Taller height classes were generally older, and very probably established on substrates that were different from the current states, and were therefore unsuitable for examining the

relationship between germination or establishment and substrate. For example, the relationship between substrate type and large (Class 4) regeneration was considerably different (see Figure 10). This may reflect changes in substrate over time beneath established regeneration. For example, all large regeneration on dry sites was located on litter. Since seedlings shed needles over time, substrate may be the result of, not the factor leading to, seedling establishment. The lack of large regeneration stems situated on shrub or kinnikinnick substrate may be the result of having outcompeted these vegetation types.

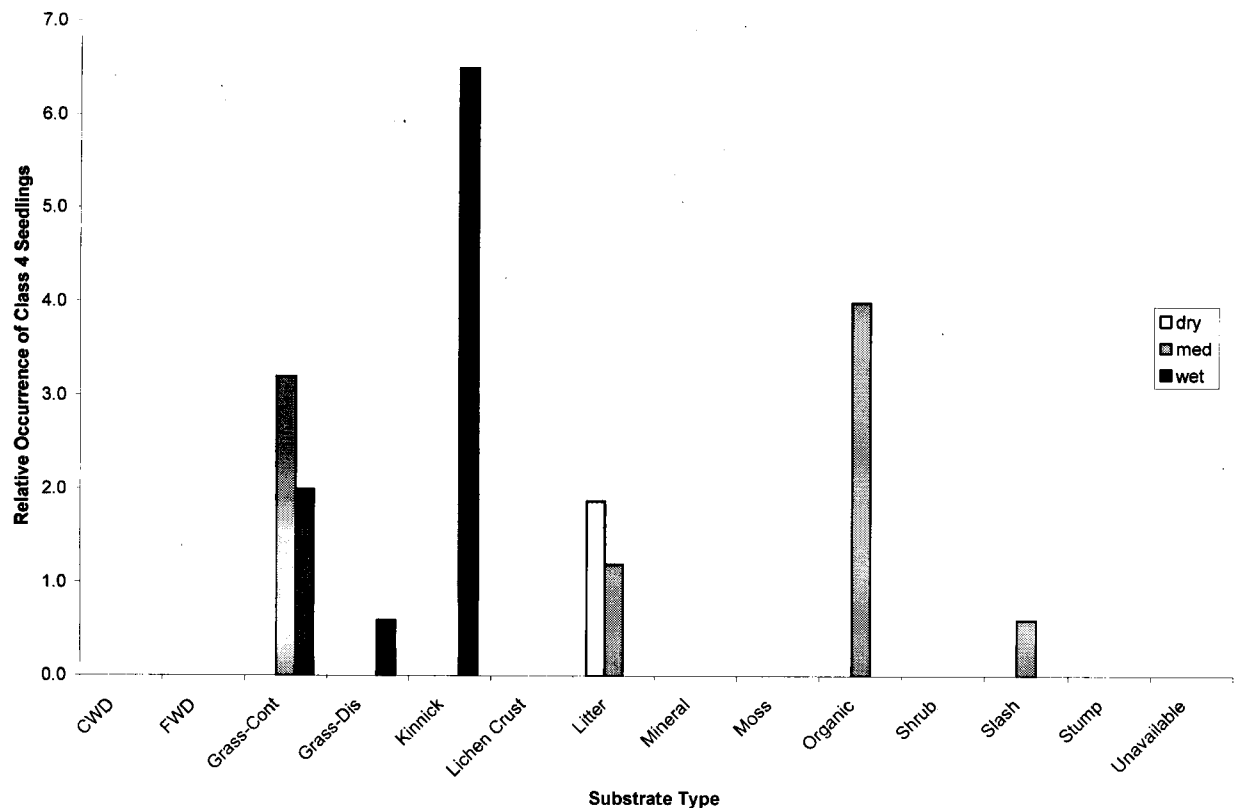


Figure 10. Relative occurrence of Class 4 regeneration by moisture class and substrate type. NOTES: CWD=woody debris >17.5 cm; FWD= decayed slash/coarse woody debris, which still retains some structure; Grass-Cont=continuous grass cover; Grass-Dis=discontinuous grass cover ("bunchy" or scattered distribution); Kinnick=relatively continuous Kinnikinnick cover with/without needle litter; Lichen Crust=continuous lichen crust; Litter=continuous cover >1 needle thick (needles, cones, etc.); Mineral=bare mineral soil or soil with discontinuous litter cover <1 needle thick; Moss=continuous moss cover; Organic=continuous organic materials; Shrub=shrub; Slash=woody debris <17.5 cm; Unavailable=unavailable for regeneration, e.g., exposed rock, preexisting trees.

Competition and Release Indices

Simple correlations between abundance of Douglas-fir regeneration and plot-level indices are presented in Table 17. None of the correlations between any of the plot-level indices and regeneration abundance by height class differed significantly from zero (all $p > 0.05$).

Table 18 provides the simple correlations between abundance of Douglas-fir regeneration and spatial indices, by height class and for three search radii (3 m, 7 m and 11 m). Incidence of germinants was positively correlated with competition indices; while the incidence of Class 1 regeneration was negatively correlated with release indices. Correlations were not significantly different from zero ($p > 0.05$) between either competition or release indices and abundance of higher class regeneration.

Table 17. Simple correlations between regeneration abundance and plot-level indices by height class.

Height Class		Stand Level Indices		
		CCF	BAHA	PCTBAREM
0-15cm	corr.	0.36	0.39	-0.29
	prob.	0.08	0.06	0.16
15-50cm	corr.	0.26	0.32	-0.26
	prob.	0.21	0.12	0.21
50-100cm	corr.	0.09	0.07	-0.04
	prob.	0.68	0.75	0.83
100-130cm	corr.	0.00	-0.01	-0.02
	prob.	0.98	0.98	0.92
130+cm	corr.	-0.16	-0.19	0.10
	prob.	0.46	0.37	0.65

NOTES: corr. is the Pearson's correlation and prob. is the associated p value, under the hypothesis that the correlation is not significantly different from 0; bold indicates that the correlation is statistically different from zero at $\alpha = 0.05$; CCF is the crown competition factor, BAHA is total basal area per hectare (m^2/ha), and PCTBAREM is the total percent basal area removed.

Correlations between germinants and competition indices were generally strongest at the 7 m and/or 11 m search radius. Examination of scatterplots illustrated the trends relative to germinant abundance. Plot-level competitive indices (Figure 11 a-c) exhibit an inverse parabolic to triangular pattern when plotted against germinant abundance, while percent basal area removal, a release index, did not exhibit any pattern. Spatial indices all show very similar patterns. At the 3 m search radii, patterns are unclear. At 7 m and 11 m, an inverse parabolic shape becomes clear (e.g., Figure 12 a-f).

Table 18. Simple correlations between regeneration abundance and spatial indices, by height class and search radius.

Search Radius	Height Class	Competition Indices										Release Indices									
		Hegy1	Hegy2	OpieA	OpieB	Bella1A	Bella1B	Bella2A	Bella2B	BAN		Hegy1	Hegy2	OpieA	OpieB	Bella1A	Bella1B	Bella2A	Bella2B	BAN	
3m	0-15cm	corr.	0.22	0.34	0.30	0.19	0.36	0.31	0.35	0.19	0.28	0.05	0.10	0.04	0.01	0.11	0.06	0.13	0.01	0.06	
		prob.	0.30	0.10	0.15	0.36	0.08	0.14	0.09	0.36	0.18	0.83	0.63	0.85	0.96	0.60	0.77	0.54	0.96	0.77	
	15-50cm	corr.	-0.17	-0.06	-0.09	-0.09	-0.04	-0.03	-0.03	-0.09	-0.04	-0.41	-0.38	-0.42	-0.43	-0.40	-0.42	-0.35	-0.43	-0.41	
		prob.	0.41	0.77	0.66	0.66	0.85	0.90	0.87	0.66	0.86	0.04	0.06	0.04	0.03	0.05	0.04	0.08	0.03	0.04	
50-100cm		corr.	-0.03	0.02	0.03	-0.02	0.04	0.01	0.04	-0.02	0.01	0.19	0.20	0.18	0.22	0.20	0.26	0.18	0.22	0.27	
		prob.	0.89	0.91	0.87	0.91	0.84	0.95	0.84	0.91	0.97	0.36	0.33	0.39	0.28	0.33	0.21	0.39	0.28	0.19	
	100-130cm	corr.	-0.14	-0.14	-0.11	-0.13	-0.13	-0.14	-0.12	-0.13	-0.13	0.12	0.10	0.12	0.19	0.11	0.20	0.09	0.19	0.22	
		prob.	0.49	0.52	0.60	0.55	0.54	0.51	0.58	0.55	0.53	0.58	0.62	0.57	0.37	0.59	0.34	0.66	0.37	0.30	
130+cm		corr.	0.01	-0.15	0.01	0.05	-0.14	-0.13	-0.16	0.05	-0.14	-0.07	-0.08	-0.07	-0.02	-0.08	-0.02	-0.08	-0.02	-0.01	
		prob.	0.97	0.49	0.97	0.81	0.51	0.54	0.45	0.81	0.49	0.74	0.71	0.74	0.94	0.72	0.92	0.71	0.94	0.97	

Search Radius	Height Class	Competition Indices										Release Indices									
		Hegy1	Hegy2	OpieA	OpieB	Bella1A	Bella1B	Bella2A	Bella2B	BAN		Hegy1	Hegy2	OpieA	OpieB	Bella1A	Bella1B	Bella2A	Bella2B	BAN	
7m	0-15cm	corr.	0.26	0.45	0.46	0.32	0.50	0.47	0.47	0.32	0.39	-0.03	0.06	0.01	-0.01	0.06	0.08	0.05	-0.01	0.01	
		prob.	0.22	0.03	0.02	0.13	0.01	0.02	0.02	0.13	0.06	0.87	0.78	0.96	0.95	0.78	0.70	0.81	0.95	0.96	
	15-50cm	corr.	-0.06	0.20	0.05	0.10	0.12	0.29	0.13	0.10	0.27	-0.42	-0.38	-0.43	-0.41	-0.35	-0.36	-0.24	-0.41	-0.35	
		prob.	0.77	0.34	0.80	0.63	0.57	0.16	0.53	0.63	0.19	0.04	0.06	0.03	0.04	0.09	0.08	0.25	0.04	0.09	
50-100cm		corr.	0.03	0.06	0.10	0.11	0.09	0.10	0.07	0.11	0.04	0.26	0.23	0.10	0.29	0.06	0.28	-0.01	0.29	0.29	
		prob.	0.89	0.77	0.63	0.60	0.67	0.63	0.73	0.60	0.87	0.21	0.26	0.64	0.17	0.77	0.18	0.95	0.17	0.15	
	100-130cm	corr.	-0.03	-0.01	0.01	0.03	-0.01	0.04	0.00	0.03	-0.02	0.25	0.19	0.07	0.30	0.03	0.26	-0.03	0.30	0.28	
		prob.	0.89	0.95	0.98	0.87	0.97	0.87	0.98	0.87	0.93	0.23	0.36	0.74	0.15	0.90	0.21	0.90	0.15	0.17	
130+cm		corr.	-0.11	-0.23	-0.05	-0.06	-0.21	-0.21	-0.23	-0.06	-0.23	0.10	0.01	-0.13	0.14	-0.17	0.07	-0.19	0.14	0.13	
		prob.	0.61	0.27	0.82	0.79	0.32	0.30	0.26	0.79	0.26	0.65	0.95	0.54	0.49	0.41	0.73	0.37	0.49	0.52	

Search Radius	Height Class	Competition Indices										Release Indices									
		Hegy1	Hegy2	OpieA	OpieB	Bella1A	Bella1B	Bella2A	Bella2B	BAN		Hegy1	Hegy2	OpieA	OpieB	Bella1A	Bella1B	Bella2A	Bella2B	BAN	
11m	0-15cm	corr.	0.21	0.43	0.46	0.34	0.50	0.48	0.47	0.34	0.35	-0.05	0.02	0.01	-0.01	0.06	0.10	0.05	-0.01	-0.04	
		prob.	0.32	0.04	0.02	0.10	0.01	0.02	0.02	0.10	0.09	0.83	0.94	0.96	0.96	0.78	0.65	0.81	0.96	0.85	
	15-50cm	corr.	0.03	0.29	0.05	0.14	0.12	0.31	0.13	0.14	0.33	-0.36	-0.25	-0.43	-0.38	-0.35	-0.30	-0.24	-0.38	-0.12	
		prob.	0.88	0.16	0.80	0.51	0.57	0.13	0.53	0.51	0.11	0.08	0.22	0.03	0.06	0.09	0.15	0.25	0.06	0.56	
50-100cm		corr.	0.04	0.09	0.10	0.12	0.09	0.11	0.07	0.12	0.08	0.15	0.12	0.10	0.28	0.06	0.27	-0.01	0.28	0.05	
		prob.	0.84	0.68	0.63	0.56	0.67	0.61	0.73	0.56	0.70	0.48	0.57	0.64	0.18	0.77	0.20	0.95	0.18	0.80	
	100-130cm	corr.	-0.02	0.01	0.01	0.05	-0.01	0.04	0.00	0.05	0.01	0.13	0.07	0.07	0.27	0.03	0.21	-0.03	0.27	0.03	
		prob.	0.92	0.96	0.98	0.82	0.97	0.83	0.98	0.82	0.95	0.53	0.74	0.74	0.20	0.90	0.32	0.90	0.20	0.89	
130+cm		corr.	-0.11	-0.20	-0.05	-0.05	-0.21	-0.20	-0.23	-0.05	-0.17	0.10	0.03	-0.13	0.15	-0.17	0.07	-0.19	0.15	0.09	
		prob.	0.61	0.34	0.82	0.80	0.32	0.34	0.26	0.80	0.42	0.63	0.87	0.54	0.49	0.41	0.74	0.37	0.49	0.68	

NOTES: corr. is the Pearson's correlation and prob. is the associated p value, under the hypothesis that the correlation is not significantly different from 0; bold indicates that the correlation is statistically different from zero at $\alpha=0.05$; see Table 7 for definition of indices.

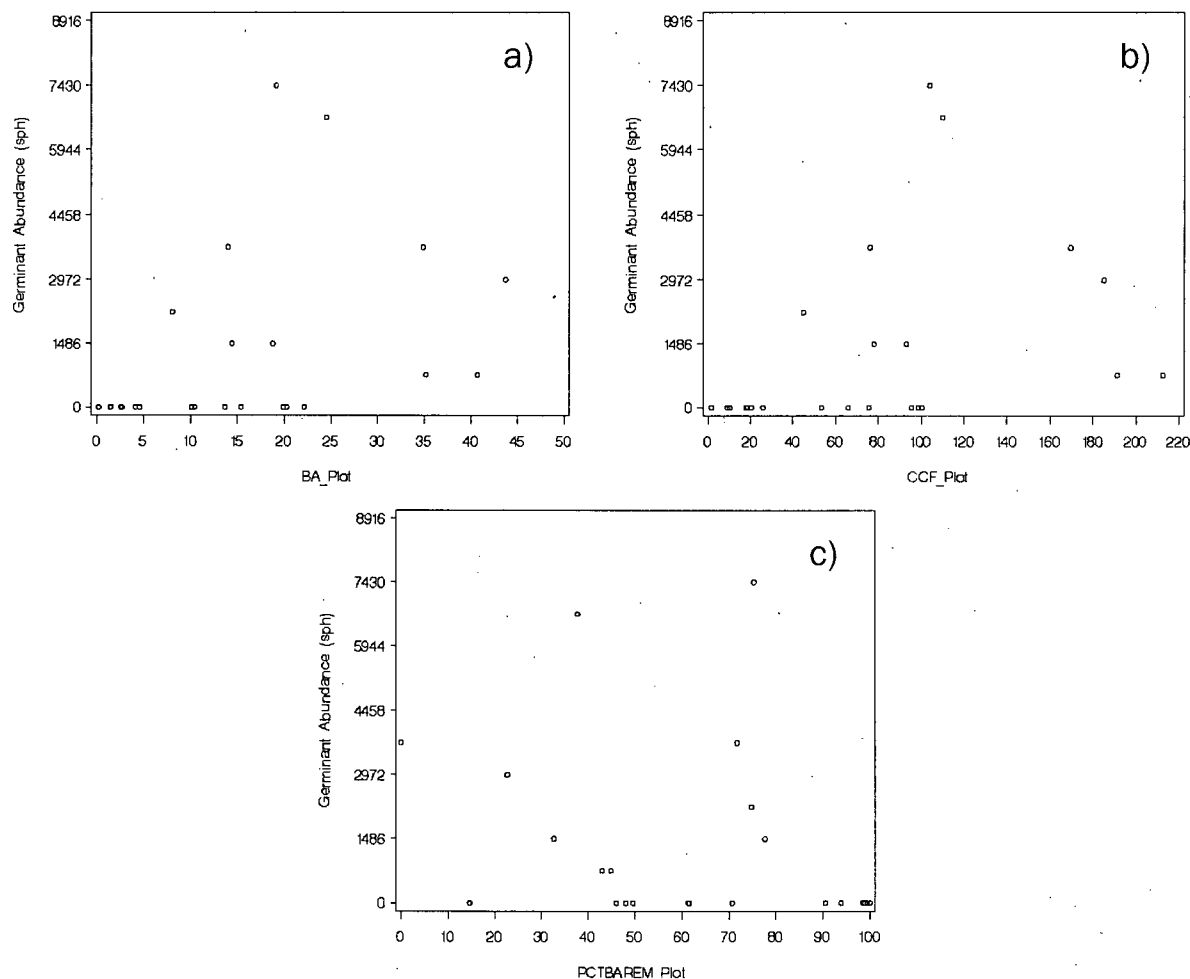


Figure 11. Stems per hectare of germinant (0-14.9 cm) regeneration vs. plot-level indices: a) basal area per hectare (BA_Plot); b) crown competition factor (CCF_plot), and c) percent basal area removed (PCTBAREM_Plot).

Correlations between Class 1 regeneration abundance and release indices generally decreased with increasing search radius. Scatterplots revealed very different trends for competition and release indices. Plot-level indices (Figure 13 a-c) did not exhibit a marked pattern in two dimensions (regeneration abundance vs. index), nor did competition indices. Release indices at a 3 m search radius revealed that the majority of variability in regeneration abundance occurred when there was no release within a 3 m radius around the centre of the (2.07 m) plot. Where some form of release did occur, regeneration abundance was low, varying from 0 to 1486 stems per hectare (0 to 2 stems per plot). This trend was consistent across all release indices.

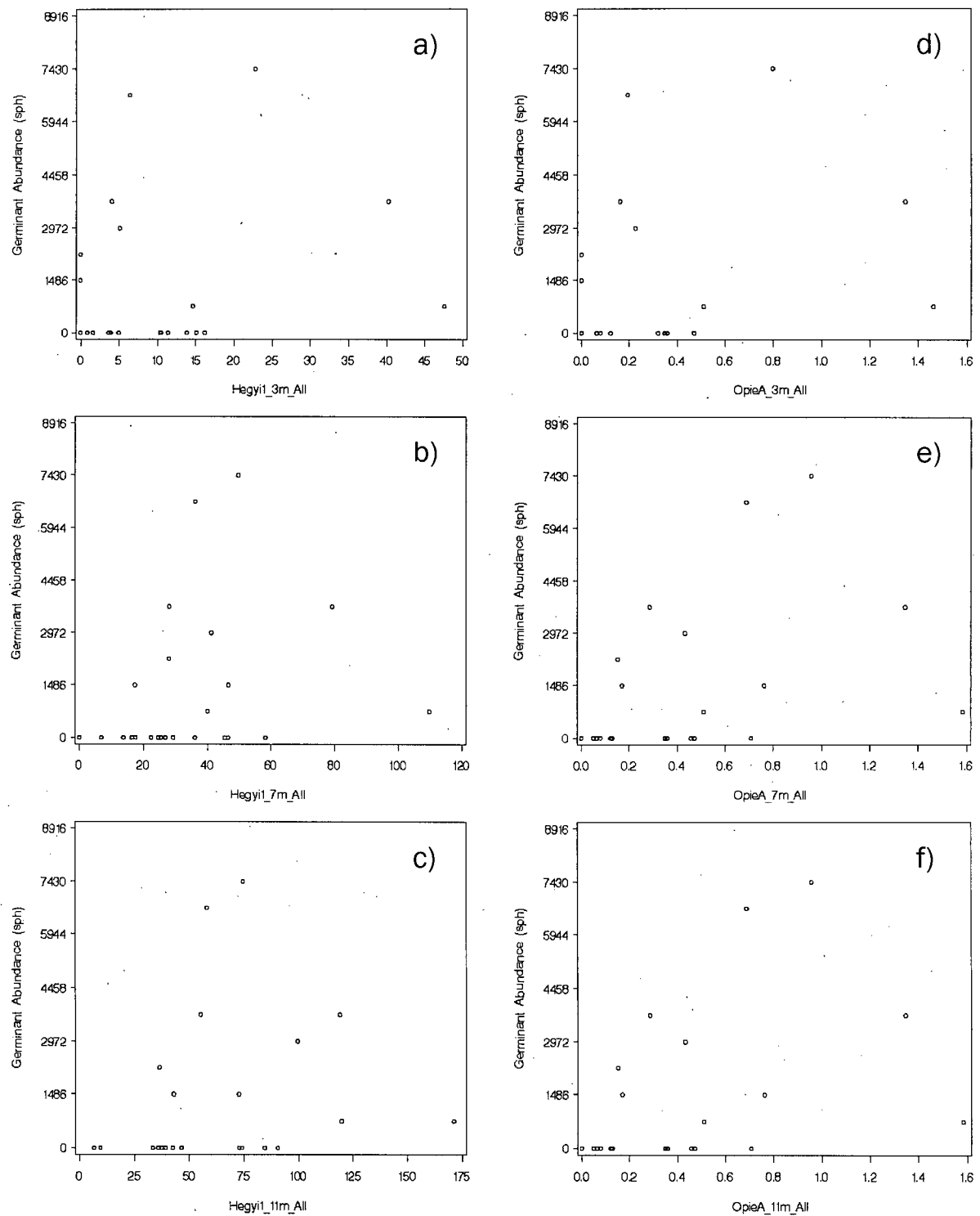


Figure 12. Stems per hectare of germinant (0-14.9 cm) regeneration vs. (a-c) Hegyi1 and (d-f) OpieA competition indices for three search radii (e.g., Hegyi1_3m_All indicates Hegyi1 index calculated based on a 3 m search radius, using all live trees).

Increasing the search radius produced a less clear pattern. Plots with the highest and most variable levels of regeneration stems per hectare were found when release was 0 m²/ha within a 3m search radius. At a 7 m search radius, the most variability was found when 10-20 m²/ha was removed; as the search radius increased, the range of basal area removal resulted in increased variability (e.g., Figure 14 a-f).

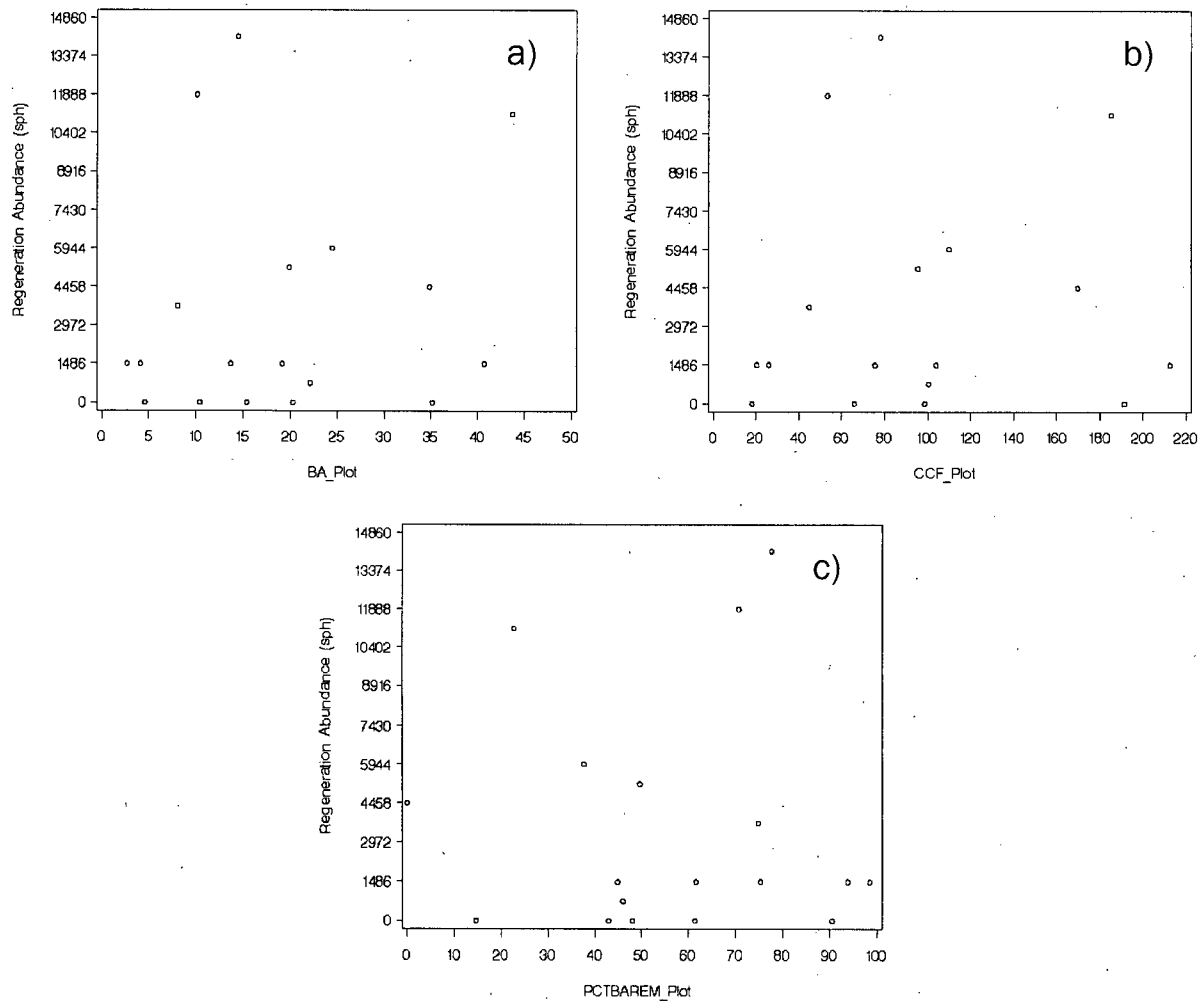


Figure 13. Stems per hectare of Class 1 (15-49.9 cm) regeneration vs. plot-level indices: a) basal area per hectare (BA_Plot); b) crown competition factor (CCF_Plot), and c) percent basal area removed (PCTBAREM_Plot).

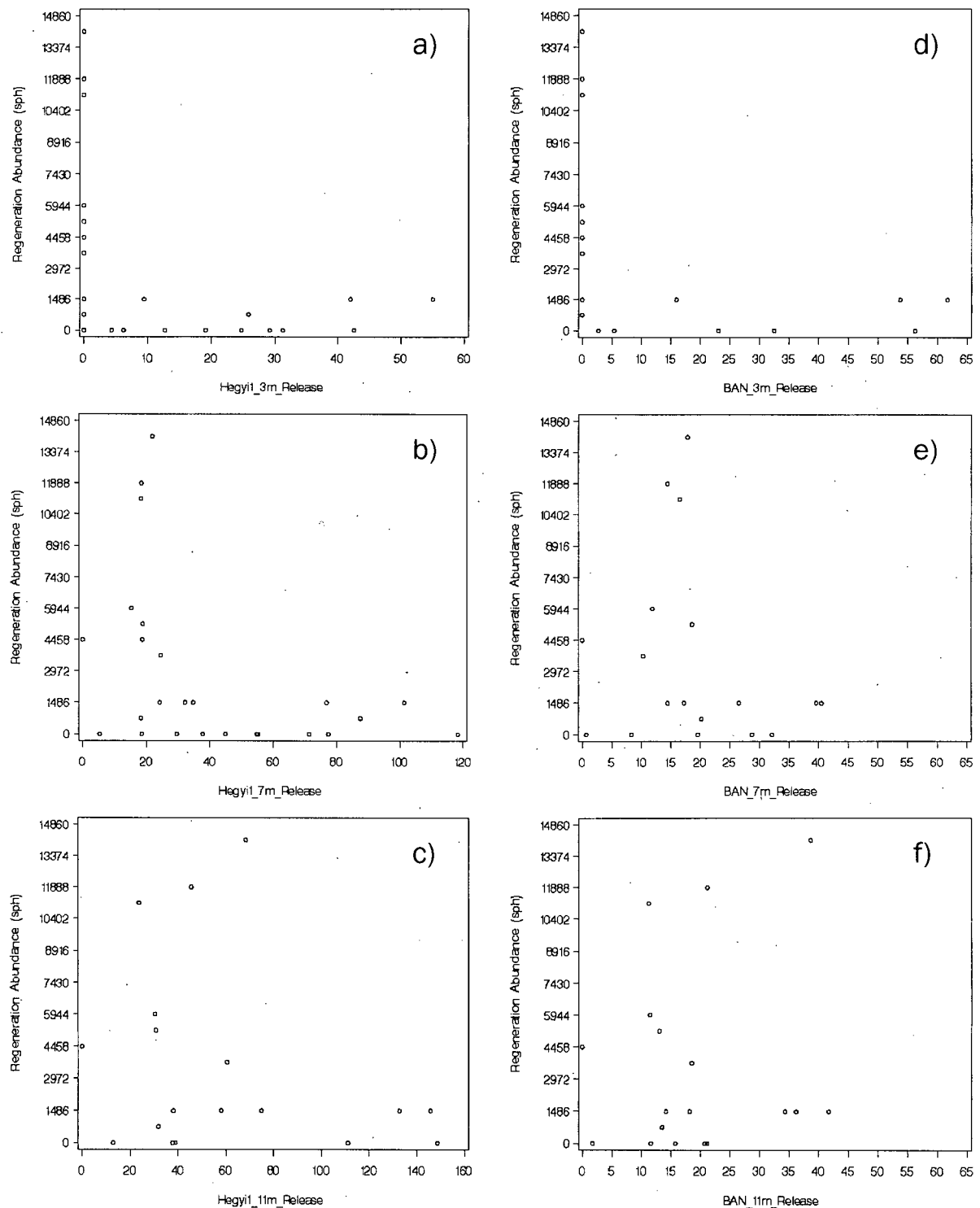


Figure 14. Stems per hectare of Class 1 (15-49.9 cm) regeneration vs. (a-c) Hegyi1 and (d-f) Neighbourhood Basal Area release indices, for three search radii (e.g., Hegyi1_3m_Release indicates Hegyi1 index calculated based on a 3 m search radius, using all dead trees).

Point Pattern Analysis

For all clump types (clumps comprised solely of subsequent regeneration, clumps with advance regeneration present, and all clumps combined), number of stems per clump had a strong positive correlation with the abundance of ponderosa pine and Douglas-fir within the sampled regeneration plot (Table 19). There was a negative correlation between percent basal area removed and the number of clumps with advance regeneration, and a concomitant positive correlation with crown competition factor and basal area per hectare. This pattern was reversed for clumps comprised solely of subsequent regeneration. The number of clumps was negatively correlated with northing and positively correlated with easting.

Results of Ripley's analyses were extremely variable, making generalizations difficult. SVS visualizations and plot photos were used to help interpret the results; these can be found in Appendix M. Summaries of univariate and bivariate analyses are presented in Tables 20 and 21, indicating whether observed patterns could be classified as clustered (aggregated) or uniform (repulsed) based on the 90% confidence envelopes generated with Monte Carlo simulation.

Univariate analyses allow overstory spatial patterns to be discussed in general terms. Total trees (live, dead and cut trees, indicative of pre-harvest sph for harvested stands or pre-mortality sph for undisturbed stands) provided the most consistent results. At small scales, trees exhibited aggregated or neutral patterns, but no uniformity. Uniformity occurred sporadically at larger scales only. Some stands exhibited clustering at larger spatial scales as well.

Harvesting and mortality affected the spatial patterning of the overstory. Group selection can increase clumpiness, while single tree selection can increase uniformity. For some plots, removing dead trees (lost to either harvesting or mortality) decreased aggregation, and for other plots it increased aggregation. One noticeable change was the appearance of uniformity at very small scales, between 0.5 and 1.5 m, in many partially cut stands.

Table 19. Simple correlations between number of clumps/clumps abundance (sph) and plot-level variables.

Variable		All Clumps		Advance + Subsequent		Subsequent Only	
		No. Clumps	Abund. (sph)	No. Clumps	Abund. (sph)	No. Clumps	Abund. (sph)
EASTING	corr.	0.40	0.28	0.48	0.50	-0.01	0.15
	prob.	0.05	0.18	0.02	0.01	0.97	0.47
NORTHING	corr.	-0.31	-0.39	-0.31	-0.48	-0.06	-0.37
	prob.	0.13	0.05	0.13	0.01	0.79	0.07
COSASPECT	corr.	0.33	0.22	0.03	0.35	0.37	0.17
	prob.	0.11	0.29	0.90	0.09	0.07	0.42
SINASPECT	corr.	-0.27	0.01	-0.36	-0.12	0.05	-0.02
	prob.	0.19	0.94	0.08	0.58	0.82	0.91
SL	corr.	0.14	-0.12	0.32	0.04	-0.17	-0.27
	prob.	0.51	0.56	0.12	0.83	0.42	0.19
ELEV	corr.	-0.14	-0.34	-0.35	-0.33	0.19	-0.22
	prob.	0.51	0.10	0.09	0.11	0.35	0.28
YRSINCE	corr.	-0.02	-0.05	-0.02	0.00	0.00	-0.02
	prob.	0.94	0.82	0.94	0.99	0.98	0.93
PLANT	corr.	-0.22	-0.24	-0.40	-0.38	0.15	-0.03
	prob.	0.30	0.25	0.05	0.06	0.48	0.88
TPH	corr.	-0.05	0.03	-0.04	-0.03	-0.03	0.04
	prob.	0.79	0.88	0.86	0.88	0.89	0.85
CCF	corr.	0.15	0.07	0.55	0.29	-0.39	-0.12
	prob.	0.48	0.75	<0.01	0.16	0.05	0.57
BAHA	corr.	0.20	0.11	0.60	0.33	-0.38	-0.10
	prob.	0.33	0.61	<0.01	0.11	0.06	0.64
PCTBAREM	corr.	-0.26	-0.17	-0.70	-0.39	0.42	0.11
	prob.	0.21	0.41	<0.01	0.06	0.04	0.59
Regen Plot At (sph)	corr.	-0.12	0.05	-0.05	0.15	-0.09	-0.08
	prob.	0.58	0.82	0.81	0.47	0.67	0.71
Regen Plot Bl (sph)	corr.	-0.34	-0.29	-0.19	-0.21	-0.22	-0.17
	prob.	0.09	0.16	0.37	0.32	0.28	0.42
Regen Plot Ep (sph)	corr.	0.21	0.00	-0.25	-0.28	0.51	0.07
	prob.	0.33	0.99	0.22	0.18	0.01	0.75
Regen Plot Fd (sph)	corr.	0.59	0.74	0.54	0.83	0.16	0.52
	prob.	<0.01	<0.01	0.01	<0.01	0.46	0.01
Regen Plot Lw (sph)	corr.	0.01	-0.05	-0.23	-0.20	0.24	0.02
	prob.	0.97	0.81	0.28	0.34	0.24	0.92
Regen Plot Pl (sph)	corr.	-0.18	-0.22	-0.50	-0.44	0.30	-0.03
	prob.	0.39	0.30	0.01	0.03	0.14	0.88
Regen Plot Py (sph)	corr.	-0.05	0.78	0.08	0.59	-0.15	0.89
	prob.	0.81	<0.01	0.69	<0.01	0.47	<0.01
Regen Plot Sxw (sph)	corr.	0.06	-0.07	-0.08	-0.13	0.16	0.04
	prob.	0.78	0.76	0.70	0.55	0.46	0.84
Regen Plot Total (sph)	corr.	0.58	0.76	0.39	0.77	0.30	0.56
	prob.	<0.01	<0.01	0.05	<0.01	0.15	<0.01

NOTES: corr. is the Pearson's correlation and prob. is the associated p value, under the hypothesis that the correlation is not significantly different from 0; bold indicates that the correlation is statistically different from zero at $\alpha=0.05$; EASTING is UTM easting (m), NORTHING is UTM northing (m), COSASPECT and SINASPECT are Stage's (1976) transformation of aspect, SL is slope ratio (slope percent/100), ELEV is elevation (m), PLANT is planting status (1=planted 0=not planted), YRSINCE is the number of years since disturbance, TPH is the number of trees per hectare, CCF is the crown competition factor, BAHA is total basal area per hectare (m^2/ha), and PCTBAREM is percent basal area removed.

Table 20. Distance (in m) of statistically significant patterning by pattern type based on Ripley's univariate analysis (e.g., undisturbed spatial plot 10 showed statistically significant clustering of Live+Dead overstory trees at 3.5 m).

Type/Plot	Univariate Ripley's Analysis			
	Live + Dead Overstory Trees		Live Overstory Trees	
	Clustering (m)	Uniformity (m)	Clustering (m)	Uniformity (m)
Undisturbed - 10	3.5	-	3.5	-
Undisturbed - 12	8.5-11	4.5	-	10
Undisturbed - 23	-	8	-	0.5-1.5
Planted - 7	-	-	0.5-3.5	-
Planted - 11	-	-	0.5-1.5/10.5	-
Planted - 14	4.5-7.0	-	-	-
Planted - 15	-	-	n/a	n/a
Planted - 19	-	5.5	1-1.5	-
Planted - 22	-	10.5	n/a	n/a
Planted - 25	3-5.5	11	n/a	n/a
Natural - 1	1-5	9.5-11	-	9.5
Natural - 2	1.5-4/9-11	7	1.5	5.5-7.5
Natural - 3	0.5-5	-	n/a	n/a
Natural - 4	2.5-3.5/11	-	3	0.5-1.5
Natural - 5	0.5-3.5	-	0.5-5	8/10
Natural - 6	1-7.5	-	-	0.5-1.5
Natural - 8	1.5/5.5	-	n/a	n/a
Natural - 9	-	9-9.5	-	0.5-1.5
Natural - 13	-	-	-	0.5-1
Natural - 16	1/4	9.5-11	-	0.5-1.5/10-11
Natural - 17	1.0-2.5	-	0.5-2.5	-
Natural - 18	-	-	-	-
Natural - 20	0.5-8.5	-	1.5/3-9	-
Natural - 21	1-1.5	-	0.5-4.5	-
Natural - 24	0.5-5.5	10-11	0.5-5.5	11

NOTES: n/a indicates that no analysis was completed due to a small ($n < 3$) or nonexistent sample; "-" indicates not significantly different from a Poisson or random pattern.

Results from bivariate analyses were much more difficult to generalize. Relationships between regeneration clumps and planted sites varied considerably. Live tree overstories in naturally regenerated stands often had dispersed (repulsed) relationships with regeneration clumps at small scales and aggregated relationships with regeneration clumps at larger scales, again with obvious exceptions. Relationships between removed overstory trees (presumed sites of resources release) and regeneration clumps also varied considerably; the only evident pattern was repulsion between clumps and removed trees at small scales for planted sites. A few selected plots are discussed in more detail, to illustrate potential sources of variability as well as some dangers inherent in interpretation.

Table 21. Distance (m) of statistically significant patterning by pattern type based on Ripley's bivariate analysis (e.g., undisturbed spatial plot 10 showed statistically significant repulsion between dead overstory trees and subsequent regeneration clumps at 0.5 to 1 m and 7.5 to 11 m).

Type/Plot	Bivariate Ripley's Analysis							
	Live + Dead Overstory Trees vs. "Advance" Clumps		Live Overstory Trees vs. "Subsequent" Clumps		Live Overstory Trees vs. All Clumps		Dead Overstory Trees vs. "Subsequent" Clumps	
	Aggregation (m)	Repulsion (m)	Aggregation (m)	Repulsion (m)	Aggregation (m)	Repulsion (m)	Aggregation (m)	Repulsion (m)
Undisturbed - 10	-	-	n/a	n/a	-	-	-	0.5-1/7.5-11
Undisturbed - 12	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Undisturbed - 23	7.5	0.5-3	n/a	n/a	7-7.5	0.5-2.5	n/a	n/a
Planted - 7	n/a	n/a	0.5-1.5	7.0	0.5-1.5	5-7	-	0.5-1
Planted - 11	n/a	n/a	n/a	n/a	n/a	n/a	-	0.5-1
Planted - 14	-	0.5-1	9-11	0.5-2.5	-	0.5-1/2-5	-	0.5-1
Planted - 15	n/a	n/a	n/a	n/a	n/a	n/a	10.5	-
Planted - 19	8.5-11	-	6.5-11	0.5-1	6.5-11	-	-	-
Planted - 22	n/a	n/a	n/a	n/a	10-11	0.5-5	-	0.5-2
Planted - 25	n/a	n/a	n/a	n/a	n/a	n/a	-	-
Natural - 1	0.5-3	-	n/a	n/a	1.5-3	-	0.5-3.5	-
Natural - 2	-	1-4.5	n/a	n/a	-	0.5-3/4.5	-	0.5-4.5
Natural - 3	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Natural - 4	-	-	-	0.5-2/7.5-11	-	0.5-4/8-8.5	0.5/6.5-8.5	-
Natural - 5	0.5-1	4	-	8-9	-	8-9	-	8-10
Natural - 6	-	5-11	6-10	0.5-1.0	-	-	-	-
Natural - 8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Natural - 9	-	9.0	6-6.5/9	-	-	0.5-1.5	-	3.5-5
Natural - 13	-	7.5-9.5	n/a	n/a	-	7.5-9.5	-	7.5-9.0
Natural - 16	5-5.5	10.5-11	n/a	n/a	-	0.5-2	2.5-5	9-11
Natural - 17	n/a	n/a	n/a	n/a	-	0.5-3.5	5	0.5-2.5
Natural - 18	n/a	n/a	-	0.5-4.5	-	0.5-6.5	-	3-6.5
Natural - 20	n/a	n/a	10	0.5-1	-	0.5-1/2.5	-	1.5-2.5/5.5
Natural - 21	n/a	n/a	0.5-1.5	6.5-11	0.5-1.5	6.5-11	7.5-9	-
Natural - 24	-	5.5-11	n/a	n/a	-	7-7.5	-	0.5-1

NOTES: n/a indicates that no analysis was completed due to a small (n<3) or nonexistent sample; "-" indicates not significantly different from a Poisson or random pattern.

Plot 7 is representative of planted sites found in the IDFdm2 (Appendix L, Figure L.7). Post harvest species consisted of predominantly lodgepole pine and western larch, with some Douglas-fir. While it is assumed that planting occurred at a fairly wide spacing, a number of clumps were still found on this site. Regeneration clump composition was predominantly Class 4 lodgepole pine and western larch, with Douglas-fir from all height classes, and a few scattered Class 1 larch regeneration. It appears that, on planted sites, natural regeneration "bridged" the spaces between planted trees, forming clumps with very different species composition than was found on naturally regenerated sites, which were generally predominantly Douglas-fir. Examination of SVS visualizations and plot photos provided graphic illustration. Clumps occurred near, and away from, existing trees, but no trend was visible. This was generally true of all plots with high basal area removal, where site conditions are more homogeneous.

In this plot, there was evidence of clustering of overstory trees at small scales (Figure 15), which reflects the fact that some of the regeneration in the clumps that formed following harvesting were maturing into large (DBH > 7.5 cm) trees. While clumps containing advance regeneration were rare, likely due to harvesting impacts, there were still a number of clumps on this plot (14 clumps, averaging approximately six stems per clump). Bivariate analysis of the location of both subsequent and all regeneration clumps against live trees indicated that there was aggregation at very small scales between the two (Figure 16), and repulsion between regeneration clumps and removed trees at very small scales (Figure 17).

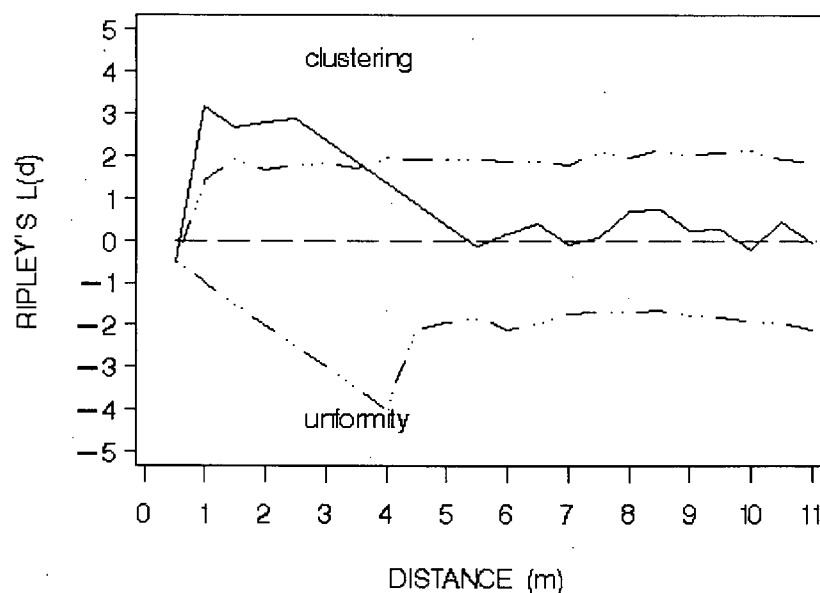


Figure 15. Univariate Ripley's analysis, live trees, Plot 7. NOTES: Dashed lines indicate 90% confidence envelopes under random spacing; solid line indicates observed values.

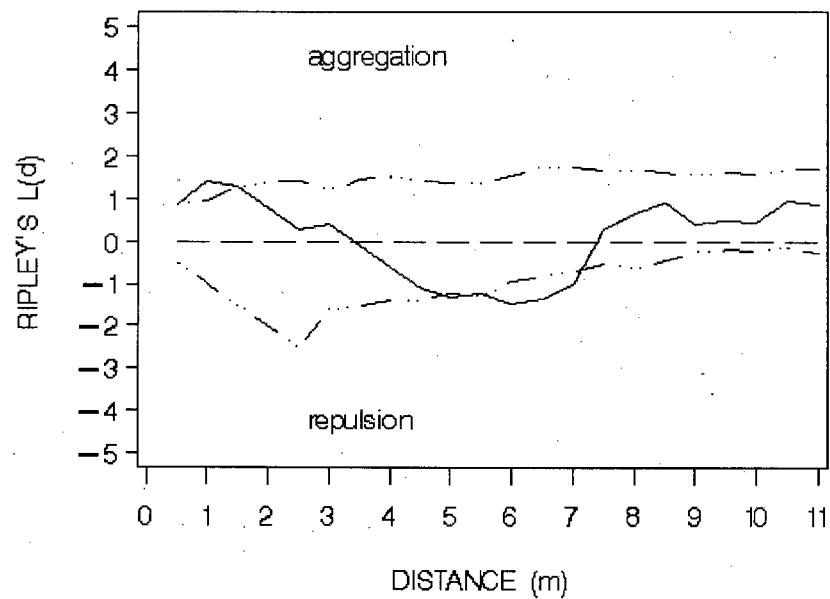


Figure 16. Bivariate Ripley's analysis, live trees vs. regeneration clumps, Plot 7. NOTES: Dashed lines indicate 90% confidence envelopes under random spacing; solid line indicates observed values.

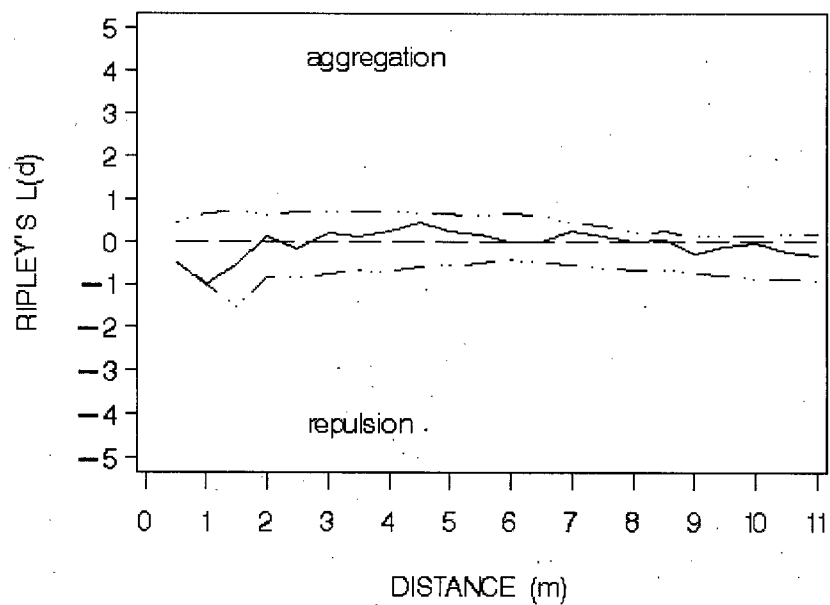


Figure 17. Bivariate Ripley's analysis, dead trees vs. regeneration clumps, plot 7. NOTES: Dashed lines indicate 90% confidence envelopes under random spacing; solid line indicates observed values.

Plot 23 (Appendix L, Figure L.23) is an “undisturbed” stand (meaning that there has been no disturbance in at least 25 years) of moderate density (33.4 m²/ha). Because it was undisturbed, all regeneration was technically advance. Overstory and understory composition was solely Douglas-fir, including regeneration. There were a large number of small trees that had been lost to mortality, and the remaining live small trees exhibited low five-year height increment rates, indicating that the stand was undergoing active stem exclusion. There were no dead large trees. There were a relatively high number of clumps, averaging 10 stems per clump.

Live overstory exhibited no real spatial trend, except an indication of uniformity at 8 m (Figure 18). Regeneration clumps exhibited repulsion from both live and dead overstory trees at small scales, from 0.5-2.5 m (Figure 19).

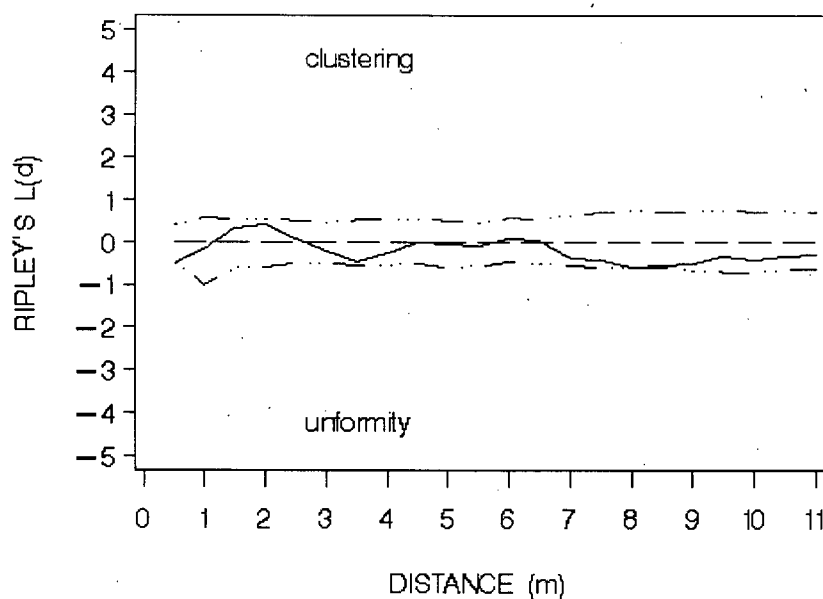


Figure 18. Univariate Ripley's analysis, live trees, Plot 23. NOTES: Dashed lines indicate 90% confidence envelopes under random spacing; solid line indicates observed values.

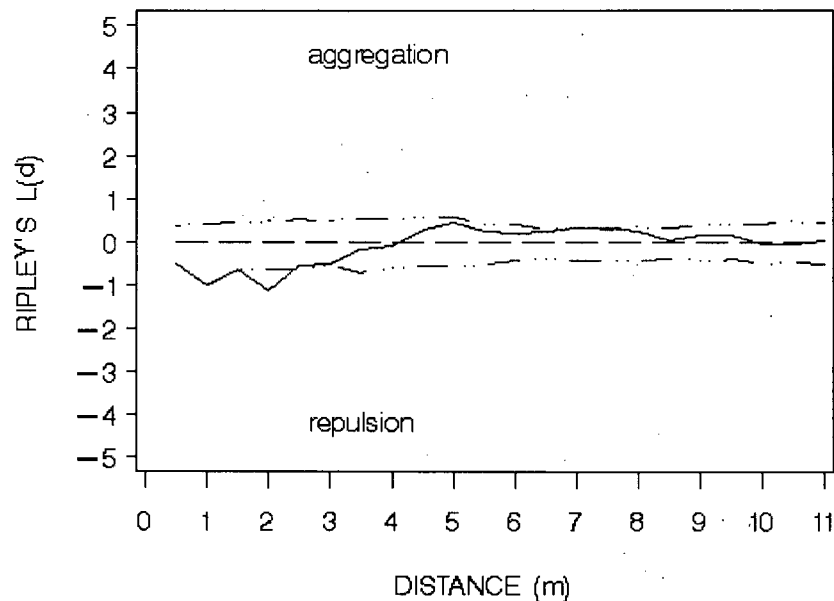


Figure 19. Bivariate Ripley's analysis, live trees vs. regeneration clumps, Plot 23. NOTES: Dashed lines indicate 90% confidence envelopes under random spacing; solid line indicates observed values.

Plots 1 and 2 were selected to illustrate the variability of Ripley's analysis results in partially cut stands (Appendix L, Figure L.1 and L.2). Both plots came from southerly locations of similar elevation and pre-harvest basal area (approx. 37 m²/ha). Plot 2 was slightly drier, and had incurred a greater removal of basal area (70% vs. 50%); both differed slightly in other plot attributes. Plots 1 and 2 were harvested in 1983 and 1990, respectively. Plot 2 had a large number of small clumps (18 clumps, averaging seven stems/clump), while Plot 1 had a smaller number of large clumps (10 clumps, averaging 39 stems/clump).

While pre-harvest basal area and location were similar, spatial patterns differed. Plot 1 exhibited clustering from 1 to 5 m, and uniformity from 9.5 to 11 m. Plot 2 exhibited clustering from 1.5 to 4 m and from 9 to 11 m. Uniformity was significant only at 7 m. Univariate patterns for Plots 1 and 2 are shown in Figure 20. After harvesting, Plot 2 exhibited clustering only at 2 m, and repulsion from 5.5 to 7 m. Plot 1 exhibited uniformity at 9.5 m (Figure 21). Where the two sites contrasted most sharply is under bivariate

analyses. Plot 1 exhibited aggregation between regeneration clumps and both live and dead trees at small scales, while Plot 2 exhibited repulsion (e.g., Figure 22).

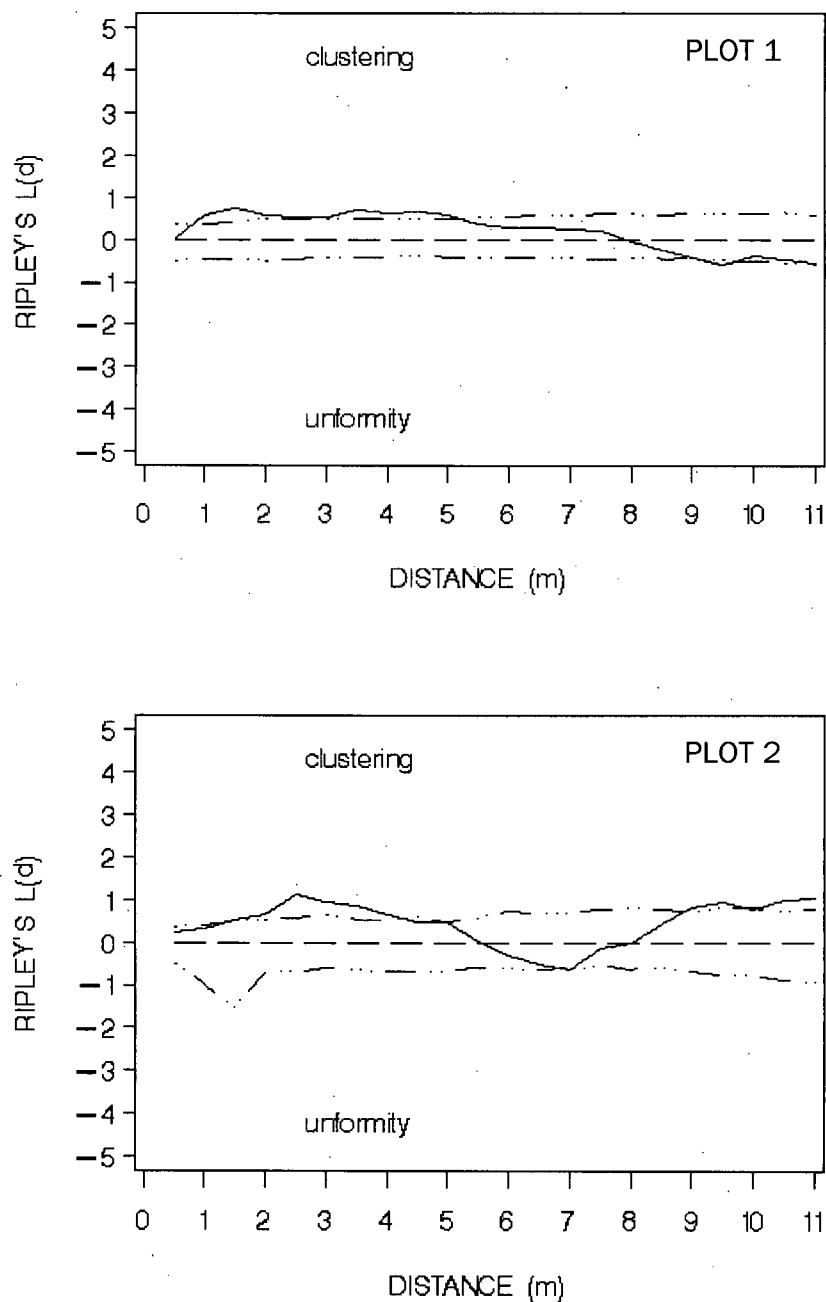


Figure 20. Univariate Ripley's analysis, pre-harvest overstory, Plots 1 and 2. NOTES: Dashed lines indicate 90% confidence envelopes under random spacing; solid line indicates observed values.

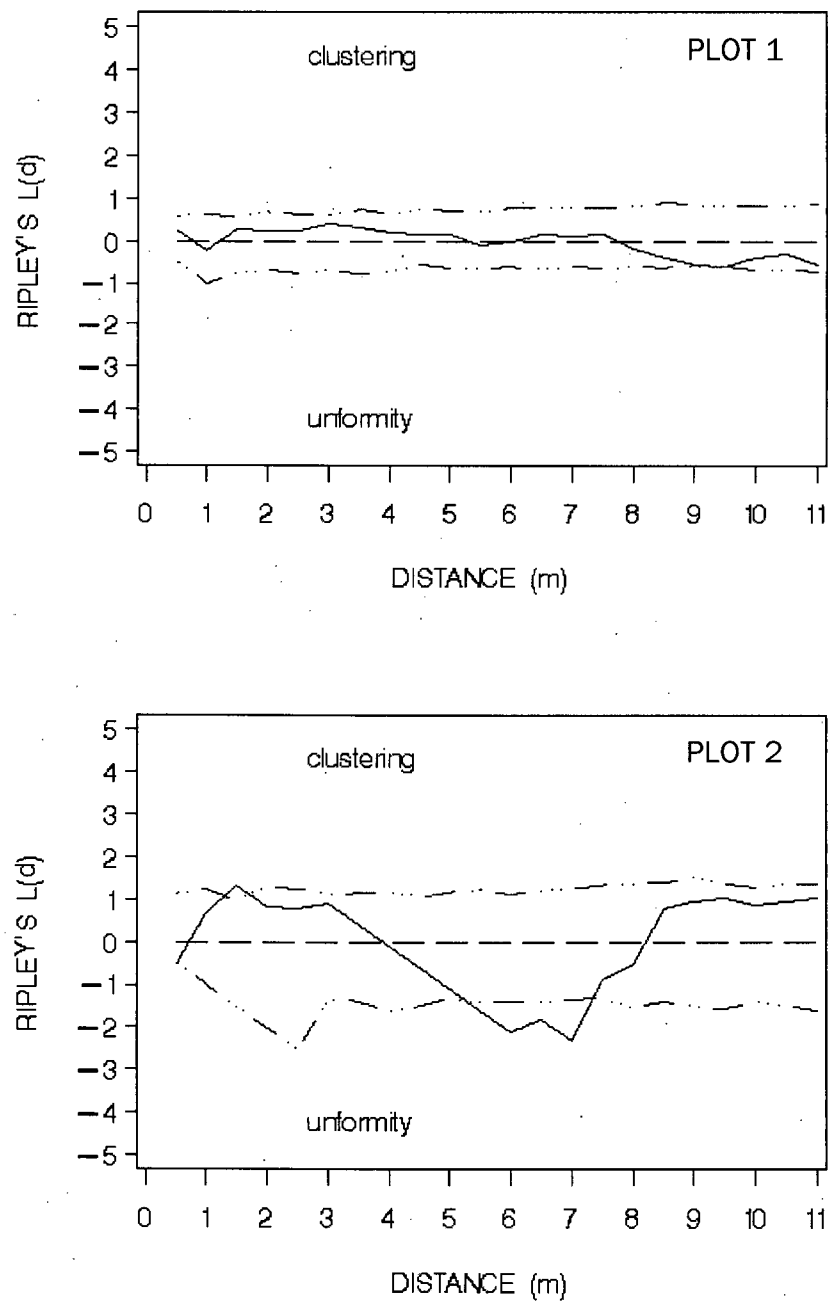


Figure 21. Univariate Ripley's analysis, post-harvest overstory, Plots 1 and 2. NOTES: Dashed lines indicate 90% confidence envelopes under random spacing; solid line indicates observed values.

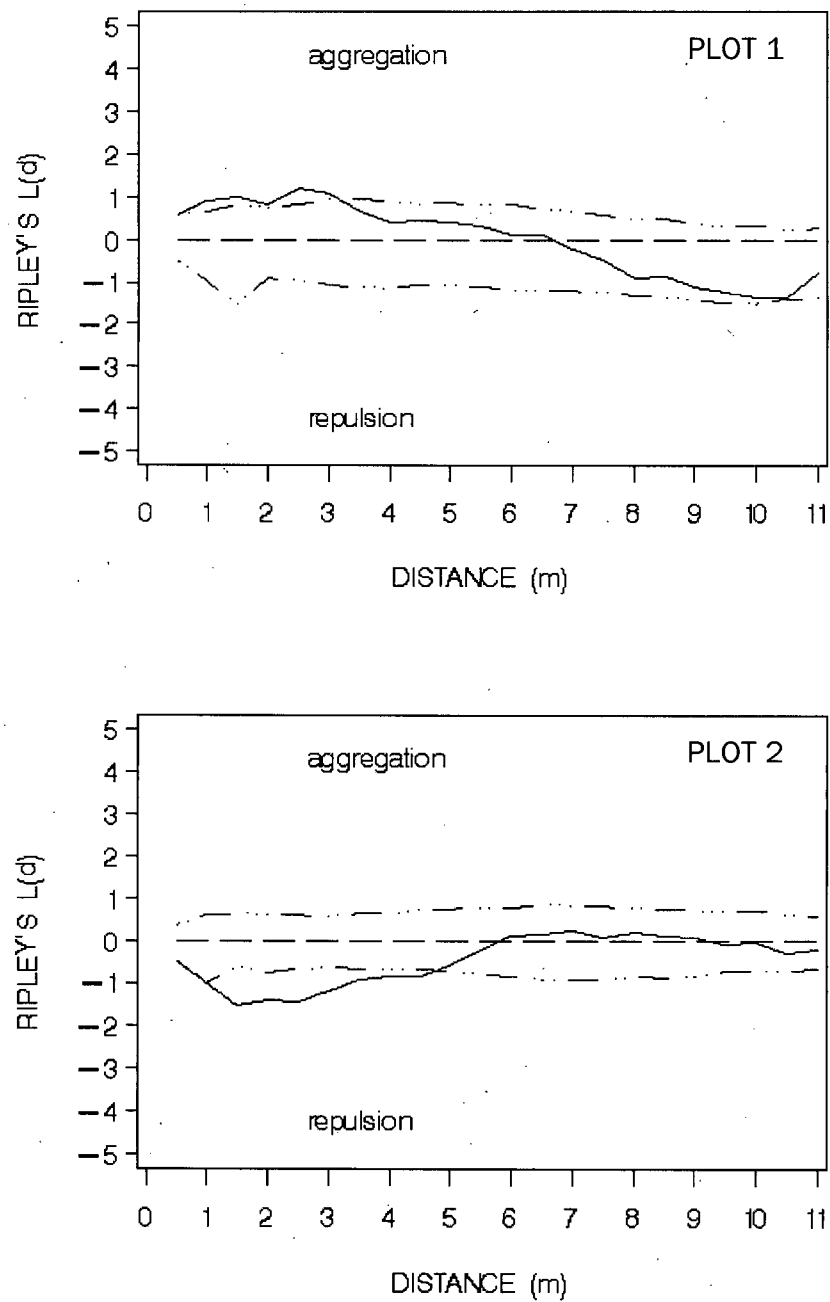


Figure 22. Bivariate Ripley's analysis, pre-harvest overstory vs. advanced regeneration clumps, Plots 1 and 2. NOTES: Dashed lines indicate 90% confidence envelopes under random spacing; solid line indicates observed values.

4.4 Discussion

4.4.1 Modelling Regeneration Abundance

Overall, MSN and k-MSN methods were better than the two tabular imputation models for predicting *Absence* of abundant species, and *Presence* of less abundant species. MSN generally had the worst fit statistics (RMSE, MAD and bias), whereas the other three approaches were comparable. However, model performance also varied by species. For example, the best fit statistics for interior spruce were provided by tabular imputation Model 1, while Douglas-fir fit statistics from tabular imputation Model 2 were superior. The MSN method provided the best predictions for lodgepole pine.

The lesser ability of tabular imputation to predict the variability in *Presence* and *Absence* of certain species relates to the limited number of variables used in generating the tables. Regeneration is one of the most variable attributes of stands, and generalizing regeneration response in this way does not adequately express variability in processes. Because each species has its own environmental preferences and seed production cycles, using the same set of variables for tabulation cannot capture species-specific variability.

MSN and k-MSN approaches incorporate correlation structures for individual species, improving the accuracy of matching. Most Similar Neighbour imputation methods retain the variability inherent in natural populations by selecting the single nearest neighbour, allowing for very large and very small regeneration estimates such as are observed in the area. However, based on the relatively small sample of stands, and the sporadic nature of many species, often these estimates did not correspond to actual observations for particular stands, with high regeneration abundances imputed onto stands with low observed abundances. k-MSN provided a balance, whereby selection was based on correlations, but estimates were averages over the three nearest neighbours.

Results may be improved by increasing the sample size, providing for "closer" nearest neighbours. Incorporating additional variables may also improve estimation. For example,

factors such as seed source and seedbed availability, or post harvest management practices, could have considerable effect and were not represented in this analysis.

Because these were not biologically based models, it was difficult to assess their relationships with understory dynamics. Given the known complexity of regeneration in the IDF, tabular methods do not even begin to incorporate enough predictors to capture the variability. Using the relationship between plot-level variables and regeneration abundance still did not improve predictions, which implies that there are factors at play which were either not measured, or were examined at the wrong scale, or both.

Incorporating more of the factors that limit germination and establishment could improve the results. For example, ponderosa pine occurred on dry sites, and drier aspects of wetter sites. However, it was generally found only in southern sites, which likely reflects the effect of latitude on growing season length and temperature. The tabular models rarely predicted the *Presence* of ponderosa pine correctly, because this was not represented in the predictor variables used. A slight improvement was made using MSN and k-MSN methods, because more predictors were used which related to aspects of the growing environment, such as UTM northing, with which ponderosa pine was correlated. However, few of the measured site level variables showed strong correlations with ponderosa pine regeneration abundance. Seedbed conditions and competition from grasses are primary factors affecting ponderosa pine regeneration (Section 2.2), which were not incorporated into these models. Understanding regeneration dynamics and knowing which factors are the most important for predicting future regeneration abundances is essential to improving performance.

4.4.2 Substrate and Spatial Data

Substrate Relationships with Regeneration Abundance

LePage *et al.* (2000) found that substrate limitations appeared to be a major factor resulting in very low rates of seedling establishment. They also found that both substrate type and substrate favourability varied by canopy cover class. The authors concluded that shifting

from partially cut to clearcut systems shifted importance from seed availability and substrate favourability to increased emphasis on microclimate effects.

Ryker (1975) studied Douglas-fir regeneration in the inland northwest of the US. He found that a greater percent of litter-covered plots were stocked than plots with exposed mineral soil, across all habitat types. The author also found that stocking increased with increasing depth of organic material. In a study of Douglas-fir regeneration in central Idaho, Geier-Hayes (1987) found that litter-covered soils and bare mineral soils were "efficient" (suitable for natural regeneration) substrates across a range of habitat types. Rotten wood ranged from efficient to inefficient, while moss mats were generally more efficient and residual duff efficiency varied. Ryker also found that grasses and sedges produced inefficient microsites for Douglas-fir regeneration, while the effect of shrub species varied.

The assessment of substrate here provides some preliminary trends in substrate abundance and relative occurrence of germinants and established regeneration. Because the dry and wet sites had only four plots each, further sampling is obviously warranted. However, the observed trends illustrate that substrate preference does exist, and that it varies based on site conditions, in this case, moisture class.

There were different substrate preferences for germination compared to those that favour establishment of regeneration. Lack of germinants on dry sites may reflect low survival rates, identified as problematic by Saceniaks and Thompson (2000). On dry sites, substrate types such as shrubs, litter and kinnikinnick may provide cover, which prevents excessive heating of the soil (reducing heat girdling) and prevents loss of soil moisture, aiding seedling survival. Grass may compete with regeneration for moisture, resulting in an underrepresentation of regeneration on these substrate types.

On wet sites, moss may provide a good germination seedbed; however, lower levels of established regeneration may indicate that survival is lower, perhaps due to late season moisture stress. Litter substrate may be preferable for establishment of regeneration on wetter sites, since these microsites lack competing vegetation. Underrepresentation of regeneration on shrub substrates may reflect the effect of competition on seedling

establishment. On mesic sites, where moisture is less limiting and competition is potentially less abundant, seedling incidence appears more closely tied to the abundance of neutral substrate rather than favourable substrates.

Further study should explore these patterns, where age defines germinants and established regeneration, rather than height class, since in the IDFdm2, height can be a poor proxy for age. Also, preferences are expected to vary by species, so sampling should focus on obtaining reasonable sample sizes of all naturally regenerating species of interest. Combining stand measures with substrate in a multivariate context may lead to a more complete picture of the regeneration environment.

Competition and Release Indices

Saceniaks and Thompson (2000) found no correlation between the number of germinants and overstory basal area, also indicated in this study. However, when examining spatial expressions of overstory (competition indices), a different picture emerges. Germinants (0-14.9 cm) appeared to be strongly affected by competitive influence; all competition indices showed a distinctive pattern, whereby germinant abundance was low at low competition levels, increasing with increasing competition then decreasing as competition became very high. The number of plots with no germinants at very low competition levels may reflect the effects of high basal area removal (e.g., clearcut harvesting) on seed availability and microsite conditions, including soil properties, moisture availability and/or substrate type. The variability in germinant density at moderate levels of competition may also be explained by additional attributes of the growing environment.

Class 1 (15-49.9 cm) regeneration, considered to be representative of established regeneration, did not appear to be as affected by competition as by release. Release within the immediate area (3 m radius) meant low to no regeneration establishment. This very likely reflects the effects of harvesting, such as reduction in substrate favourability, changes to soil properties (e.g., soil compaction or turning up of calcareous soils), and other effects on microsite factors. Examining release within a 7 m radius indicated that removal of moderate (10-20 m²/ha) levels of overstory resulted in the most variable regeneration

abundances; part of this variation may be explained by the number of years since disturbance and/or substrate favourability. Examining release within larger radii (e.g., 11 m) led to less clear patterning.

Examination of competition and release indices relative to seedling abundance is difficult due to the variability within the sites, and the small sample size. However, indications are that smaller search radii of 3 to 7 m may be more appropriate scales for examining response to competition and release. This fits with theory that microsite conditions have a greater effect on seedling germination and establishment than on subsequent growth. However, because different species have different relationships with their surroundings, examination of other species is recommended.

Ripley's K(t) Point Pattern Analysis

Using Ripley's K(t) statistic, Nigh (1997) was able to identify spatial patterns of regenerating lodgepole pine, and based on the pattern, modelled the pattern using different point processes. However, he was unable to discern the reasons for the different patterns. In this study, while overstory trees were often clustered at short distances, the spatial location of regeneration clumps was not consistently affected by the location of the overstory trees, nor by the removal of overstory trees. This may indicate that overstory removal had some effect on clumps, although it was not motivated by access to light, since clumps could be significantly aggregated towards trees, as well as repulsed by them. These patterns were not explained by site variables such as moisture, pre-or post harvest basal area, or aspect.

Because tree heights and live crown length were not available, the effect of vertical structure could not be examined, to determine whether variability in results lay in restricting analysis to the horizontal plane. Marked point pattern analysis, which examines the distribution of "marks" (additional variables such as DBH or clump area) relative to their horizontal distribution, was not pursued, since interpretation of results is more difficult. Both clustering of points on the horizontal plane and clustering of marks, or regularity of points and regularity of marks, is required for easy interpretation. Given the variability of

spatial point patterns without including marks, the spatially mapped data did not make a good candidate for marked point pattern analysis.

The clustering of overstory trees also indicates that aboveground competition is not the driving factor behind stand structure or dynamics. The lack of an inhibition zone, even in mature stands, may indicate that overstory trees compete primarily for soil moisture and/or nutrients, since root systems can be diffuse and extend over large areas. In addition, the clustered pattern at small scales may indicate that large trees grew out of cohort "clumps".

While western larch and lodgepole pine often formed clumps on planted sites, and lodgepole pine was capable of forming clumps via natural regeneration, the predominant species responsible for localized regeneration was Douglas-fir. Often, other species appeared to be included in a clump simply because Douglas-fir clumps formed around them. These localized clumps of regeneration may be the result of a combination of a very favourable microsite, abundant seed source, and sufficient moisture, light and protection.

Most of the regeneration clumps did not appear to be even-aged in nature, often consisting of both advance and subsequent regeneration. Therefore, it does not appear that clump formation occurred within a short time interval. It may be that the establishment of Douglas-fir regeneration makes the site more favourable for additional regeneration, possibly by providing protection and/or amelioration of other environmental effects.

Coates (2002) found that regeneration abundance was similar by location within gaps of $<300 \text{ m}^2$, but that in larger gaps, gap position was an important factor. Gap analysis at this scale was not feasible in this case, because plot sizes were too small and gap sizes could not be calculated for gaps that fell along plot boundaries. However, some of the differences in patterning of clump locations may have been affected by relative size of gaps. Certainly, where canopy closure was high, very few clumps were found. One way by which gap position could be examined would be by calculating directional-specific Ripley's analysis, where only neighbours in a certain direction from the subject tree are examined. This would require a larger plot size, to ensure a sufficient number of large trees for the analysis.

This analysis illustrates the need for replication prior to drawing conclusions from point pattern analyses. Plot 1 exhibited all of the anticipated trends for overstory trees, and relationships with regeneration clumps. However, Plot 2 had completely contrary results for relationships with regeneration clumps, and other results varied considerably. Examining a number of different site types ensures that generalizations are not drawn before the full scope of variability is examined.

In addition, patterns are often difficult to interpret, and interpretation must proceed cautiously. For example, the appearance of attraction between clumps and overstory trees on planted sites can reflect the maturation of a clump member to large tree status, rather than a causal relationship that reflects overstory influence on clump locations.

5. SMALL TREE HEIGHT INCREMENT

5.1 Introduction

Understanding the factors that affect the growth of small trees is important. The difference in relative height growth rate between two trees affects their relative vertical position within a stand, and therefore their competitive status. At the stand level, relative height increment rates affect canopy differentiation, which affects stand structure. Differences in stand structure can affect growing space availability for other understory components (such as regeneration), susceptibility to pests and pathogens, patterns of resource use (above- and below-ground), and a host of other factors. Species, initial height, site conditions, competitive influence, resource availability, climate, and a number of other factors interrelate to affect height increment.

In this chapter, small tree five-year height increment in the IDFdm2 is studied. Specific objectives were:

- 3) to examine the potential use of aspatial, plot-level variables to model five-year height increment using regression techniques; and
- 1) to examine the potential of subsampled information for model improvement by assessing spatial indices based on plot-level spatial information.

Modelling small tree height increment was based on the current models used in Prognosis^{BC} (Temesgen 2002) to provide useable components for the model, and to allow examination of the explanatory ability of models based on plot-level attributes. Subsampled spatial data were used to examine the potential of spatial indices for improving estimates of small tree height increment. Spatial information was available for only a subset of the sampled plots. As such, the number of trees available for analysis with spatial information was much smaller than for modelling using plot-level variables.

5.2 Methods

5.2.1 Modelling Small Tree Height Increment

Model Forms and Variable Selection

Small tree height increment was modelled using trees from all 111 plots and plot-level predictor variables. Four base model forms were selected for modelling small tree height increment. Each contained the same seven base variables, which corresponded to those used in the current small tree height increment model for Prognosis^{BC} (Temesgen 2002): total height in m (HEIGHT), the natural log of total height (LNHEIGHT), the cosine of aspect * slope ratio (COSASPECT), the sine of aspect * slope ratio (SINASPECT), slope ratio (SL), crown competition factor (CCF), and basal area in larger trees/100 (BAL). Base models were:

$$(1) LNHTG = b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF + b_7 BAL100$$

$$(2) HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF + b_7 BAL100)$$

$$(3) HTG = b_0 + b_1 HEIGHT + b_2 HTSQ + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF + b_7 BAL100$$

$$(4) SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF + b_7 BAL100$$

where exp is the base of the natural logarithm (Napierian constant, approx. 2.7182818), b_0 to b_7 are parameters to be estimated, and all other variables are defined in Table 22.

Models 1 and 2 are the same except that Model 1 is a linearized version of Model 2, and was fit using multiple linear regression⁵, which generally results in model bias (Baskerville 1972). Model 2 was fit using nonlinear regression techniques, resulting in zero bias; however, because a search algorithm was used, its properties are asymptotic, and model fitting may not result in optimal parameter estimates. Model 4 included a transformation of

⁵ All analyses were completed using SASTM, version 8.02 (SAS Institute Inc. 1999-2001), except where noted.

the variable of interest (square root of five-year height increment). Models 1, 3 and 4 were fit using multiple linear regression techniques.

Table 22. Variables used in regression analysis for small tree height increment.

VARIABLE	DESCRIPTION
Variables of Interest	
HTG	predicted five-year height increment (m)
LNHTG	predicted natural log of five-year height increment
SQRHTG	predicted square root of five-year height increment
Base Predictor Variables	
HEIGHT	total height (m)
LNHEIGHT	natural log of total height
COSASPECT	cosine of aspect(in radians) x percent slope
SINASPECT	sine of aspect(in radians) x percent slope
SL	slope ratio (percent slope/100)
CCF	crown competition factor
BAL100	basal area in larger trees/100 (dm ² /ha)
Additional Predictor Variables	
HTSQ	total height squared
SQRHT	square root of total height
DBH	diameter outside bark at breast height (cm)
LNDBH	natural log of DBH
DBHSQ	DBH squared
LNDBH	natural log of DBH
SQRDBH	square root of DBH
HDR	height to diameter ratio (cm/cm)
ELEV	elevation (m)
ELEVSQ	elevation squared
ELEVBYCOS	interaction between elevation and COSASPECT
ELEVBY SIN	interaction between elevation and SINASPECT
NORTHING	UTM northing (m)
BAHA	basal area of stand (m ² /ha)
QMD	quadratic mean diameter (cm)
YRSINCE	number of years since disturbance
MOISTCLASS1,MOISTCLASS2	dummy variables to represent three moisture classes
MOISTBYCOS1,MOISTBYCOS2	interaction between moisture class and COSASPECT
MOISTBYSIN1,MOISTBYSIN2	interaction between moisture class and SINASPECT
MOISTBYBA1,MOISTBYBA2	interaction between moisture class and BAHA

Selected variables were then added, to determine whether their inclusion could improve the model fit. These were: DBH (and transformations), HDR, ELEV, ELEVSQ, ELEVBYCOS, ELEVBY SIN, NORTHING, BAHA, QMD, YRSINCE, MOISTCLASS1, MOISTCLASS2, MOISTBYBA1, MOISTBYBA2, MOISTBYCOS1, MOISTBYCOS2, MOISTBYSIN1, and MOISTBYSIN2.

Because of sample size issues, the only categorical variable included was moisture class: dry (site series 03 and 03/01), mesic (site series 01/03, 01, and ¼) and wet (site series 04/01, 04, and 04/05).

Many calculated variables relating to stand structure and density, such as SDI, RD, QMD, BAHA, BAL100 and CCF were very highly correlated, generally exceeding 0.95, and correlations were significantly different from zero at $\alpha=0.05$. Preliminary analyses indicated that generally either BAL100 or CCF were selected using stepwise selection, and were generally interchangeable in terms of fit statistics. Occasionally, both variables were selected, resulting in high associated variance inflation factors (VIF), indicating instability of parameter estimates (Neter *et al.* 1996). In that case, removal of one of the two variables did not strongly impact the calculated fit statistics. QMD was less correlated with other density related variables, and was therefore considered an appropriate variable to include along with other stand structure and density variables.

In a natural system, most or all of its parts interact. Therefore, including interactions between predictor variables may improve modelling efforts. Burkhart (2002) stated that by adding first-order interaction terms, a simple model could be improved more than by adding more predictor variables. However, only a limited selection of interactions were selected, based on theory presented in Chapter 2, to reduce the possibility of model overfitting.

Model Fitting

Models were fit separately by species. Because of the very small sample size ($n=10$), no model was fit for subalpine fir. The four base models were fit first, then the additional variables were used to try to improve the model fit.

PROC REG (SAS Institute Inc. 1999-2001, Version 8.02) was used for fitting linear and/or linearized models (Models 1, 3 and 4). Stepwise selection was used to determine which variables to include in the model. For small data sets, RSQUARE selection was used to determine potential variable combinations which could provide the best results with the fewest number of variables. Combinations were selected preferentially, with emphasis

placed on finding those combinations that included each of an expression of tree size, competition, and site productivity. Where there were two variables with a variance inflation factor greater than 10, one was removed, and the model was refit and assessed to ensure that fit statistics were not greatly impacted. For species with small sample sizes, variable selection proceeded with caution, since selection of too many predictor variables could lead to overfitting.

PROC NLIN (SAS Institute Inc. 1999-2001, Version 8.02) was used to fit Model 2 for the base and extended models. Results from Model 1 were used to obtain starting values for parameters in Model 2. Variables were then removed one at a time, based on asymptotic confidence intervals (where the 95% confidence interval included zero), and the model was reassessed. Variance inflation factors could not be obtained using PROC NLIN, therefore decisions on removing correlated variables were based on previous experience in fitting the linear models and simple correlations. Removal of one of two correlated predictor variables was followed by reassessment of the model, to ensure that fit statistics were not seriously altered.

For all procedures, if either COSASPECT or SINASPECT was included by the stepwise selection process, the selection process was rerun, using the INCLUDE command to force retention of both variables in order to maintain the biological function as described by Stage (1976). Similarly, if an interaction with aspect was included, both were included, such as ELEVBYCOS and ELEVBY SIN. Because MOISTCLASS1 and MOISTCLASS2 were dummy variables that represented moisture classes (dry, medium, wet), if one was included in the model, the other was forced into the model as well. Interaction terms were also grouped together in a similar fashion. The exception to this was where a species occurred only in two moisture classes, such as trembling aspen. In such a case, MOISTCLASS1 and interactions with MOISTCLASS1 were admitted to the model singly.

Model Comparison

Fit statistics were calculated for each model. For Model 3, which used HTG as the variable of interest, the multiple coefficients of determination (R^2) and standard error of the estimate (SEE) were calculated. For the remaining models, the multiple coefficient of determination for transformed response variables (l^2) was calculated using:

$$l^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$$

where y_i is the measured five-year height increment, $\hat{y}_i$ is the predicted five-year height increment in original units, $\bar{y}$ is the mean five-year height increment, and n is the number of observations. The empirical estimate of the standard error of the estimate was calculated using:

$$SEE' = \sqrt{\frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{n - p}}$$

where p is the number of parameters, and other variables are as previously defined.

For all models, bias was calculated using:

$$Bias = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)}{n}$$

Following initial model fitting, the data set was split, four times, into 75% (model) and 25% (test) data sets. Because small sample sizes result in very small test data sets, they can provide unclear results. Therefore, the data splitting procedure was limited to those species

with large data sets: Douglas-fir and lodgepole pine. Models were fit using the model data and variables determined in preliminary model fitting, and then tested using the test data set. Fit statistics were calculated for both the model and test sets, for each of the four splits. These statistics were used to examine model performance. Poor model performance was noted if coefficients of multiple determination (R^2 or I^2 values), standard errors of the estimate (SEE or SEE'), or biases varied widely between model and test data sets, or between different model sets. Generally, low or negative I^2 values, very high SEE' values, and very high or very low (negative) biases calculated from test sets indicated very poor prediction accuracy. The full data set was used for the final fit of each model.

Residuals were examined for normality by examining normal probability plots, stem leaf plots and results from the Shapiro-Wilk test for normality ($\alpha=0.05$). Residual plots were examined for evidence of heteroskedasticity, and to assess the aptness of the model. Model selection was based on a combination of fit statistics, residuals, overall model performance and biological reasoning.

5.2.2 *Spatial Data*

Calculation of Spatial Position

Distances to large trees were converted to distances to center points of large trees by adding $\frac{1}{2}$ DBH to each distance measurement. Angle and distance data were converted to Cartesian coordinates as described in Section 4.2.2. All x and y coordinates were then converted to positive values by adding 11.28 m (large and small tree plot size) to each x and y measurement, shifting the reference point (origin) to the southwest.

Competition and Release Indices

Competition and release indices were examined relative to small tree height increment from trees within the spatially mapped plots. Douglas-fir ($n=78$) and lodgepole pine ($n=51$) were the only two species with sufficient sample size for this analysis. Four aspatial and five

spatial indices and modifications thereof were selected for assessment (Table 23), based on results from Nienaber (1999), comparability to plot-level measures of competition, and data availability. Competition indices were calculated using 1) all competitors (small and large trees) and 2) all competitors larger than the subject trees. Release indices were calculated using all dead trees, whether the result of harvesting or mortality. Indices were calculated for three search radii: 3 m, 7 m, and 11 m, for each species.

Table 23. Formulae for competition and release indices by variable of interest.

Name	Formula	Description
Plot-Level Indices (Aspatial)		
BAHA	$\sum_{\text{all trees}} BA / \text{area}$	Basal area per hectare, all trees
BAL	$\sum_{j=1}^k BA_j / \text{area}, DBH_j > DBH_i$	Basal area in trees larger than subject
CCF	$\sum_{\text{all trees}} MCA / \text{area}$	Crown competition factor, all trees (Krajicek et al. 1961)
PCTBAREM	$\sum_{\text{all trees}} BA_{\text{dead}} / \sum_{\text{all trees}} BA_{\text{total}} \times 100$	Percent basal area removed
Size and Size-Distance Indices (Spatial and Semi-Spatial)		
BAN	$\sum_{j=1}^k BA_j, u_{ij} \leq SR$	Basal area of neighbourhood trees
Lorimer1	$\sum_{j=1}^k \frac{DBH_j}{DBH_i}$	Ratio of diameters (Lorimer 1983)
Lorimer2	$\sum_{j=1}^k \frac{DBH_j^2}{DBH_i^2}$	Ratio of diameters squared (Nienaber 1999)
Hegyi1	$\sum_{j=1}^k \frac{(DBH_j / DBH_i)}{u_{ij}}$	Distance weighted ratio of diameters (Hegyi 1974)
Hegyi2	$\sum_{j=1}^k \frac{(DBH_j^2 / DBH_i^2)}{u_{ij}}$	Distance weighted ratio of diameters squared (Nienaber 1999)

NOTES: Spatial and semi-spatial indices were calculated separately for three index types (all competing (live) trees, competitors>subject and release (dead) trees) and three search radii (3, 7 and 11 m); BA_j is the basal area of competitor j (m^2), area is the plot area (ha), DBH_j is the diameter at breast height of competitor j (cm), DBH_i is the diameter at breast height of subject i (cm), MCA is the maximum area that could be occupied by the crown of a tree of specified DBH , expressed in terms of percent area, u_{ij} is the distance between subject i and competitor j (m), SR is the search radius (m), A_i is the area of influence of subject tree i (m^2), A_j is the area of influence of subject tree j (m^2), A_{oij} is the area of overlap of A_i and A_j (m^2), R is the radius (m) used to calculate areas of influence A_i and A_j , and CW is mean crown width (m).

Table 23 (cont'd). Formulae for competition and release indices by variable of interest.

Name	Formula	Description
Zone of Influence Indices (Spatial)		
OpieA	$\sum_{j=1}^k \frac{A_{oij}}{A_i}, R = CW / 2$	Area of overlap of zones of influence (Opie 1968)
OpieB	$\sum_{j=1}^k \frac{A_{oij}}{A_i}, R = CW$	Area of overlap of zones of influence
Bella1A	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) \left(\frac{DBH_j}{DBH_i} \right), R = CW / 2$	Size ratio-weighted area of overlap (Bella 1971)
Bella1B	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) \left(\frac{DBH_j}{DBH_i} \right), R = CW$	Size ratio-weighted area of overlap
Bella2A	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) \left(\frac{DBH_j}{DBH_i} \right)^2, R = CW / 2$	Squared size ratio-weighted area of overlap
Bella2B	$\sum_{j=1}^k \left(\frac{A_{oij}}{A_i} \right) \left(\frac{DBH_j}{DBH_i} \right)^2, R = CW$	Squared size ratio-weighted area of overlap

NOTES: Spatial and semi-spatial indices were calculated separately for three index types (all competing (live) trees, competitors>subject and release (dead) trees) and three search radii (3, 7 and 11 m); BA_j is the basal area of competitor j (m^2), $area$ is the plot area (ha), DBH_j is the diameter at breast height of competitor j (cm), DBH_i is the diameter at breast height of subject i (cm), MCA is the maximum area that could be occupied by the crown of a tree of specified DBH , expressed in terms of percent area, u_{ij} is the distance between subject i and competitor j (m), SR is the search radius (m), A_i is the area of influence of subject tree i (m^2), A_j is the area of influence of subject tree j (m^2), A_{oij} is the area of overlap of A_i and A_j (m^2), R is the radius (m) used to calculate areas of influence A_i and A_j , and CW is mean crown width (m).

Where the search radius extended across the plot boundary, an edge effect correction was calculated to account for unsampled competitors outside of the plot boundary, and applied to each index calculation. The edge effect correction w_{ij} was calculated for each subject-competitor pair using the equation presented in Section 4.2.2. The edge effect calculation was used to weight each index calculation by the proportion of sampled area relative to the unsampled area, increasing the index using:

$$Index_i = \sum_{j=1}^k \frac{Index_{ij}}{w_{ij}}$$

To reduce the number of indices used in further analysis, Pearson's correlation coefficients ($\alpha=0.05$) were examined to select one search radius for regression analysis. For small trees, the 11.0 m search radius results were selected. Base equation forms were selected from results of modelling small tree height increment, but refit using the reduced data set with spatial information, and a reduced number of variables. The equation for each species included an expression of size (height or natural logarithm of height) and moisture (dummy variables representing moisture class) as predictor variables for each species:

For Douglas-fir:

$$LNHTG = b_0 + b_1HEIGHT + b_2LNHEIGHT + b_3MOISTCLASS1 + b_4MOISTCLASS2 + e_i$$

For lodgepole pine:

$$LNHTG = b_0 + b_1LNHEIGHT + b_2MOISTCLASS1 + b_3MOISTCLASS2 + e_i$$

Regression analysis was executed using PROC REG (SAS Institute Inc. 1999-2001, Version 8.02). The base model was first fit without spatial indices, to calculate the baseline mean square error (MSE). Each index was then added separately, to assess any improvement over the base model. Residuals were examined for evidence of heteroskedasticity and nonnormality. Percent MSE was used to calculate any improvement over the base model following Biging and Dobbertin (1995):

$$\frac{MSE_{index+base\ model}}{MSE_{base\ model}} \times 100$$

This is similar to the use of relative efficiency in sampling, whereby a smaller value indicates a more precise equation.

5.3 Results

5.3.1 *Modelling Small Tree Height Increment*

Many correlations between site variables and five-year height increment were significantly different from zero ($\alpha=0.05$), but these correlations varied by species (Table 24). For example, many species had moderate to strong negative correlations between five-year height increment and elevation, yet western larch and Douglas-fir showed a strong positive correlation. Measures of stand competition (CCF, BAL100, BAHA) often showed strong negative correlations. These correlations were used to gain some idea of the relationship between five-year height increment and other variables under consideration for each species.

Douglas-fir Models

Stepwise selection resulted in similar variable selection regardless of model fit for Douglas-fir (Table 25). For Models 1, 2 and 3, some expression of height (HEIGHT, LNHEIGHT, HTSQ, SQRTHT), influence of aspect (COSASPECT, SINASPECT), and some measure of stand density/competition (BAL100, CCF) was selected. Slope was selected for two of the models. Model 4 did not include any measure of size, and included BAL100 rather than CCF.

For all of the models tested, results were generally consistent for Douglas-fir based on data splitting (Table 26). The four base models all provided relatively low multiple coefficients of determination (R^2 or I^2 values), ranging from 0.287 to 0.392, and high standard errors of the estimate (SEE or SEE'), ranging from 0.428 to 0.463 m. Because they were based on transformed values of the response variable, Models 1 and 4 showed an overall bias (underprediction) for predicting five-year height increment of 0.135 and 0.067 m, respectively. Models 2 and 3 provided essentially zero bias. Residuals from Model 1 showed evidence of nonnormality, and those from Model 3 exhibited some heteroskedasticity.

Table 24. Simple correlations between small tree five-year height increment and site variables by species.

Species		HEIGHT	DBH	HDR	EASTING	NORTHING	COSASPECT	SINASPECT	SL	ELEV	ELEVSO	YRSINCE	CCF	BAHA	BAL100
At	corr.	0.17	0.08	0.20	-0.15	0.12	-0.11	-0.03	0.07	0.04	0.03	-0.39	-0.25	-0.24	-0.26
	prob.	0.21	0.53	0.14	0.28	0.39	0.43	0.85	0.62	0.78	0.83	<.01	0.06	0.07	0.05
Bl	corr.	0.16	0.32	-0.21	0.71	-0.71	0.32	-0.51	-0.37	-0.87	-0.87	-0.85	-0.82	-0.81	-0.84
	prob.	0.65	0.37	0.56	0.02	0.02	0.37	0.13	0.30	<.01	<.01	<.01	<.01	0.01	<.01
Ep	corr.	0.22	0.23	0.09	-0.46	0.55	0.00	-0.39	-0.43	-0.55	-0.54	0.10	0.20	0.27	0.25
	prob.	0.23	0.21	0.62	0.01	<.01	0.98	0.03	0.01	<.01	<.01	0.58	0.27	0.13	0.17
Fd	corr.	-0.13	-0.01	-0.19	0.25	-0.21	0.09	0.05	0.05	0.17	0.17	0.01	-0.51	-0.52	-0.53
	prob.	0.01	0.87	<.01	<.01	<.01	0.09	0.29	0.31	<.01	<.01	0.89	<.01	<.01	<.01
Lw	corr.	0.05	0.18	-0.37	-0.21	-0.01	-0.17	-0.31	0.01	0.55	0.55	-0.37	-0.76	-0.77	-0.80
	prob.	0.74	0.25	0.02	0.17	0.94	0.27	0.04	0.93	<.01	<.01	0.01	<.01	<.01	<.01
Pl	corr.	0.17	0.27	-0.16	0.02	0.12	0.04	0.04	0.02	-0.22	-0.21	-0.13	-0.24	-0.24	-0.28
	prob.	0.02	<.01	0.02	0.76	0.08	0.58	0.54	0.74	<.01	<.01	0.07	<.01	<.01	<.01
Py	corr.	0.18	0.32	-0.29	0.56	-0.02	-0.49	0.14	0.43	0.16	0.16	-0.20	-0.53	-0.51	-0.53
	prob.	0.37	0.09	0.13	<.01	0.93	0.01	0.48	0.02	0.42	0.40	0.31	<.01	0.01	<.01
Sxw	corr.	-0.23	0.02	-0.34	0.49	-0.28	0.11	-0.45	-0.56	-0.49	-0.50	-0.54	-0.62	-0.66	-0.67
	prob.	0.17	0.93	0.04	<.01	0.09	0.51	0.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01

NOTES: corr. is the Pearson's correlation and prob. is the associated p value, under the hypothesis that the correlation is not significantly different from 0; bold indicates that the correlation is statistically different from zero at $\alpha=0.05$; HEIGHT is total tree height (m), DBH is tree diameter at breast height (cm), HDR is height to diameter ratio (cm/cm), EASTING is the UTM easting (m), NORTHING is the UTM northing (m), COSASPECT and SINASPECT are Stage's (1976) transformation of aspect, SL is slope ratio (slope percent/100), ELEV is elevation (m), ELEVSO is elevation squared (m²), YRSINCE is the number of years since disturbance, CCF is the crown competition factor, BAHA is total basal area per hectare (m²/ha), and BAL100 is basal area of trees larger than the subject tree/100 (dm²/ha).

Models 2a, 2b, and 4a showed the most improvement (Table 25). Model 2b did not include interaction terms. The models all provided improved R^2 or I^2 values over the base models and comparable standard errors of the estimate. However, Model 4a had an overall bias of 0.047 m, while the other two models had essentially zero bias. Model 2a provided the highest coefficient of multiple determination (0.555), the lowest standard error of the estimate (0.371 m), and the least model bias (0.001 m). It is therefore the preferred model.

Table 25. Height increment models for Douglas-fir. Estimated parameters for the preferred model (highlighted in grey) are given in Appendix M.

Model	
1*	$LNHTG = b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 CCF$
2	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF)$
2a	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 COSASPECT + b_4 SINASPECT + b_5 CCF + b_6 ELEVBYCOS + b_7 ELEVBY SIN + b_8 NORTHING + b_9 QMD + b_{10} YRSINCE + b_{11} MOISTCLASS\ 1 + b_{12} MOISTCLASS\ 2 + b_{13} MOISTBYCOS\ 1 + b_{14} MOISTBYCOS\ 2 + b_{15} MOISTBYSIN\ 1 + b_{16} MOISTBYSIN\ 2)$
2b	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 SL + b_4 CCF + b_5 HDR + b_6 DBH + b_7 LNDBH + b_8 QMD + b_9 YRSINCE + b_{10} MOISTCLASS\ 1 + b_{11} MOISTCLASS\ 2)$
3**	$HTG = b_0 + b_1 HEIGHT + b_2 HTSQ + b_3 COSASPECT + b_4 SINASPECT + b_5 SL + b_6 CCF$
4	$SQRTHTG = b_0 + b_1 COSASPECT + b_2 SINASPECT + b_3 BAL100$
4a	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 COSASPECT + b_4 SINASPECT + b_5 BAL100 + b_6 ELEVBYCOS + b_7 ELEVBY SIN + b_8 NORTHING + b_9 YRSINCE + b_{10} MOISTCLASS\ 1 + b_{11} MOISTCLASS\ 2 + b_{12} MOISTBYCOS\ 1 + b_{13} MOISTBYCOS\ 2 + b_{14} MOISTBYSIN\ 1 + b_{15} MOISTBYSIN\ 2$

NOTES: “*” indicates that the model exhibits nonnormal distribution of residuals; “**” indicates that the model exhibits heteroskedasticity; n=number of trees.

Interior Spruce Models

For interior spruce, all four base models had similar standard errors of the estimate, ranging from 0.322 to 0.344 m (Table 27). R^2 or I^2 values ranged from 0.383 to 0.476. Models 1 and 4 had overall biases (underprediction) of 0.065 m and 0.034 m, respectively. Model 2 showed evidence of a nonnormal distribution of residuals.

Table 26. Fit statistics and summary data from data splitting, Douglas-fir.

Model	Split	Fitting Data				Testing Data			
		N	Bias or Bias'	R ² or I ²	SEE or SEE'(m)	n	Bias or Bias'	R ² or I ²	SEE or SEE'(m)
1	1	267	0.129	0.274	0.456	112	0.200	0.221	0.520
	2	298	0.137	0.251	0.478	81	0.055	0.462	0.401
	3	281	0.135	0.304	0.457	98	0.110	0.305	0.472
	4	291	0.136	0.328	0.458	88	0.143	0.101	0.499
	Full	379	0.135	0.287	0.463				
2	1	267	0.008	0.378	0.423	112	0.083	0.399	0.459
	2	298	0.006	0.349	0.446	81	-0.070	0.523	0.380
	3	281	0.008	0.408	0.422	98	-0.025	0.324	0.468
	4	291	0.010	0.449	0.416	88	0.021	0.139	0.491
	Full	379	0.008	0.392	0.428				
2a	1	267	0.002	0.549	0.368	112	0.036	0.541	0.422
	2	298	0.000	0.543	0.381	81	-0.042	0.542	0.400
	3	281	-0.001	0.543	0.378	98	-0.077	0.547	0.406
	4	291	0.003	0.616	0.353	88	0.049	0.280	0.480
	Full	379	0.001	0.555	0.371				
2b	1	267	0.009	0.529	0.372	112	0.049	0.488	0.434
	2	298	0.001	0.498	0.396	81	-0.035	0.587	0.366
	3	281	0.003	0.518	0.385	98	-0.060	0.515	0.408
	4	291	0.010	0.588	0.363	88	0.057	0.247	0.474
	Full	379	0.006	0.526	0.380				
3	1	267	0.000	0.315	0.444	112	0.058	0.325	0.486
	2	298	0.000	0.301	0.463	81	-0.073	0.387	0.431
	3	281	0.000	0.336	0.447	98	0.001	0.276	0.484
	4	291	0.000	0.357	0.449	88	0.008	0.191	0.477
	Full	379	0.000	0.325	0.451				
4	1	267	0.066	0.274	0.455	112	0.129	0.263	0.513
	2	298	0.067	0.270	0.470	81	-0.009	0.366	0.444
	3	281	0.068	0.291	0.460	98	0.057	0.291	0.484
	4	291	0.067	0.327	0.457	88	0.067	0.151	0.494
	Full	379	0.067	0.289	0.461				
4a	1	267	0.045	0.515	0.380	112	0.069	0.490	0.442
	2	298	0.046	0.523	0.388	81	0.009	0.534	0.401
	3	281	0.047	0.525	0.384	98	-0.026	0.508	0.420
	4	291	0.045	0.571	0.373	88	0.089	0.276	0.478
	Full	379	0.047	0.527	0.382				

NOTE: n=number of trees.

BAL100 was the sole variable selected for Models 1, 2 and 4, while Model 3 also included slope. The addition of moisture class (MOISTCLASS1, MOISTCLASS2) provided the best improvement in the fit statistics for the least number of added variables (Models 3a and 3b). Model 3a had the lowest standard error of the estimate (0.299 m), the highest coefficient of multiple determination (0.561), and no overall bias, and was therefore the preferred equation.

Table 27. Height increment models and fit statistics for interior spruce (n=38). Estimated parameters for the preferred model (highlighted in grey) are given in Appendix M.

Model		R ² or I ²	SEE or SEE'(m)	Bias or Bias'
1	$LNHTG = b_0 + b_1 BAL100$	0.383	0.344	0.065
2*	$HTG = \exp(b_0 + b_1 BAL100)$	0.418	0.334	-0.005
3	$HTG = b_0 + b_1 SL + b_2 BAL100$	0.476	0.322	0.000
3a	$HTG = b_0 + b_1 BAL100 + b_2 MOISTCLASS\ 1 + b_3 MOISTCLASS\ 2$	0.561	0.299	0.000
4	$SQRTHTG = b_0 + b_1 BAL100$	0.425	0.332	0.034
4a	$SQRTHTG = b_0 + b_1 BAL100 + b_2 MOISTCLASS\ 1 + b_3 MOISTCLASS\ 2$	0.553	0.301	0.028

NOTES: "*" indicates that the model exhibits nonnormal distribution of residuals; n=number of trees.

Lodgepole Pine Models

Stepwise selection resulted in selection of similar variables for different model forms. All models included some measure of height and some indication of stand density/competition. Only Model 1 included measures relating to the influence of aspect. The base models (Models 1, 2, 3 and 4) exhibited variability in fit statistics based on test data (Table 29): all four base models had a negative I² value for Split 4, indicating that the model trend was incorrect for the data. All four base models had very low R² or I² values, ranging from 0.129 to 0.173, and high standard errors of the estimate, ranging from 0.420 to 0.432 m (Table 29). Models 1 and 4 had overall biases of 0.071 m and 0.036 m, respectively. Models 2 and 3 showed evidence of a nonnormal distribution of residuals. The improved models (Models 2a, 2b, 4a and 4b) showed much more consistency overall, with no negative I² values and less variability in standard errors of the estimate and bias.

Models 2a, 2b, 4a and 4b provided the best overall model improvements (Table 29). Models 2a and 4a are the result of stepwise selection including all additional variables mentioned in section 3.2. Models 2b and 4b did not include any interaction terms. Models 2a and 4a had essentially same variable selection, differing only in measures of height. Models 2b and 4b were similarly comparable.

Models 2a and 4a provided the highest coefficients of multiple determination, 0.467 and 0.470 respectively, and lowest standard errors of the estimate, both with 0.343 m. Model 2a showed negligible bias, while model 4a exhibited an overall bias of 0.023 m (underprediction). The lack of overall bias makes Model 2a the preferred model.

Table 28. Height increment models for Lodgepole pine. Estimated parameters for the preferred model (highlighted in grey) are given in Appendix M.

Model	
1	$LNHTG = b_0 + b_1 LNHEIGHT + b_2 COSASPECT + b_3 SINASPECT + b_4 CCF$
2*	$HTG = \exp(b_0 + b_1 LNHEIGHT + b_2 CCF)$
2a	$HTG = \exp(b_0 + b_1 LNHEIGHT + b_2 BAL100 + b_3 ELEV + b_4 NORTHING + b_5 QMD + b_6 MOISTCLASS\ 1 + b_7 MOISTCLASS\ 2 + b_8 MOISTBYBA\ 1 + b_9 MOISTBYBA\ 2)$
2b	$HTG = \exp(b_0 + b_1 LNHEIGHT + b_2 BAL100 + b_3 ELEV + b_4 NORTHING + b_5 QMD + b_6 MOISTCLASS\ 1 + b_7 MOISTCLASS\ 2)$
3*	$HTG = b_0 + b_1 HEIGHT + b_2 HTSQ + b_3 BAL100$
4	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 BAL100$
4a	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 BAL100 + b_4 ELEV + b_5 NORTHING + b_6 QMD + b_7 MOISTCLASS\ 1 + b_8 MOISTCLASS\ 2 + b_9 MOISTBYBA\ 1 + b_{10} MOISTBYBA\ 2$
4b	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 BAL100 + b_4 ELEV + b_5 NORTHING + b_6 QMD + b_7 MOISTCLASS\ 1 + b_8 MOISTCLASS\ 2$

NOTES: "*" indicates that the model exhibits nonnormal distribution of residuals; n=number of trees.

Paper Birch Models

Variables expressing the influence of aspect (COSASPECT and SINASPECT) and slope (SL) were selected for base Models 1, 3 and 4, while Model 2 was fit with measures of height (HEIGHT, LNHEIGHT,) and slope (Table 30). All four base models had relatively high standard errors of the estimate, ranging from 0.448 to 0.484 m. R^2 or I^2 values ranged from 0.212 to 0.323. Models 1 and 4 had overall biases (underprediction) of 0.068 m and 0.034 m, respectively. The use of average five-year height increment, Model 5, provided the poorest fit statistics.

Table 29. Fit statistics and summary data from data splitting, lodgepole pine.

Model	Fitting Data					Testing Data			
	Split	N	Bias or Bias'	R ² or I ²	SEE or SEE'(m)	n	Bias or Bias'	R ² or I ²	SEE or SEE'(m)
1	1	151	0.068	0.128	0.426	52	0.127	0.096	0.481
	2	157	0.069	0.134	0.427	46	0.081	0.083	0.484
	3	151	0.077	0.075	0.450	52	0.087	0.270	0.402
	4	150	0.068	0.210	0.424	53	0.004	-0.312	0.498
	Full	203	0.071	0.129	0.432				
2	1	151	0.000	0.150	0.418	52	0.068	0.138	0.460
	2	157	0.000	0.146	0.421	46	0.019	0.171	0.450
	3	151	0.000	0.109	0.439	52	-0.001	0.265	0.395
	4	150	0.000	0.233	0.415	53	-0.060	-0.259	0.478
	Full	203	0.000	0.154	0.424				
2a	1	151	-0.001	0.472	0.337	52	-0.013	0.427	0.405
	2	157	0.000	0.505	0.328	46	0.059	0.223	0.476
	3	151	0.000	0.432	0.359	52	-0.009	0.543	0.337
	4	150	-0.001	0.496	0.345	53	-0.011	0.253	0.397
	Full	203	-0.001	0.467	0.343				
2b	1	151	-0.002	0.414	0.353	52	-0.049	0.343	0.424
	2	157	-0.002	0.419	0.353	46	0.103	0.315	0.435
	3	151	-0.002	0.375	0.374	52	-0.023	0.441	0.364
	4	150	-0.002	0.455	0.356	53	0.016	0.067	0.433
	Full	203	-0.002	0.404	0.360				
3	1	151	0.000	0.161	0.416	52	0.079	0.164	0.458
	2	157	0.000	0.170	0.417	46	0.021	0.176	0.454
	3	151	0.000	0.144	0.432	52	-0.009	0.249	0.403
	4	150	0.000	0.233	0.416	53	-0.086	-0.142	0.460
	Full	203	0.000	0.173	0.420				
4	1	151	0.035	0.155	0.418	52	0.111	0.128	0.488
	2	157	0.036	0.156	0.420	46	0.059	0.176	0.477
	3	151	0.038	0.132	0.435	52	0.024	0.258	0.419
	4	150	0.034	0.226	0.418	53	0.042	-0.149	0.481
	Full	203	0.036	0.163	0.423				
4a	1	151	0.021	0.475	0.337	52	0.006	0.332	0.443
	2	157	0.020	0.520	0.324	46	0.097	0.190	0.493
	3	151	0.025	0.434	0.360	52	-0.006	0.562	0.333
	4	150	0.022	0.507	0.342	53	0.016	0.188	0.418
	Full	203	0.023	0.470	0.343				
4b	1	151	0.023	0.416	0.353	52	-0.028	0.334	0.431
	2	157	0.023	0.455	0.343	46	0.133	0.272	0.454
	3	151	0.026	0.394	0.370	52	-0.015	0.486	0.353
	4	150	0.023	0.476	0.350	53	0.037	0.078	0.436
	Full	203	0.024	0.422	0.356				

NOTE: n=number of trees.

Models 3a and 4a (Table 5.8) showed the most improvement (Table 30). Model 4a included a measure of tree size (SQRTDBH), while Model 3a relied on external factors (BAL100, ELEV, NORTHING). The preferred model, Model 4a, had the lowest standard error of the estimate

(0.390 m), the highest coefficient of multiple determination (0.489), and an overall bias of 0.025 m.

Table 30. Height increment models and fit statistics for paper birch (n=32). Estimated parameters for the preferred model (highlighted in grey) are given in Appendix M.

Model		R ² or I ²	SEE or SEE'(m)	Bias or Bias'
1	$LNHTG = b_0 + b_1COSASPECT + b_2SINASPECT + b_3SL$	0.212	0.484	0.068
2	$HTG = \exp(b_0 + b_1HEIGHT + b_2LNHEIGHT + b_3SL)$	0.313	0.452	0.000
3	$HTG = b_0 + b_1COSASPECT + b_2SINASPECT + b_3SL$	0.323	0.448	0.000
3a	$HTG = b_0 + b_1BAL100 + b_2ELEV + b_3NORTHING$	0.486	0.391	0.000
4	$SQRTHTG = b_0 + b_1COSASPECT + b_2SINASPECT + b_3SL$	0.285	0.461	0.034
4a	$SQRTHTG = b_0 + b_1CCF + b_2ELEV + b_3SQRTDBH$	0.489	0.390	0.025
5	$HTG = b_0$	0.000	0.518	0.000

NOTE: n=number of trees.

Ponderosa Pine Models

All four base models had similar R² or I² values, ranging from 0.462 to 0.480 (Table 31). Standard errors of the estimate ranged from 0.324 to 0.329 m. Models 1 and 4 had overall biases (underprediction) of 0.053 and 0.027 m, respectively. Model 4 exhibited evidence of a nonnormal distribution of residuals. Model 5 provided the poorest fit statistics. Both HEIGHT and CCF were consistently selected for each model. Adding NORTHING in Model 3a and MOISTBYBA1 to Model 4a improved fit statistics.

The multiple coefficients of determination for Models 3a and 4a were similar, at 0.519 and 0.522, respectively, (Table 31). The standard errors of the estimate were also very similar, at 0.318 m and 0.317 m, respectively. Although Model 4a had an overall bias of 0.024 m and slightly poorer fit statistics, it was selected as the preferred model due based on the parameter estimates. Model 3a had an intercept (b₀) of 37 m, and relied mainly on the

NORTHING value to reduce the predicted five-year height increment. This had the potential for poor predictions outside of the modelled range of observations.

Table 31. Height increment models and fit statistics for ponderosa pine (n=28). Estimated parameters for the preferred model (highlighted in grey) are given in Appendix M.

Model		R ² or I ²	SEE or SEE'(m)	Bias or Bias'
1	$LNHTG = b_0 + b_1HEIGHT + b_2CCF$	0.462	0.329	0.053
2	$HTG = \exp(b_0 + b_1HEIGHT + b_2CCF)$	0.480	0.324	0.000
3	$HTG = b_0 + b_1HEIGHT + b_2CCF$	0.469	0.327	0.000
3a	$HTG = b_0 + b_1HEIGHT + b_2CCF + b_3NORTHING$	0.519	0.318	0.000
4*	$SQRTHTG = b_0 + b_1HEIGHT + b_2CCF$	0.472	0.326	0.027
4a	$SQRTHTG = b_0 + b_1HEIGHT + b_2CCF + b_3MOISTBYBAL$	0.522	0.317	0.024
5	$HTG = b_0$	0.000	0.432	0.000

NOTES: "*" indicates that the model exhibits nonnormal distribution of residuals; n=number of trees.

Trembling Aspen Models

Selected variables were similar for each base model (Table 32). All four models had some expression of height (LNHEIGHT, HEIGHT, or SQRTHT) and stand density/competition (BAL100, CCF). Model 1 also included the influence of aspect with COSASPECT and SINASPECT. All four base models had low R² or I² values, ranging from 0.150 to 0.181. Standard errors of the estimate ranged from 0.368 m to 0.385 m. Models 1 and 4 had overall biases (underprediction) of 0.043 m and 0.023 m, respectively. Models 2 and 3 showed evidence of nonnormality of residuals. The use of average five-year height increment, Model 5, provided the poorest fit statistics.

Models 3a and 3b showed the most improvement (Table 32). Model 3b had the lowest standard error of the estimate (0.324 m), the highest coefficient of multiple determination (0.378), and no overall bias and was therefore selected as the preferred model.

Table 32. Height increment models and fit statistics for trembling aspen (n=57). Estimated parameters for the preferred model (highlighted in grey) are given in Appendix M.

Model		R ² or I ²	SEE or SEE'(m)	Bias or Bias'
1	$LNHTG = b_0 + b_1 LNHEIGHT + b_2 COSASPECT + b_3 SINASPECT + b_4 BAL100$	0.137	0.385	0.043
2*	$HTG = \exp(b_0 + b_1 LNHEIGHT + b_2 CCF)$	0.171	0.370	0.000
3*	$HTG = b_0 + b_1 HEIGHT + b_2 CCF$	0.181	0.368	0.000
3a	$HTG = b_0 + b_1 HEIGHT + b_2 CCF + b_3 MOISTCLASS 1$	0.354	0.330	0.000
3b	$HTG = b_0 + b_1 HDR + b_2 YRSINCE + b_3 MOISTBYBA 1$	0.378	0.324	0.000
4	$SQRTHTG = b_0 + b_1 SQRTHT + b_2 BAL100$	0.150	0.375	0.023
5	$HTG = b_0$	0.000	0.399	0.000

NOTES: "*" indicates that the model exhibits nonnormal distribution of residuals; n=number of trees.

Western Larch Models

BAL100 was common to all four models, while measures of height (HEIGHT, LNHEIGHT, HTSQ) were included in Models 2, 3 and 4. Measures of the influence of aspect (SINASPECT, COSASPECT) were included in Models 3 and 4. All four base models had high multiple correlation coefficients, ranging from 0.673 to 0.849. Standard errors of the estimate were more variable, ranging from 0.290 m to 0.415 m (Table 33). Models 1 and 4 had overall biases of 0.050 m and 0.012 m, respectively. Model 1 showed evidence of a nonnormal distribution of residuals.

No improvements of fit statistics were obtained by adding variables without model overfitting (Table 33). Model 2 was selected as the preferred model since it had few variables, a high R² value (0.849), negligible bias, and the lowest standard error of the estimate (0.290 m). Associated parameter estimates are summarized in Appendix M.

Table 33. Height increment models and fit statistics for western larch (n=43). Estimated parameters for the preferred model (highlighted in grey) are given in Appendix M.

Model		R ² or I ²	SEE or SEE'(m)	Bias or Bias'
1*	$LNHTG = b_0 + b_1 BAL100$	0.673	0.415	0.050
2	$HTG = \exp(b_0 + b_1 HEIGHT + b_2 LNHEIGHT + b_3 BAL100)$	0.849	0.290	0.003
3	$HTG = b_0 + b_1 HEIGHT + b_2 HTSQ + b_3 COSASPECT + b_4 SINASPECT + b_5 BAL100$	0.832	0.313	0.000
4	$SQRTHTG = b_0 + b_1 HEIGHT + b_2 SQRTHT + b_3 COSASPECT + b_4 SINASPECT + b_5 BAL100$	0.852	0.294	0.012

NOTES: "*" indicates that the model exhibits nonnormal distribution of residuals; n=number of trees.

5.3.2 Spatial Data

For the reduced data set with spatial information, both lodgepole pine and Douglas-fir showed a moderate to strong negative correlation between height increment and plot-level competition indices (CCF, BAHA, BAL) and a moderate to strong positive correlation with the plot-level release index (percent BAHA removed) (Table 34). Tables 35 and 36 present the simple correlations between five-year height growth and spatial indices by species and search radius. In general, five-year height increment was negatively correlated with competition indices and positively correlated with release indices; many of these correlations were statistically different from zero ($\alpha=0.05$). Correlation between indices and small tree height increment generally increased with increasing search radius; this occurred for both competition and release indices, indicating that the effects of both competition and release of resources on small tree height increment occurs at relatively large scales.

For lodgepole pine, correlations with ratio-based competition indices were slightly higher and correlations for area of influence indices were slightly lower. For Douglas-fir, area of influence-based indices had stronger correlations than ratio-based indices, but plot-level indices generally had the strongest correlations. Lodgepole pine showed consistently stronger correlations for competition indices calculated using only competitors larger than

the subject tree; Douglas-fir did not exhibit such a clear trend. While most correlations between height increment and release indices were statistically different from zero ($\alpha=0.05$), this was not the case for lodgepole pine.

Table 34. Simple correlations between five-year height increment and plot-level indices by species.

Species	n		CCF	BAHA	BAL100	PCTBAREM
Fd	78	corr.	-0.60	-0.58	-0.59	0.61
		prob.	<0.01	<0.01	<0.01	<0.01
PI	51	corr.	-0.51	-0.54	-0.56	0.57
		prob.	<0.01	<0.01	<0.01	<0.01

NOTES: corr. is the Pearson's correlation and prob. is the associated p value, under the hypothesis that the correlation is not significantly different from 0; bold indicates that the correlation is statistically different from zero at $\alpha=0.05$; CCF is the crown competition factor, BAHA is total basal area per hectare (m^2/ha), BAL100 is the total basal area of trees larger than the subject tree/100 (dm^2/ha), and PCTBAREM is percent basal area removed.

Table 35. Simple correlations between five-year height increment and spatial indices, Douglas-fir (n=78).

Index	Search Radius		Lorimer1	Lorimer2	Hegyi1	Hegyi2	OpieA	OpieB	Bella1A	Bella1B	Bella2A	Bella2B	BAN
All Competitors	3m	corr.	-0.38	-0.33	-0.15	-0.28	-0.37	-0.32	-0.38	-0.43	-0.26	-0.33	-0.41
		prob.	<0.01	<0.01	0.18	0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
	7m	corr.	-0.51	-0.40	-0.19	-0.38	-0.37	-0.49	-0.39	-0.53	-0.27	-0.36	-0.60
		prob.	<0.01	<0.01	0.09	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
	11m	corr.	-0.50	-0.36	-0.22	-0.38	-0.37	-0.49	-0.39	-0.52	-0.27	-0.37	-0.56
		prob.	<0.01	<0.01	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
Competitors >Subject	3m	corr.	-0.41	-0.33	-0.16	-0.28	-0.43	-0.41	-0.38	-0.44	-0.25	-0.32	-0.42
		prob.	<0.01	<0.01	0.18	0.01	<0.01	<0.01	<0.01	<0.01	0.03	<0.01	<0.01
	7m	corr.	-0.51	-0.40	-0.19	-0.37	-0.43	-0.57	-0.39	-0.52	-0.26	-0.36	-0.60
		prob.	<0.01	<0.01	0.09	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
	11m	corr.	-0.49	-0.35	-0.22	-0.38	-0.43	-0.57	-0.39	-0.52	-0.26	-0.36	-0.56
		prob.	<0.01	<0.01	0.06	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
Release	3m	corr.	0.31	0.26	0.29	0.26	0.29	0.27	0.29	0.30	0.23	0.26	0.43
		prob.	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.05	0.02	<0.01
	7m	corr.	0.20	0.21	0.28	0.26	0.33	0.38	0.33	0.34	0.26	0.23	0.36
		prob.	0.08	0.07	0.01	0.02	<0.01	<0.01	<0.01	<0.01	0.02	0.04	<0.01
	11m	corr.	0.28	0.26	0.30	0.28	0.33	0.38	0.33	0.34	0.26	0.23	0.49
		prob.	0.01	0.02	0.01	0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.04	<0.01

NOTES: corr. is the Pearson's correlation and prob. is the associated p value, under the hypothesis that the correlation is not significantly different from 0; bold indicates that the correlation is statistically different from zero at $\alpha=0.05$; see Table 23 for definition of indices.

Table 36. Simple correlations between five-year height increment and spatial indices, lodgepole pine (n=51).

Index	Search Radius		Lorimer1	Lorimer2	Hegyi1	Hegyi2	OpieA	OpieB	Bella1A	Bella1B	Bella2A	Bella2B	BAN
All Competitors	3m	corr.	-0.09	-0.21	-0.24	-0.30	-0.19	-0.12	-0.30	-0.23	-0.24	-0.27	-0.03
		prob.	0.55	0.14	0.09	0.03	0.18	0.40	0.03	0.10	0.09	0.06	0.84
	7m	corr.	-0.46	-0.51	-0.26	-0.40	-0.19	-0.18	-0.30	-0.38	-0.24	-0.40	-0.38
		prob.	<0.01	<0.01	0.06	<0.01	0.18	0.22	0.03	0.01	0.09	<0.01	0.01
	11m	corr.	-0.52	-0.51	-0.28	-0.48	-0.19	-0.18	-0.30	-0.38	-0.24	-0.40	-0.46
		prob.	<0.01	<0.01	0.04	<0.01	0.18	0.22	0.03	0.01	0.09	<0.01	<0.01
Competitors >Subject	3m	corr.	-0.19	-0.23	-0.39	-0.42	-0.39	-0.26	-0.34	-0.27	-0.25	-0.27	-0.07
		prob.	0.18	0.10	<0.01	<0.01	0.01	0.07	0.02	0.06	0.08	0.05	0.63
	7m	corr.	-0.50	-0.51	-0.51	-0.55	-0.39	-0.30	-0.34	-0.40	-0.25	-0.40	-0.39
		prob.	<0.01	<0.01	<0.01	<0.01	0.01	0.03	0.02	<0.01	0.08	<0.01	<0.01
	11m	corr.	-0.57	-0.51	-0.59	-0.55	-0.39	-0.30	-0.34	-0.40	-0.25	-0.40	-0.48
		prob.	<0.01	<0.01	<0.01	<0.01	0.01	0.03	0.02	<0.01	0.08	<0.01	<0.01
Release	3m	corr.	0.21	0.11	0.19	0.08	0.38	0.28	0.27	0.22	0.13	0.11	0.33
		prob.	0.14	0.44	0.18	0.58	0.01	0.05	0.06	0.13	0.36	0.44	0.02
	7m	corr.	0.13	-0.08	0.18	0.01	0.39	0.24	0.27	-0.01	0.14	-0.20	0.27
		prob.	0.38	0.60	0.21	0.94	0.01	0.09	0.05	0.92	0.34	0.17	0.06
	11m	corr.	0.10	-0.06	0.15	-0.01	0.39	0.24	0.27	-0.02	0.14	-0.20	0.24
		prob.	0.49	0.66	0.29	0.93	0.01	0.09	0.05	0.91	0.34	0.17	0.09

NOTES: corr. is the Pearson's correlation and prob. is the associated p value, under the hypothesis that the correlation is not significantly different from 0; bold indicates that the correlation is statistically different from zero. at $\alpha=0.05$; see Table 23 for definition of indices.

Table 37 summarizes the effects of each competition and spatial index on mean square error for Douglas-fir height increment, relative to the base model outlined in Section 5.2.2. Because the highest correlations were generally found at the largest search radius, indices based on an 11 m search radius were used. For each type of index, the four greatest percent reductions in MSE are in bold. In general, plot-level indices performed as well or better than tree-level spatial indices. The semi-spatial indices, neighbourhood basal area and indices based on Lorimer, outperformed other index types. Neighbourhood basal area performed slightly better than plot-level basal area indices, for all competitors (62.0 vs. 62.3) and competitors>subject (60.2 vs. 62.1).

Percent reduction for lodgepole pine is summarized in Table 38. Again, plot-level indices performed as well or better than competition and release indices. Some release indices actually increase MSE, indicating very poor performance. Ratio-based competition indices generally outperformed zone of influence competition indices.

Table 37. Percent MSE of Index+Base Model vs. Base Model, Douglas-fir small tree height increment, where base model=100% and values smaller than 100% indicate improvement.

Plot Level Indices			
	All Competitors	Competit.>Subject	Release
BA	62.3	-	-
BAL100	-	62.1	-
CCF	60.1	-	-
PCTBAREM	-	-	70.6
Size and Size-Dependant Indices			
	All Competitors	Competit.>Subject	Release
BAN	62.0	60.2	83.7
Lor1	66.4	63.0	94.5
Lor2	76.7	76.0	91.2
Heg1	94.5	93.5	92.2
Heg2	77.0	76.6	90.8
Zone of Influence Indices			
	All Competitors	Competit.>Subject	Release
OpieA	89.0	83.5	91.5
OpieB	73.2	63.6	96.0
Bel1A	87.6	86.4	97.8
Bel1B	67.9	66.8	92.9
Bel2A	93.9	92.9	97.9
Bel2B	82.3	81.7	97.8

NOTES: "-" =not applicable; for example, basal area in larger trees could not be calculated using all competitors, since by definition it is the sum of all competitors larger than the subject tree; see Table 23 for definition of indices.

Table 38. Percent MSE of Index+Base Model vs. Base Model, lodgepole pine small tree height increment, where base model=100% and values smaller than 100% indicate improvement.

Plot Level Indices			
	All Competitors	Competit.>Subject	Release
BA	77.7	-	-
BAL100	-	76.7	-
CCF	80.6	-	-
PCTBAREM	-	-	76.3
Size and Size-Dependant Indices			
	All Competitors	Competit.>Subject	Release
BAN	81.9	82.1	101.2
Lor1	88.1	83.5	102.2
Lor2	82.3	82.0	102.3
Heg1	93.7	79.9	100.2
Heg2	81.4	78.4	101.7
Zone of Influence Indices			
	All Competitors	Competit.>Subject	Release
OpieA	98.1	83.6	99.4
OpieB	98.7	92.9	103.1
Bel1A	93.6	90.0	99.3
Bel1B	90.2	88.4	102.5
Bel2A	97.1	96.8	100.4
Bel2B	83.2	83.0	101.9

NOTES: "-" =not applicable; for example, basal area in larger trees could not be calculated using all competitors, since by definition it is the sum of all competitors larger than the subject tree; see Table 23 for definition of indices.

Competition indices based on competitors larger than subject trees provided better results for both species, with few exceptions. For competition indices, area of influence indices based on twice the crown radius performed better than those based on crown radius, and distance weighted area of influence indices based on diameter ratios performed better than those based on squared diameter ratios. The opposite was true for zone of influence release indices.

Release indices generally performed poorly, except at the plot level. CCF and neighbourhood basal area of larger trees provided the most improvement over the base model for Douglas-fir, while percent basal area removed and basal area in larger trees provided the best improvements over the base model for lodgepole pine.

5.4 Discussion

5.4.1 *Modelling Small Tree Height Increment*

The usefulness of data splitting is illustrated in the results for lodgepole pine. Since sample size was relatively large, the initial variability in fit statistics from test data sets (including negative I^2 values) indicated that the base models did not properly describe the trend within the data. The addition of new variables resulted in much more consistent results.

The inclusion of additional variables greatly improved the fit statistics for most of the models. Adding interaction terms also improved the fit (i.e., residual patterns and tests of normality) of the models over many of the base models. This makes biological sense, since in nature, all factors interact to form the growing environment. An increase in the sample size for those species with small data sets would allow the inclusion of more variables, which would likely improve the precision of the estimates. For example, the selected model for interior spruce relies solely on basal area in larger trees and moisture class to predict five-year height increment.

Models do not imply causal relationships between predictor and response variables, but in many cases, the variables that provide the best model fit also agree with biological reasoning. For example, Lopushinsky (1991) stated that water deficits are the largest factors in reducing growth of interior Douglas-fir, and Hermann and Lavender (1990) stated that the proportion of Douglas-fir found in mixed-species stands depends on aspect, elevation, soil and history. The preferred model for Douglas-fir included a number of variables which relate to moisture, aspect and their interactions with elevation.

Lodgepole pine grows under a wide variety of ecological conditions, including wide variations in climatic temperatures. Armit (1966) stated that physiography, climate, soil and ecological factors rarely limit its growth, except in extreme situations. Lodgepole pine is resistant to frost injury, able to grow in very nutrient poor sites and sites with extreme water conditions (Klinka *et al.* 1989). However, lodgepole pine is very intolerant of shade and competition (Armit 1966). Many of the variables included in the preferred model form related to various environmental factors, but the interaction between moisture and basal area was significant only for this species, indicating the relative importance of competition.

Paper birch provides another interesting example. It is predominantly limited by high average July temperatures and shade intolerance following establishment (Safford *et al.* 1990), but can tolerate high temperatures, provided that sufficient moisture is available (Simard 1996). The preferred model for paper birch included CCF, SQRTDBH and ELEV. CCF is a competition index that which reflects the effect of competition for light. Although paper birch was predominantly found at higher elevations and on wetter sites, elevation was negatively correlated with small tree height increment. Therefore, while elevation may have provided cooler and/or wetter sites, allowing paper birch to establish, a shorter growing season may result in lower height increment relative to paper birch growing on a low elevation moist site. These results illustrate the fact that factors favouring establishment and persistence of species may not necessarily provide the optimal conditions for growth.

Trembling aspen is tolerant of many environmental factors. Chen *et al.* (2002) found that latitude, longitude, elevation, aspect, moisture and nutrient regimes all had an affect on aspen site index. Trembling aspen is limited by temperatures (maximum mean July

temperatures of 24°C), precipitation (occurs only in areas of water surplus), and competition (Perala 1990). It is a very shade intolerant species. The preferred model includes a competition index (HDR) and a measure of moisture (MOISTBYBA1) as it interacts with basal area, both biologically feasible variables.

Western larch is a particularly interesting species, providing good results with very few variables. This may be because larch is generally planted on very similar sites in the IDFdm2, resulting in similar growth rates. Representative data from more varied conditions may show more variability in height increment. The other explanation could be that larch has very consistent growth rates regardless of outside influences.

However, overall, many of the models still only performed moderately well. For some species, this may relate to small sample size. However, for well sampled species such as Douglas-fir, the variability in height increment indicates that the predictor variables used do not have the hoped-for explanatory power.

5.4.2 Spatial Data

The fact that correlations between small tree height growth and spatial indices generally became stronger with increasing search radius indicates that competitive effects occur over a large scale. Because of this, it is doubtful that access to light resources is the primary factor driving competition for resources. Below-ground competition for resources (resource depletion), is the probable cause. However, competition for light cannot be denied a role in small tree height increment; both below- and above-ground competition can occur concurrently, and attempting to categorize competition in such a neat and tidy fashion does not reflect the variability that these stands contain. As such, combining indices which are based on presumption of different competitive effects may provide better results than a single index, since they would describe different aspects of stand variability.

Spatial release indices did not perform well relative to competition indices, in high contrast to the performance of the plot-level release index. At times, the release index actually

reduced performance relative to the base model. The fact that correlations between height increment and release indices varied from positive to negative indicates that the trend is not stable, and therefore may be adding noise to the predictions through its inclusion. Because each equation is based on assumptions regarding the nature of the effect (proportional to size, in the case of size-distance indices, and based on overlap of effect, in the case of area of influence indices), it may be that the underlying assumptions do not lend themselves well to the study of resource release.

However, the plot-level index, which calculated release relative to original competition levels, performed very well. Perhaps altering the release index formulation to create a relative release index, or combining indices of release with indices of competition in a model, would improve results. On the whole, plot-level indices equaled or outperformed tree-level indices. This may again indicate a diffuse competition mechanism, indicating that focusing on the above ground environment may not be as important as focusing on the below ground component.

6. CONCLUSIONS AND RECOMMENDATIONS

Within the Invermere Forest District, the inherent complexity of the Interior Douglas-fir subzone is complicated by a history of fire suppression and harvesting, and its associated effects on the natural system. Different levels of complexity (both spatial and aspatial, from plot level to substrate level) were examined relative to different understory components (regeneration abundance and small tree height increment), in an attempt to elucidate some of this complexity. The motivations were both operational and research-oriented, trying to balance the need for prediction with the need to increase understanding of the processes involved.

Modelling regeneration abundance using plot-level variables was moderately successful. Given the variability inherent in regeneration dynamics, the relatively small sample size, and the limited selection of variables used in modelling, imputation methods performed well. MSN and k-MSN methods are preferred, because they take into account the correlations between predictor and response variables and therefore incorporate more aspects of biological variability. Tabular imputation could be improved by creating tables based on species-specific preferences.

Substrate abundance was demonstrated to vary by moisture condition, as did substrate suitability for regeneration. Because sample size was limited, analysis focused solely on abundance of Douglas-fir regeneration. Other species will likely exhibit different behaviour and should be examined separately. Studies of substrate should also be placed within a multivariate context. In particular, substrate information should be combined with studies of aspatial or spatial indices of competition and release, since it is anticipated that the two interact to affect substrate type and abundance, as well as seedling germination and establishment, along with other factors such as seed source availability. A larger sample size will allow a more detailed investigation in this multivariate context, while data on microclimate and subsurface conditions (e.g., soil structure and growing season moisture availability), could help to account for more of this variability.

Spatial indices showed interesting patterns between germinants and competition indices, and established (Height Class 1) regeneration and release indices. These patterns may not translate to competition for resources, but should be further examined. For example, the fact that established (Height Class 1) regeneration occurs infrequently if there is release within 3 m can represent harvesting effects, or it could reflect the release of resources. Because the effects of competition and release on regeneration appeared to be on a smaller scale than for small trees, a smaller plot size than the 11 m radius could be used for assessing the effects of competition and/or release. Since neighbourhood basal area is a semi-spatial method that provided similar results to other indices, it could be used to obtain the necessary information while requiring less data collection effort.

The value of using Ripley's analysis for examining spatial patterns was not established. While statistical significance was found using Monte Carlo methods, the direction of influence varied in a manner that was not easily described. If competition is underground or more diffuse, or substrate has a great impact on clump loci, then the failure of this analysis to provide consistent results is not surprising. It might also be that point pattern analysis is not an appropriate tool for examining clumps, which can cover considerable area, or for examining these stands in general, since vertical structure is not taken into account. Because of the difficulty in reconciling the differences in patterning between sites, this tool might be better applied to examining trends in stand structure over time, on repeatedly measured plots, or discarded for another tool altogether. Gap analysis or directional-specific indices may better represent horizontal spatial distributions, while incorporating information of the vertical distribution within the stand may improve overall performance.

Small tree height increment models were all improved by the addition of variables not currently included in Prognosis^{BC} small tree five-year height increment models, such as moisture class, elevation and UTM northing. Interactions also appeared to improve the explanatory ability of the models. The selected predictor variables were generally those that were expected to have an influence on small tree height increment, based on the literature. Because western larch was sampled on a limited range of site types, models performed very well with very few variables. However, outside of these site types, model performance may be unpredictable.

As with regeneration, results were only moderately good. Part of this can be explained by the small sample size for many species, but not for Douglas-fir or lodgepole pine. Further sampling to increase sample size would allow the inclusion of more predictor variables in some models. Obtaining samples of western larch on a wider range of sites may not improve model performance, but it would improve its applicability within the area.

Spatial indices showed little potential for improvements over plot-level indices for predicting small tree five-year height increment. Calculating release indices relative to the amount of initial competition may improve performance of these indices. However, these analyses indicate that the addition of spatial indices will not improve model performance to any substantial degree. It appears that competition for resources occurs over relatively large and disperse scales, as is expected with resource depletion scenarios, where access to below ground resources is the primary constraint. As such, the question of whether or not to expend increased time and effort in order to collect spatial data may be unnecessary. Since indications are that competition appears to be diffuse in nature, an examination of subsurface factors may be more important to improving understanding of small tree height increment. Soil moisture is without a doubt a limiting factor in these stands; how much so and its relationship with small tree height increment is uncertain.

The spatial data collected for this thesis work were horizontal attribute data only. Because they were mapped at the point of germination, the effect of lean and variation in overstory position on understory light patterns (offset) was not incorporated into analyses. The lack of vertical structure, particularly in these uneven aged stands, was also a limiting factor. Spatial indices, which are calculated based upon more complex data (including height to live crown and total tree height, over all trees), may yield improved results. Spatial statistics which incorporate attributes of stand structure, such as vertical differentiation, species mixtures, and crown position, may provide better results than the horizontal patterning of points examined using Ripley's $K(t)$ statistic.

Stands of the Interior Douglas-fir BEC zone provide a very interesting challenge. While most research studies a system by examining its component parts, as in this thesis, tying the story together remains difficult, particularly when both operational and research-oriented goals

are combined. At a practical level, the question is whether or not moderately good is good enough. At a research level, the question is whether or not the answers we seek are attainable with the tools and knowledge we have.

This thesis has provided a few areas that show promise for future investigation. Further focus on substrate conditions and their effect on regeneration, within a multivariate context and over all species, is one of the most promising of these. In general, subsurface (soil) properties are be an unexplored avenue that merits investigation, particularly since evidence points to below-ground competition for resources. Finally, spatial tools may be more illustrative if data are gathered for both horizontal and vertical structures, or at larger scales.

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APPENDIX A. DETERMINATION OF ADVANCE VERSUS SUBSEQUENT REGENERATION

The ability to determine which of the stems classified as regeneration existed prior to harvesting ("advance") and which developed following harvesting ("subsequent") is crucial to the sampling methods for all components of this study. Ferguson and Carlson (1993) defined regeneration as seedlings 3 years old or older at the time of disturbance. Since the date of harvesting is known, any trees older than [2001 minus date of harvest plus 2] can be considered advance regeneration.

Generally, for determinate, shade intolerant species, estimating age can be done by simply counting whorls on the stem. However, for indeterminate, or more suppressed shade tolerant species, estimation of age can be more difficult. Where counting of whorls is problematic, destructive sampling is required to differentiate between advance and subsequent regeneration. The following measurement method was used in order to be able to make the distinction, with the least amount of destructive sampling:

Destructively sample an "average" class four tree.

1. If it is determined to be advance, and all class four trees appear to be of similar form, assume that all class four trees are advance.
2. If it is determined to be subsequent, and all class four trees appear to be of a similar form, assume that all class four trees are subsequent. In addition, if all lower class trees appear to be of similar form, assume that they, too are subsequent, and end destructive sampling.
3. If, in either case, class four trees are not of the same form (some appear to be suppressed while others appear to be open grown), sample one tree from each form class, and assign type (advance vs. subsequent) based upon the results.
4. Where not all class four trees are determined to be subsequent, repeat the four steps, substituting class three trees. If all class three trees are determined to be subsequent, assume that all lower class trees are also subsequent, and stop destructive sampling. If not, repeat the steps for class two, then class one, if necessary.

APPENDIX B. TABULAR IMPUTATION MODEL 1¹

Section B.1. Planted Sites

Table B.1.1. Average regeneration stems per hectare by height class and species for years since disturbance class 1 (5-9 years), basal area class "open" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	3	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	2576	1833	495	743	5647
		Lw		50	0	0	50
		Pl		50	0	0	50
		Py		0	0	0	0
		Sxw	149	50	50	50	297
		Total	2724	1981	545	793	6043

Table B.1.2. Average regeneration stems per hectare by height class and species for years since disturbance class 2 (10-14 years), basal area class "open" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	7	At		21	42	21	85
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	764	425	106	127	1422
		Lw		85	64	255	403
		Pl		509	425	1401	2335
		Py		0	0	0	0
		Sxw	21	64	42	0	127
		Total	785	1104	679	1804	4373

Table B.1.3. Average regeneration stems per hectare by height class and species for years since disturbance class 2 (10-14 years), basal area class "open" and moisture class "wet".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
wet	6	At		74	0	396	471
		Bl	0	0	0	0	0
		Ep		50	124	198	372
		Fd	421	149	124	347	1040
		Lw		0	0	0	0
		Pl		248	74	594	916
		Py		0	0	0	0
		Sxw	25	0	25	0	50
		Total	446	520	347	1536	2848

¹ Height class 1 regeneration abundance is not predicted for shade intolerant species. See methods section.

Table B.1.4. Average regeneration stems per hectare by height class and species for years since disturbance class 3 (15-19 years), basal area class "open" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	11	At		81	27	230	338
		Bl	0	0	0	14	14
		Ep		0	0	0	0
		Fd	1081	946	135	675	2837
		Lw		0	27	68	95
		Pl		108	95	1635	1837
		Py		0	0	0	0
		Sxw	27	14	14	27	81
		Total	1108	1148	297	2648	5201

Table B.1.5. Average regeneration stems per hectare by height class and species for years since disturbance class 4 (20-24 years), basal area class "open" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	2	At		0	0	74	74
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	74	74	74	0	223
		Lw		0	0	0	0
		Pl		74	0	594	669
		Py		0	0	0	0
		Sxw	0	74	0	0	74
		Total	74	223	74	669	1040

Table B.1.6. Average regeneration stems per hectare by height class and species for years since disturbance class 4 (20-24 years), basal area class "open" and moisture class "wet".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
wet	2	At		669	223	1412	2303
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	372	0	0	149	520
		Lw		0	0	0	0
		Pl		0	74	0	74
		Py		0	0	0	0
		Sxw	0	0	0	0	0
		Total	372	669	297	1560	2898

Section B.2. Unplanted Sites

Table B.2.1. Average regeneration stems per hectare by height class and species for years since disturbance class 1 (5-9 years), basal area class "open" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	7	At		42	0	0	42
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	1061	425	191	509	2187
		Lw		21	21	0	42
		Pl		127	42	0	170
		Py		0	0	0	0
		Sxw	0	0	0	0	0
		Total	1061	616	255	509	2441

Table B.2.2. Average regeneration stems per hectare by height class and species for years since disturbance class 2 (10-14 years), basal area class "open" and moisture class "dry".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
dry	6	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	2279	793	223	2031	5325
		Lw		0	0	0	0
		Pl		0	0	0	0
		Py		0	25	25	50
		Sxw	0	0	0	0	0
		Total	2279	793	248	2056	5374

Table B.2.3. Average regeneration stems per hectare by height class and species for years since disturbance class 2 (10-14 years), basal area class "open" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	14	At		138	32	74	244
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	3513	1858	403	1337	7112
		Lw		11	0	11	21
		Pl		127	32	626	785
		Py		11	0	11	21
		Sxw	11	11	0	0	21
		Total	3524	2155	467	2059	8205

Table B.2.4. Average regeneration stems per hectare by height class and species for years since disturbance class 3 (15-19 years), basal area class "open" and moisture class "dry".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
dry	2	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	966	520	223	817	2526
		Lw		0	0	0	0
		Pl		0	0	0	0
		Py		0	0	0	0
		Sxw	0	0	0	0	0
		Total	966	520	223	817	2526

Table B.2.5. Average regeneration stems per hectare by height class and species for years since disturbance class 3 (15-19 years), basal area class "open" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	12	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		50	12	0	62
		Fd	3145	1895	693	1870	7603
		Lw		12	0	50	62
		Pl		37	25	173	235
		Py		74	0	37	111
		Sxw	12	12	0	12	37
		Total	3158	2080	731	2142	8111

Table B.2.6. Average regeneration stems per hectare by height class and species for years since disturbance class 3 (15-19 years), basal area class "open" and moisture class "wet".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
wet	3	At		297	99	297	693
		Bl	0	0	0	0	0
		Ep		248	594	842	1684
		Fd	2130	793	297	1238	4458
		Lw		0	0	0	0
		Pl		0	99	149	248
		Py		0	0	0	0
		Sxw	0	0	0	0	0
		Total	2130	1337	1090	2526	7083

Table B.2.7. Average regeneration stems per hectare by height class and species for years since disturbance class 4 (20-24 years), basal area class "open" and moisture class "dry".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
dry	2	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	3121	2601	372	520	6613
		Lw		0	0	0	0
		Pl		743	149	372	1263
		Py		0	0	74	74
		Sxw	0	0	0	0	0
		Total	3121	3344	520	966	7950

Table B.2.8. Average regeneration stems per hectare by height class and species for years since disturbance class 4 (20-24 years), basal area class "open" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	2	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	2749	1932	743	817	6241
		Lw		0	0	74	74
		Pl		149	149	297	594
		Py		0	0	0	0
		Sxw	0	149	0	0	149
		Total	2749	2229	892	1189	7059

Table B.2.9. Average regeneration stems per hectare by height class and species for years since disturbance class 4 (20-24 years), basal area class "open" and moisture class "wet".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
wet	2	At		74	74	149	297
		Bl	74	74	74	0	223
		Ep		0	74	297	372
		Fd	3269	1635	372	1189	6464
		Lw		0	0	0	0
		Pl		74	0	0	74
		Py		0	0	0	0
		Sxw	297	0	0	0	297
		Total	3641	1858	594	1635	7727

Table B.2.10. Average regeneration stems per hectare by height class and species for years since disturbance class 1 (5-9 years), basal area class "dense" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	5	At		30	0	30	59
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	1189	208	238	1367	3002
		Lw		0	0	0	0
		Pl		0	0	0	0
		Py		0	0	0	0
		Sxw	0	0	0	0	0
		Total	1189	238	238	1397	3061

Table B.2.11. Average regeneration stems per hectare by height class and species for years since disturbance class 2 (10-14 years), basal area class "dense" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	3	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	5151	1981	50	545	7727
		Lw		0	0	0	0
		Pl		50	0	0	50
		Py		0	0	0	0
		Sxw	0	0	0	0	0
		Total	5151	2031	50	545	7777

Table B.2.12. Average regeneration stems per hectare by height class and species for years since disturbance class 3 (15-19 years), basal area class "dense" and moisture class "wet".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
wet	2	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	1412	892	297	1189	3789
		Lw		0	0	0	0
		Pl		0	0	0	0
		Py		0	0	0	0
		Sxw	0	0	0	223	223
		Total	1412	892	297	1412	4012

Table B.2.13. Average regeneration stems per hectare by height class and species for years since disturbance class 5 (undisturbed), basal area class "dense" and moisture class "mesic".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
mesic	7	At		0	0	0	0
		Bl	0	0	0	21	21
		Ep		0	0	0	0
		Fd	1995	849	85	340	3269
		Lw		0	0	0	0
		Pl		0	0	0	0
		Py		0	0	0	0
		Sxw	0	0	0	0	0
		Total	1995	849	85	361	3290

Table B.2.14. Average regeneration stems per hectare by height class and species for years since disturbance class 5 (undisturbed), basal area class "dense" and moisture class "wet".

Moisture Class	Number of Plots	Species	Height Class				Total
			1	2	3	4	
wet	3	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	3864	1981	545	396	6786
		Lw		0	0	0	0
		Pl		0	0	0	0
		Py		0	0	0	0
		Sxw	0	0	0	0	0
		Total	3864	1981	545	396	6786

APPENDIX C. TABULAR IMPUTATION MODEL 2²

Section C.1. Planted Sites

Table C.1.1. Average regeneration stems per hectare by height class and species for years since disturbance class 1 (5-9 years) and basal area class "open".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
5-9 years	4	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	2043	1412	409	594	4458
		Lw		74	0	0	74
		Pl		74	0	0	74
		Py		0	0	0	0
		Sxw	111	37	37	74	260
		Total	2155	1597	446	669	4867

Table C.1.2. Average regeneration stems per hectare by height class and species for years since disturbance class 2 (10-14 years) and basal area class "open".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
10-14 years	14	At		41	27	135	203
		Bl	0	0	0	0	0
		Ep		0	0	81	81
		Fd	662	432	203	365	1662
		Lw		41	27	162	230
		Pl		297	216	757	1270
		Py		0	0	0	0
		Sxw	27	41	41	0	108
		Total	689	851	513	1500	3553

Table C.1.3. Average regeneration stems per hectare by height class and species for years since disturbance class 3 (15-19 years) and basal area class "open".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
15-19 years	12	At		89	15	253	357
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	1189	1010	149	713	3061
		Lw		0	15	74	89
		Pl		104	104	1248	1456
		Py		0	0	0	0
		Sxw	30	15	15	30	89
		Total	1219	1219	297	2318	5052

² Height class 1 regeneration abundance is not predicted for shade intolerant species.

Table C.1.4. Average regeneration stems per hectare by height class and species for years since disturbance class 4 (20-24 years) and basal area class "open".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
20-24 years	4	At		198	149	842	1189
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	149	50	50	0	248
		Lw		0	0	0	0
		Pl		50	50	396	495
		Py		0	0	0	0
		Sxw	0	50	0	0	50
		Total	149	347	248	1238	1981

Section C.2. Unplanted Sites

Table C.2.1. Average regeneration stems per hectare by height class and species for years since disturbance class 1 (5-9 years) and basal area class "open".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
5-9 years	8	At		42	0	0	42
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	1316	425	191	509	2441
		Lw		21	42	0	64
		Pl		127	21	0	149
		Py		0	0	0	0
		Sxw	191	21	0	0	212
		Total	1507	637	255	509	2908

Table C.2.2. Average regeneration stems per hectare by height class and species for years since disturbance class 2 (10-14 years) and basal area class "open".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
10-14 years	20	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	3005	1651	380	1618	6654
		Lw		8	0	8	17
		Pl		99	25	462	586
		Py		8	8	17	33
		Sxw	0	8	0	0	8
		Total	3005	1775	413	2105	7298

Table C.2.3. Average regeneration stems per hectare by height class and species for years since disturbance class 3 (15-19 years) and basal area class "open".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
15-19 years	17	At		74	25	74	173
		Bl	0	0	0	0	0
		Ep		111	161	211	483
		Fd	2229	1263	483	1238	5213
		Lw		12	0	50	62
		Pl		25	37	173	235
		Py		0	0	25	25
		Sxw	12	12	0	12	37
		Total	2241	1498	706	1783	6229

Table C.2.4. Average regeneration stems per hectare by height class and species for years since disturbance class 4 (20-24 years) and basal area class "open".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
20-24 years	6	At		0	30	0	30
		Bl	0	0	0	0	0
		Ep		0	30	30	59
		Fd	3180	2259	535	832	6806
		Lw		0	0	30	30
		Pl		357	119	267	743
		Py		0	0	30	30
		Sxw	0	59	0	0	59
		Total	3180	2675	713	1189	7757

Table C.2.5. Average regeneration stems per hectare by height class and species for years since disturbance class 1 (5-9 years) and basal area class "dense".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
5-9 years	6	At		30	0	30	59
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	713	178	178	1308	2378
		Lw		0	0	0	0
		Pl		0	0	0	0
		Py		0	0	0	0
		Sxw	535	0	0	0	535
		Total	1248	208	178	1337	2972

Table C.2.6. Average regeneration stems per hectare by height class and species for years since disturbance class 2 (10-14 years) and basal area class "dense".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
10-14 years	3	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	5151	1981	50	545	7727
		Lw		0	0	0	0
		Pl		50	0	0	50
		Py		0	0	0	0
		Sxw	0	0	0	0	0
		Total	5151	2031	50	545	7777

Table C.2.7. Average regeneration stems per hectare by height class and species for years since disturbance class 3 (15-19 years) and basal area class "dense".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
15-19 years	4	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	1412	892	297	1189	3789
		Lw		0	0	0	0
		Pl		0	0	0	0
		Py		0	0	0	0
		Sxw	0	0	0	223	223
		Total	1412	892	297	1412	4012

Table C.2.8. Average regeneration stems per hectare by height class and species for years since disturbance class 4 (20-24 years) and basal area class "dense".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
20-24 years	2	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	297	0	0	297	594
		Lw		0	0	0	0
		Pl		0	0	0	0
		Py		0	0	0	0
		Sxw	892	297	0	149	1337
		Total	1189	297	0	446	1932

Table C.2.9. Average regeneration stems per hectare by height class and species for years since disturbance class 5 (undisturbed) and basal area class "dense".

Years Since Disturbance	Number of Plots	Species	Height Class				Total
			1	2	3	4	
undisturbed	11	At		0	0	0	0
		Bl	0	0	0	0	0
		Ep		0	0	0	0
		Fd	3588	1677	318	488	6071
		Lw		0	0	0	0
		Pl		0	0	0	0
		Py		0	0	0	0
		Sxw	0	0	0	0	0
		Total	3588	1677	318	488	6071

APPENDIX D. FIT STATISTICS FOR TABULAR IMPUTATION MODEL 1

Table D.1. Fit statistics for regeneration stems per hectare, data splitting Run 1, by species and height class.

Run Number Number Of Plots Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias						
	Height Class				Height Class				Height Class						
	1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
18															
At		134	50	177	330		426	116	354	812		91	9	2	102
Bl	4	4	4	16	28	18	18	18	44	69	4	4	4	13	26
Ep		30	49	25	96		65	150	63	247		-3	20	3	20
Fd	1616	904	234	663	2790	2052	1175	325	1111	4082	-220	-380	-76	-48	-725
Lw		9	13	33	31	17	35	35	67	45		-2	10	-33	-25
Pl		96	74	483	622	207	156	156	1115	1340		26	20	283	330
Py		47	0	16	54		128	0	32	154		28	0	-3	24
Sxw	34	9	6	5	52	78	17	13	9	88	15	-9	-6	-5	-5
Total	1886	1065	346	1127	3569	2460	1391	448	1624	4860	-256	-302	-37	258	-336

Table D.2. Fit statistics for regeneration stems per hectare, data splitting Run 2, by species and height class.

Run Number Number Of Plots. Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias								
	Height Class				Total	Height Class				Total	Height Class				Total		
	1	2	3	4		1	2	3	4		1	2	3	4			
2	24	At		56	40	181	236		84	97	430	507		-45	-3	20	-28
		Bl		0	0	5	5		0	0	10	10		0	0	-5	-5
		Ep		11	17	25	53		27	54	86	162		-11	-17	-25	-53
		Fd		2358	1468	311	892	4234	3087	2066	473	1609	5583	-29	-137	38	252
		Lw		22	21	86	129		53	43	167	260		-22	-21	-86	-129
		Pl		182	120	670	938		365	195	1017	1381		-120	-50	-480	-650
		Py		9	3	15	27		26	11	35	54		-9	-3	-2	-15
		Sxw		28	40	17	9	83	59	86	41	27	155	20	9	5	35
		Total		2359	1581	383	1417	4553	3096	2227	530	1899	5565	-9	-335	-51	-324
																	-719

Table D.3. Fit statistics for regeneration stems per hectare, data splitting Run 3, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
3	21	At		151	48	172	339		253	99	525	729		-60	-36	95	-1
		Bl	0	0	0	4	4		0	0	0	9		0	0	0	-4
		Ep		41	86	120	248		135	331	406	792		30	83	120	234
		Fd	1948	1385	375	795	3373		2330	2156	557	1027	4653	341	587	173	-2
		Lw		22	22	109	149		52	63	298	376		13	4	89	106
		Pl		106	79	547	584		193	148	918	1013		25	-5	-230	-210
		Py		11	7	11	25		28	32	19	50		-11	7	-11	-15
		Sxw		15	37	13	62		30	82	35	25	102	-2	19	1	-13
		Total	1957	1388	437	1002	3318	2330	2147	651	1269	4275	338	603	227	45	1213

Table D.4. Fit statistics for regeneration stems per hectare, data splitting Run 4, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias					
			Height Class				Height Class				Height Class					
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4
4	17	At	78	37	53	164	180	102	130	312	49	33	-36	46		
		Bl	0	0	4	4	0	0	11	11	0	0	-4	-4		
		Ep	34	75	127	205	95	225	365	633	-34	-75	-31	-139		
		Fd	1813	1130	265	777	2881	1797	364	1066	5189	709	593	17	-179	1140
		Lw	36	27	47	98	78	57	103	180	27	6	16	49		
		Pl	96	45	261	380	139	72	478	609	-54	2	-233	-285		
		Py	5	4	11	16	20	13	37	41	-5	-4	6	-3		
		Sxw	28	30	36	38	54	60	69	114	-10	-30	-4	-20	-64	
		Total	1815	1182	296	1069	2888	1823	391	1300	5300	698	547	-25	-481	739

Table D.5. Fit statistics for regeneration stems per hectare, data splitting Run 5, by species and height class.

Run Number Of Plots Species			Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
5	19	At		83	22	61	151		121	43	108	226		-83	-7	-61	-151
		Bl	8	8	8	4	27	34	34	34	10	103	-8	-8	-8	-4	-27
		Ep		31	16	16	47		136	48	68	174		31	16	-16	31
		Fd	2004	1194	406	1013	3260	2564	1560	503	1439	3853	-621	-281	-64	95	-870
		Lw		12	7	20	35		18	16	46	55		-12	-7	7	-12
		Pl		216	58	710	977		414	100	1658	1971		146	35	550	730
		Py		17	0	31	39		45	0	81	91		-2	0	14	13
		Sxw	39	13	1	38	81	137	35	3	112	178	-39	3	-1	38	1
		Total	1971	1165	401	1345	2834	2549	1729	492	1858	3465	-668	-205	-36	624	-285

Table D.6. Fit statistics for regeneration stems per hectare, full (model) data set by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)					Root Mean Squared Error (RMSE)					Bias					
			Height Class					Height Class					Height Class					
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total	
Full Data	101	At		74	28	117	198		203	68	299	482		0	0	0	0	0
		Bl	1	1	1	5	10		10	10	10	20	37	0	0	0	0	0
		Ep		23	34	35	78		76	131	142	262		0	0	0	0	0
		Fd	1636	1014	266	718	2943		2210	1470	378	1126	4066	0	0	0	0	0
		Lw		17	14	50	74		39	37	137	182		0	0	0	0	0
		Pl		114	65	471	602		206	122	975	1169		0	0	0	0	0
		Py		16	2	14	29		59	13	38	81		0	0	0	0	0
		Sxw	24	20	11	14	57		58	41	29	41	100	0	0	0	0	0
		Total	1632	1022	299	958	2942		2211	1480	409	1336	3918	0	0	0	0	0

APPENDIX E. FIT STATISTICS FOR TABULAR IMPUTATION MODEL 2

Table E.1. Fit statistics for regeneration stems per hectare, data splitting Run 1, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
1	23	At		162	55	199	352		427	120	370	824		101	21	74	196
		Bl	6	6	6	13	32	31	31	31	44	103	6	6	6	13	32
		Ep		37	69	80	183		81	172	141	356		-11	-4	-25	-41
		Fd	1941	1084	257	688	3440	2471	1322	335	1151	4609	269	-238	-80	23	-26
		Lw		13	16	40	48		27	40	67	80		-3	6	-40	-37
		Pl		100	90	493	662		232	192	1143	1428		18	2	235	256
		Py		39	1	12	48		131	2	29	155		38	-1	-2	36
		Sxw	111	29	7	31	172	255	66	15	73	335	-47	-29	-7	-31	-113
		Total	1854	1160	287	1002	3591	2430	1392	362	1447	4718	228	-117	-56	247	303

Table E.2. Fit statistics for regeneration stems per hectare, data splitting Run 2, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)					Root Mean Squared Error (RMSE)					Bias				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
2	24	At		80	44	211	314		105	95	479	648		-38	-6	17	-28
		Bl	3	3	3	4	14	11	11	11	9	33	-3	-3	-3	-4	-14
		Ep		19	38	62	119		37	63	98	193		-19	-38	-62	-119
		Fd	2273	1394	289	858	4113	3060	1866	434	1500	5407	-28	-92	22	186	89
		Lw		17	17	67	101		31	27	100	154		-17	-17	-67	-101
		Pl		142	99	555	712		214	150	784	974		-72	-23	-406	-500
		Py		10	2	14	26		23	5	34	49		-10	-2	-2	-14
		Sxw	63	36	17	9	115	132	65	41	28	192	-15	13	6	2	5
		Total	2288	1502	380	1227	4490	3085	1950	501	1605	5426	-46	-238	-61	-337	-681

Table E.3. Fit statistics for regeneration stems per hectare, data splitting Run 3, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)					Root Mean Squared Error (RMSE)					Bias				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
3	22	At		104	25	179	302		140	36	522	656		-8	-13	101	80
		Bl	1	1	1	3	7	6	6	6	8	21	-1	-1	-1	-3	-7
		Ep		37	86	124	247		120	320	398	757		21	74	105	201
		Fd	1683	1264	357	795	3158	2168	2079	549	999	4515	157	431	141	-38	691
		Lw		24	22	109	151		55	64	299	387		13	4	84	102
		Pl		93	65	543	576		168	107	877	970		14	13	-208	-181
		Py		20	7	16	39		36	32	22	61		-20	7	-16	-29
		Sxw	133	49	12	21	187	283	101	33	42	362	-35	32	2	-7	-9
		Total	1712	1254	405	913	2756	2193	2047	635	1151	4073	120	483	226	19	847

Table E.4. Fit statistics for regeneration stems per hectare, data splitting Run 4, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)					Root Mean Squared Error (RMSE)					Bias				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
4	19	At		94	41	117	229		190	100	174	384		27	22	-50	-1
		Bl	0	0	0	2	2	0	0	0	6	6	0	0	0	-2	-2
		Ep		18	35	70	111		34	59	205	222		-18	-35	21	-33
		Fd	1745	1190	289	646	3612	2678	1708	375	768	4847	404	395	34	43	876
		Lw		38	36	69	137		75	63	116	201		13	10	2	24
		Pl		144	92	384	581		191	142	596	860		-105	-19	-326	-450
		Py		7	1	11	17		19	3	34	41		-7	-1	4	-4
		Sxw	98	31	25	18	139	312	49	50	42	354	66	-16	3	-10	43
		Total	1830	1182	275	857	3846	2748	1734	345	1004	5044	471	290	13	-320	454

Table E.5. Fit statistics for regeneration stems per hectare, data splitting Run 5, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
5	23	At		113	40	171	314		210	77	407	682		-113	-27	-171	-311
		Bl	3	3	3	3	13		11	11	7	34		-3	-3	-3	-13
		Ep		26	13	21	45		114	40	55	119		22	3	-18	6
		Fd	1585	882	317	888	2509	2145	1152	406	1258	3078	-524	-219	-53	-73	-868
		Lw		11	9	19	37		24	22	44	58		-3	-9	4	-7
		Pl		181	53	622	837		363	85	1541	1816		136	19	526	680
		Py		12	2	24	32		36	5	68	77		1	-2	13	12
		Sxw	175	28	3	36	227	569	51	11	104	583	58	-2	-3	36	89
		Total	1727	858	331	1221	2242	2233	1263	401	1687	2779	-469	-181	-75	314	-412

Table E.6. Fit statistics for regeneration stems per hectare, full (model) data set by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)					Root Mean Squared Error (RMSE)					Bias					
			Height Class					Height Class					Height Class					
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total	
Full Data	111	At		92	34	152	257		213	75	335	542		0	0	0	0	0
		Bl	2	2	2	5	12	13	13	13	19	43	0	0	0	0	0	0
		Ep		25	43	66	129		80	154	191	357		0	0	0	0	0
		Fd	1628	1024	276	723	2928	2206	1469	390	1111	4063	0	0	0	0	0	0
		Lw		18	15	52	81		41	39	139	189		0	0	0	0	0
		Pl		120	75	475	622		219	135	961	1175		0	0	0	0	0
		Py		16	3	14	30		58	14	38	80		0	0	0	0	0
		Sxw	96	27	11	17	137	275	51	28	46	300	0	0	0	0	0	0
		Total	1652	1037	305	960	2903	2223	1494	420	1319	3977	0	0	0	0	0	0

APPENDIX F. ACCURACY OF MATCHING FOR TABULAR IMPUTATION MODEL 1³

Table F.1. Match accuracy for regeneration stems per hectare, data splitting Run 1, by species and height class.

Run Number Number Of Plots Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
	Height Class					Height Class					Height Class				
	1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
18 At		0.22	0.20	0.38	0.56		0.56	0.76	0.67	0.69		0.61	0.78	0.72	0.78
BI	0.00	0.00	0.00	0.00	0.00	0.94	0.94	0.94	0.89	0.83	0.94	0.94	0.94	0.89	0.83
Ep		0.00	0.00	0.67	0.25		0.67	0.61	0.94	0.63		0.67	0.61	0.94	0.67
Fd	0.78	0.76	0.53	0.67	0.83	0.00	0.20	0.11	0.00	0.00	0.78	0.78	0.56	0.67	0.83
Lw		0.11	0.67	0.00	0.20		0.53	0.94	0.50	0.50		0.56	0.94	0.50	0.56
PI		0.38	0.23	0.64	0.57		0.38	0.33	0.64	0.40		0.56	0.44	0.78	0.67
Py		0.00	-	0.14	0.43		0.72	1.00	0.65	0.73		0.72	1.00	0.67	0.78
Sxw	0.00	0.00	0.00	0.00	0.08	0.39	0.50	0.78	0.67	0.35	0.39	0.50	0.78	0.67	0.39
Total	0.78	0.83	0.67	0.83	0.94	0.00	0.00	0.00	0.00	0.00	0.78	0.83	0.67	0.83	0.94

Table F.2. Match accuracy for regeneration stems per hectare, data splitting Run 2, by species and height class.

Run Number Number Of Plots Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
	Height Class					Height Class					Height Class				
	1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
24 At		0.21	0.00	0.25	0.36		0.48	0.54	0.57	0.53		0.54	0.54	0.63	0.63
BI	-	-	-	0.00	0.00	1.00	1.00	1.00	0.79	0.79	1.00	1.00	1.00	0.79	0.79
Ep		0.00	0.00	0.00	0.00		0.83	0.83	0.92	0.83		0.83	0.83	0.92	0.83
Fd	0.88	0.59	0.57	0.68	0.92	0.00	0.18	0.25	0.22	0.00	0.88	0.63	0.63	0.71	0.92
Lw		0.00	0.00	0.00	0.00		0.67	0.71	0.46	0.46		0.67	0.71	0.46	0.46
PI		0.29	0.19	0.56	0.50		0.37	0.38	0.53	0.40		0.50	0.46	0.71	0.63
Py		0.00	0.00	0.00	0.00		0.79	0.92	0.67	0.67		0.79	0.92	0.67	0.67
Sxw	0.10	0.00	0.17	0.17	0.40	0.61	0.58	0.78	0.78	0.50	0.63	0.58	0.79	0.79	0.63
Total	0.88	0.83	0.63	0.96	1.00	0.00	0.00	0.00	0.00	-	0.88	0.83	0.63	0.96	1.00

³ Entries with a "-" indicate a category where there were no observed nor predicted values.

Table F.3. Match accuracy for regeneration stems per hectare, data splitting Run 3, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration				Absence of Regeneration				Overall Match			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
3	21	At	0.23	0.09	0.17	0.23	0.44	0.50	0.47	0.44	0.52	0.52	0.52	0.52
		Bl	-	-	0.00	0.00	1.00	1.00	1.00	0.81	1.00	1.00	1.00	0.81
		Ep	0.00	0.00	0.00	0.00	0.81	0.81	0.90	0.81	0.81	0.81	0.90	0.81
		Fd	0.81	0.71	0.67	0.86	0.00	0.00	0.00	0.00	0.81	0.71	0.67	0.86
		Lw	0.20	0.17	0.25	0.29	0.80	0.75	0.50	0.41	0.81	0.76	0.57	0.52
		Pl	0.50	0.33	0.57	0.69	0.50	0.38	0.54	0.50	0.67	0.52	0.71	0.76
		Py	0.00	0.00	0.00	0.13	0.71	0.95	0.62	0.65	0.71	0.95	0.62	0.67
		Sxw	0.17	0.00	0.00	0.23	0.47	0.52	0.71	0.67	0.52	0.52	0.71	0.67
		Total	0.81	0.95	0.95	1.00	0.00	0.00	0.00	-	0.81	0.95	0.95	1.00

Table F.4. Match accuracy for regeneration stems per hectare, data splitting Run 4, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration				Absence of Regeneration				Overall Match			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
4	17	At	0.29	0.00	0.33	0.38	0.67	0.82	0.73	0.64	0.71	0.82	0.76	0.71
		Bl	-	-	0.00	0.00	1.00	1.00	1.00	0.82	1.00	1.00	1.00	0.82
		Ep	0.00	0.00	0.33	0.25	0.76	0.76	0.88	0.81	0.76	0.76	0.88	0.82
		Fd	0.88	0.76	0.31	0.82	0.00	0.00	0.00	0.00	0.88	0.76	0.35	0.82
		Lw	0.20	0.25	0.75	0.50	0.75	0.81	0.93	0.79	0.76	0.82	0.94	0.82
		Pl	0.30	0.44	0.57	0.45	0.50	0.62	0.77	0.50	0.59	0.71	0.82	0.65
		Py	0.00	0.00	0.00	0.33	0.94	0.88	0.88	0.88	0.94	0.88	0.88	0.88
		Sxw	0.13	0.00	0.17	0.33	0.56	0.65	0.69	0.57	0.59	0.65	0.71	0.76
		Total	0.88	0.88	0.63	0.94	0.00	0.00	0.14	0.00	0.88	0.88	0.65	0.94

Table F.5. Match accuracy for regeneration stems per hectare, data splitting Run 5, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration				Absence of Regeneration				Overall Match			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
5	19	At		0.00	0.00	0.00		0.42	0.63	0.58		0.42	0.63	0.58
		Bl	0.00	0.00	0.00	0.00	0.95	0.95	0.95	0.84	0.95	0.95	0.95	0.84
		Ep		0.00	0.00	1.00	0.50	0.95	0.89	1.00	0.94	0.95	0.89	1.00
		Fd	0.84	0.74	0.32	0.58	0.89	0.00	0.00	0.00	0.00	0.84	0.74	0.32
		Lw		0.00	0.00	0.25	0.18	0.47	0.79	0.83	0.47	0.47	0.79	0.84
		Pl		0.36	0.33	0.44	0.43	0.36	0.47	0.67	0.38	0.53	0.58	0.74
		Py		0.00		0.25	0.25	0.84	1.00	0.83	0.83	0.84	1.00	0.84
		Sxw	0.00	0.00	0.00	0.33	0.30	0.53	0.63	0.95	0.56	0.53	0.63	0.95
		Total	0.84	0.89	0.58	0.68	0.95	0.00	0.00	0.00	0.00	0.84	0.89	0.58
														0.68
														0.95

Table F.6. Match accuracy for regeneration stems per hectare, full (model) data set by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration				Absence of Regeneration				Overall Match						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
Full Data	101	At		0.26	0.18	0.29	0.36		0.51	0.66	0.57	0.53		0.58	0.68	0.63	0.62
		Bl	0.50	0.50	0.50	0.11	0.15	0.99	0.99	0.99	0.84	0.83	0.99	0.99	0.99	0.84	0.83
		Ep		0.19	0.22	0.55	0.30		0.82	0.81	0.95	0.83		0.83	0.82	0.95	0.84
		Fd	0.84	0.73	0.55	0.74	0.89	0.00	0.07	0.04	0.07	0.00	0.84	0.73	0.55	0.74	0.89
		Lw		0.16	0.20	0.20	0.25		0.62	0.79	0.60	0.52		0.64	0.80	0.63	0.58
		Pl		0.44	0.35	0.63	0.61		0.43	0.45	0.66	0.45		0.60	0.57	0.78	0.70
		Py		0.15	0.17	0.15	0.24		0.77	0.95	0.70	0.72		0.78	0.95	0.71	0.74
		Sxw	0.16	0.18	0.19	0.18	0.33	0.50	0.54	0.77	0.76	0.49	0.54	0.58	0.78	0.77	0.59
		Total	0.84	0.89	0.73	0.89	0.97	0.00	0.00	0.00	0.00	0.00	0.84	0.89	0.73	0.89	0.97

APPENDIX G. ACCURACY OF MATCHING FOR TABULAR IMPUTATION MODEL 24

Table G.1. Match accuracy for regeneration stems per hectare, data splitting Run 1, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration				Absence of Regeneration				Overall Match						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
1	23	At		0.13	0.07	0.20	0.31		0.33	0.41	0.40	0.39		0.39	0.43	0.48	0.52
		Bl	0.00	0.00	0.00	0.00	0.00	0.96	0.96	0.96	0.91	0.87	0.96	0.96	0.96	0.91	0.87
		Ep		0.00	0.00	0.22	0.22		0.74	0.70	0.67	0.67		0.74	0.70	0.70	0.70
		Fd	0.78	0.65	0.45	0.70	0.83	0.00	0.00	0.08	0.00	0.00	0.78	0.65	0.48	0.70	0.83
		Lw		0.09	0.33	0.00	0.14		0.55	0.81	0.43	0.43		0.57	0.83	0.43	0.48
		Pl		0.38	0.20	0.50	0.59		0.41	0.40	0.47	0.46		0.57	0.48	0.65	0.70
		Py		0.00	0.00	0.13	0.38		0.78	0.91	0.68	0.75		0.78	0.91	0.70	0.78
		Sxw	0.00	0.00	0.00	0.00	0.11	0.35	0.30	0.78	0.57	0.19	0.35	0.30	0.78	0.57	0.26
		Total	0.78	0.78	0.64	0.87	0.96	0.00	0.00	0.11	0.00	0.00	0.78	0.78	0.65	0.87	0.96

Table G.2. Match accuracy for regeneration stems per hectare, data splitting Run 2, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration				Absence of Regeneration				Overall Match						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
2	24	At		0.14	0.00	0.19	0.24		0.14	0.17	0.15	0.16		0.25	0.17	0.29	0.33
		Bl	0.00	0.00	0.00	0.00	0.00	0.92	0.92	0.92	0.75	0.67	0.92	0.92	0.92	0.75	0.67
		Ep		0.00	0.00	0.00	0.00		0.67	0.58	0.58	0.58		0.67	0.58	0.58	0.58
		Fd	0.88	0.67	0.58	0.71	0.92	0.00	0.00	0.00	0.00	0.00	0.88	0.67	0.58	0.71	0.92
		Lw		0.00	0.00	0.00	0.00		0.46	0.63	0.21	0.21		0.46	0.63	0.21	0.21
		Pl		0.24	0.20	0.45	0.48		0.16	0.20	0.27	0.21		0.33	0.33	0.54	0.54
		Py		0.00	0.00	0.00	0.00		0.67	0.79	0.63	0.63		0.67	0.79	0.63	0.63
		Sxw	0.07	0.00	0.17	0.14	0.29	0.39	0.38	0.78	0.74	0.17	0.42	0.38	0.79	0.75	0.38
		Total	0.88	0.88	0.71	1.00	1.00	0.00	0.00	0.00	-	-	0.88	0.88	0.71	1.00	1.00

⁴ Entries with a "-" indicate a category where there were no observed nor predicted values.

Table G.3. Match accuracy for regeneration stems per hectare, data splitting Run 3, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration				Absence of Regeneration				Overall Match			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
3	22	At		0.16	0.06	0.11	0.16	0.24	0.20	0.16	0.16	0.27	0.27	0.27
		Bl	0.00	0.00	0.00	0.00	0.95	0.95	0.82	0.77	0.95	0.95	0.95	0.82
		Ep		0.33	0.29	0.00	0.29	0.80	0.75	0.82	0.75	0.82	0.77	0.82
		Fd	0.86	0.68	0.67	0.86	0.91	0.00	0.13	0.00	0.00	0.68	0.68	0.86
		Lw		0.20	0.17	0.18	0.21	0.81	0.76	0.26	0.17	0.82	0.77	0.36
		Pl		0.42	0.33	0.56	0.55	0.21	0.25	0.33	0.18	0.50	0.45	0.64
		Py		0.00	0.00	0.00	0.08	0.50	0.95	0.45	0.48	0.50	0.95	0.45
		Sxw	0.09	0.00	0.00	0.00	0.18	0.00	0.32	0.73	0.00	0.09	0.32	0.73
		Total	0.86	0.95	0.95	0.95	1.00	0.00	0.00	0.50	-	0.86	0.95	0.95
														1.00

Table G.4. Match accuracy for regeneration stems per hectare, data splitting Run 4, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration				Absence of Regeneration				Overall Match			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
4	19	At		0.21	0.00	0.18	0.21	0.31	0.68	0.47	0.31	0.42	0.68	0.53
		Bl	-	-	-	0.00	0.00	1.00	1.00	0.84	0.84	1.00	1.00	0.84
		Ep		0.00	0.00	0.14	0.14	0.63	0.63	0.67	0.67	0.63	0.63	0.68
		Fd	0.89	0.74	0.47	0.79	0.89	0.00	0.00	0.00	0.00	0.89	0.74	0.79
		Lw		0.17	0.13	0.30	0.29	0.41	0.61	0.56	0.33	0.47	0.63	0.63
		Pl		0.24	0.31	0.36	0.35	0.13	0.40	0.53	0.15	0.32	0.53	0.63
		Py		0.00	0.00	0.25	0.25	0.79	0.89	0.83	0.83	0.79	0.89	0.84
		Sxw	0.08	0.00	0.25	0.17	0.21	0.33	0.32	0.65	0.31	0.37	0.32	0.68
		Total	0.89	0.89	0.68	0.89	0.95	0.00	0.00	0.00	0.00	0.89	0.89	0.89
														0.95

Table G.5. Match accuracy for regeneration stems per hectare, data splitting Run 5, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration				Absence of Regeneration				Overall Match			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
5	23	At		0.00	0.00	0.07	0.11	0.22	0.48	0.36	0.24	0.22	0.48	0.39
		Bl	0.00	0.00	0.00	0.00	0.00	0.91	0.91	0.83	0.74	0.91	0.91	0.83
		Ep		0.50	0.33	0.25	0.50		0.95	0.91	0.90		0.91	0.87
		Fd	0.83	0.68	0.36	0.52	0.91	0.00	0.13	0.07	0.00	0.83	0.70	0.52
		Lw		0.09	0.00	0.17	0.21		0.55	0.83	0.77		0.57	0.83
		Pl		0.41	0.33	0.38	0.56		0.38	0.44	0.56		0.57	0.65
		Py		0.00	0.00	0.22	0.22		0.87	0.78	0.67		0.87	0.70
		Sxw	0.00	0.00	0.00	0.50	0.24	0.35	0.39	0.91	0.32	0.35	0.39	0.91
		Total	0.83	0.87	0.61	0.70	0.96	0.00	0.00	0.00	0.00	0.83	0.87	0.70
														0.96

Table G.6. Match accuracy for regeneration stems per hectare, full (model) data set by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration				Absence of Regeneration				Overall Match			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
Full Data	111	At		0.18	0.10	0.19	0.24	0.21	0.33	0.29	0.22	0.32	0.38	0.40
		Bl	0.17	0.17	0.17	0.09	0.10	0.95	0.95	0.81	0.76	0.95	0.95	0.81
		Ep		0.13	0.14	0.16	0.19		0.75	0.70	0.71		0.71	0.72
		Fd	0.85	0.69	0.52	0.72	0.89	0.00	0.00	0.00	0.00	0.85	0.69	0.53
		Lw		0.13	0.18	0.13	0.20		0.47	0.73	0.41		0.50	0.75
		Pl		0.36	0.28	0.51	0.53		0.24	0.34	0.45		0.47	0.48
		Py		0.11	0.05	0.12	0.19		0.69	0.83	0.64		0.70	0.83
		Sxw	0.13	0.13	0.17	0.18	0.25	0.22	0.24	0.76	0.16	0.31	0.32	0.77
		Total	0.85	0.87	0.72	0.88	0.97	0.00	0.00	0.06	0.00	0.85	0.87	0.73
														0.88
														0.97

APPENDIX H. FIT STATISTICS FOR MOST SIMILAR NEIGHBOUR IMPUTATION

Table H.1. Fit statistics for regeneration stems per hectare, data splitting Run 1, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)					Root Mean Squared Error (RMSE)					Bias				
			Height Class				Total	Height Class				Total	Height Class				Total
			1	2	3	4		1	2	3	4		1	2	3	4	
1	23	At		26	65	155	233		62	139	462	575		-13	0	13	0
		Bl	6	6	6	0	19	31	31	31	0	93	-6	-6	-6	0	-19
		Ep		19	52	52	58		93	248	181	208		19	52	-52	19
		Fd	2106	1331	465	1066	4620	3368	2184	676	1485	6464	129	-258	-26	136	-19
		Lw		39	13	58	97		76	44	149	178		0	0	-6	-6
		Pl		52	52	258	323		164	124	735	916		-52	13	-220	-258
		Py		26	0	6	32		124	0	31	155		-26	0	-6	-32
		Sxw	200	19	13	26	220	628	54	44	62	609	174	-6	0	-26	142
		Total	2016	2177	840	1370	5382	3070	2986	1034	1690	7349	-413	-924	-168	-413	-1919

Table H.2. Fit statistics for regeneration stems per hectare, data splitting Run 2, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
2	24	At		111	31	68	198		402	101	225	709		74	31	43	149
		Bl	6	6	6	19	37	30	30	30	53	105	6	6	6	-6	12
		Ep		0	6	25	31		0	30	96	109		0	6	25	31
		Fd	1864	984	229	1096	3616	2722	1647	322	2151	5156	-378	-415	-43	-601	-1436
		Lw		0	19	37	43		0	53	86	109		0	6	-12	-6
		Pl		105	50	260	316		221	96	543	584		-43	-12	161	105
		Py		0	6	25	19		0	30	74	68		0	6	-25	-19
		Sxw	31	19	6	6	62	125	53	30	30	142	31	-6	-6	6	25
		Total	2266	1443	279	731	4025	3340	2180	392	954	5353	-495	-601	-68	-12	-1176

Table H.3. Fit statistics for regeneration stems per hectare, data splitting Run 3, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)					Root Mean Squared Error (RMSE)					Bias				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
3	22	At		142	41	270	453		431	119	630	1058		-101	-14	-162	-277
		Bl	0	0	0	0	0		0	0	0	0		0	0	0	0
		Ep		41	101	41	182		110	274	110	494		-41	-101	-41	-182
		Fd	2837	2297	351	838	5876	3694	3340	455	1136	7636	-1540	-1000	-108	108	-2540
		Lw		14	0	34	47		45	0	105	114		0	0	7	7
		Pl		115	41	155	270		278	78	296	478		61	0	115	176
		Py		27	0	20	47		100	0	55	145		14	0	7	20
		Sxw	34	14	20	20	47	71	45	55	55	138	-20	14	20	7	20
		Total	2844	1743	358	885	5397	3560	2459	462	1237	6544	-1412	-270	7	-101	-1776

Table H.4. Fit statistics for regeneration stems per hectare, data splitting Run 4, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
4	19	At		94	78	297	407		205	174	663	870		16	-47	-94	-125
		Bl	0	0	0	8	8	0	0	0	34	34	0	0	0	8	8
		Ep		55	63	149	266		156	187	433	627		39	31	-23	47
		Fd	2776	2166	516	931	6202	3703	3094	786	1413	7800	524	477	156	242	1400
		Lw		16	0	55	70		48	0	132	156		0	0	-8	-8
		Pl		78	47	235	328		193	96	506	733		78	0	109	188
		Py		8	0	23	31		34	0	76	96		8	0	23	31
		Sxw	8	23	16	16	31	34	59	48	48	68	8	-8	0	16	16
		Total	2839	1846	579	876	5811	3962	3011	812	1353	7548	23	532	78	266	899

Table H.5. Fit statistics for regeneration stems per hectare, data splitting Run 5, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
5	23	At		32	32	142	168		93	93	513	599		19	-19	142	142
		Bl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Ep		19	52	32	39		93	248	155	186		-19	-52	32	-39
		Fd	2410	1092	381	853	4503	3152	1750	560	1292	5847	420	187	-6	258	859
		Lw		39	32	103	136		76	82	232	286		-26	19	-13	-19
		Pl		129	116	497	614		215	196	866	1065		26	0	123	149
		Py		39	0	13	52		131	0	44	175		-39	0	-13	-52
		Sxw	58	58	13	32	149	194	112	44	103	335	45	32	-13	19	84
		Total	2197	1350	523	1396	4432	3106	2114	835	1813	6233	762	187	-97	413	1266

Table H.6. Fit statistics for regeneration stems per hectare, full (model) data set by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)					Root Mean Squared Error (RMSE)					Bias					
			Height Class					Height Class					Height Class					
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total	
Full Data	111	At		64	31	150	234		218	103	479	675		19	9	0	0	28
		Bl	4	4	4	5	17	24	24	24	28	79	-1	-1	-1	0	0	-4
		Ep		21	44	33	70		96	202	145	262		3	-4	7	7	5
		Fd	2145	1332	420	926	4325	2892	2071	618	1376	5793	-134	-216	-59	3	3	-406
		Lw		17	20	46	75		51	58	141	181		-1	-1	8	5	5
		Pl		88	71	317	439		211	140	651	852		21	-9	44	44	56
		Py		7	3	9	19		47	20	42	80		4	0	7	7	11
		Sxw	71	20	8	15	92	241	58	35	51	260	-1	1	5	7	7	12
		Total	2196	1382	407	1047	4399	3039	2177	606	1487	5897	-335	-94	-27	-86	-86	-541

APPENDIX I. FIT STATISTICS FOR K-MOST SIMILAR NEIGHBOUR IMPUTATION

Table I.1. Fit statistics for regeneration stems per hectare, data splitting Run 1, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)					Root Mean Squared Error (RMSE)					Bias				
			Height Class				Total	Height Class				Total	Height Class				Total
			1	2	3	4		1	2	3	4		1	2	3	4	
1	23	At		50	47	149	237		95	120	418	597		-6	17	15	26
		Bl	4	4	4	2	15	15	15	15	10	45	-4	-4	-4	-2	-15
		Ep		26	67	54	146		114	290	167	485		22	54	-37	39
		Fd	2024	1340	396	1040	4159	3015	1930	511	1384	5483	-4	-345	-17	-88	-454
		Lw		37	17	52	75		69	48	134	173		6	-4	-43	-41
		Pl		47	30	282	282		81	58	753	780		-34	22	-248	-261
		Py		15	0	9	24		54	0	21	69		-15	0	-9	-24
		Sxw	198	24	11	17	224	627	52	27	36	617	177	-11	-2	-17	146
		Total	1831	1663	545	1312	4122	2729	2191	693	1641	5442	0	-646	45	-515	-1116

Table I.2. Fit statistics for regeneration stems per hectare, data splitting Run 2, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias						
			Height Class				Height Class				Height Class						
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
2	24	At		116	39	66	217		391	105	214	694		66	23	41	130
		Bl	6	6	6	12	31	30	30	30	35	98	6	6	6	0	19
		Ep		10	19	10	35		36	74	42	145		-10	-19	-6	-35
		Fd	1804	1251	225	925	3729	2406	1597	298	1361	4601	-252	-566	-85	-372	-1273
		Lw		4	17	21	33		14	45	64	88		-4	8	4	8
		Pl		105	60	380	343		185	104	829	648		-52	-27	297	219
		Py		0	6	27	21		0	30	66	59		0	6	-27	-21
		Sxw	33	17	2	8	56	124	38	10	32	134	25	-4	-2	4	23
		Total	1490	949	262	621	2543	2141	1158	328	818	3501	8	-338	-56	221	-165

Table I.3. Fit statistics for regeneration stems per hectare, data splitting Run 3, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
3	22	At	72	34	167	272	167	75	365	552	-36	-7	-81	-124
		Bl	0	0	0	0	0	0	0	0	0	0	0	0
		Ep	14	38	52	104	37	104	144	284	-14	-38	-52	-104
		Fd	2423	1617	216	615	4334	3010	2251	291	-1211	-563	-54	-1817
		Lw	9	11	38	54	26	24	103	116	0	-11	2	-9
		Pl	119	54	173	329	260	87	351	518	47	-23	56	81
		Py	25	0	16	41	106	0	46	142	20	0	11	32
		Sxw	23	18	23	20	42	47	56	48	-5	14	18	34
		Total	2040	1601	286	696	2497	2180	360	922	-982	-259	-52	-34
						4181				5163				-1326

Table I.4. Fit statistics for regeneration stems per hectare, data splitting Run 4, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
4	19	At	96	36	133	182	219	87	272	398	65	-5	50	109
		Bl	0	0	0	8	0	0	34	34	0	0	0	8
		Ep	60	78	107	245	163	221	289	561	34	16	18	68
		Fd	2268	1804	467	769	2722	2477	689	1289	459	501	159	232
		Lw	16	5	42	63	39	16	87	119	0	-5	5	0
		Pl	104	68	242	352	220	132	542	832	63	-10	96	149
		Py	8	0	23	31	34	0	76	96	8	0	23	31
		Sxw	39	29	10	18	92	69	28	50	-13	-13	0	-13
		Total	1710	1530	495	829	2393	2391	703	1193	209	508	130	182
						3877				5545				1030

Table I.5. Fit statistics for regeneration stems per hectare, data splitting Run 5, by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
5	23	At		39	17	144	179		99	39	513	22	-13	140
		Bl	0	0	0	4	4	0	0	0	15	0	0	-4
		Ep		2	9	52	41		10	41	248	-2	-9	52
		Fd	2406	1288	325	833	4512	3141	1925	441	1297	592	142	235
		Lw		19	28	90	116		40	77	259	2	24	30
		Pl		162	134	573	752		283	219	1121	41	17	314
		Py		4	0	9	13		15	0	25	-4	0	0
		Sxw	69	47	17	28	127	197	99	39	99	34	34	-17
		Total	1917	1195	403	1197	3976	2699	1911	540	1690	676	209	-11
														685
														1559

Table I.6. Fit statistics for regeneration stems per hectare, full (model) data set by species and height class.

Run Number	Number Of Plots	Species	Mean Absolute Deviation (MAD)				Root Mean Squared Error (RMSE)				Bias			
			Height Class				Height Class				Height Class			
			1	2	3	4	1	2	3	4	1	2	3	4
Full Data	111	At		69	29	112	192		226	86	345	20	9	37
		Bl	3	3	3	4	14	17	17	17	22	0	0	1
		Ep		17	32	37	75		83	159	166	9	12	16
		Fd	1768	1076	333	796	3457	2463	1669	474	1251	-51	-21	8
		Lw		14	13	44	65		40	42	147	3	3	7
		Pl		109	70	291	386		222	142	615	8	1	60
		Py		11	2	14	25		55	15	44	1	1	1
		Sxw	62	22	11	18	96	248	50	34	55	29	3	0
		Total	1752	1152	339	822	3431	2347	1733	485	1175	-83	-82	-10
														42
														-133

APPENDIX J. ACCURACY OF MATCHING FOR MOST SIMILAR NEIGHBOUR IMPUTATION⁵

Table J.1. Match accuracy for regeneration stems per hectare, data splitting Run 1, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
1	23	At		0.60	0.00	0.50	0.38		0.90	0.74	0.90	0.75		0.91	0.74	0.91	0.78
		Bl	0.00	0.00	0.00	-	0.00	0.96	0.96	0.96	1.00	0.96	0.96	0.96	1.00	1.00	0.96
		Ep		1.00	1.00	0.50	0.50		1.00	1.00	0.95	0.95		1.00	1.00	0.96	0.96
		Fd	0.73	0.65	0.41	0.38	0.86	0.14	0.30	0.38	0.13	0.25	0.74	0.70	0.57	0.43	0.87
		Lw		0.17	0.00	0.00	0.11		0.77	0.91	0.83	0.64		0.78	0.91	0.83	0.65
		Pl		0.80	0.60	0.63	0.75		0.95	0.90	0.83	0.88		0.96	0.91	0.87	0.91
		Py		0.00	-	0.00	0.00		0.96	1.00	0.96	0.96		0.96	1.00	0.96	0.96
		Sxw	0.00	0.00	0.00	0.00	0.38	0.78	0.87	0.91	0.83	0.75	0.78	0.87	0.91	0.83	0.78
		Total	0.82	0.87	0.61	0.70	1.00	0.20	0.00	0.00	0.00	-	0.83	0.87	0.61	0.70	1.00

Table J.2. Match accuracy for regeneration stems per hectare, data splitting Run 2, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
2	24	At		0.00	0.00	0.00	0.13		0.79	0.88	0.83	0.70		0.79	0.88	0.83	0.71
		Bl	0.00	0.00	0.00	0.00	0.00	0.96	0.96	0.96	0.88	0.83	0.96	0.96	0.96	0.88	0.83
		Ep		-	0.00	0.00	0.00		1.00	0.96	0.92	0.92		1.00	0.96	0.92	0.92
		Fd	0.76	0.75	0.35	0.86	0.90	0.38	0.44	0.39	0.50	0.60	0.79	0.79	0.54	0.88	0.92
		Lw		-	0.00	0.00	0.17		1.00	0.88	0.79	0.78		1.00	0.88	0.79	0.79
		Pl		0.25	0.25	0.36	0.50		0.73	0.73	0.65	0.59		0.75	0.75	0.71	0.71
		Py		-	0.00	0.00	0.33		1.00	0.96	0.88	0.91		1.00	0.96	0.88	0.92
		Sxw	0.00	0.00	0.00	0.00	0.00	0.92	0.88	0.96	0.96	0.71	0.92	0.88	0.96	0.96	0.71
		Total	0.73	0.70	0.55	0.91	0.92	0.25	0.13	0.31	0.33	0.00	0.75	0.71	0.63	0.92	0.92

⁵ Entries with a "-" indicate a category where there were no observed nor predicted values.

Table J.3. Match accuracy for regeneration stems per hectare, data splitting Run 3, by species and height class.

Run Number Of Plots Species			Presence of Regeneration					Absence of Regeneration					Overall Match							
			Height Class					Total	Height Class					Total	Height Class					Total
			1	2	3	4	1		2	3	4	1	2		3	4				
3	22	At		0.00	0.00	0.17	0.17		0.73	0.86	0.76	0.76		0.73	0.86	0.77	0.77			
		Bl	-	-	-	-	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00			
		Ep		0.00	0.00	0.00	0.00		0.86	0.86	0.86	0.86		0.86	0.86	0.86	0.86			
		Fd	0.77	0.52	0.22	0.70	0.77	0.00	0.09	0.22	0.25	0.00	0.77	0.55	0.36	0.73	0.77			
		Lw		0.00	-	0.00	0.00		0.91	1.00	0.86	0.77		0.91	1.00	0.86	0.77			
		Pl		0.50	0.29	0.44	0.46		0.78	0.75	0.72	0.56		0.82	0.77	0.77	0.68			
		Py		0.50	-	0.00	0.33		0.95	1.00	0.86	0.90		0.95	1.00	0.86	0.91			
		Sxw	0.20	0.33	0.00	0.00	0.50	0.81	0.90	0.86	0.86	0.84	0.82	0.91	0.86	0.86	0.86			
		Total	0.68	0.71	0.37	0.81	0.91	0.00	0.14	0.20	0.20	0.00	0.68	0.73	0.45	0.82	0.91			

Table J.4. Match accuracy for regeneration stems per hectare, data splitting Run 4, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class				Total	Height Class				Total	Height Class				Total
			1	2	3	4		1	2	3	4		1	2	3	4	
4	19	At		0.33	0.00	0.40	0.50		0.76	0.79	0.82	0.81		0.79	0.79	0.84	0.84
		Bl	-	-	-	0.00	0.00	1.00	1.00	1.00	0.95	0.95	1.00	1.00	1.00	0.95	0.95
		Ep		0.00	0.00	0.00	0.00		0.84	0.84	0.84	0.79		0.84	0.84	0.84	0.79
		Fd	0.83	0.53	0.36	0.44	0.83	0.25	0.20	0.36	0.09	0.25	0.84	0.58	0.53	0.47	0.84
		Lw		0.00	-	0.00	0.00		0.89	1.00	0.79	0.74		0.89	1.00	0.79	0.74
		Pl		0.50	0.20	0.38	0.45		0.81	0.78	0.69	0.57		0.84	0.79	0.74	0.68
		Py		0.00	-	0.00	0.00		0.95	1.00	0.89	0.89		0.95	1.00	0.89	0.89
		Sxw	1.00	0.00	0.00	0.00	0.20	1.00	0.84	0.89	0.89	0.78	1.00	0.84	0.89	0.89	0.79
		Total	0.94	0.94	0.56	0.94	1.00	0.50	0.50	0.30	0.50	-	0.95	0.95	0.63	0.95	1.00

Table J.5. Match accuracy for regeneration stems per hectare, data splitting Run 5, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
5	23	At		0.50	0.00	0.00	0.60		0.90	0.87	0.83	0.90		0.91	0.87	0.83	0.91
		Bl	-	-	-	-	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Ep		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00
		Fd	0.70	0.68	0.47	0.63	0.85	0.33	0.40	0.40	0.36	0.50	0.74	0.74	0.61	0.70	0.87
		Lw		0.33	0.00	0.29	0.50		0.81	0.83	0.76	0.79		0.83	0.83	0.78	0.83
		Pl		0.53	0.33	0.63	0.67		0.53	0.58	0.54	0.45		0.70	0.65	0.74	0.74
		Py		1.00	-	0.33	1.00		1.00	1.00	0.91	1.00		1.00	1.00	0.91	1.00
		Sxw	0.00	0.00	0.00	0.00	0.11	0.83	0.70	0.91	0.87	0.64	0.83	0.70	0.91	0.87	0.65
		Total	0.76	1.00	0.86	0.95	0.96	0.29	1.00	0.40	0.50	0.00	0.78	1.00	0.87	0.96	0.96

Table J.6. Match accuracy for regeneration stems per hectare, full (model) data set by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
Full Data	111	At		0.24	0.00	0.35	0.37		0.82	0.89	0.85	0.81		0.83	0.89	0.86	0.83
		Bl	0.00	0.00	0.00	0.00	0.00	0.97	0.97	0.97	0.96	0.94	0.97	0.97	0.97	0.96	0.94
		Ep		0.33	0.29	0.38	0.33		0.96	0.95	0.95	0.94		0.96	0.95	0.95	0.95
		Fd	0.77	0.62	0.38	0.65	0.86	0.11	0.21	0.32	0.20	0.17	0.77	0.66	0.52	0.68	0.86
		Lw		0.23	0.00	0.07	0.11		0.91	0.87	0.87	0.78		0.91	0.87	0.87	0.78
		Pl		0.47	0.28	0.46	0.47		0.75	0.71	0.64	0.53		0.79	0.74	0.72	0.67
		Py		0.60	0.00	0.00	0.30		0.98	0.98	0.95	0.94		0.98	0.98	0.95	0.94
		Sxw	0.22	0.22	0.00	0.10	0.34	0.87	0.87	0.95	0.92	0.79	0.87	0.87	0.95	0.92	0.81
		Total	0.83	0.83	0.75	0.89	0.98	0.28	0.14	0.44	0.29	0.33	0.84	0.84	0.79	0.89	0.98

APPENDIX K. ACCURACY OF MATCHING FOR K-MOST SIMILAR NEIGHBOUR IMPUTATION⁶

Table K.1. Match accuracy for regeneration stems per hectare, data splitting Run 1, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
1	23	At		0.33	0.00	0.29	0.36		0.70	0.74	0.76	0.63		0.74	0.74	0.78	0.70
		Bl	0.00	0.00	0.00	0.00	0.00	0.91	0.91	0.91	0.96	0.87	0.91	0.91	0.91	0.96	0.87
		Ep		0.50	0.33	0.33	0.33		0.95	0.91	0.91	0.91		0.96	0.91	0.91	0.91
		Fd	0.96	0.65	0.48	0.61	0.96	0.00	0.00	0.15	0.00	0.00	0.96	0.65	0.52	0.61	0.96
		Lw		0.13	0.00	0.22	0.36		0.68	0.87	0.67	0.63		0.70	0.87	0.70	0.70
		Pl		0.36	0.57	0.38	0.47		0.63	0.84	0.56	0.50		0.70	0.87	0.65	0.65
		Py		0.00	-	0.00	0.00		0.87	1.00	0.83	0.83		0.87	1.00	0.83	0.83
		Sxw	0.00	0.00	0.25	0.00	0.23	0.74	0.74	0.86	0.74	0.50	0.74	0.74	0.87	0.74	0.57
		Total	0.96	0.91	0.74	0.74	1.00	0.00	0.00	0.00	0.00	-	0.96	0.91	0.74	0.74	1.00

Table K.2. Match accuracy for regeneration stems per hectare, data splitting Run 2, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
2	24	At		0.11	0.00	0.17	0.18		0.65	0.79	0.78	0.59		0.67	0.79	0.79	0.63
		Bl	0.00	0.00	0.00	0.00	0.00	0.96	0.96	0.96	0.83	0.79	0.96	0.96	0.96	0.83	0.79
		Ep		0.00	0.50	1.00	1.00		0.92	0.96	1.00	1.00		0.92	0.96	1.00	1.00
		Fd	0.75	0.71	0.45	0.83	0.88	0.00	0.00	0.14	0.00	0.00	0.75	0.71	0.50	0.83	0.88
		Lw		0.00	0.00	0.00	0.29		0.92	0.83	0.79	0.77		0.92	0.83	0.79	0.79
		Pl		0.31	0.17	0.50	0.59		0.55	0.55	0.59	0.50		0.63	0.58	0.71	0.71
		Py		-	0.00	0.00	0.25		1.00	0.96	0.83	0.87		1.00	0.96	0.83	0.88
		Sxw	0.25	0.00	0.00	0.00	0.10	0.87	0.75	0.96	0.92	0.61	0.88	0.75	0.96	0.92	0.63
		Total	0.75	0.79	0.59	0.92	0.96	0.00	0.00	0.18	0.00	0.00	0.75	0.79	0.63	0.92	0.96

⁶ Entries with a "-" indicate a category where there were no observed nor predicted values.

Table K.3. Match accuracy for regeneration stems per hectare, data splitting Run 3, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
3	22	At		0.14	0.00	0.43	0.27		0.71	0.64	0.79	0.58		0.73	0.64	0.82	0.64
		Bl	-	-	-	-	-	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
		Ep		0.00	0.00	0.00	0.00		0.86	0.86	0.86	0.86		0.86	0.86	0.86	0.86
		Fd	0.86	0.68	0.45	0.68	0.86	0.00	0.00	0.15	0.00	0.00	0.86	0.68	0.50	0.68	0.86
		Lw		0.33	0.00	0.00	0.11		0.90	0.77	0.73	0.62		0.91	0.77	0.73	0.64
		Pl		0.55	0.36	0.58	0.50		0.69	0.61	0.67	0.43		0.77	0.68	0.77	0.64
		Py		0.50	-	0.00	0.33		0.95	1.00	0.86	0.90		0.95	1.00	0.86	0.91
		Sxw	0.13	0.25	0.00	0.00	0.33	0.67	0.86	0.82	0.77	0.68	0.68	0.86	0.82	0.77	0.73
		Total	0.91	0.82	0.64	0.82	0.91	0.00	0.00	0.00	0.00	0.00	0.91	0.82	0.64	0.82	0.91

Table K.4. Match accuracy for regeneration stems per hectare, data splitting Run 4, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
4	19	At		0.25	0.00	0.71	0.63		0.65	0.79	0.86	0.79		0.68	0.79	0.89	0.84
		Bl	-	-	-	0.00	0.00	1.00	1.00	1.00	0.95	0.95	1.00	1.00	1.00	0.95	0.95
		Ep		0.00	0.00	0.00	0.00		0.84	0.84	0.84	0.79		0.84	0.84	0.84	0.79
		Fd	0.89	0.68	0.39	0.68	0.89	0.00	0.00	0.08	0.00	0.00	0.89	0.68	0.42	0.68	0.89
		Lw		0.00	0.00	0.00	0.00		0.79	0.89	0.63	0.42		0.79	0.89	0.63	0.42
		Pl		0.50	0.11	0.40	0.69		0.64	0.56	0.60	0.60		0.74	0.58	0.68	0.79
		Py		0.00	-	0.00	0.00		0.95	1.00	0.89	0.89		0.95	1.00	0.89	0.89
		Sxw	0.17	0.00	0.33	0.00	0.25	0.72	0.74	0.89	0.84	0.65	0.74	0.74	0.89	0.84	0.68
		Total	0.89	0.89	0.58	1.00	1.00	0.00	0.00	0.00	1.00	-	0.89	0.89	0.58	1.00	1.00

Table K.5. Match accuracy for regeneration stems per hectare, data splitting Run 5, by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class				Total	Height Class				Total	Height Class				Total
			1	2	3	4		1	2	3	4		1	2	3	4	
5	23	At		0.33	0.20	0.00	0.38		0.81	0.82	0.78	0.75		0.83	0.83	0.78	0.78
		Bl	-	-	-	0.00	0.00	1.00	1.00	1.00	0.91	0.91	1.00	1.00	1.00	0.91	0.91
		Ep		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00		1.00	1.00	1.00	1.00
		Fd	0.74	0.70	0.67	0.61	0.83	0.00	0.00	0.22	0.00	0.00	0.74	0.70	0.70	0.61	0.83
		Lw		0.29	0.00	0.22	0.40		0.76	0.83	0.67	0.68		0.78	0.83	0.70	0.74
		Pl		0.47	0.33	0.67	0.62		0.29	0.44	0.45	0.20		0.57	0.57	0.74	0.65
		Py		1.00	-	0.33	1.00		1.00	1.00	0.91	1.00		1.00	1.00	0.91	1.00
		Sxw	0.00	0.25	0.00	0.00	0.33	0.65	0.71	0.78	0.87	0.58	0.65	0.74	0.78	0.87	0.65
		Total	0.74	0.96	0.83	0.96	1.00	0.00	0.00	0.00	0.00	-	0.74	0.96	0.83	0.96	1.00

Table K.6. Match accuracy for regeneration stems per hectare, full (model) data set by species and height class.

Run Number	Number Of Plots	Species	Presence of Regeneration					Absence of Regeneration					Overall Match				
			Height Class					Height Class					Height Class				
			1	2	3	4	Total	1	2	3	4	Total	1	2	3	4	Total
Full Data	111	At		0.22	0.05	0.32	0.33		0.72	0.84	0.79	0.70		0.74	0.84	0.81	0.74
		Bl	0.00	0.00	0.00	0.00	0.00	0.95	0.95	0.95	0.95	0.91	0.95	0.95	0.95	0.95	0.91
		Ep		0.25	0.22	0.44	0.40		0.94	0.94	0.95	0.94		0.95	0.94	0.95	0.95
		Fd	0.85	0.64	0.45	0.72	0.89	0.00	0.00	0.08	0.12	0.00	0.85	0.64	0.48	0.73	0.89
		Lw		0.14	0.13	0.07	0.14		0.83	0.87	0.77	0.64		0.84	0.87	0.77	0.66
		Pl		0.41	0.34	0.43	0.49		0.56	0.62	0.47	0.34		0.67	0.68	0.62	0.59
		Py		0.38	0.00	0.06	0.28		0.95	0.98	0.85	0.88		0.95	0.98	0.85	0.88
		Sxw	0.22	0.18	0.13	0.06	0.35	0.80	0.78	0.88	0.85	0.67	0.81	0.79	0.88	0.85	0.72
		Total	0.83	0.87	0.69	0.88	0.97	0.00	0.00	0.06	0.07	0.00	0.83	0.87	0.69	0.88	0.97

APPENDIX L. PHOTOS AND STAND VISUALIZATION SYSTEM GRAPHICS FOR SPATIALLY SAMPLED PLOTS



Stand Visualization System

PLOT1.SVS

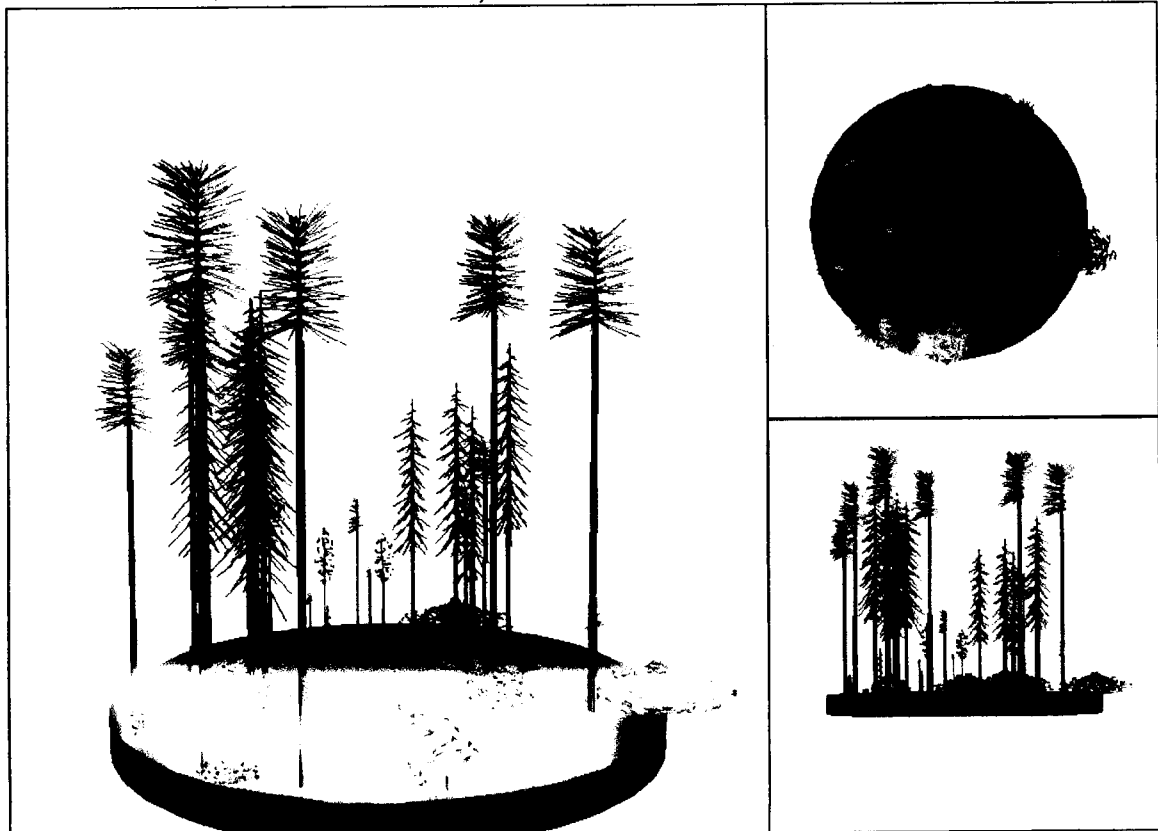


Figure L.1. Spatial plot 1, plot photo and SVS visualization image.



Stand Visualization System

PLOT2.SVS

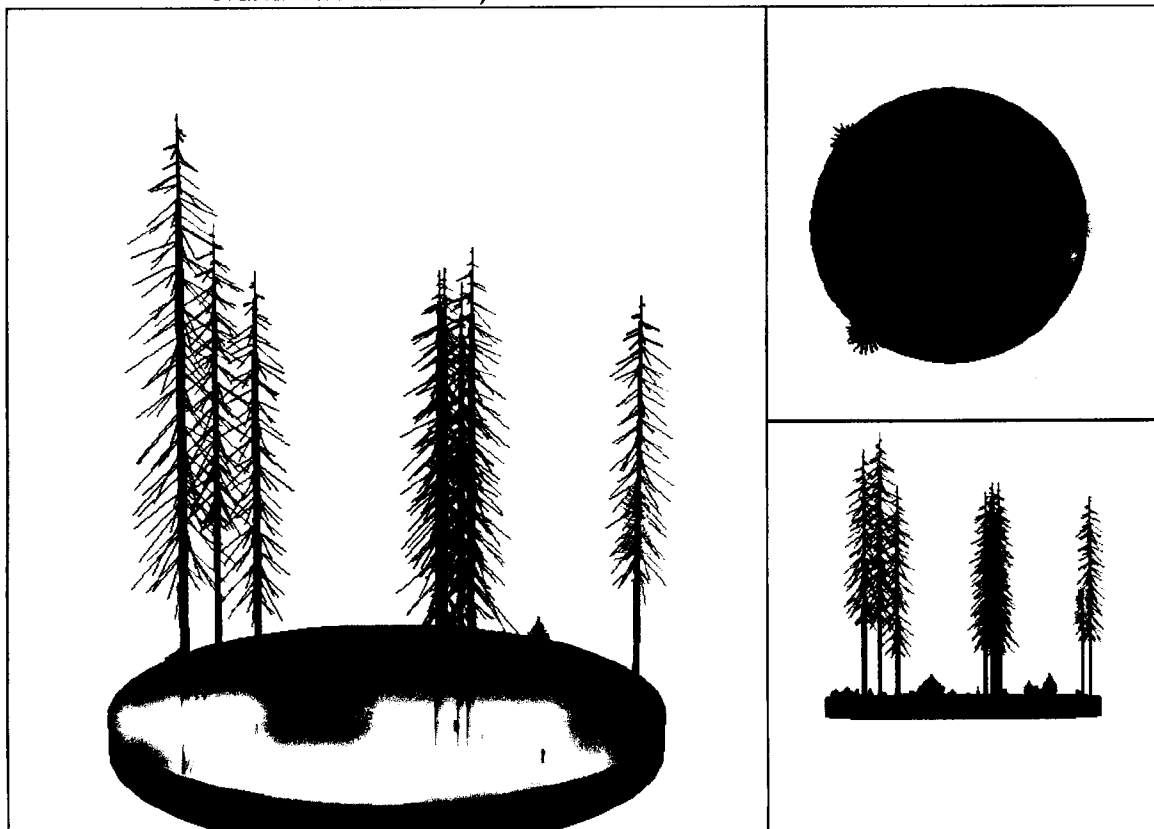


Figure L.2. Spatial plot 2, plot photo and SVS visualization image.



Stand Visualization System

PLOT3.SVS

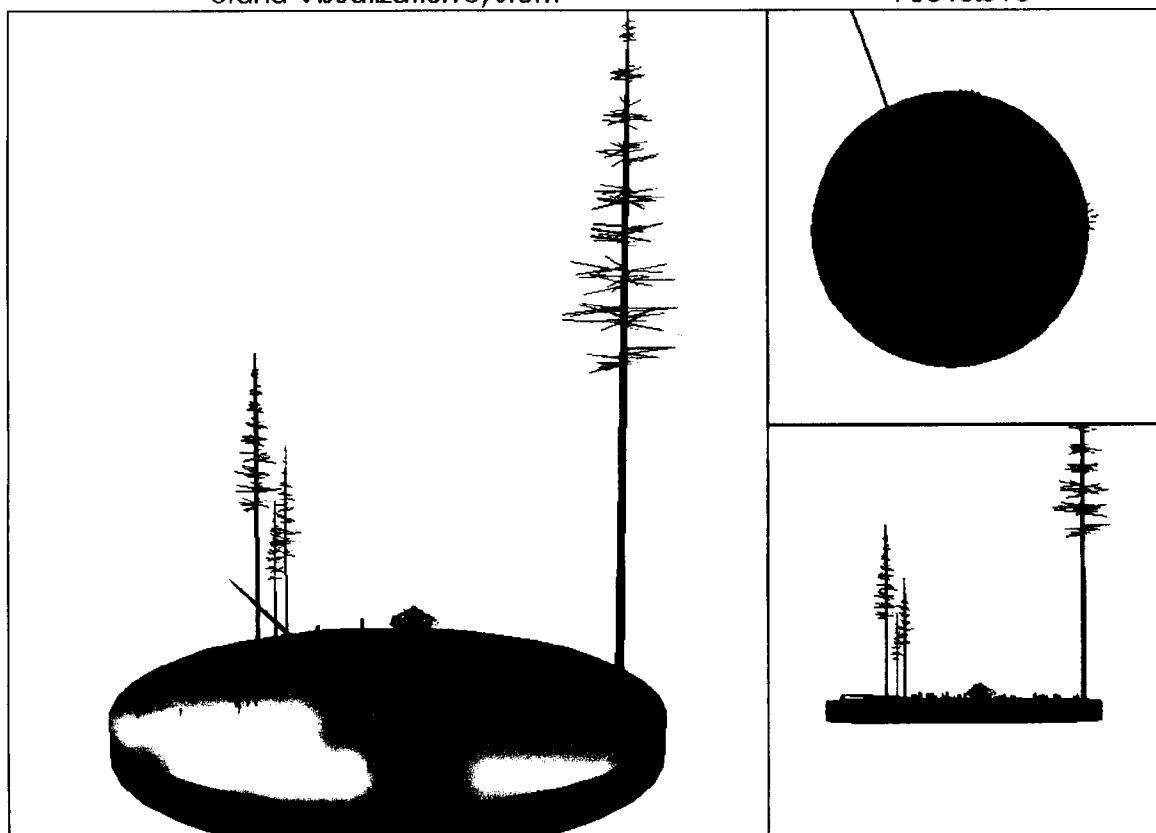


Figure L.3. Spatial plot 3, plot photo and SVS visualization image.



Stand Visualization System

PLOT4.SVS

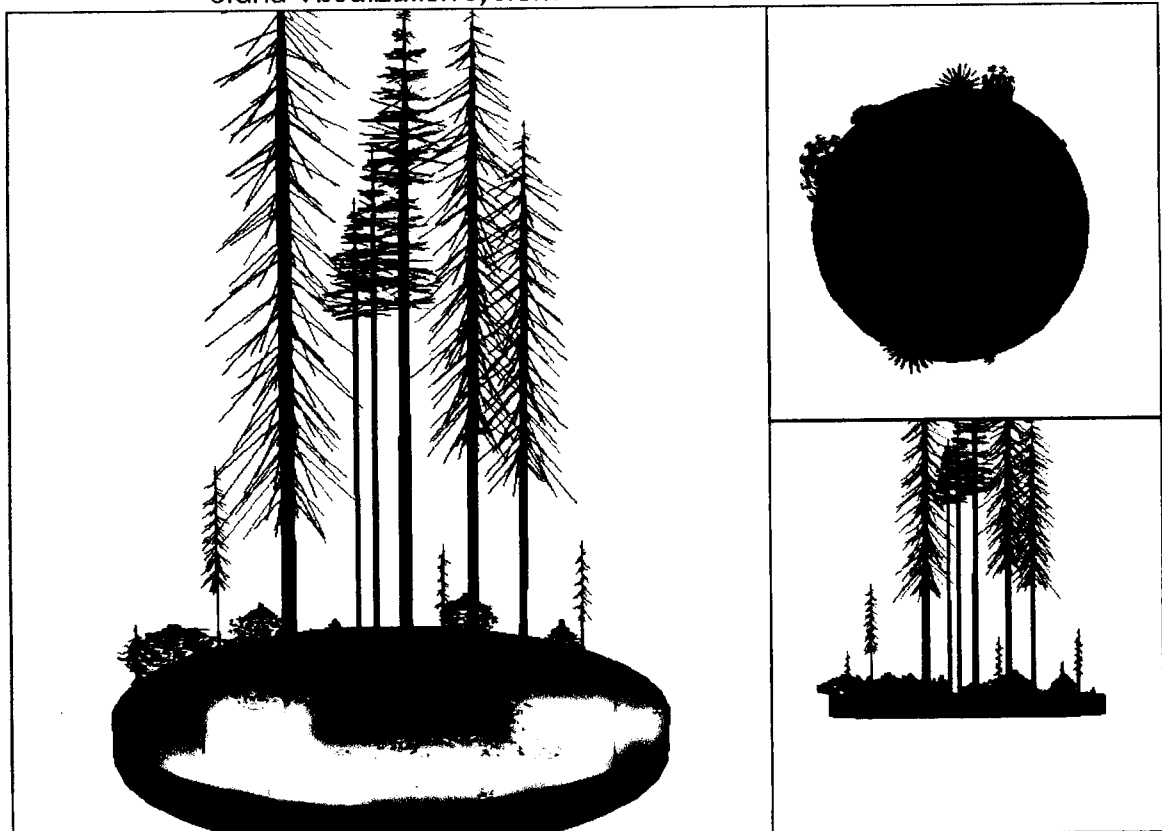


Figure L.4. Spatial plot 4, plot photo and SVS visualization image.



Stand Visualization System

PLOT5.SVS

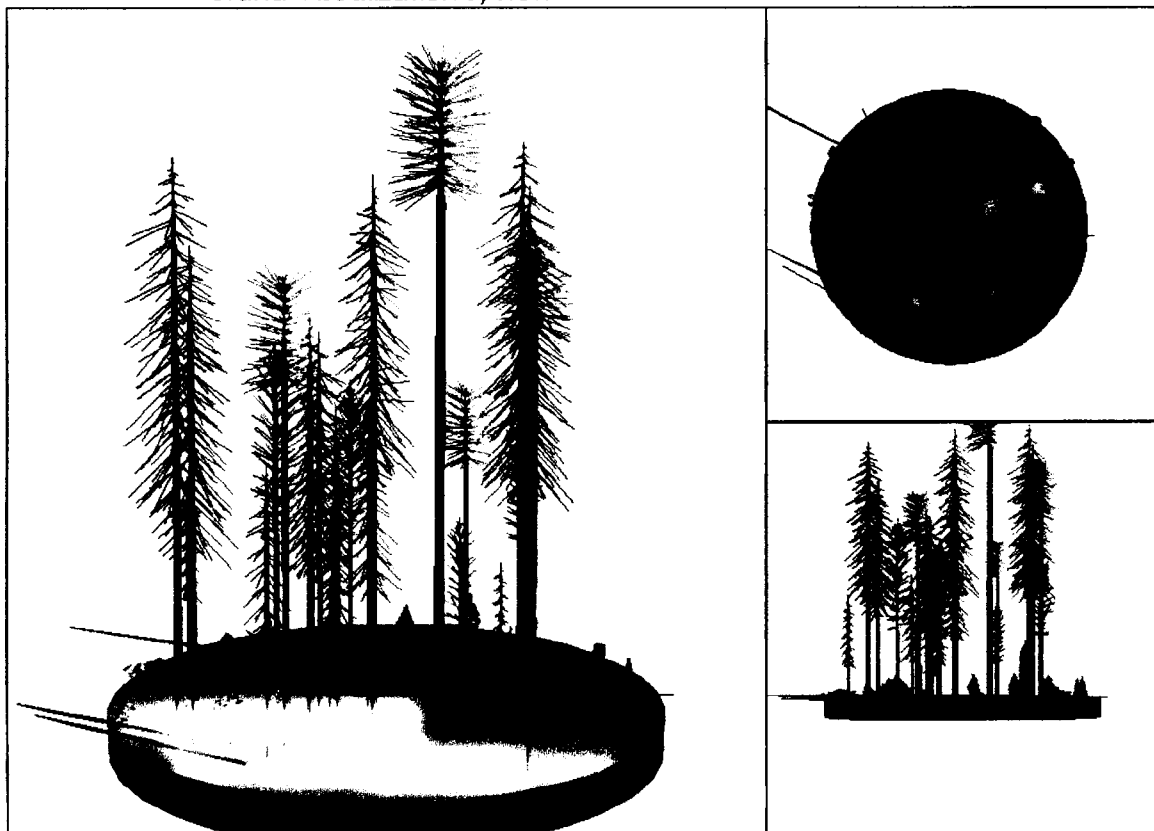
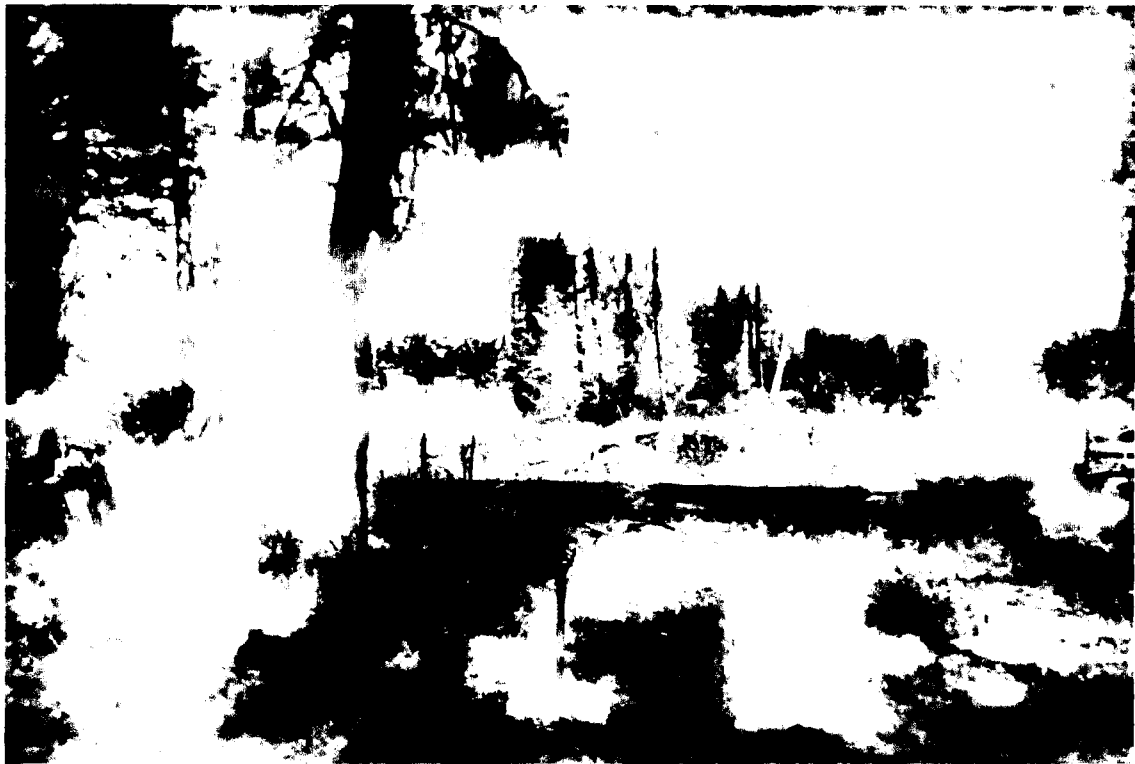


Figure L.5. Spatial plot 5, plot photo and SVS visualization image.



Stand Visualization System

PLOT6.SVS

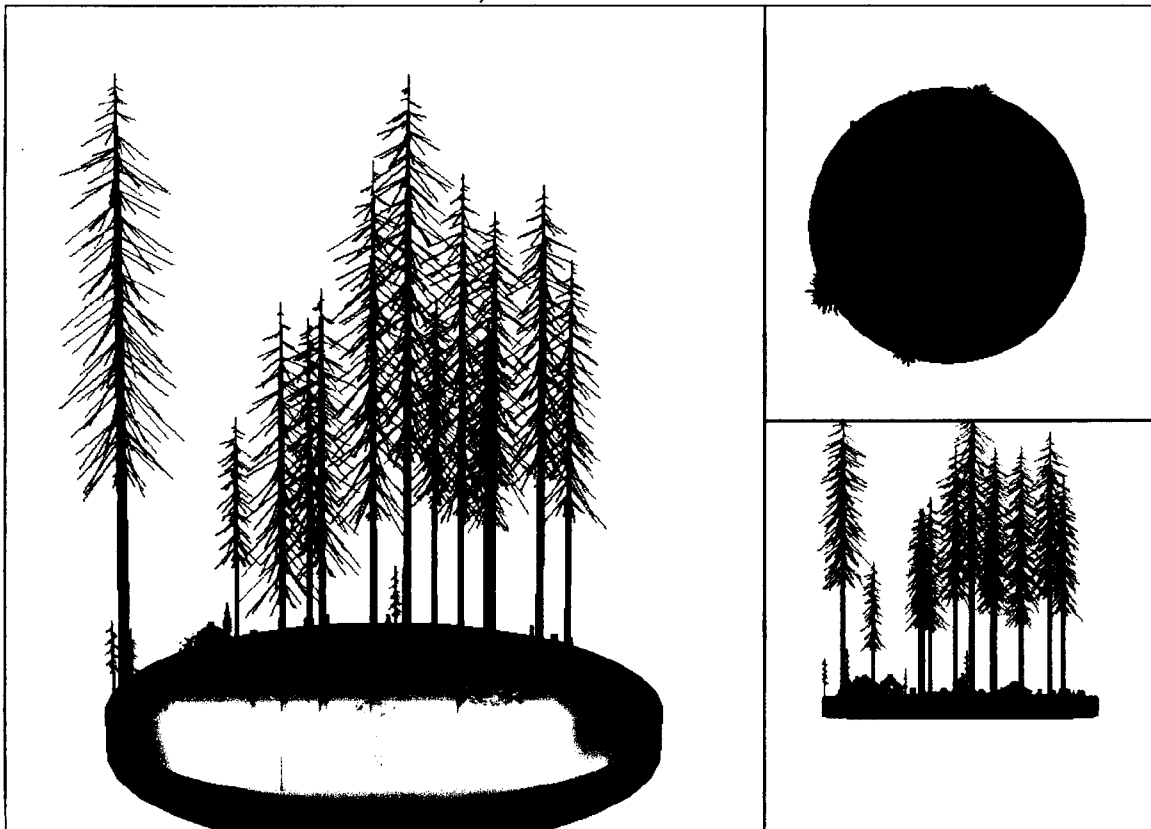


Figure L.6. Spatial plot 6, plot photo and SVS visualization image.



Stand Visualization System

PLOT7.SVS

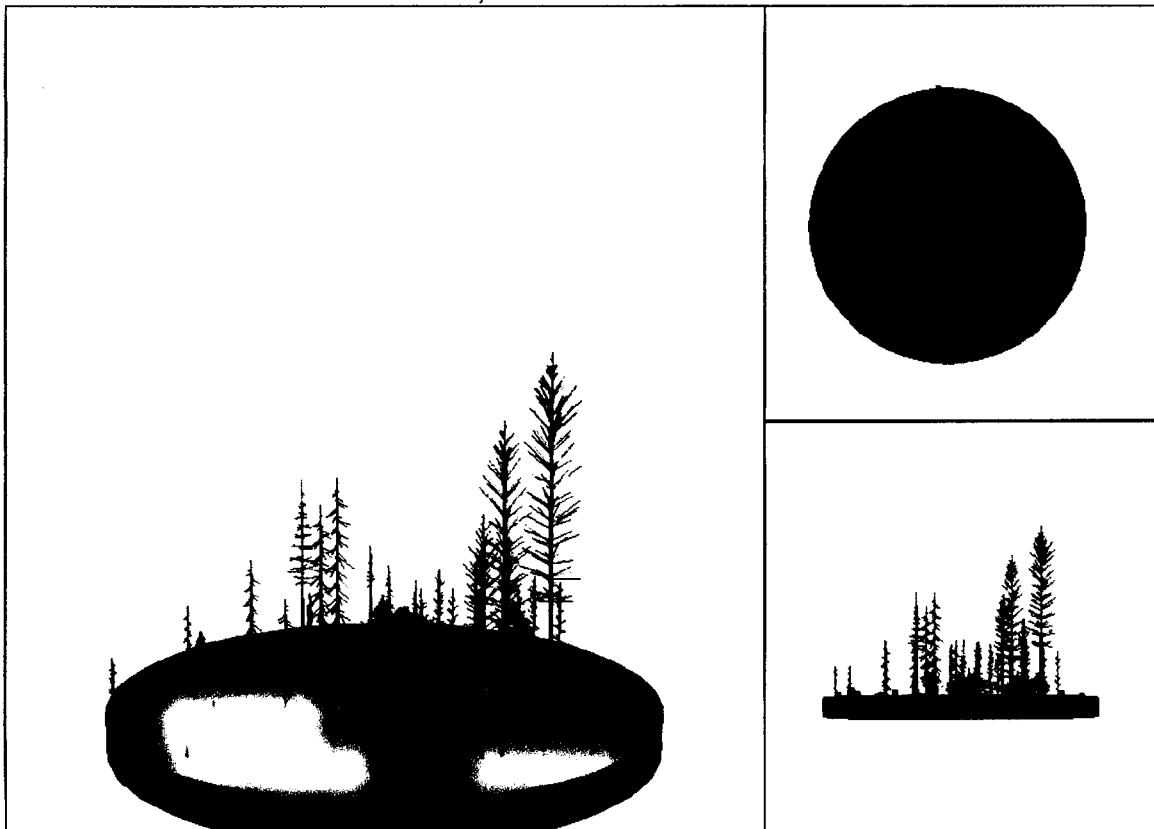


Figure L.7. Spatial plot 7, plot photo and SVS visualization image.



Stand Visualization System

PLOT8.SVS

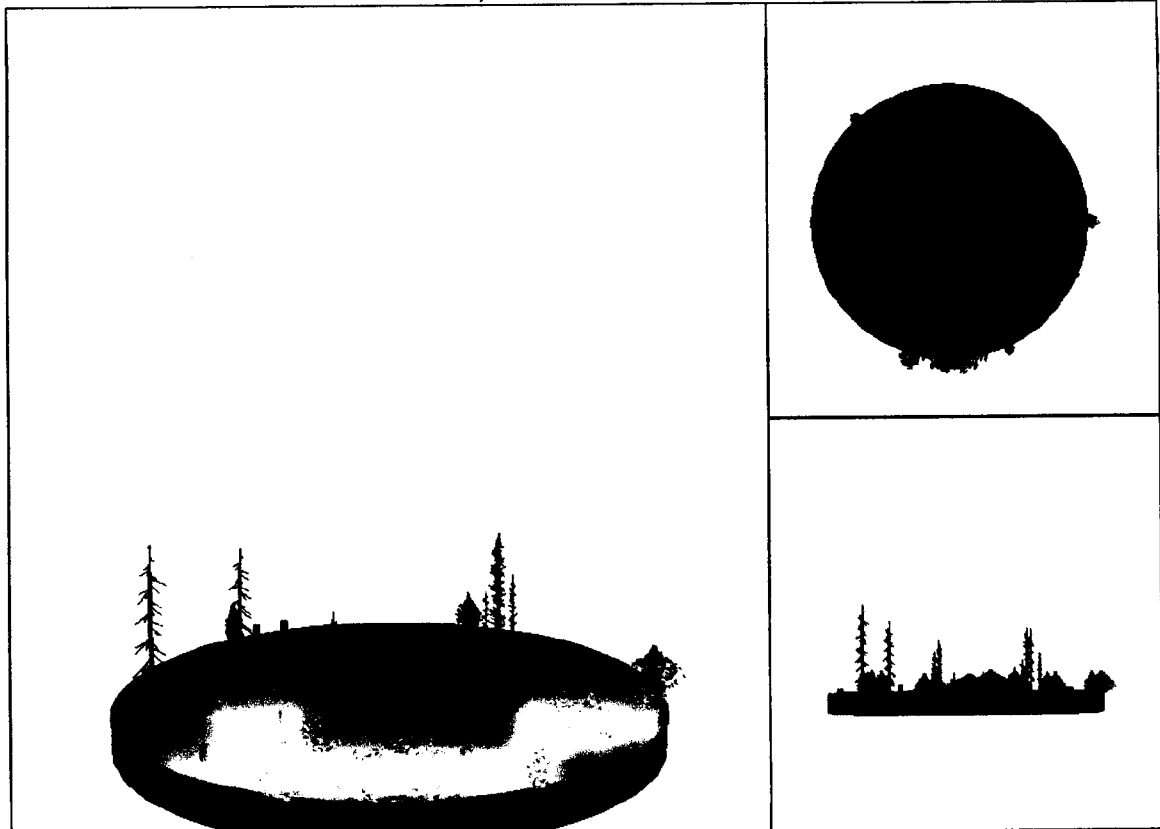


Figure L.8. Spatial plot 8, plot photo and SVS visualization image.



Stand Visualization System

PLOT9.SVS

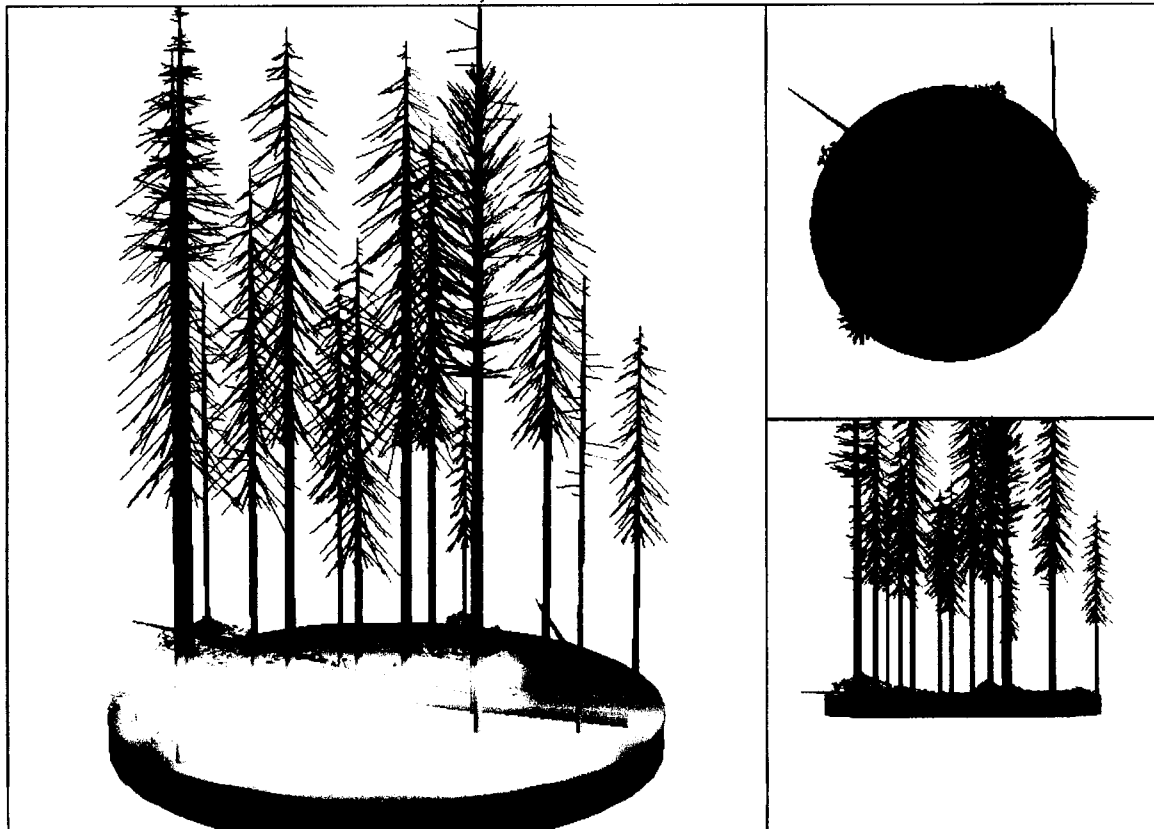
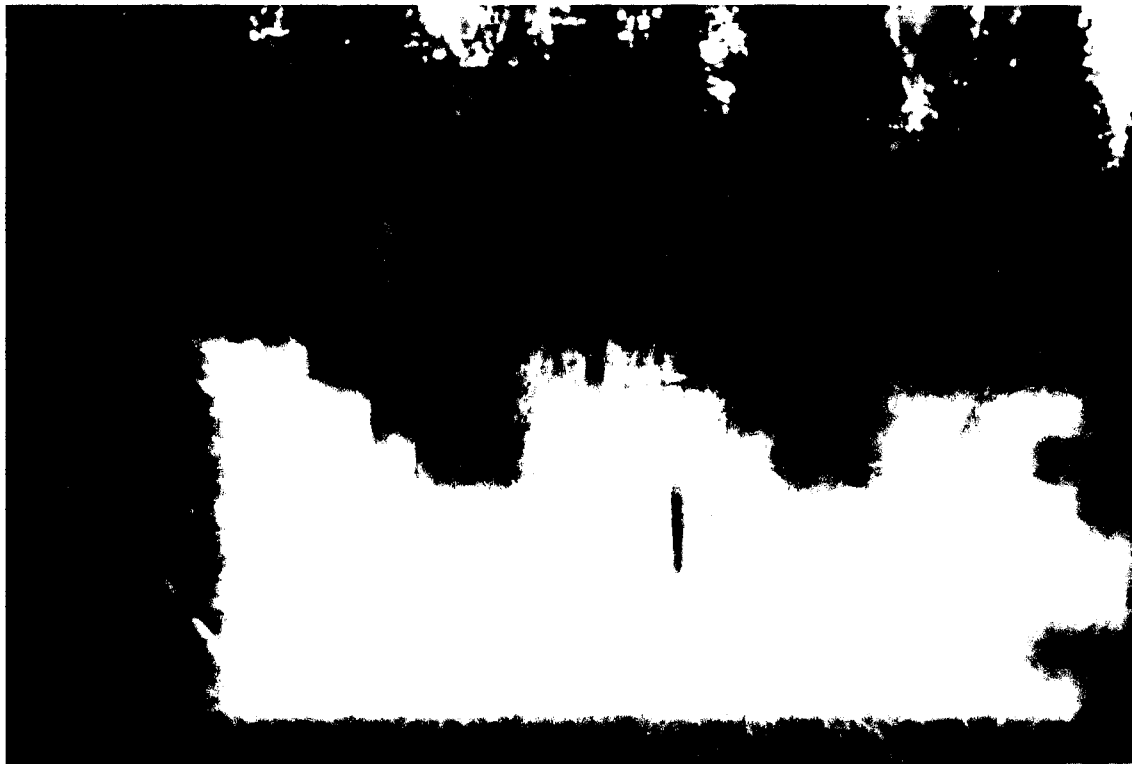


Figure L.9. Spatial plot 9, plot photo and SVS visualization image.



Stand Visualization System

PLOT10.SVS

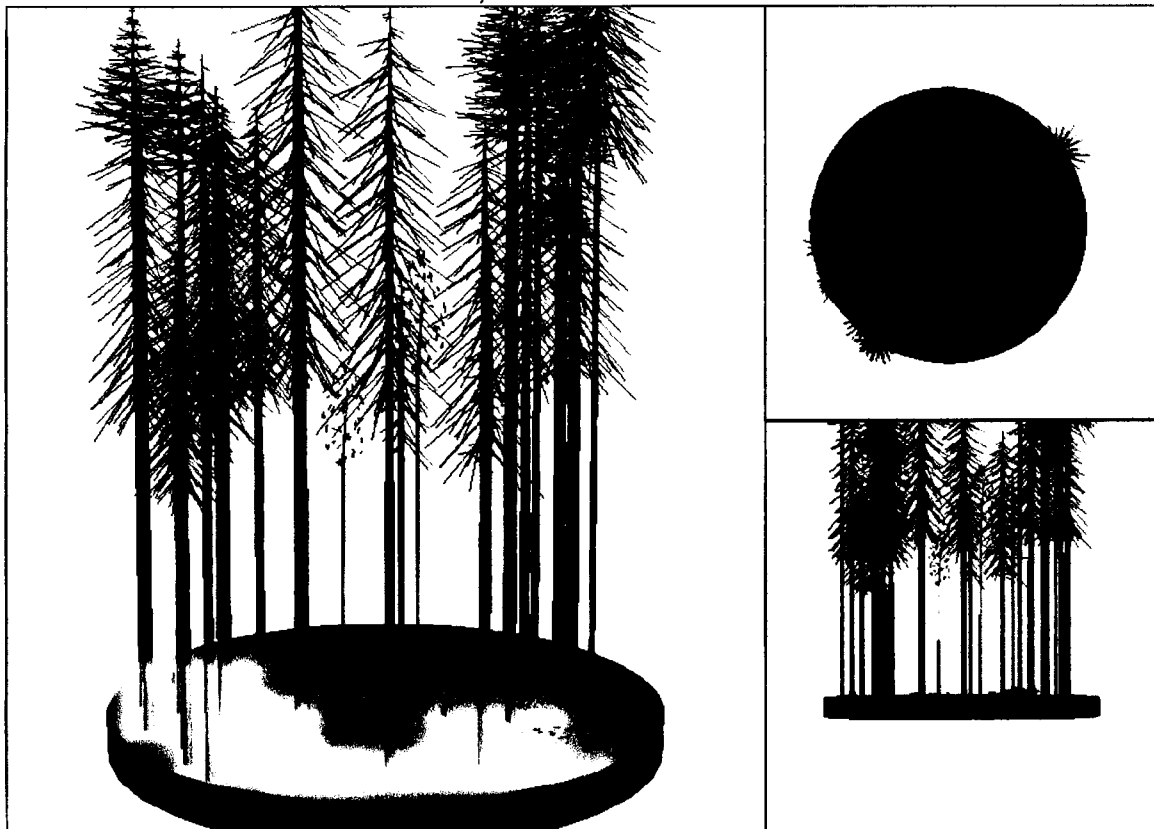


Figure L.10. Spatial plot 10, plot photo and SVS visualization image.



Stand Visualization System

PLOT11.SVS

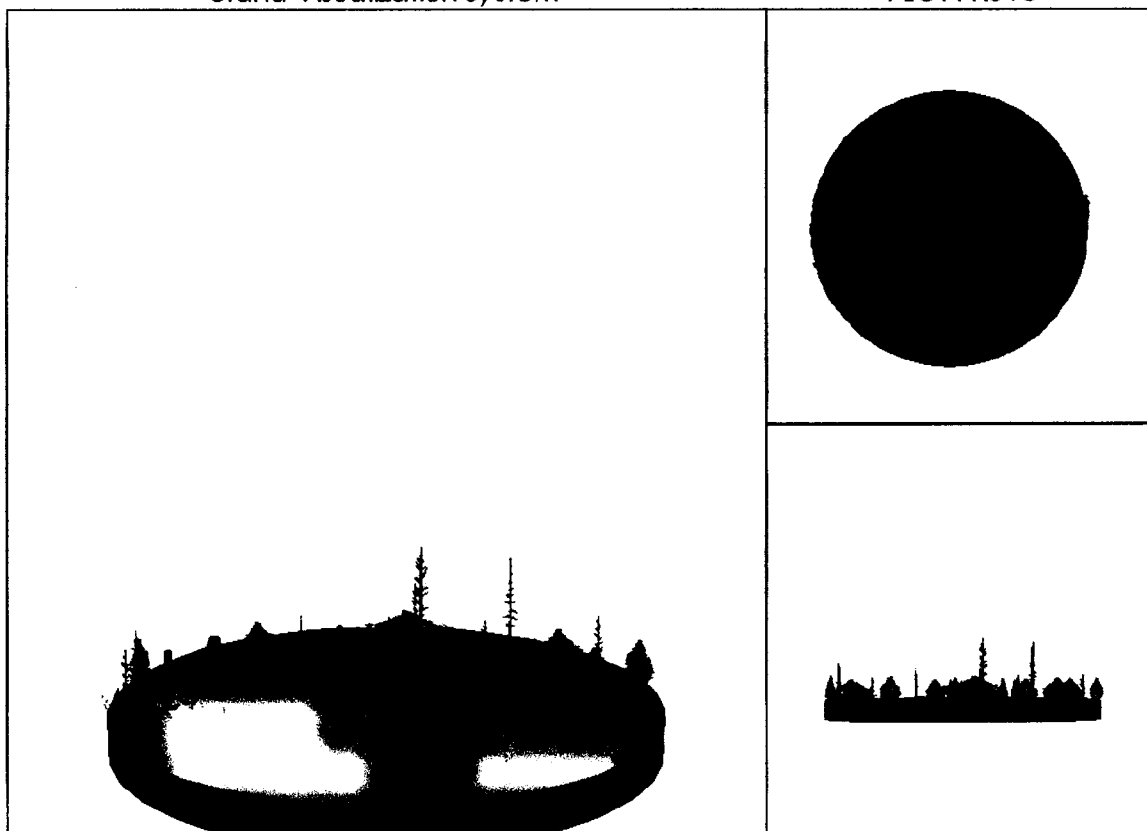


Figure L.11. Spatial plot 11, plot photo and SVS visualization image.



Stand Visualization System

PLOT12.SVS

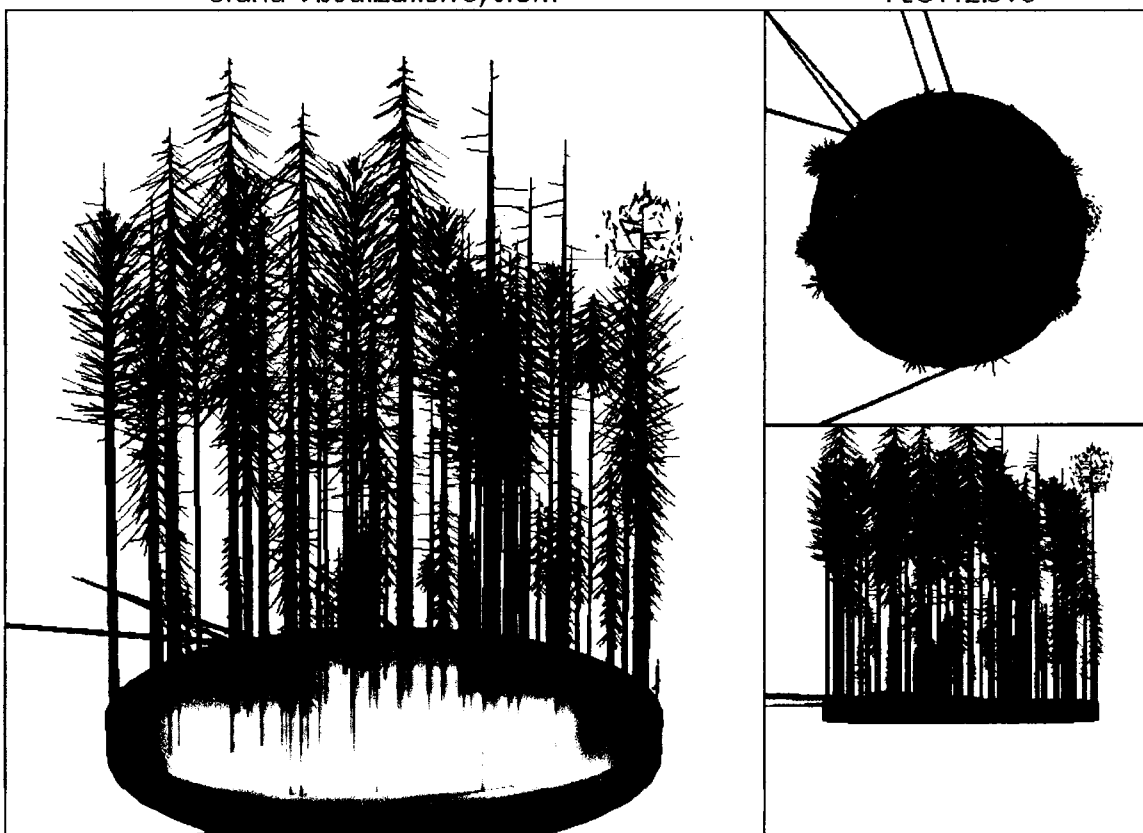
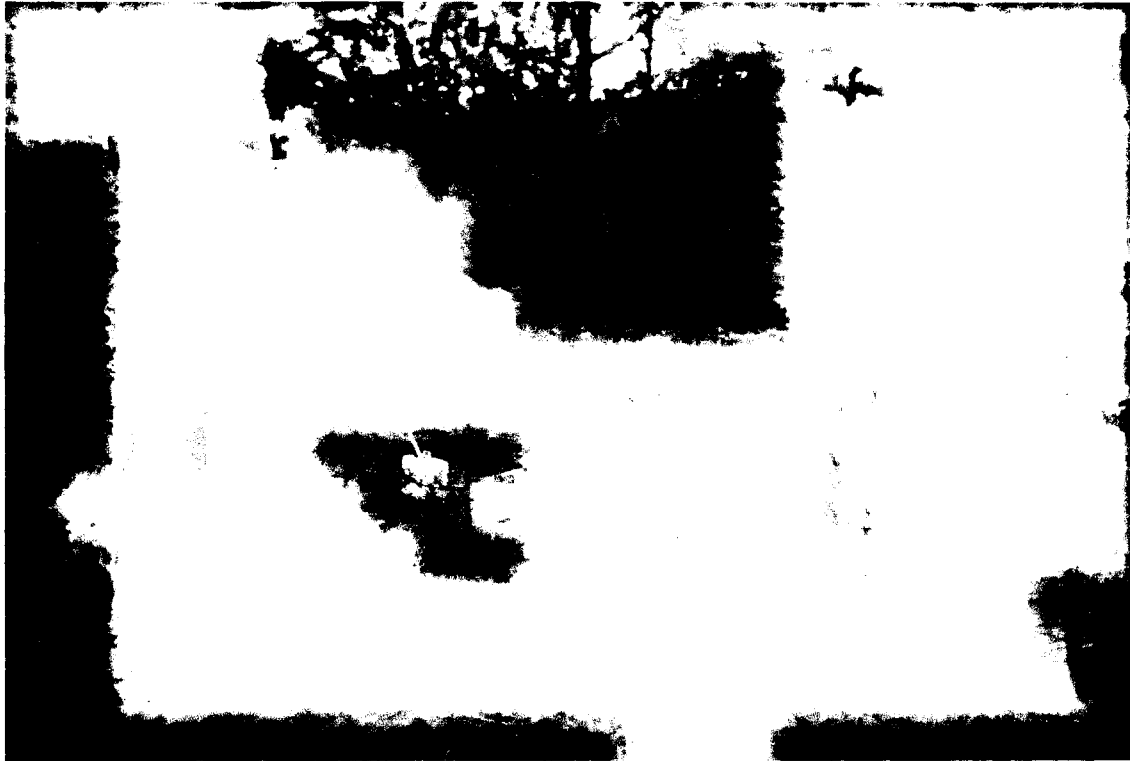


Figure L.12. Spatial plot 12, plot photo and SVS visualization image.



Stand Visualization System

PLOT13.SVS

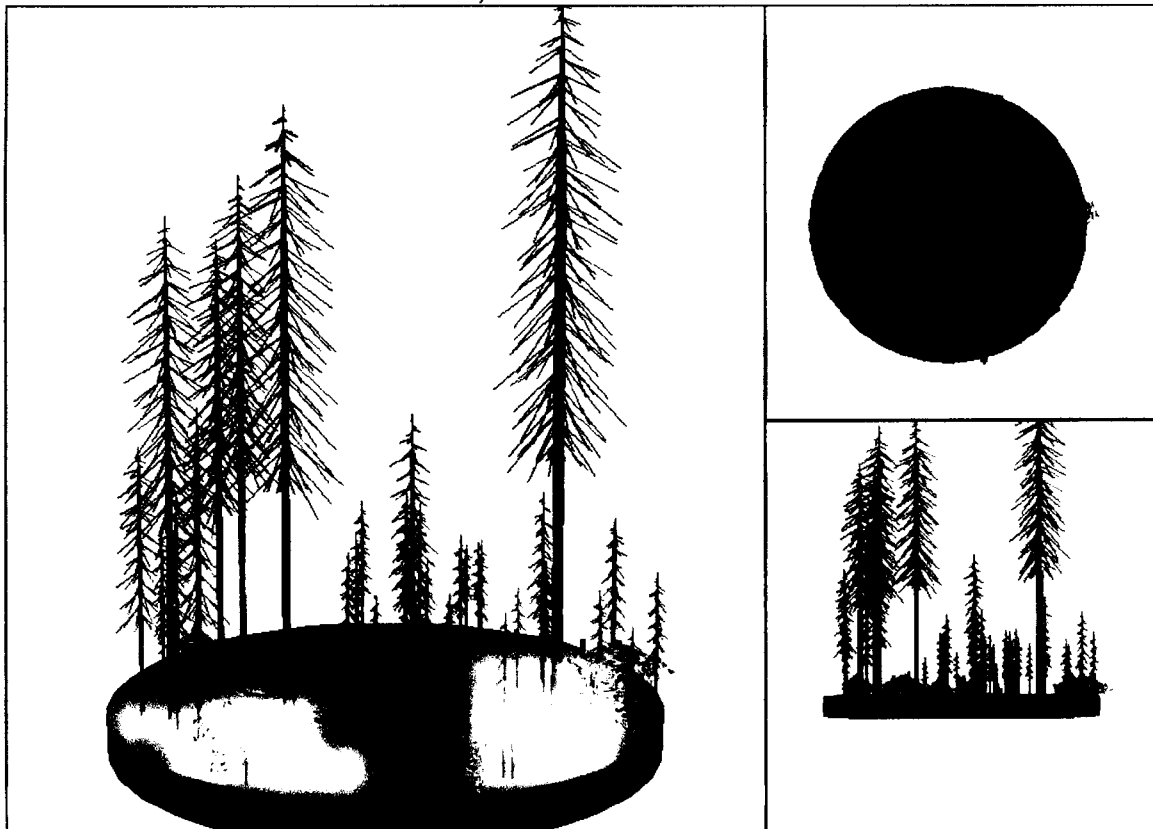


Figure L.13. Spatial plot 13, plot photo and SVS visualization image.



Stand Visualization System

PLOT14.SVS

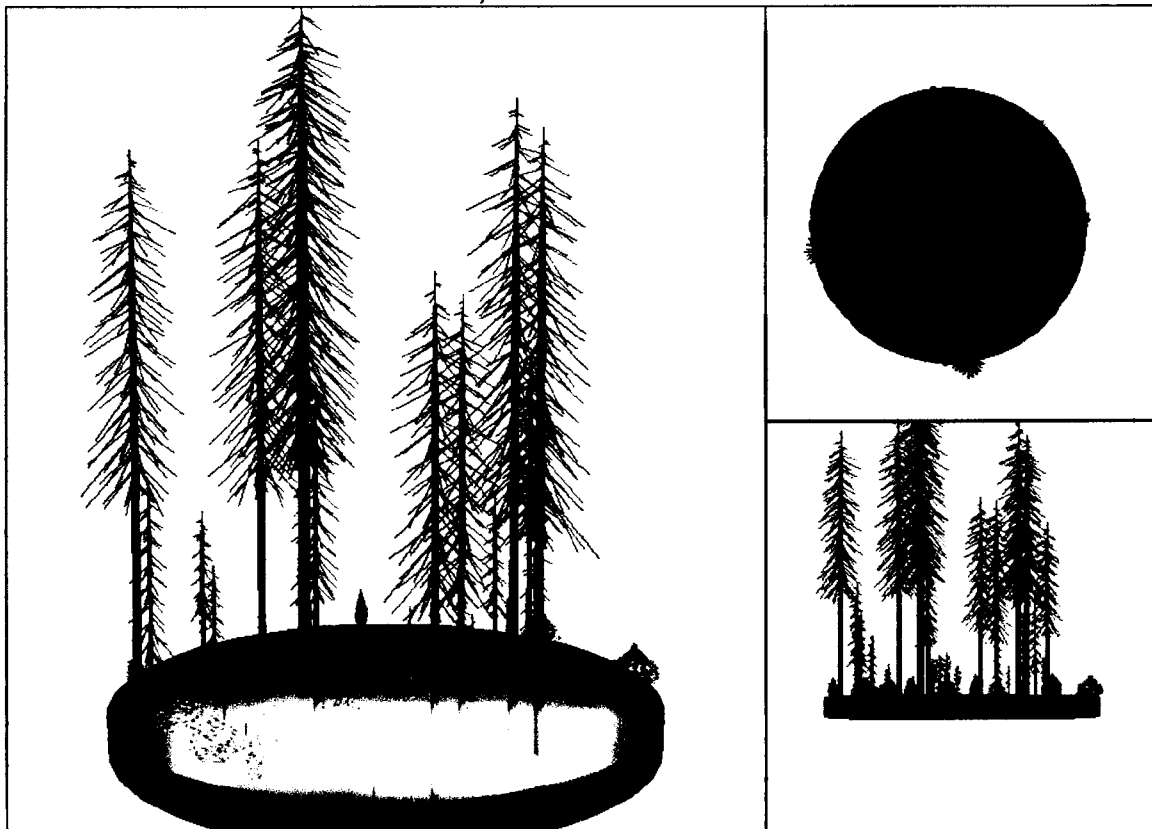


Figure L.14. Spatial plot 14, plot photo and SVS visualization image.



Stand Visualization System

PLOT15.SVS

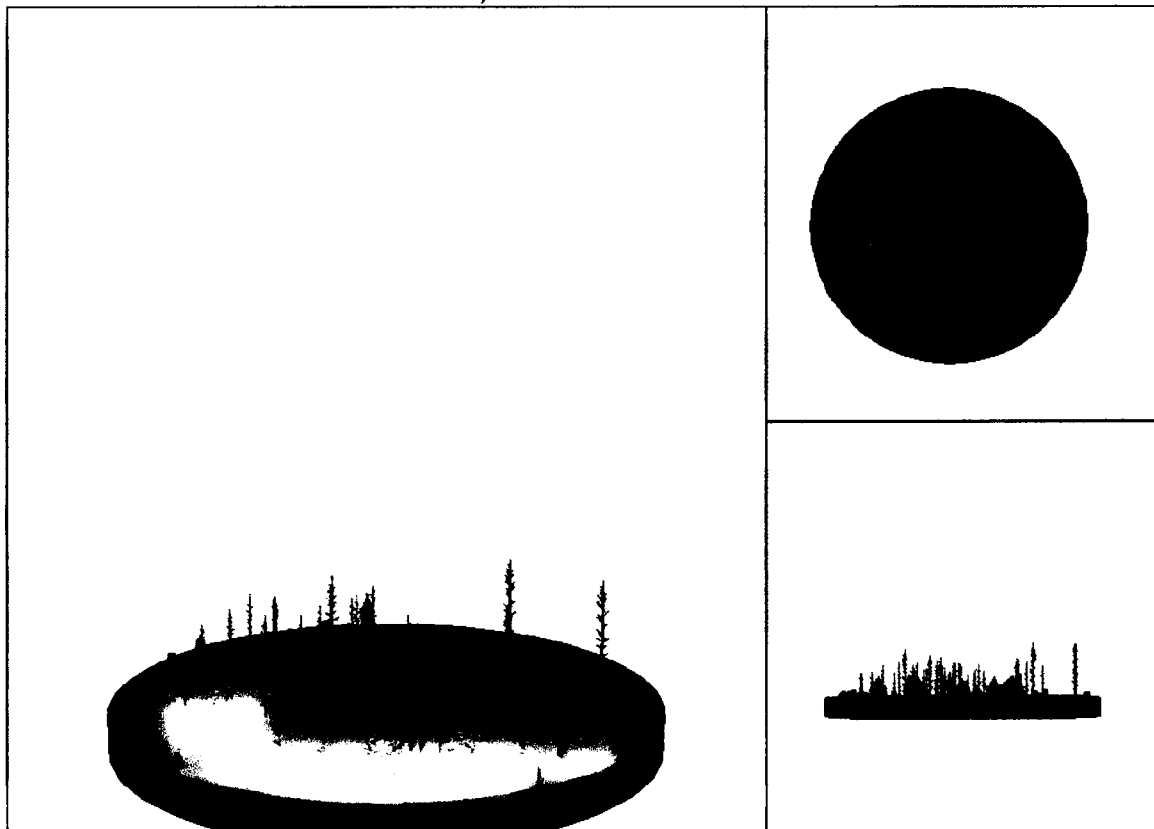


Figure L.15. Spatial plot 15, plot photo and SVS visualization image.



Stand Visualization System

PLOT16.SVS

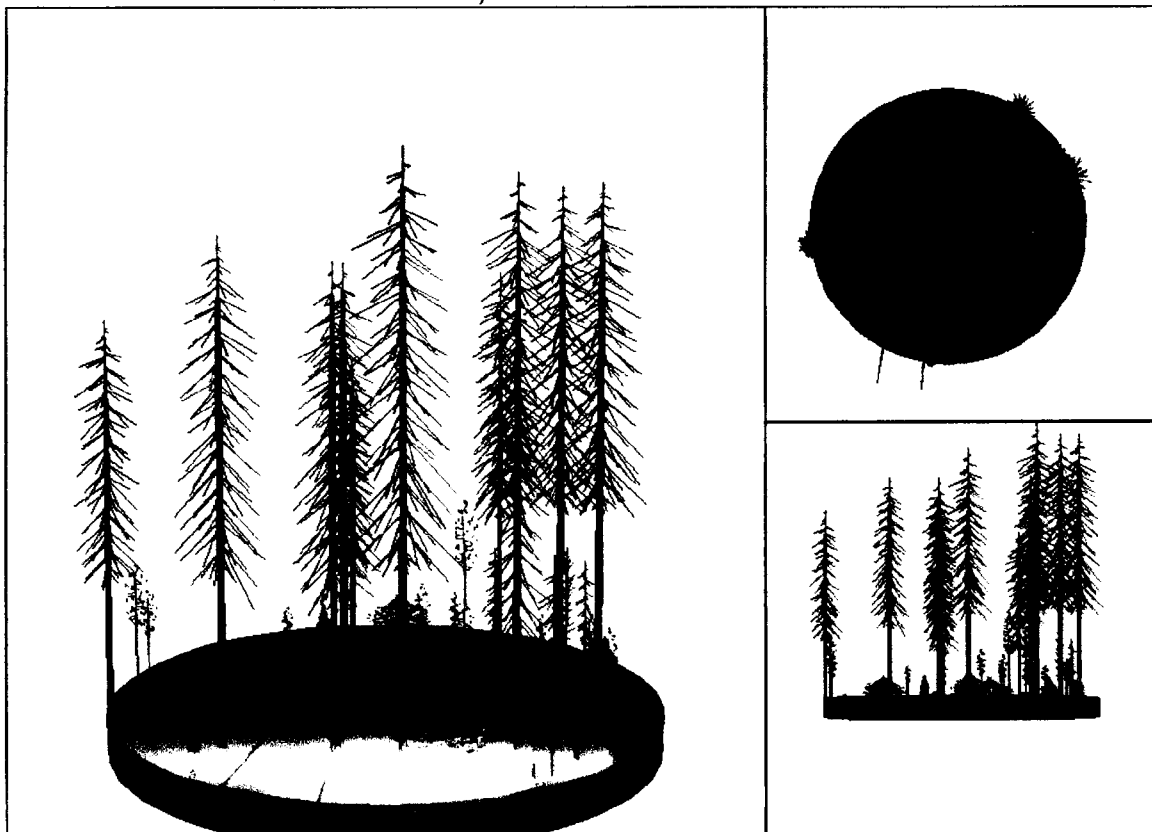


Figure L.16. Spatial plot 16, plot photo and SVS visualization image.



Stand Visualization System

PLOT17.SVS

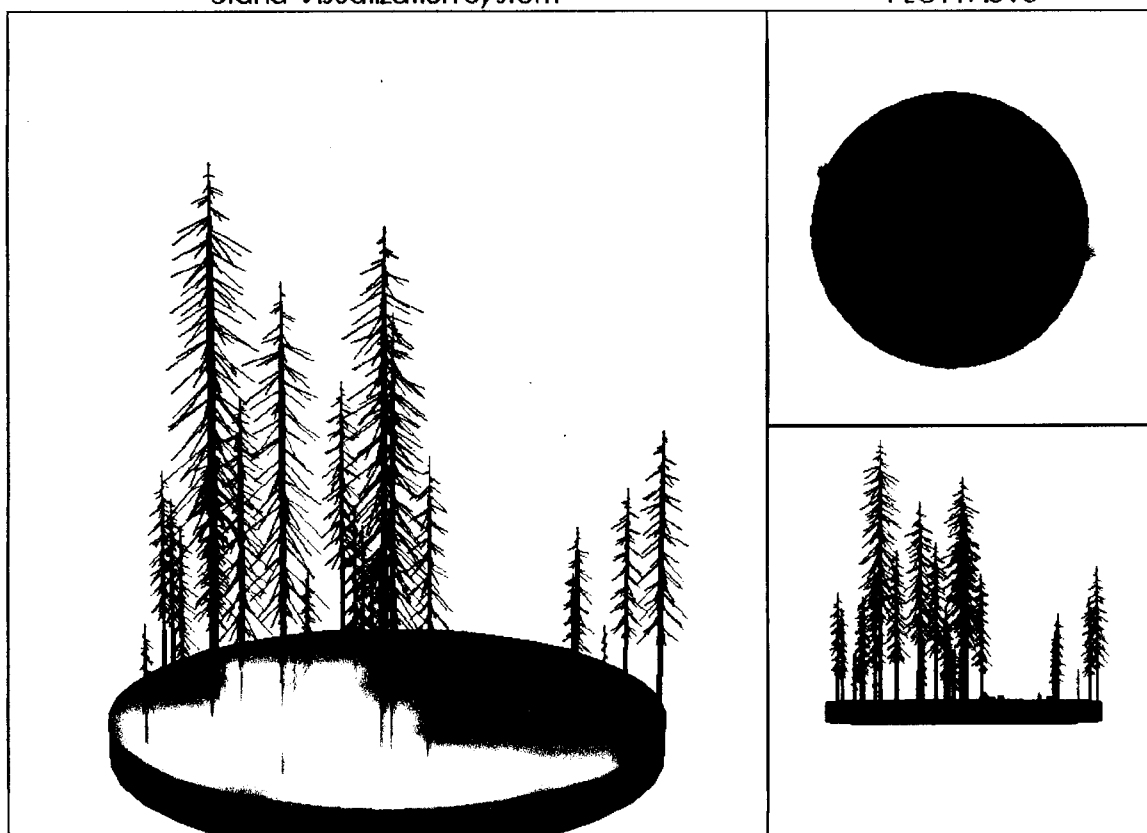


Figure L.17. Spatial plot 17, plot photo and SVS visualization image.



Stand Visualization System

PLOT18.SVS

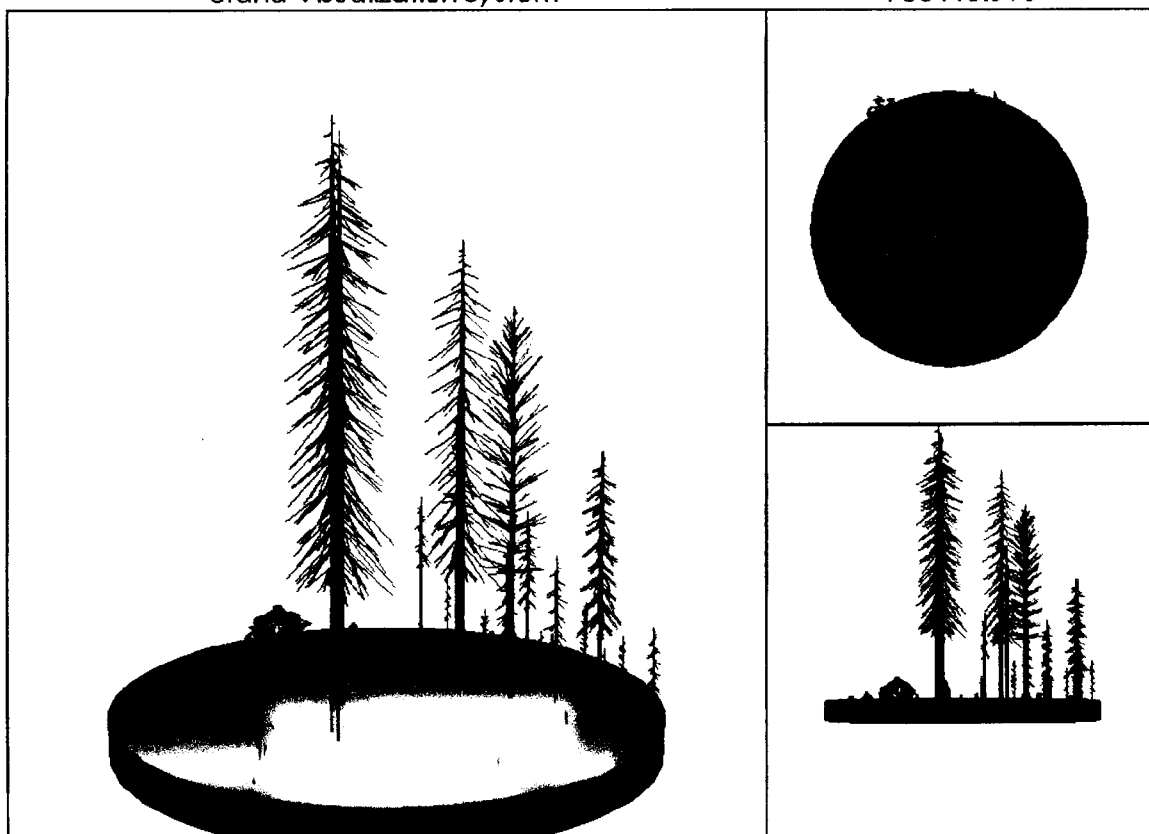
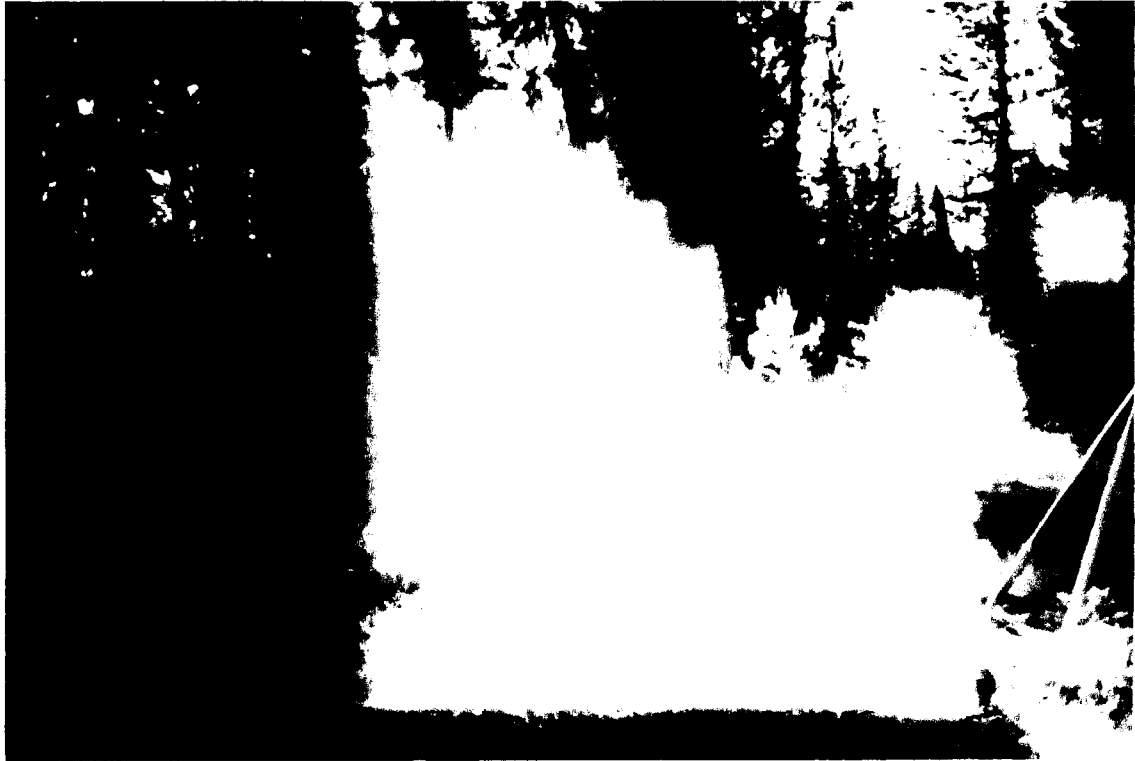


Figure L.18. Spatial plot 18, plot photo and SVS visualization image.



Stand Visualization System

PLOT19.SVS

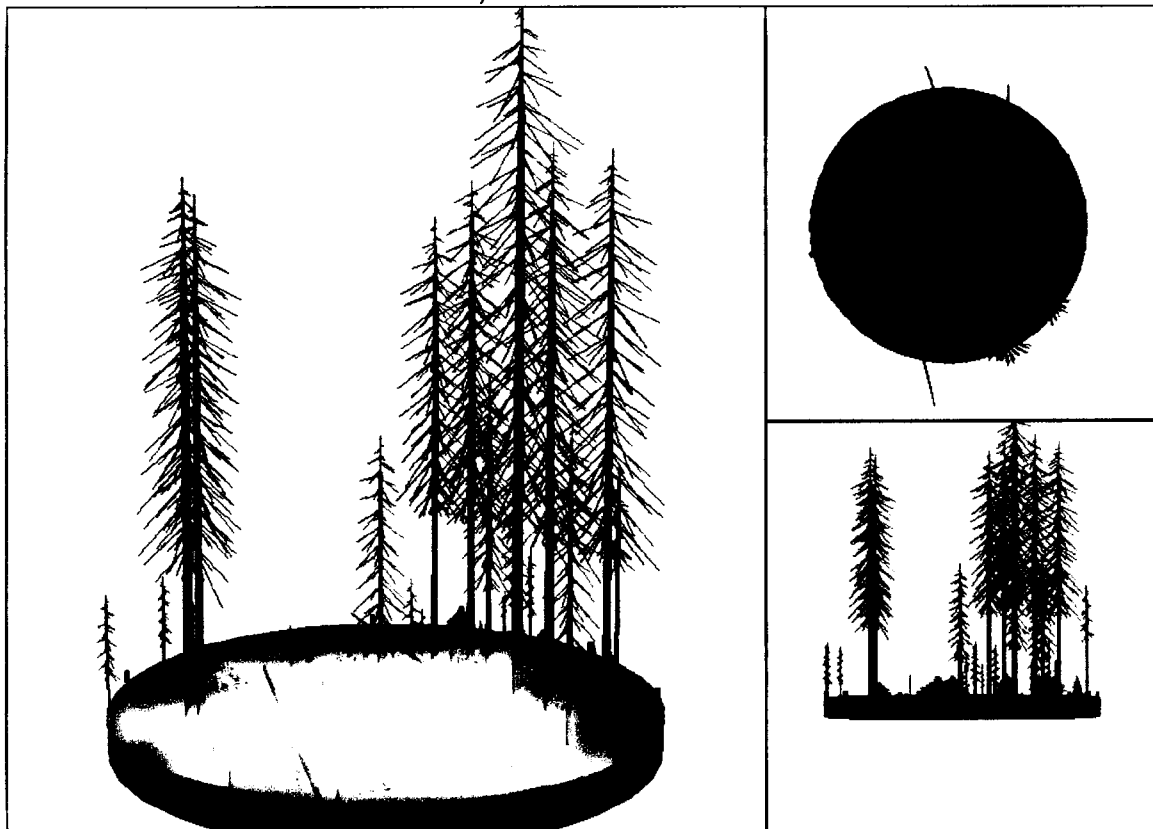


Figure L.19. Spatial plot 19, plot photo and SVS visualization image.



Stand Visualization System

PLOT20.SVS

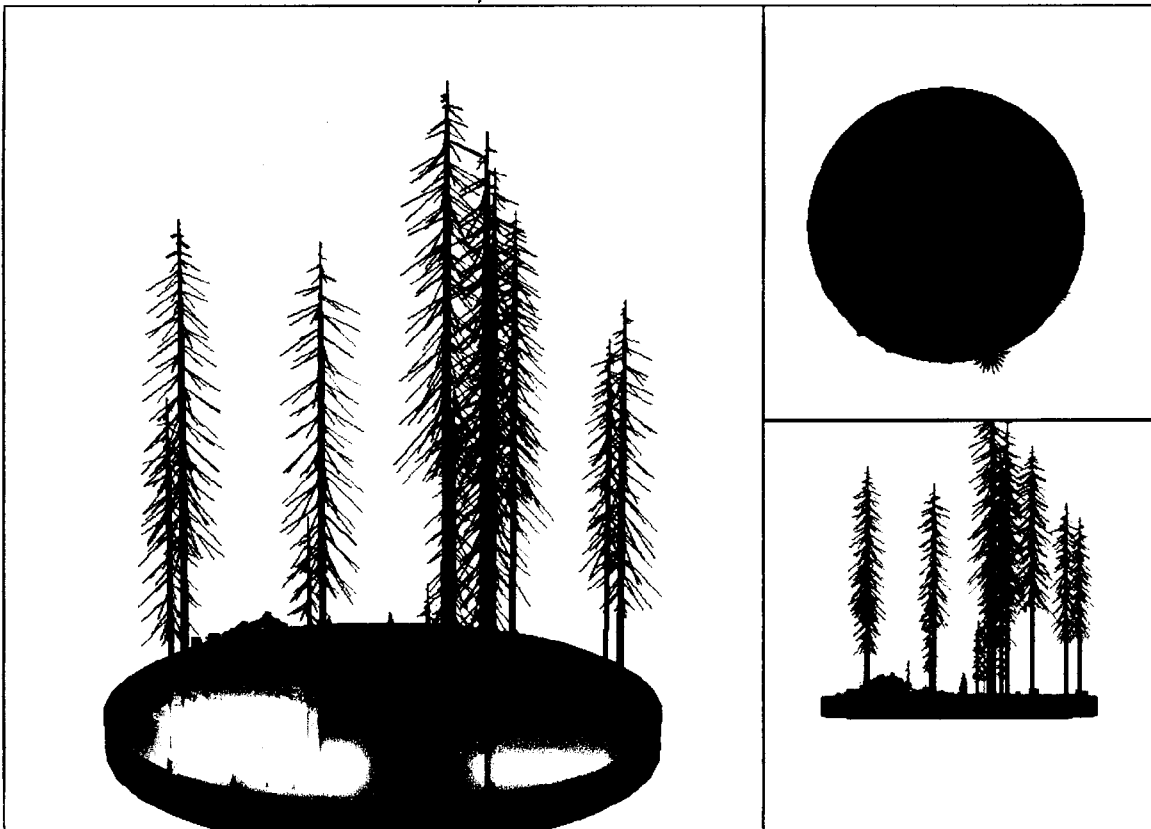


Figure L.20. Spatial plot 20, plot photo and SVS visualization image.



Stand Visualization System

PLOT21.SVS

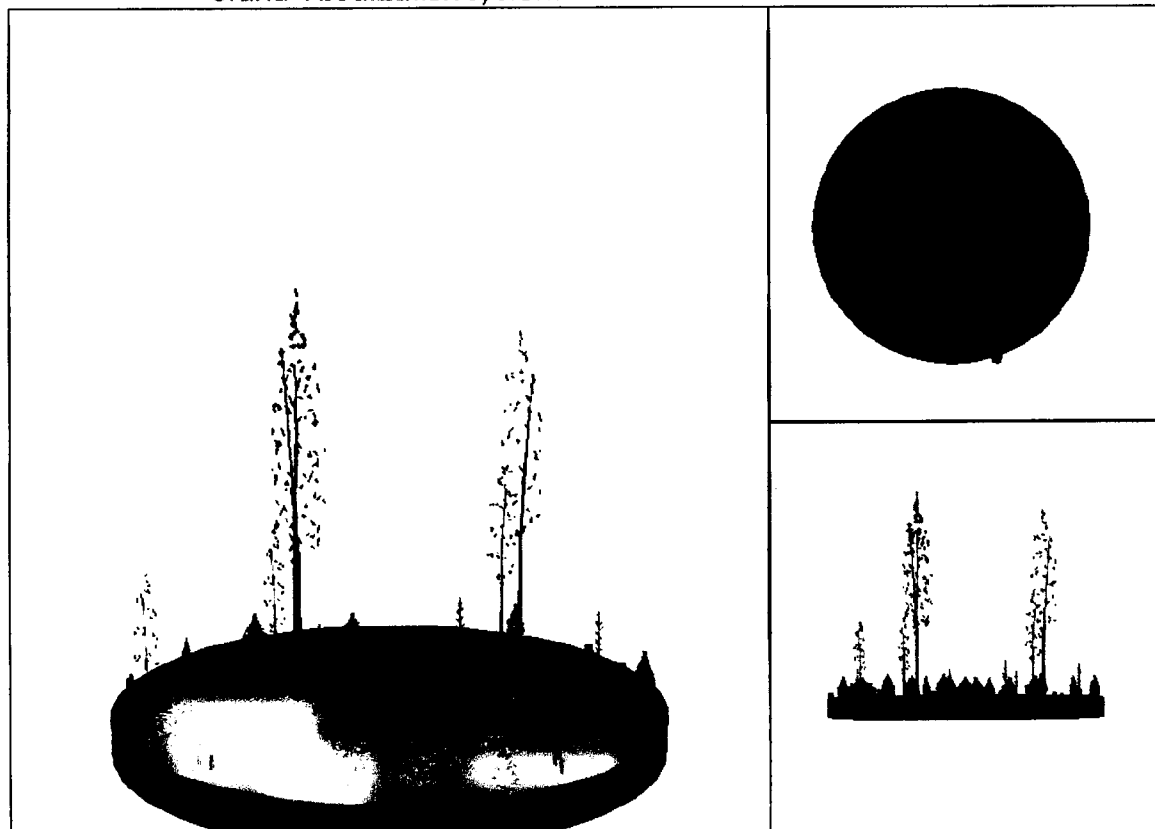


Figure L.21. Spatial plot 21, plot photo and SVS visualization image.



Stand Visualization System

PLOT22.SVS

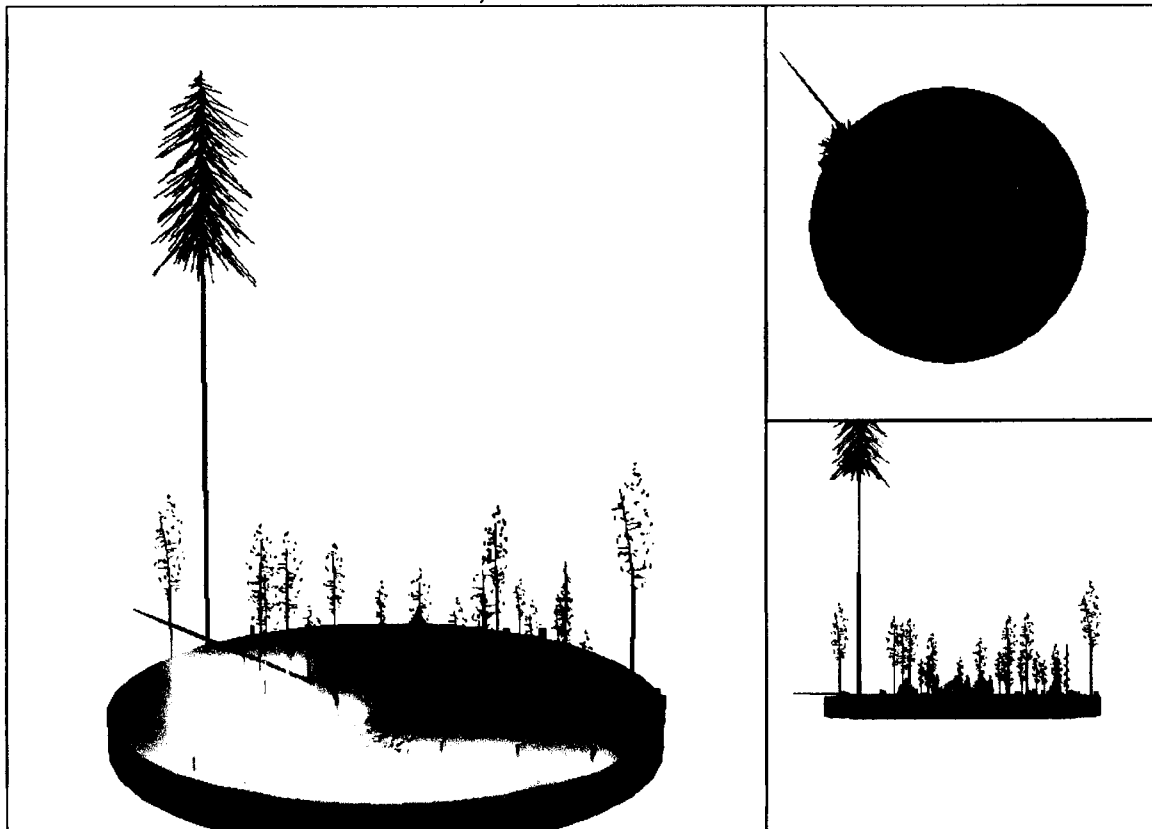


Figure L.22. Spatial plot 22, plot photo and SVS visualization image.



Stand Visualization System

PLOT23.SVS

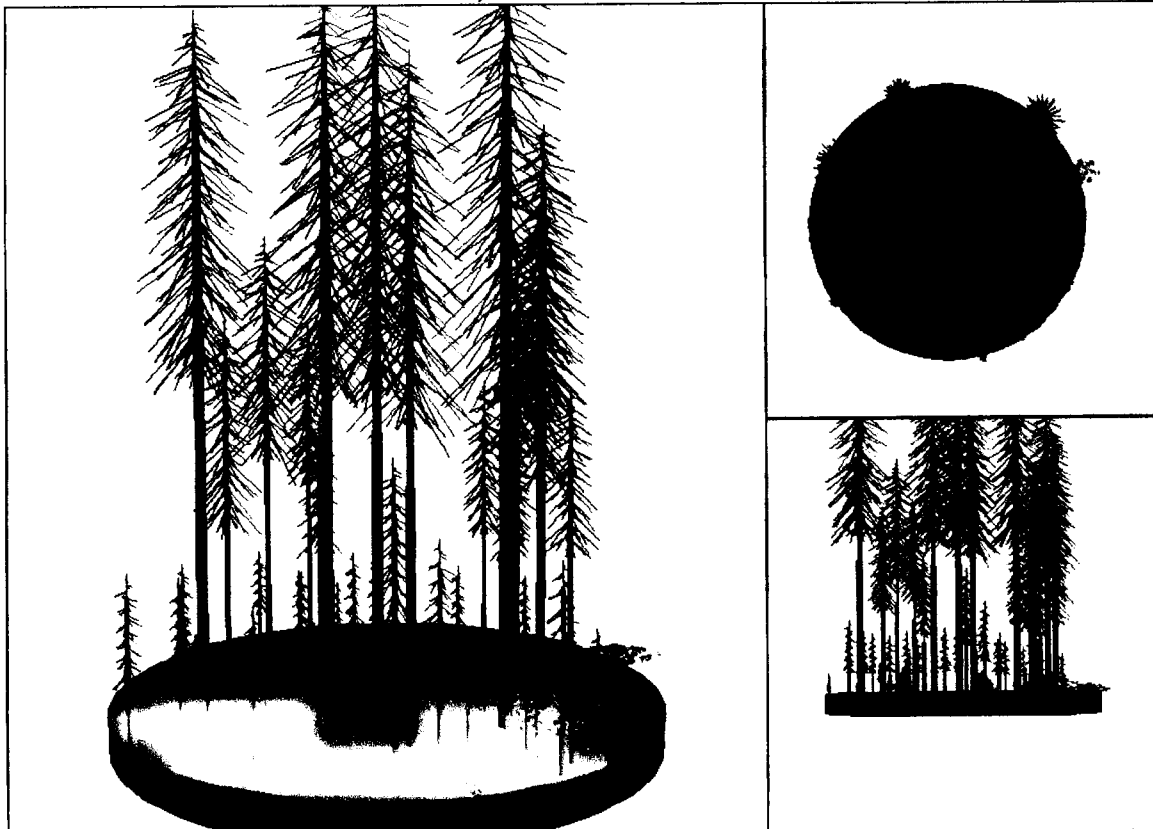


Figure L.23. Spatial plot 23, plot photo and SVS visualization image.



Stand Visualization System

PLOT24.SVS

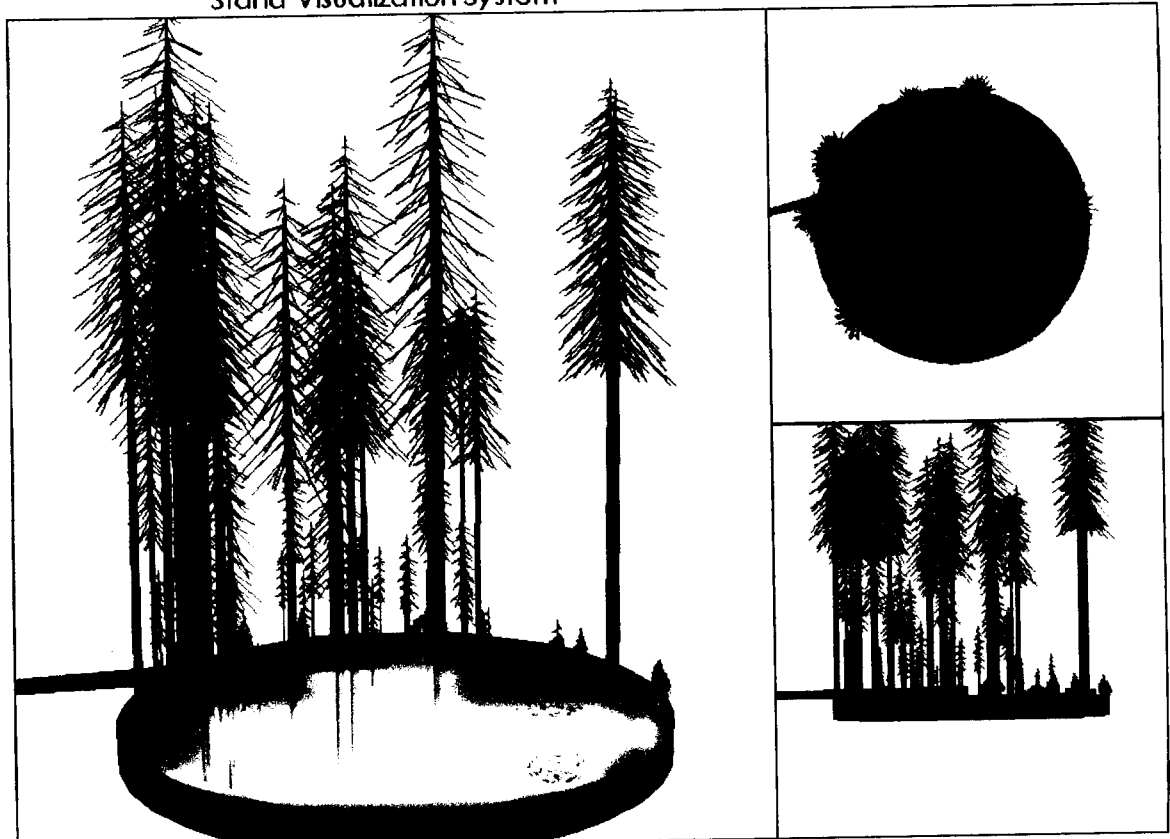
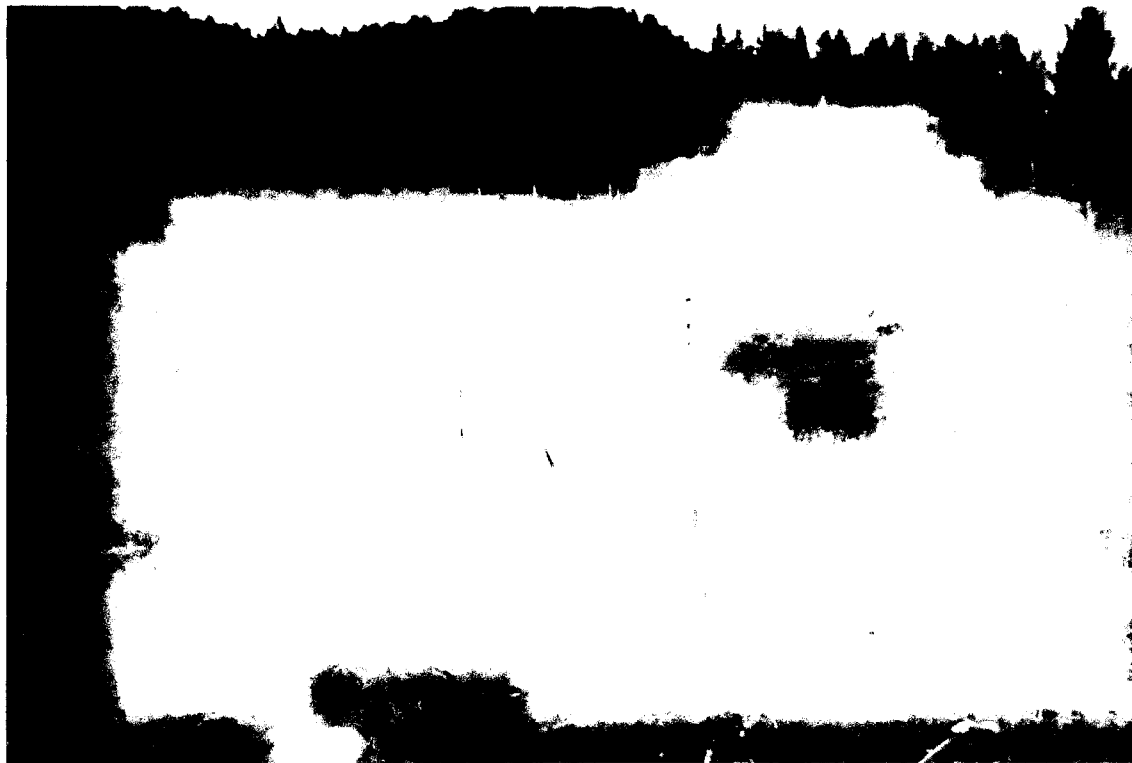


Figure L.24. Spatial plot 24, plot photo and SVS visualization image.



Stand Visualization System

PLOT25.SVS

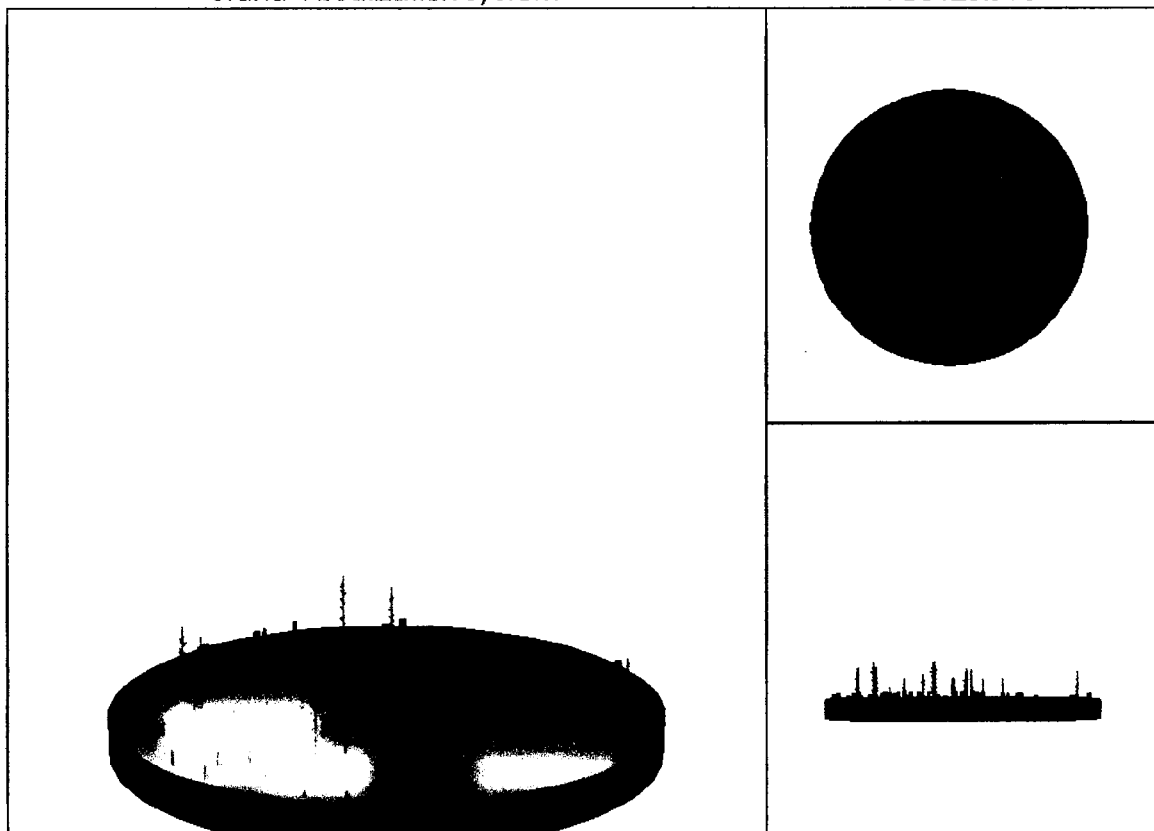


Figure L.25. Spatial plot 25, plot photo and SVS visualization image.

APPENDIX M. PARAMETER ESTIMATES FOR SELECTED MODELS, FIVE-YEAR SMALL TREE HEIGHT INCREMENT

Table M1. Parameter estimates for selected models⁷.

	Species						
	At	Ep	Fd	Lw	Pl	Py	Sxw
Intercept	1.55449	2.58101	11.56360	-0.17910	11.50740	0.86277	0.78463
HEIGHT	-	-	-0.51200	-0.48170	-	0.14431	-
LNHEIGHT	-	-	2.19630	2.30770	0.34570	-	-
HTSQ	-	-	-	-	-	-	-
SQRTH	-	-	-	-	-	-	-
DBH	-	-	-	-	-	-	-
LNDBH	-	-	-	-	-	-	-
DBHSQ	-	-	-	-	-	-	-
LNDBH	-	-	-	-	-	-	-
SQRTH	-	0.23886	-	-	-	-	-
HDR	0.00492	-	-	-	-	-	-
COSASPECT	-	-	4.66600	-	-	-	-
SINASPECT	-	-	10.33500	-	-	-	-
SL	-	-	-	-	-	-	-
ELEV	-	-0.00187	-	-	-0.00069	-	-
ELEVSQ	-	-	-	-	-	-	-
ELEVBYCOS	-	-	-0.00576	-	-	-	-
ELEVBY SIN	-	-	-0.00945	-	-	-	-
NORTHING	-	-	-2.31E-06	-	-1.97E-06	-	-
CCF	-	0.00332	-0.00654	-	-	-0.00634	-
BA	-	-	-	-	-	-	-
BAL100	-	-	-	-5.05560	-5.13110	-	-2.81086
QMD	-	-	-0.01880	-	0.02440	-	-
YRSINCE	-0.03711	-	0.02380	-	-	-	-
MOISTCLASS1	-	-	0.72660	-	0.35190	-	0.58843
MOISTCLASS2	-	-	0.50400	-	0.19510	-	0.39782
MOISTBYCOS1	-	-	2.72900	-	-	-	-
MOISTBYCOS2	-	-	2.06080	-	-	-	-
MOISTBYSIN1	-	-	1.04470	-	-	-	-
MOISTBYSIN2	-	-	-1.49350	-	-	-	-
MOISTBYBA1	-0.02490	-	-	-	0.03430	0.00886	-
MOISTBYBA2	-	-	-	-	0.00491	-	-

⁷ NOTES: At=trembling aspen, Ep=paper birch, Fd=Douglas-fir, Lw=western larch, Pl=lodgepole pine, Py=ponderosa pine, and Sxw=interior spruce; see Table 22 for description of variables used in regression analysis; trembling aspen (At) and Ponderosa pine (Py) were only found on two out of three moisture classes, therefore only a single dummy variable was required for moisture class and first order interactions with moisture class.