MODELLING THE RECOVERY OF OLD-GROWTH ATTRIBUTES IN COASTAL WESTERN HEMLOCK FORESTS FOLLOWING MANAGEMENT AND NATURAL DISTURBANCES

by

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Abstract

Since the early 1900's logging activities in coastal British Columbia (BC) have reduced the extent of old-growth forest area from its historical distribution of 90% to approximately 55% of the forest landbase at present. Presently, the province employs an age threshold approach to identify old-growth forest throughout BC. While this approach allows for a rapid inventory assessment, there are several factors that limit its efficacy: the age-based classification method does not capture the gradual development of old-growth features, the development of old-growth structure is not always well correlated with age, and it does not work well in multi-aged stands created through variable retention (VR) harvesting. The objectives of this thesis were to: 1) develop a set of structural attributes for assessing the old-growth condition based on a chronosequence analysis, 2) evaluate capability of the FORECAST model to project the temporal trends in structural development observed in the chronosequence, and 3) employ FORECAST to assess the implications of alternative dispersed retention scenarios on the recovery of old-growth structural attributes.

A chronosequence study was established including 33 sites varying in age from 60 to 300+ years on Vancouver Island. Data collection from the sites included stand structural attributes, vegetation, soil properties, disturbance history, and stand age. A set of attributes representing stand structure was developed that showed clear trends in the recovery of old-growth forest characteristics. The ecosystem management model, FORECAST, was evaluated against the chronosequence in terms of its ability to project patterns of development of old-growth structure. The model evaluation showed that FORECAST could be employed to project the impact of different silviculture systems on temporal trends in the development of old-growth conditions for the vh and vm subzones of the coastal western hemlock zone in BC. The analysis of dispersed retention scenarios using FORECAST showed that VR can help to mitigate the effects of harvesting on the maintenance of old-growth structural attributes. The analysis also showed that starting condition prior harvesting influenced the outcome and that the time required for structural elements to recover to old-growth levels was generally not reduced with increasing levels of dispersed retention.

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Acknowledgements

Dedication

To my parents, Sergei and Inna Gerzon, who invested time, energy and love to raise me; to Igor and Lyudmila Mushkatin, whose theatre studio transformed my personality; and finally, to the magnificent continent of South America. Its beautiful landscapes inspired me to continue in my environmental education.

Co-authorship statement

Chapter 2: The temporal development of old-growth structural attributes in second-growth stands: a chronosequence study in the Coastal western hemlock zone in BC.

Michael Gerzon executed the research, carried out the field work, and wrote the manuscript. Brad Seely helped to identify the main guidelines of the study and to coordinate the field work, and provided edits to the manuscript. Rod Negrave, Andy MacKinnon, and Sari Saunders provided the guidelines for the chronosequence study and field work. Hamish Kimmins, Andy Mackinnon, and Tom Sullivan provided edits for the manuscript.

Chapter 3: Simulating the development of old-growth structural attributes in second-growth coastal western hemlock forests: Evaluation of the mechanistic forest growth model FORECAST

Michael Gerzon executed the research and wrote the manuscript. Brad Seely helped to identify the main guidelines of the study and provided edits to the manuscript. Hamish Kimmins, Andy Mackinnon, and Tom Sullivan provided edits for the manuscript.

Chapter 4: Exploring the implications of variable retention harvesting on the recovery of old-growth attributes in the context of multiple-objective management

Michael Gerzon executed the research and wrote the manuscript. Brad Seely helped to identify the main guidelines of the study and provided edits to the manuscript. Hamish Kimmins, Andy Mackinnon, and Tom Sullivan provided edits for the manuscript.

Chapter 1. Introduction: predicting the recovery of old-growth characteristics.

1.1 Old-growth forest in coastal British Columbia

Much of the coastal region of British Columbia (BC) is covered by coastal western hemlock (CWH) forests. Stand replacing disturbances are rare in this region, and hence much of the unlogged CWH forest is in an old-growth condition (Price and Daust 2003). Old-growth forests have high structural complexity (Wells et al. 1998, Franklin et al. 2002) which has been shown to be important for providing a wide variety of habitat types and ultimately for the maintenance of species richness and genetic diversity in forest ecosystems (Spies and Franklin 1991, Carey 2009). Managed forests in coastal BC have historically been logged using clearcut methods (D'Anjou 2003) that typically result in development of post-harvested stands with more uniform structure (diversity of trees sizes, understory development and amounts of deadwood) relative to old-growth stands. Logging activities in coastal BC, which began in earnest in the early 1900s, have reduced the extent of old-growth forest area from its historical distribution of 90% (Price and Daust 2003) to approximately 55% of the forest landbase at present (MacKinnon 2003).

This substantial decline in the abundance of old-growth forest led the province to explore and pursue options and policies to both conserve and promote the development of old-growth characteristics in managed forest landscapes. Given the lack of field data describing the rate of recovery of old-growth structural characteristics following logging operations, recommendations for old-growth management have been primarily based solely upon expert opinion (Negrave et al. 2008) and designed to facilitate landscape scale assessments. For example, in coastal BC, a stand is classified as old-growth once it reaches an age of 250 years (Ministry of Forests and Range 2004). Although the use of this general age-based classification method allows for a cost-efficient, rapid inventory assessment, there are several factors that limit its efficacy. Firstly, the change in stand class from mature to an old-growth within a year (at age 250) is abrupt and does not take into account the fact that changes in forest structure and function are much more gradual in nature (Hunter and White 1997). Secondly, estimation of stand age is problematic when a forest regenerates following a harvest in which some residual trees are left behind. For instance, shade from trees left after variable retention (VR) logging can substantially suppress the growth of new trees (Aubry et al. 2009 in press), consequently slowing the rate of stand development. In contrast, the presence of large residual stems clearly enhances the recruitment of large snags and coarse woody debris (CWD) relative to a stand developing after a clearcut. Another fundamental

setback from the age-based classification of old-growth is that age, is not always well correlated with the presence of old-growth characteristics in a given stand. This is due to the fact that the development of old-growth characteristics is also dependent on many other factors including site productivity, species composition, stem density and low-intensity (endemic) disturbance regimes (Oliver and Larson 1996).

1.2 Use of structural attributes to quantify the old-growth condition of a stand

An alternative approach to evaluate the degree to which second-growth stands have transitioned towards an old-growth condition is to employ specific, quantifiable structural attributes that can be measured in field plots and projected with forest growth models. Old-growth indices based on structural attributes have been found to be practical for distinguishing old-growth forest from younger sites (Spies and Fraklin 1991). More recently, a series of studies have demonstrated the effectiveness of structural attributes in quantifying old growth characteristics (e.g. Villeneuve and Brisson, 2003; Morgantini and Kansas, 2003; Harrison et al., 2002). Chronosequence analysis can be used to identify structural attributes to useful for assessing long-term patterns in stand development as well as the recovery of old-growth structural attributes (e.g., Trofymow et al. 1997, Wells 1996, Van Pelt and Nadkarni 2004). While valuable for establishing the set of structural attributes, chronosequence analysis is limited in the application of these attributes to project ecosystem recovery following VR logging, because the assessed sites in a chronosequence must be similar in terms of site productivity and disturbance/management history. As management systems become more complex it becomes more difficult to predict ecosystem recovery using chronosequence analysis. Another method for predicting development patterns is to utilize knowledge gained from long-term field trials of different harvesting methods on the same site (e.g., Thompson 2007, Arnott and Beese 1997). While this type of experience is highly useful, such studies are usually limited to several decades and the variability of available management options and site types is high relative to the amount of long-term studies that can be feasibly established. A third option for prediction of management outcomes is to use forest growth models (e.g., Kimmins et al. 1999, Pacala et al. 1996, Choi et al. 2001). Relative to chronosequence analysis and field trials, models are far more flexible in their application and can be parameterized to represent many site conditions and a variety of silviculture systems. Hence, models can be used to project the outcome of alternative silviculture systems for which we have limited field experience, and in situations where management activities change the properties of the site (Kimmins et al. 2008).

To effectively evaluate the development of old growth characteristics in second-growth stands, a model has to include explicit representations of the structural features that can be used to distinguish old growth conditions (e.g., Choi et al. 2007). Such features include individual tree size measures, characteristics of CWD including log sizes and state of decay, and characteristics of standing dead trees including, species and dimensions (Franklin and Spies 1991b, Tyrrell and Crow 1994). It is also helpful if a model is capable of adequately representing the ecosystem processes that lead to the formation, accumulation and loss of these features. Such processes include density dependent mortality (stand self-thinning), minor (non-stand-replacing) disturbance events such as insect mortality and windthrow, harvesting events, snag fall rates, and organic matter decomposition rates (including snags and logs of different species and size classes).

One model that meets these criteria is the mechanistic forest growth model FORECAST (Kimmins et al. 1999). FORECAST was designed to accommodate a wide variety of harvesting and silvicultural systems in order to compare and contrast their effect upon forest productivity, stand dynamics, and various biophysical and social indicators of non-timber values. The model has been applied to a variety of forest types: mixed Douglas-fir and paper birch forest (Sachs 1996), mixed aspen and white spruce forest (Welham et al. 2002, Seely et al. 2002), Chinese-fir plantations (Bi et al. 2007), coastal Douglas-fir forest (Blanco et al. 2007). FORECAST has been validated against field data for a range of growth and yield and structural variables in: coastal Douglas-fir forests (Blanco et al. 2007, Boldor 2007), and interior mixedwood forests in BC (Seely et al. 2008).

To be effective for guiding management decisions, it is essential to establish a level of confidence with respect to the reliability of model predictions. Regional chronosequence studies can provide data that is suitable for model evaluation (e.g. Bugmann et al. 2001). An evaluation of the performance of forest growth and development models can be divided into a few key components or perspectives (after Vanclay and Skovsgaard 1997 and Huang et al. 2003): Assessment of biological consistency, graphical (visual) inspection of predicted versus observed values, statistical tests for goodness-of-fit, and analysis of model sensitivity and bias.

1.3 Evaluating the impact of VR harvesting on structural development and the old-growth condition

In recent years VR harvesting has gained momentum and credibility in BC and the Pacific Northwest of the US as a harvesting approach designed to meet the diverse goals of multi-

objective forest management (Franklin et al. 1997, Clayoquot Sound Scientific Panel 1995, Arnott and Beese 1997). This gradual transition to VR harvesting in coastal BC has implications for the conservation and recruitment of old-growth forest. While traditional silviculture systems such as clearcut, shelterwood, etc. have generally focused on maximizing timber production and assuring future regeneration with target species, the fundamental objective of VR harvesting is to retain forest structural elements at the stand or harvest block level for at least one rotation to conserve environmental values associated with structurally complex forests (e.g. Mitchell and Beese 2002, Franklin et al. 2002). Benefits include greater connectivity of forest cover, improved habitat suitability through the maintenance of key structural elements such as large-diameter live and dead trees and logs, enhanced carbon storage, improved soil stabilization, and reduced visual impact from harvesting activities (Franklin et al. 1997, Bunnell et al. 2003). Despite evidence of the short-term benefits of VR management, uncertainty remains with respect to the long-term impacts of VR on stand growth dynamics and ecological interactions. Past studies suggest that selective harvesting may alter regeneration patterns, change competitive interactions between species, and influence growth rates (Sullivan et al. 2009, Bowden-Dunham 1998, Thysell and Carey 2000).

Retained forest structure can be left in patches (aggregate retention) or can be left evenly distributed in the stand (dispersed retention). During use of aggregate retention entries into aggregate patches can be avoided. Therefore, the soil, CWD and snags inside such patch are not disturbed. Moreover, trees retained within aggregate groups tend to be less susceptible to windthrow than dispersed trees (Scott and Mitchell 2005), and due to aggregation cast less shade on the newly regenerated trees in the openings (Battaglia et al. 2002). Conversely, dispersed retention generally provides greater connectivity of forest habitat important for species with low spread capabilities (e.g. epiphytes – Sillett et al. 2000), provide distributed refugia habitats for bellow ground ecosystem (e.g. mycorrhizal associations - Luoma et al. 2006), and serves as distributed source of deadwood.

In the CWH zone of BC, there are many factors ranging from pre-harvest conditions, to species interactions, to specific management objectives, which must be carefully considered when designing and implementing VR management systems. With respect to pre-harvest conditions, forests in this region can generally be divided into two distinct groups: 1) old-growth forests with high levels of structural diversity and lower levels of net primary productivity (Wells et al. 1998), and 2) second-growth stands regenerating after stand replacing disturbance (usually logging) with high levels of net primary productivity, but lower structural diversity. Target

retention levels under these initial stand conditions will vary depending on management objectives. For example, in a modelling study, Fraser et al. (2007) have found that lower levels of dispersed retention (≤15%) were required in second-growth stands to achieve reasonable survival and growth of regenerated trees. In contrast, when starting from an old-growth condition, reasonably high levels of production could be achieved from regenerating trees established under dispersed retention levels up to 40%. The difference between the two conditions was the greater vigour of the younger retained stems in the second-growth stands, which allowed them to expand crowns and close canopy quickly thereby limiting light availability for regenerating trees. The opposite trend was observed when the objective of retention was to maintain a supply of large diameter snags and coarse woody debris. In this case the larger trees and greater CWD loads in the old-growth stands, allowed for higher levels of structural diversity relative to the VR stands originating from a second-growth condition.

1.4 Thesis objectives and structure

The fundamental goal of this research is to quantify the recovery of old-growth characteristics in coastal western hemlock forests following disturbance and to evaluate the implications of alternative logging scenarios. Towards this end the following specific objectives were identified:

1. Develop a set of structural attributes which are indicative of the old-growth condition and correlated with stand age. This set of attributes should be based on a chronosequence data from the CWH zone in BC.

2. Evaluate forest growth model FORECAST against chronosequence data with the use of developed structural attributes.

3. Employ FORECAST to assess the implications of alternative dispersed retention scenarios on the recovery of old-growth structural conditions.

The thesis is structured in a manuscript based format. The introduction provides brief literature review and gives background information to understand the objectives of the thesis. Chapters 2-4 are stand alone articles and have extended literature reviews in their introduction sections. Chapter-2 describes the development of old-growth structural attributes. It suggests fine-tuning the abrupt provincial classification of old-growth forest with a quantified set of structural attributes that provide information regarding the recovery of old-growth features on a continuous scale of time. Chapter-3 deals with evaluation of FORECAST model against

chronosequence data. Chapter-4 describes the simulations of dispersed retention scenarios and evaluates the recovery of old-growth characteristics based on the set of structural attributes defined in chapter-2. The closing chapter-5 provides overview on the research and summarizes the main conclusions.

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Chapter 2. The temporal development of old-growth structural attributes in second-growth stands: a chronosequence study in the Coastal western hemlock zone in BC[1]

2.1 Introduction

One of the key issues facing forest resource planners throughout British Columbia (BC) is the conservation and promotion of old-growth characteristics in managed forest landscapes. Yet, quantitative data and associated knowledge regarding the recovery of old-growth attributes in second-growth forests in the province are limited at best (Negrave et al. 2008). As a result, current guidelines for management decisions regarding the timing of recovery of old-growth characteristics in BC forests are relatively simple and based primarily on expert opinion. For example, in coastal forest regions, a stand is classified as old-growth once it reaches an age of 250 years (Ministry of Forests, British Columbia 2004). While the use of this general age-based classification method allows for a low-cost, rapid inventory assessment, there are several problems with the approach. Firstly, the transition of a forest to an old-growth condition in 1 year (at age 250) is extremely abrupt and does not take into account the fact that changes in forest structure and function are much more gradual and incremental in nature (Hunter and White 1997). Secondly, age estimation may be problematic when a forest regenerates following a disturbance in which large live trees are left behind and a multi-cohort structure develops. Variable retention (VR) logging, an increasingly common harvesting system applied in coastal BC, often creates such multi-aged stand conditions. Imagine, for example, a 150-year-old stand is harvested using a dispersed retention harvest system in which only 75% of the canopy trees are removed and regeneration occurs with planting and naturals. What is the new age of the resulting stand? Is it still 150 years old or should exactly 250 years pass until an old-growth condition is reached again? Shade from residual trees left after VR logging can substantially suppress the growth of new trees (Aubry et al. 2009 in press), thus slowing the rate of stand development. On the other hand, the presence of large live structure provided by the residual trees will no doubt enhance the recruitment of large snags and coarse woody debris relative to a stand developing after a clearcut. This type of uncertainty presents a serious problem for the age-based method of classification.

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[1] A version of this chapter will be submitted for publication. Gerzon, M., Seely, B., MacKinnon, A.. The temporal development of old-growth structural attributes in second-growth stands: a chronosequence study in the Coastal western hemlock zone in BC.

Another fundamental problem with the age-based classification method for defining old-growth is that age, even when measured accurately, is not always well correlated with the presence of old-growth characteristics in a given stand. This is due to the fact that the development of old-growth characteristics is also dependent on many other factors including site productivity, species composition, stem density and low-intensity disturbance regimes (Oliver and Larson 1996) (low-intensity disturbance here refers to disturbance events that affect only a small proportion of trees in the stand). Low productivity sites, for example, may require relatively more time to reach an old-growth condition because the trees grow slower and hence most tree-size dependent stand development processes are delayed. In coastal BC site index (top height at breast-height-age 50) for western hemlock *Tsuga heterophylla* can range from 8 m to 34 m (Ministry of Forests and Range 2008). Differences in initial stem density can also lead to variation in stand-structural patterns, which in turn may influence the rate at which stands transition through the various phases of stand development and ultimately develop old-growth features (e.g. Tappeiner et al. 1997, Sullivan et al. 2009). Finally, the frequency and mechanisms of a low-intensity disturbance regime operating over the lifetime of a stand also influences the rate of recovery of old-growth features as well. Specifically, disturbance regimes play an influential role in creating structural diversity by influencing live trees, creating deadwood and establishing canopy gaps (Franklin et al. 2002).

An alternative approach to evaluate the degree to which second-growth stands have transitioned towards an old-growth condition is to employ specific, quantifiable structural attributes that can be measured in field plots and projected with forest growth models. Old-growth indices based on structural attributes have been found to be practical for distinguishing old-growth forest from younger sites (Franklin and Spies 1991). While Franklin and Spies (1991) found that single structural attributes could be used to differentiate forest structural stage, they suggest the use of a combination of several attributes to support a classification system. Further, they showed that use of stepwise discriminant analysis allows for the selection of structural attributes that are better suited to characterize old growth. More recently, a series of studies have demonstrated the effectiveness of structural attributes in quantifying old growth characteristics (e.g. Villeneuve and Brisson, 2003; Morgantini and Kansas, 2003; Harrison et al., 2002). While most of the attention has been focused on live and dead tree structure, other forest characteristics may be used as well. For example, in a detailed analysis of a series of second-growth and old-growth sites in coastal BC, Banner and LePage (2008) showed that understory vegetation alone could be used to create discrimination indices for old-growth forest.

Chronosequence studies have been employed to examine temporal trends in the development of stand structure in coastal forests (e.g. Wells 1996, Wells and Trofymow (1997), Blackwell et al. 2002). These studies explored changes in live and dead wood, tree mortality, understory vegetation as well as the recovery of biodiversity, and changes in nutrient and carbon balance following the conversion of old growth to managed stands. The studies conducted by Wells and Trofymow (1997) and Blackwell et al. (2002) focused on relatively few sites localized in a coastal and interior region on Vancouver Island. Their sites were grouped in four broad age classes: newly regenerated, young, mature and old-growth. They found significant differences between these defined age classes with respect to structural attributes. In contrast, Wells (1996) described trajectories of stand structure development (with the exception of deadwood) within a continuous chronosequence of ages from year 15 to year 300 which included 190 sites. The large number of sites used in the analysis coupled with a broad distribution of stand ages allowed him to define robust patterns of structural development. While these studies were useful for examining patterns of structural development, they were not designed to evaluate the recovery of old-growth characteristics in second-growth stands. The primary goal of the current work was to quantify and evaluate the temporal pattern of development of old-growth features in second-growth stands of maritime CWH forests using a chronosequence study design. The following specific objectives were determined:

1. Identify structural attributes for potential use in the chronosequence analysis. Successful attributes should show time dependent patterns of change and be indicative of the old-growth condition in the vm1 and vh1 variants of the CWH zone.
2. Calculate the average and confidence interval of selected attributes for old-growth stands.
3. Quantify and evaluate patterns of change in selected attributes as a stand matures and develops towards the old-growth condition which is defined by the above objective #2.

The first objective implies that for each attribute time dependent curves should be produced based on field data. Each curve should follow theoretical assumptions for time dependency of the attribute. To test the significance of time dependency, a hypothesis of correlation between stand age and stand attribute was raised. Hence, to support the hypothesis there was a need to show statistically significant correlation.

2.2 Methods

2.2.1 Study area

The research was conducted in the Coastal Western Hemlock (CWH) biogeoclimatic zone on Vancouver Island, BC, Canada. Specifically, we focused on the widespread and economically important very wet maritime (vm1) and very wet hypermaritime (vh1) variants (Green and Klinka 1994). The CWHvh1 variant is located close to the ocean shore with an elevation range of 0-200 m above sea level. The climate is cool with very little snowfall; fog is common. Mean annual precipitation is 3120 mm; mean May to September precipitation is 617 mm/year; total mean annual snowfall is 450 mm; mean annual temperature is 9.1ºC; frost free period is 229 days/year. The CWHvm1 variant is one of the most extensive units in coastal BC. Its location relative to the windward coast is several kilometers inland and, by definition, forest development is under less influence from the coastal climate than the vh1 variant. The elevation range for the vm1 variant is 200-650 m above sea level. It has a very wet, humid climate with mean precipitation of 2682 mm/year; mean May to September precipitation of 611 mm/year; total mean annual snowfall of 1950 mm; mean annual temperature of 8.3 ºC with cool summers and mild winters; frost free period of 199 days/year. Soils on both variants are predominantly Humo-Ferric or Ferro-Humic Podzols derived from morainal parent material (Soil Classification Working Group 1998).

Western hemlock (*Tsuga heterophylla*) is the most abundant tree species in the stands followed by western redcedar (*Thuja plicata*) and amabilis fir (*Abies amabilis*). Douglas-fir (*Pseudotsuga menziesii*) is common on drier sites and in sites that developed following fire disturbance. Sitka spruce (*Picea sitchensis*) and shore pine (*Pinus contorta var. contorta*) also occur in these variants. Red alder (*Alnus rubra*) is often present in riparian and recently disturbed sites. Saplings of western hemlock, amabilis fir and western redcedar are commonly found in the understory.

Common minor vegetation species of zonal or near zonal sites include shrub species (*Vaccinium parvifolium, Vaccinium alaskaense* and *Gaultheria shallon*), and ferns (*Blechnum spicant and Polystichnum munitum*). Other minor species of vegetation are listed in the Field Guide for Vancouver Forest Region (Green and Klinka 1994) and in MacKinnon (2003). Since major stand-replacing disturbances are relatively rare (every 1400-20,000 years), most of the unlogged forest in these variants is in the old-growth phase of stand development (Price and Daust 2003).

2.2.2 Selection of chronosequence sites

A population of candidate sites was identified from inventory maps and, upon visual inspection, a total of 33 sites were selected to represent a chronosequence of second-growth and old-growth stands. The fundamental assumption of the chronosequence approach is that site differences are minimal and that time is the primary manipulated variable. Of the 33 sites, 9 were classified as old-growth sites based on their visual appearance. Visual criteria that were used for old-growth classification included: absence of evidence for stand-replacing disturbance, many trees with very large DBH, living trees with progressed decay, high diversity of tree sizes, large amount of dead wood and large snags, and a well developed understory. Site locations were selected to be accessible from logging roads within less than half an hour walk. Sites were limited to 2 BEC variants (7 sites in CWHvh1 and 26 sites in CWHvm1) and an effort was made to focus on zonal or similar site series to avoid the influence of site productivity on stand dynamic processes. Another important criterion was to avoid stands with many residual trees that survived a previous stand replacing disturbance. This was done to sustain the chronosequence assumption that there is no difference in post disturbance legacy between forested sites. However, some sampled sites still had several veteran trees. Additionally, the cause of stand replacing disturbance was different among the stands. The disturbances were caused by variety of agents including fire, logging, insect attack and windthrow. Some stands were affected by fire that followed logging. Geographical locations were spread along Vancouver Island to cover the broad spatial extent of these biogeoclimatic variants. The distance between the southern sites near Port Renfrew to the sites on the northern tip of the island was 360 km. Field sampling was conducted during summer of 2008.
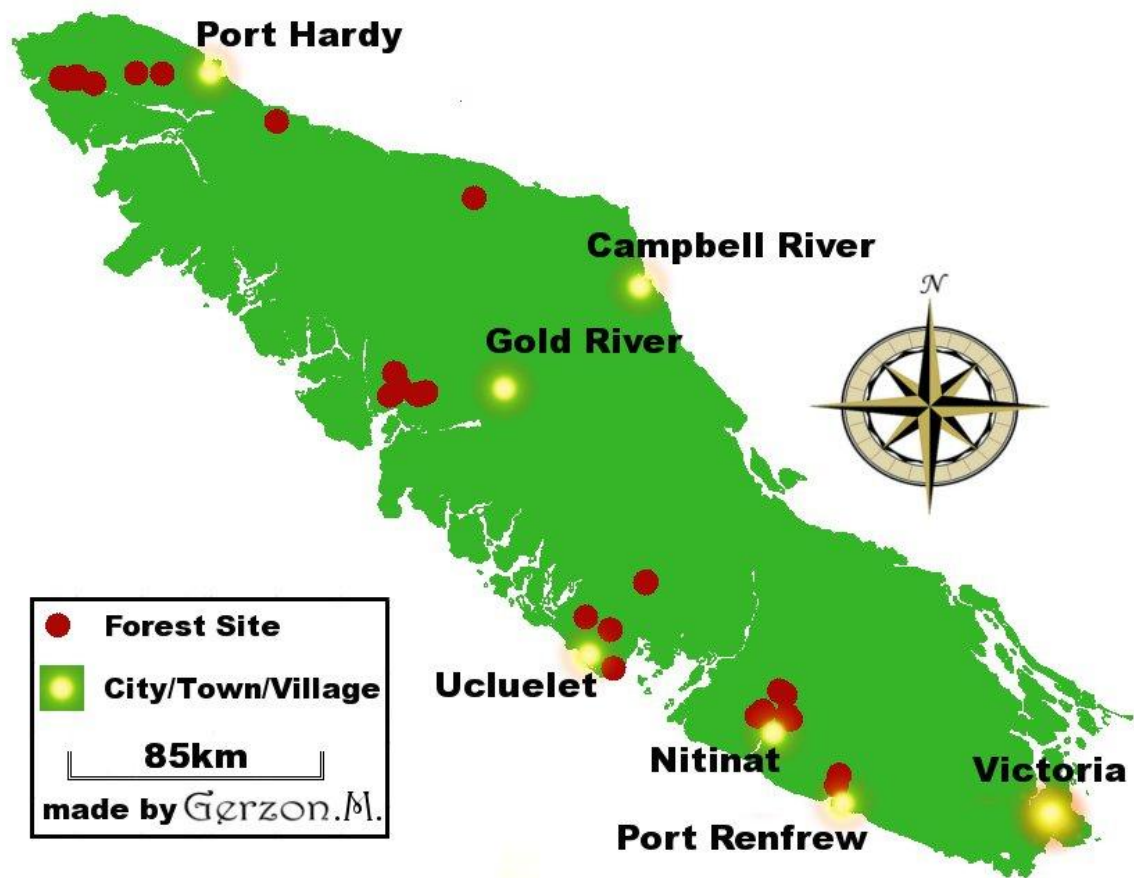
Fig 2.1 Location of the 33 chronosequence study sites on Vancouver Island.

2.2.3 Field sampling protocol

Field sampling protocols were designed to provide a description of site disturbance history, a detailed summary of stand structure (live and dead), and a description of vegetation communities. It was necessary to balance the need for detailed measurements (sampling intensity) with the goal of maximizing the number of sites to increase the representation of stands across a wide range of age classes and from a broad geographical area. Time and resources were constraining factors. To assure consistency with previous and ongoing related projects, the sampling methodology was based on the Field Manual for Describing Terrestrial Ecosystems (BC Ministry of Forests and Ministry of Environment 1998).

The sampling regime for each site provided a description of: site age, disturbance history, basic soil characteristics, minor vegetation cover, natural regeneration, coarse woody debris, and standard mensurational variables of stand structure. Each site was visually inspected for evidence with respect to its originating disturbance and low-intensity disturbance regime. Sampling on each site included: 1 soil pit, 1 vegetation plot, 2 regeneration plots, 2 CWD transects, and 2 mensuration plots.

Estimation of stand age

Stand age for each second-growth site was determined based on ages of dominant trees. Two trees per species, per plot, were cored and aged to provide estimates of stand age. Only non-residual, dominant or co-dominant trees were selected for aging. Tree age was first determined at DBH height and then corrected to germination age using BC MoFR software (Ministry of Forests and Range 2001).

Old-growth sites could not be aged using the coring method for a number of reasons. Many trees were too big for coring or had internal rot, and hence their age could not be determined. Additionally, an old-growth stand can be older than the age of individual trees, because trees may die and be replaced by regenerated trees from the same stand. Nonetheless, some trees were cored in each old-growth site to determine a minimum stand age.

BEC classification and vegetation sampling

The sites were classified to BEC site series based upon standard soil and physiographic properties and vegetation analysis (Green and Klinka 1994). Soil pits included an assessment of mineral and organic horizons to determine soil moisture and nutrient regimes. A vegetation plot (20 x 20 m) was randomly located and laid out in each site. All trees and understory vegetation in the plot were classified by species and canopy layers. Canopy layer classification was designed to separate dominant, co-dominant and suppressed tree layers as well as to differentiate between tree, shrub and herb layers (Ministry of Forests and Ministry of Environment 1998) Percentage of canopy cover was visually estimated for each species and layer. In addition, 2 natural regeneration plots with a fixed radius of 5.64 m were established in each site. Seedlings inside the plot that were older than 1 year were counted by species. Average site index (SI) was estimated from height-age relationships in sites younger than 100 years. Only young sites were used due to the fact that trees accumulate damage with age, and hence the site may diverge from

the SI fitting curve. Also, SI fitting equations in British Columbia are more reliable for sites between ages 20-120 years (Marshall and LeMay 2005).

CWD sampling

The CWD sampling methodology followed the approach described by Marshall et al. (2000). Two CWD transects were established in each site perpendicular to each other and 24 m in length. Each log intercepted by a transect was documented by: species, decay class, diameter at point of intersection, length and angle relative to the ground. Dead wood volume per ha was calculated for each CWD transect using equation 2.1 (Marshall et al. 2000).

$$\text{Equation 2.1} \quad \text{for a single transect: CWD volume/ha} = \frac{\pi^2}{8 \cdot L} \sum \frac{d_k^2}{\cos \lambda_k}$$

L – transect length;

d_k – diameter of $\log_k$ measured at the intersect of the transect line and the log;

λ – acute angle of the log from the horizontal.

Volume of CWD per ha was calculated as the average of volumes calculated for each transect. The biomass of CWD was calculated based on the approach outlined by Holub et al. (2001). The authors calculate log density as a function of decay class and tree species. Using the derived wood densities in the article biomass of CWD per ha was calculated using equation 2.2

$$\text{Equation 2.2} \quad \text{for a single transect: CWD biomass/ha} = \frac{\pi^2}{8 \cdot L} \sum \frac{d_k^2 \cdot \rho_k}{\cos \lambda_k}$$

ρ_k – is the density of the $\log_k$ based on its species and decay class.

The average of two transects was used to estimate the biomass per ha for each site. The error of measurement for each site equaled $\frac{\sigma}{\sqrt{N}}$ where σ was standard deviation and N was the number of transects.

Stand structure sampling

Two prism mensuration plots were established in each site following procedures described in the Cruise Compilation Manual (Revenue Branch, Ministry of Forests 2008). Plot centers were separated by at least 15 m. The prism Basal Area Factor (BAF) was selected such that the plot would include at least 14 living trees >7.5 cm DBH per site. Height and DBH were measured for

each tree included in the prism plots. The following parameters were also recorded: tree species, tree class, canopy class and stem defects. Gross volume was calculated for each live tree in the plot using published empirical volume equations based on tree DBH and height volume (BC Forest Service 1976). The error of volume and stem density for each site equaled $\frac{\sigma}{\sqrt{N}}$ where σ was standard deviation and N was the number of plots. Snag volumes could not be calculated since the top end diameter of the snags was difficult to measure. Plot data were extrapolated to per hectare values using Equation 2.3 (Revenue Branch, Ministry of Forests 2008).

$$\text{Equation 2.3} \quad \text{Trees/ha for tree k} = \frac{BAF \cdot 40{,}000}{\pi \cdot (DBH_k)^2}$$

2.2.4. Chronosequence analysis

A chronosequence analysis was conducted using the following structural attributes calculated for each site: tree volume/ha (by diameter class), stems/ha (by diameter class), snags/ha (by diameter class), CWD mass and volume, percentage of plant cover, standard deviation of DBH of living trees. Field data for each attribute were plotted as a function of stand age to evaluate temporal trends in its development. Errors of field data were calculated as half of the difference between two plots on the site. Some graphs do not show errors, because only one plot was used to collect information for a particular attribute. Curves or trend lines were fitted to field data (where meaningful) to illustrate general temporal patterns of change. Curve functions were selected to be consistent with existing biological understanding for each attribute. If the fit was statistically significant, the hypothesis of correlation between stand attribute and stand age could be supported.

A threshold was calculated using the 9 old-growth sites to help determine when a specific attribute approached old-growth conditions. The old-growth threshold for each structural attribute was determined based on the mean value for the attribute for the old-growth sites. Ninety-five percent confidence intervals (CI) were calculated for each attribute to account for the considerable variability observed among old-growth sites.

2.3 Results

2.3.1 Stand age estimation

Results from the tree coring indicated that there was typically a range in ages among sampled dominant trees that increased with stand age. A comparison of the age of the oldest sampled tree and the average tree age for each site is shown in Figure 2.2.
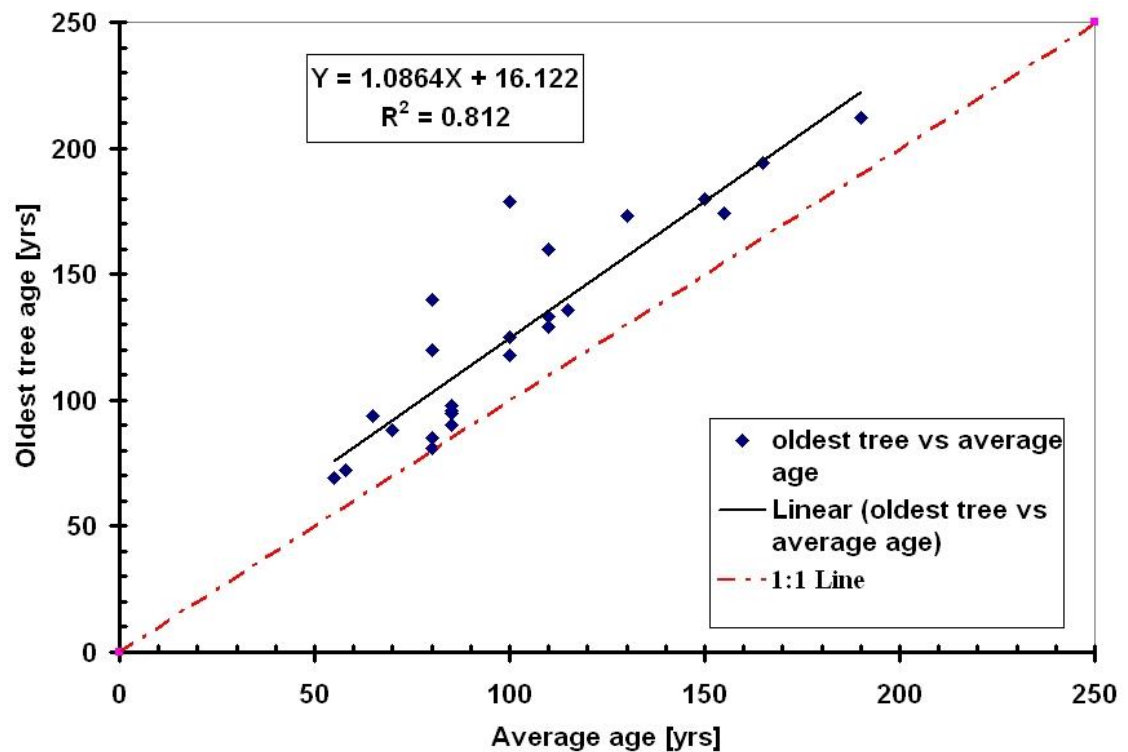
Figure 2.2 Oldest tree age vs. Average age (old-growth sites not included). Black line is a linear fit to data points. Equation of the line is presented on the graph with its R^2 value.

Generally the oldest tree age was 20-30% greater than average site age. Differences in measured tree ages among dominant site trees were likely due to early growth suppression in some trees prior to release and/or to the fact that trees likely established during an extended time period (10-20 yrs) following the stand initiating disturbance event. In either case, the chronosequence stand age for second-growth sites was determined as the age of the oldest sampled tree.

2.3.2 General site characteristics

A description of general characteristics including chronosequence age, BEC classification, disturbance history, proportion of residual stems (stems that originated prior to the last stand-initiating disturbance), and species composition is shown for each field site in Table 2.1. The most common leading species among all sites was western hemlock followed by amabilis fir. These are both shade tolerant species with similar growth rates and ecological characteristics. Secondary species included western redcedar, Douglas-fir and Sitka spruce. Logging was the most common disturbance type in young second-growth stands while windthrow and fire were more frequent among second-growth stands aged greater than 100 years. Six of the 24 second-growth sites had a small proportion of residual trees. However, it was assumed that those trees did not have a significant effect on the long-term growth of second-growth trees.

An analysis of calculated site index based on field-measured western hemlock trees did not show significant differences between vh1 and vm1 variants. The average site index for CWHvm1 variant from field data is 30.1 ± 1.5. This is comparable to reports from Ministry of Forests SI=27.7 ± 0.1 for Hemlock in CWHvm1 on zonal site in Vancouver region (Ministry of Forests and Range 2008). Unexpectedly, the four young CWHvh1 sites had an average SI of 29.5 ± 2.4, substantially higher than the value (SI=16) suggested in the BC SIBEC report for the 01 site series of the vh1 variant.

Table 2.1 Summary of site information. Brackets indicate that the site is under influence of the site series or variant in the brackets. Species are abbreviated as follows: Ba - Abies amabilis, Fd - Pseudotsuga menziesii, Dr - Alnus rubra, Hw - Tsuga heterophylla, Cw - Thuja plicata, Ss - Picea sitchensis. Variants and site series follow the BC BEC system.

Chronosequence age [yrs]	Site I.D.	Variant	Site Series	Stand initiating disturbance	% of residual trees from total by Volume/ha	Species composition in % Stems/ha by species
69	SG-1	vh1	1	Logging	0	Fd:Hw:Ba 46:39:15
72	SG-2	vm1	1	Wind	0	Hw:Ba 97:3
81	SG-3	vh1	11(1)	Logging	0	Cw:Hw 64:36
85	SG-4	vh1	1	Wind	0	Hw 100
88	SG-5	vm1	1	Logging	0	Hw:Ba:Ss 93:6:1
90	SG-6	vm1	1	Logging	0	Hw:Ba:Dr: 85:13:2
94	SG-7	vm1	1	Logging	0	Hw:Cw 96:4
95	SG-8	vh1	6	Wind	0	Hw:Ba 98:2
96	SG-9	vm1	1	Insects	11%	Hw:Cw 99.5:0.5
98	SG-10	vm1	1	Fire	5%	Hw:Cw 81:19
118	SG-11	vm1	01(5)	Fire	17%	Hw:Cw:Fd 71:24:5
120	SG-12	vm1(vh1)	1	Logging	0	Hw 100
125	SG-13	vm1	1	Logging	0	Hw:Ba 86:14
129	SG-14	vm1	1	Wind	0	Hw 100
133	SG-15	vm1	05,07	Wind	0	Hw:Ss 95:5
136	SG-16	vm1	01(3)	Wind	0	Ba:Hw 99:1
140	SG-17	vm1	01(5)	Wind	15%	Hw:Ba:Cw 73:25:2
160	SG-18	vm1	1	Wind	0	Ba:Hw 56:44
173	SG-19	vm1	5	Wind	31%	Hw:Ba 99:1
174	SG-20	vm1	5	Wind	36%	Hw:Ba 73:27
179	SG-21	vm1	1	Probably Wind	0	Hw 100
180	SG-22	vm1	1	Fire	0	Hw:Fd 97:3

Chronosequence age [yrs]	Site I.D.	Variant	Site Series	Stand initiating disturbance	% of residual trees from total by Volume/ha	Species composition in % Stems/ha by species
194	SG-23	vm1	1	Wind	0	Hw:Fd 96:4
212	SG-24	vh1	6	Wind	0	Ba 100
Old-growth	OG-1	vh1	11,01	Unknown	0	Hw:Ba:Cw 80:10:10
Old-growth	OG-2	vm1	1	Unknown	0	Hw:Ba:Cw 94:3:3
Old-growth	OG-3	vh1	1	Unknown	0	Hw:Ba 99:1
Old-growth	OG-4	vm1	1	Unknown	0	Ba:Hw 84:16
Old-growth	OG-5	vm1	01(3)	Unknown	0	Hw:Cw:Ba 97:2:1
Old-growth	OG-6	vm1	1	Unknown	0	Ba:Hw:Cw 76.5:23:0.5
Old-growth	OG-7	vm1	1	Unknown	0	Hw:Ba:Cw:Fd 81:9:8:2
Old-growth	OG-8	vm1	05(1)	Unknown	0	Hw:Ba 75:25
Old-growth	OG-9	vm1	03(1)	Unknown	0	Hw:Cw:Ba:Fd 78:11:9:2

2.3.3 Chronosequence analysis

An initial analysis of stand structure variables across all sites indicated that there were no significant differences among sites when grouped by variant, sites series or leading species. Differences may have been detected if more sites in each class had been measured. Thus, all sites were grouped together for the chronosequence analysis. This decision is supported by the fact that there were no significant differences in calculated site index between variants. All second-growth sites were assigned a stand age (see Table 2.1) while old-growth sites were treated as a group.

A decision was made to exclude trees < 12.5 cm DBH from stand structure analyses as the data suggest that prism plots do not provide an accurate estimate of small diameter trees. In our field sites these trees tended to be suppressed trees with patchy spatial distributions which, in turn, led to errors when plot data were extrapolated to stand-level values.

The chronosequence analysis focused on the structural variables shown in Table 2.2. These variables and their DBH cutoffs were selected both because they showed significant positive correlations with age and because they have been found to be useful for identifying old-growth characteristics in previous studies (e.g. Morgantini and Kansas 2003, Villeneuve and Brisson 2003, Wells et al. 1998). In addition, several variables (including snags, plant cover and CWD) have been identified as being medium filter indicators of habitat quality (e.g. Kremsater et al. 2003, Bunnell et al. 1999, Bunnell et al. 2002).

Table 2.2 Stand attributes considered in the chronosequence analysis.

1. Volume per hectare of trees with DBH > 50 cm
2. Frequency of trees per hectare with DBH > 50 cm
3. Standard deviation of living tree DBH
4. Frequency of snags per hectare with DBH > 50 cm
5. CWD volume per hectare
6. CWD mass per hectare
7. Plant percentage cover

Live tree volume and frequency of stems by size class

Total volume per hectare in live trees greater than 12.5 cm DBH is shown in Figure 2.3. While there was an upward trend in volume >12.5 cm DBH with increasing stand age in second-growth stands, there was no significant correlation with age. The main reason for the lack of correlation was the high degree of variability among the older second-growth sites. Total volume in this size class appears to level off and decline as stands move towards an old-growth condition. The trend in stand density in second-growth stands (stems >12.5 cm DBH) declines with increasing stand age as average tree size increases. Old growth sites, while highly variable, show an increase in stems > 12.5 cm DBH relative to older second-growth stands (Fig. 2.3). This is likely due to the recruitment and development of additional cohorts as the canopies in older stands gradually open. The oldest second-growth stand (age 212) is approaching the confidence interval for this variable.
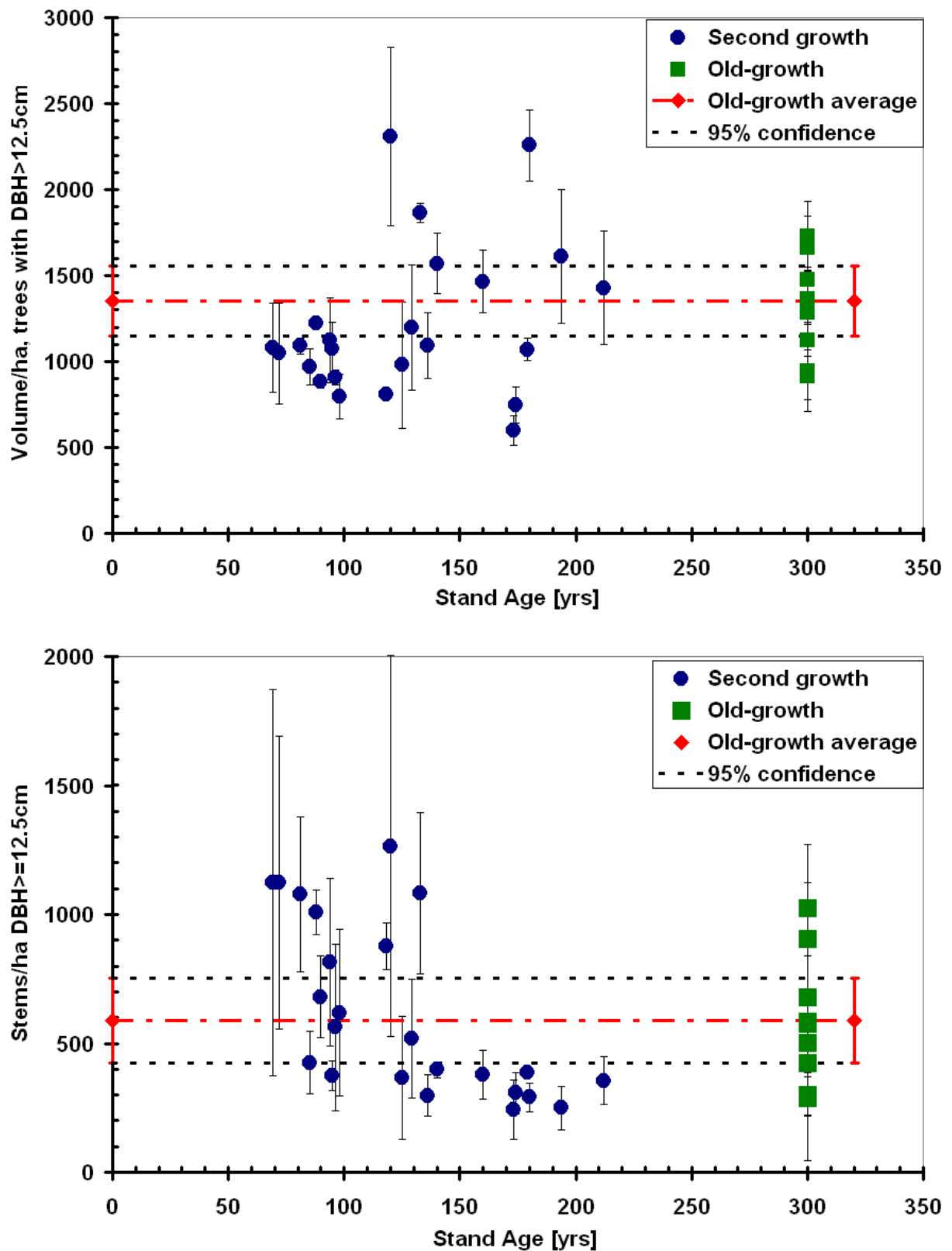
Figure 2.3 Volume m³/ha and stems/ha of live trees > 12.5cm DBH in both second-growth and old-growth sites. A 95% confidence interval threshold is shown for old-growth sites. Error bars for second-growth and old-growth sites represent standard errors.

The rate of accumulation of large live structure (trees > 50 cm DBH) in second-growth sites is shown for volume and stem density in Figure 2.4. Volume accumulation in large stems shows a clear asymptotic trend in second-growth stands (significant correlation with age, $r^2 = 0.49$, p<0.001) reaching the lower 95% confidence threshold of old-growth sites at around year 137 and the old-growth average by year 190. One clear outlier among the second-growth sites was site SG-22 (age 180 yr.), which is a hemlock-dominated, fire-originated stand. This site probably had lower tree mortality, and hence a higher density of big trees relative to other sites with a volume of 2100 m^3 in stems > 50 cm DBH. Interestingly, the old growth sites tended to separate into two groups with respect to volume of large live structure (Fig. 2.4). A similar asymptotic trend was observed for the number of large trees in second-growth stands ($r^2 = 0.51$). However, in the case of stem density, the second-growth sites reached the lower old-growth confidence interval by age 97 and the old-growth average by age 112 (based on the trend line). This difference in timing between the two measures of large live structure (volume and stems·ha^{-1}) is related to the fact that there are many trees substantially larger than 50 cm DBH in the old-growth sites. This contributes to the greater time required for second-growth stands to achieve the old-growth volume average.
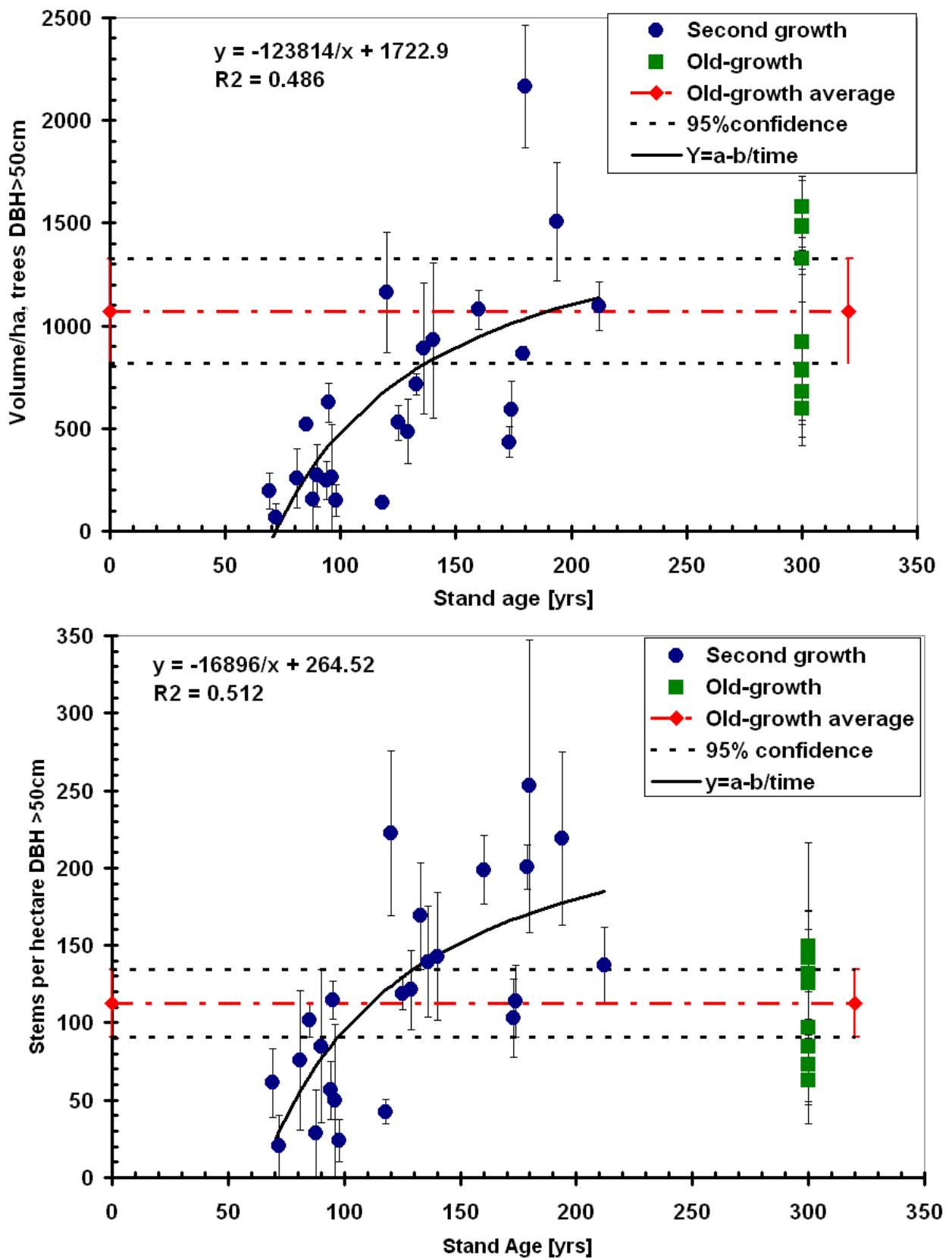
Figure 2.4 Volume m³/ha and stems/ha of live trees > 50 cm DBH in both second-growth and old-growth sites. A 95% confidence interval threshold is shown for old-growth sites. Error bars for second-growth and old-growth sites represent standard errors.

Clearly, the DBH value used to define large live structure will substantially influence the time required to reach the old-growth average. For example, frequency of large stems with DBH > 75 cm showed only low correlation (R^2=0.19) with significant amount of stands having no large stems above 75 cm diameter (Fig. 2.4a). Nonetheless, the trend line of second-growth sites did not cross the old-growth average within 300 years. Frequency of large stems with DBH > 100 cm had only three second-growth sites with such large trees. The old growth sites contain some very large trees, with diameters up to 185 cm for hemlock and 310 cm for cedar.
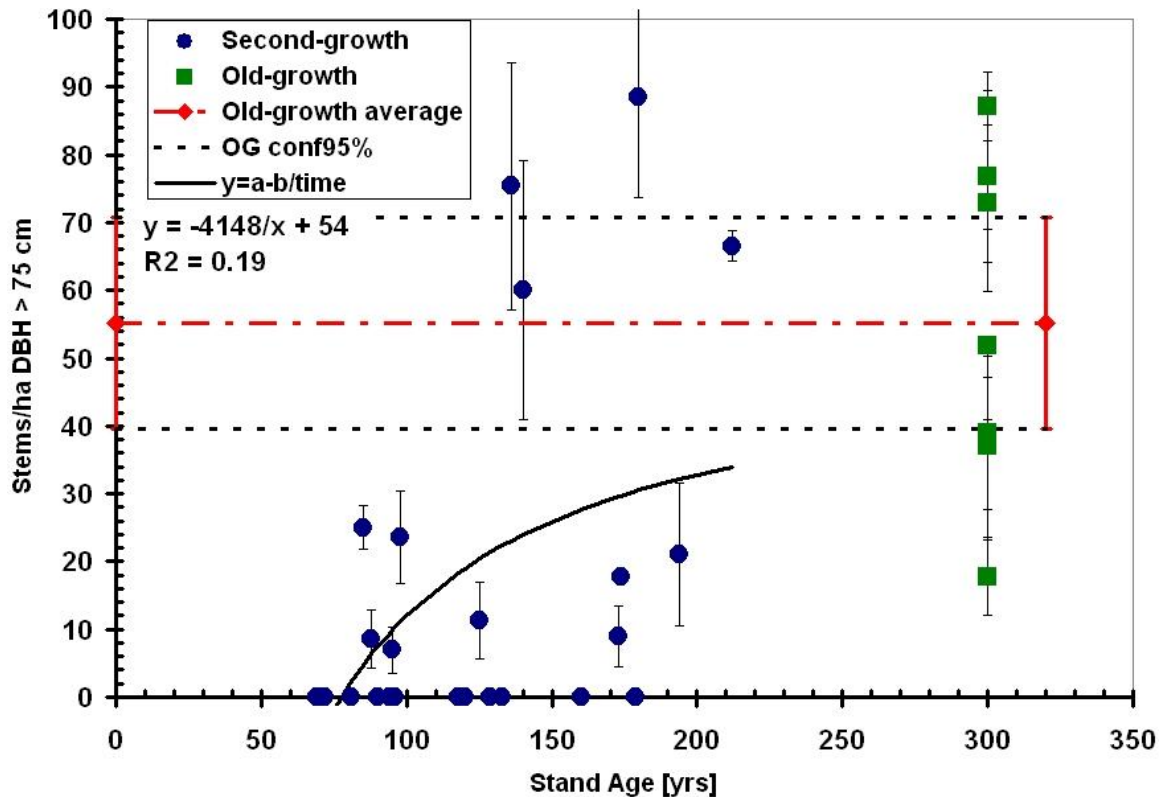
Figure 2.4a stems/ha of live trees > 75 cm DBH in both second-growth and old-growth sites. A 95% confidence interval threshold is shown for old-growth sites. Error bars for second-growth and old-growth sites represent standard errors.

Standard deviation of living tree DBH

The standard deviation (SD) and coefficient of variation (CV) of tree DBH were calculated for all sites as measures of tree size diversity. SD showed a steady linear increase with stand age in second-growth sites (r^2=0.28, p=0.007) (Fig 2.5). The trend in SD in second-growth sites was approaching the old-growth average by stand age 220, but was still well below the mean for old-growth sites.

There was no significant correlation between stand age and CV in second-growth sites (not shown). This is primarily related to the fact that mean DBH tends to increase proportionately with SD. However, an ANOVA comparison between second-growth and old-growth sites showed that CV was significantly greater for old-growth sites. (N=33, Old-growth mean = 75, second-growth mean = 35, p<0.001).
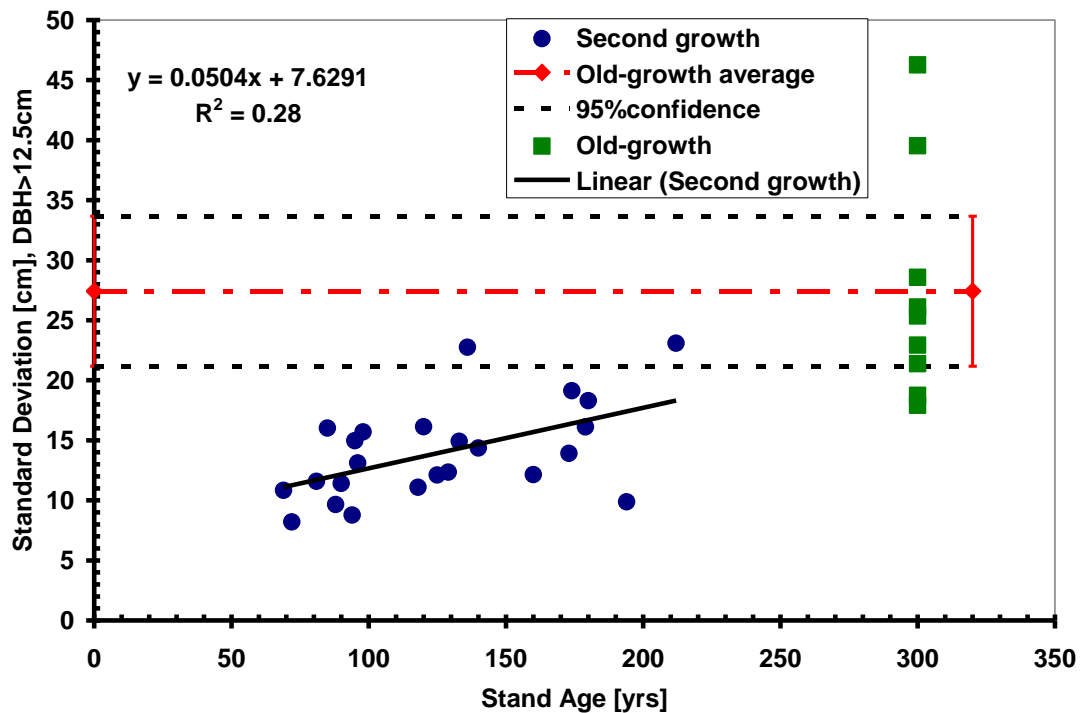
Figure 2.5 The relationship between standard deviation of stem DBH and stand age in second-growth sites. A 95% confidence interval threshold is shown for old-growth sites. Lower limit for DBH is 12.5 cm.

Frequency of snags

The number of snags greater than 25 cm DBH and 1.3m height measured in each site is shown for different diameter classes in Table 2.3. Snags were identified as residuals if their diameter was greater than the biggest non-residual live tree on the site. The data show a high level of variability in the quantity of snags present in a particular site making age trends difficult to discern. Interestingly, several of the older second-growth sites had no large snags detected in the prism plots (> 50 cm DBH). Data for snags with DBH 25-50 cm did not present any significant trends with time. There were no snags larger than 100 cm DBH in the second-growth sites indicating that the recruitment of very large snags may take more than 220 years.

Table 2.3 Frequency of snags measured in each field site including second-growth and old-growth sites.

Chronosequence age [yrs]	Site I.D.	Residual Snags/ha	Snags/ha DBH 25-50cm	Snags/ha DBH>50cm	Snags/ha DBH>100cm
69	SG-1	0	0	0	0
72	SG-2	6	261	0	0
81	SG-3	18	0	0	0
85	SG-4	0	0	0	0
88	SG-5	0	0	0	0
90	SG-6	0	0	0	0
94	SG-7	18	0	0	0
95	SG-8	0	29	0	0
96	SG-9	33	95	0	0
98	SG-10	10	101	9	0
118	SG-11	27	0	0	0
120	SG-12	11	0	0	0
125	SG-13	3	0	0	0
129	SG-14	0	30	23	0
133	SG-15	16	0	16	0
136	SG-16	0	0	44	0
140	SG-17	11	91	0	0
160	SG-18	0	0	0	0
173	SG-19	0	25	0	0
174	SG-20	37	0	27	0
179	SG-21	6	87	14	0
180	SG-22	0	60	19	0
194	SG-23	0	184	0	0
212	SG-24	0	92	57	0
Old-growth	OG-1	0	67	9	9
Old-growth	OG-2	0	0	21	0
Old-growth	OG-3	0	0	43	9
Old-growth	OG-4	0	0	20	20
Old-growth	OG-5	0	73	8	8
Old-growth	OG-6	0	58	37	0
Old-growth	OG-7	0	64	0	0
Old-growth	OG-8	0	0	35	10
Old-growth	OG-9	0	0	36	0

To provide a better evaluation of the rate of recruitment of large snags (>50cm) in second-growth stands, sites were grouped into 50-year age classes and average snag densities of each class were calculated (Fig. 2.6). The age class analysis shows a consistent increase in the frequency of large snags with increasing stand age. However, only youngest age class (50-100 years) was significantly different than the old-growth sites ($p<0.019$)
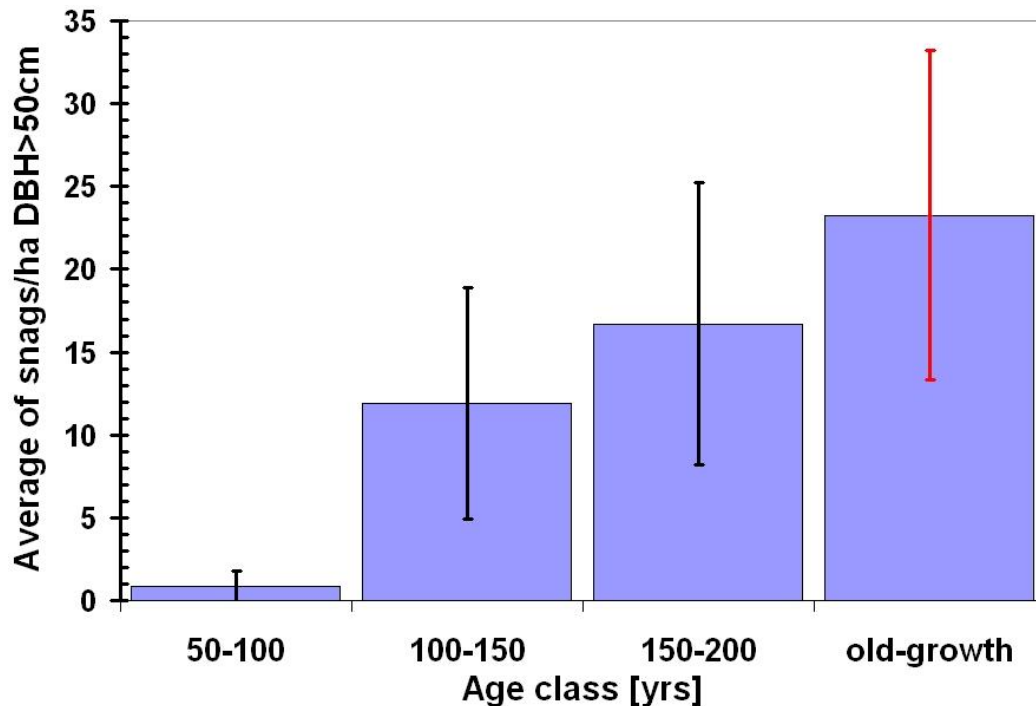
Figure 2.6 Average frequency of large snags (>50cm DBH) in second-growth sites grouped into 50-year age classes compared to old growth sites. Residual snags were excluded as explained in the text. Error bars for second-growth sites represent standard errors. Error bar for old-growth sites represent 95% confidence interval.

Coarse woody debris mass and volume

The total accumulation of CWD including residual logs is shown for all sites in Figure 2.7. There was no significant correlation between stand age and total CWD. This was mostly due to the fact that the CWD includes large residual logs derived from trees that originated prior to the stand initiating disturbance event. Much of the significant variation in total CWD mass measured in the younger sites comes from the presence of large residual logs that are still relatively intact in terms of decay, and hence contribute more to biomass. The unusually high amount of CWD on the 180-year-old site was the result of the presence of a few very large (> 170 cm diameter) western red cedar logs which were likely killed from a stand-replacing fire in the previous stand.

To reduce the error caused by the presence of residual logs and focus on the recruitment of 'current' CWD, two criteria were used to exclude at least some residual logs. The first was to exclude logs with diameters that were greater than the DBH of the largest live second-growth trees on the site. The second was to exclude large diameter logs that were identified as decay class 5, as it generally takes decades to reach this state (Feller et al., 1997).
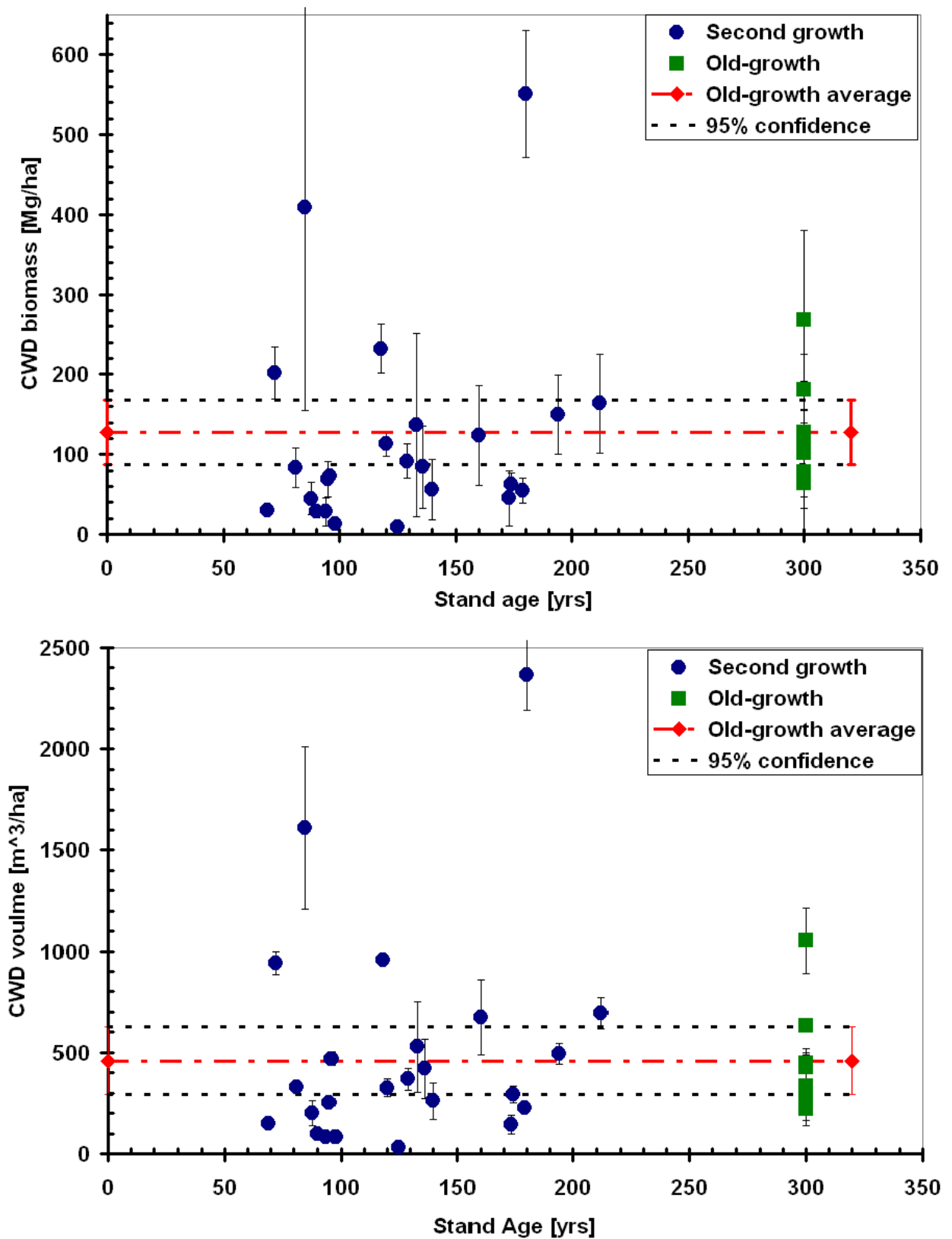
Figure 2.7 The relationship between total CWD A) mass and B) volume and stand age in second-growth sites with residual logs included. A 95% confidence interval threshold is shown for old-growth sites. Error bars for second-growth and old-growth sites represent standard errors.

When residual logs were excluded, CWD showed a significant positive linear relationship for biomass ($r^2 = 0.27$, p<0.01) and for volume ($r^2 = 0.24$, p < 0.015) with stand age in second-growth sites (Fig 2.8). It is important to note that some residuals logs were likely included as current CWD as it is impossible to exclude all of them based on the data that was collected. The extremely low amount of CWD in the site aged 125 years, was likely due to low disturbance-related mortality rates on the site as further indicated by the absence of any snags. The trend line for second-growth stands reached the lower old-growth confidence interval around year 170 for biomass and year 160 for volume. However, the average old-growth threshold for CWD had not been reached by age 220 for biomass or volume.
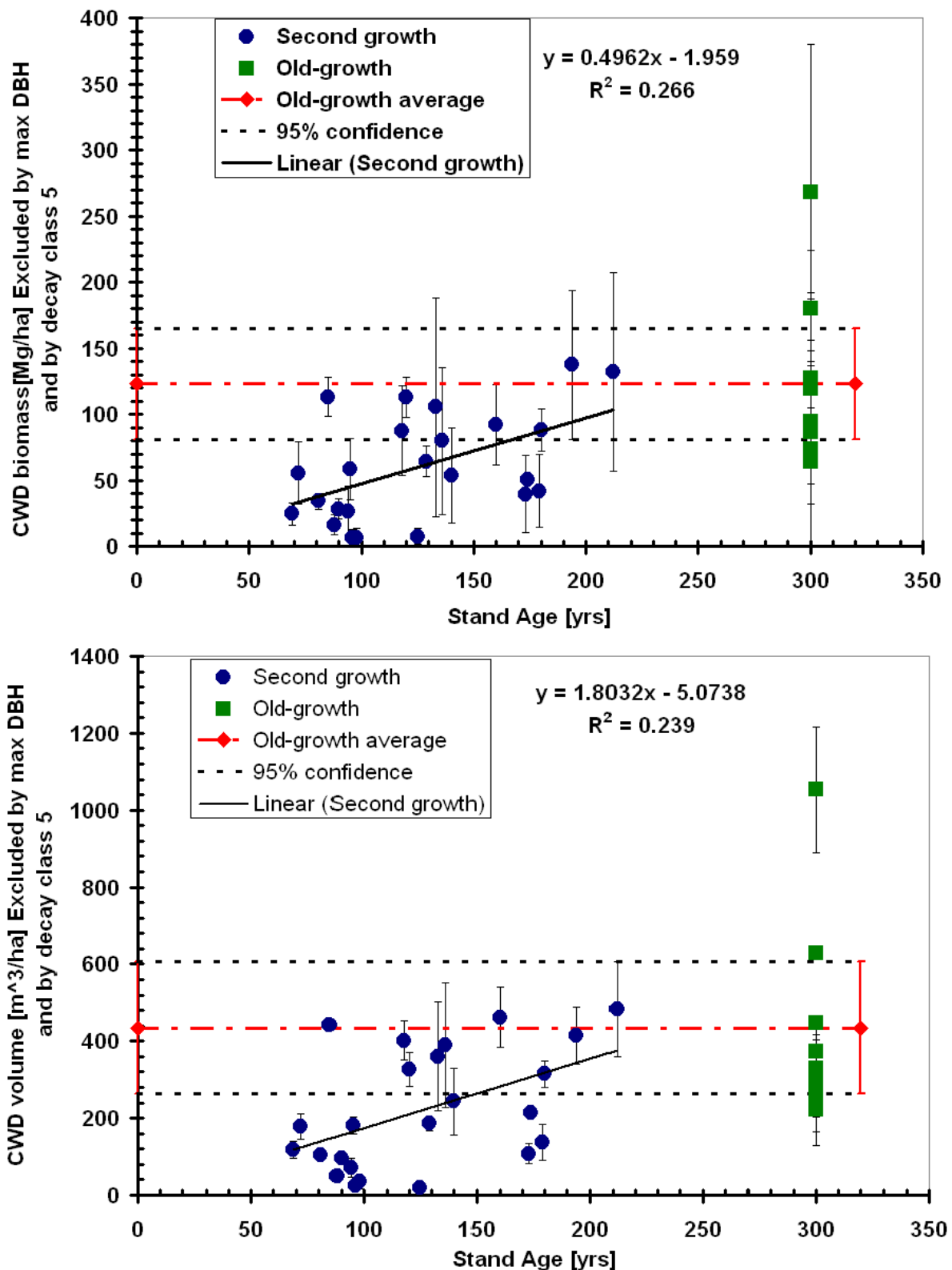
Figure 2.8 The relationship between total CWD A) biomass Mg/ha and B) volume m³/ha and stand age in second-growth sites excluding residual logs (All logs with decay class 5 and logs with diameter greater than maximum DBH of living second-growth stems). A 95% confidence interval threshold is shown for all old-growth sites. Error bars for second-growth and old-growth sites represent standard errors.

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Plant percentage cover

The temporal trend in percent cover of total understory vegetation is shown for second-growth sites in Figure 2.9. Total understory cover was calculated as the sum of shrub and herb layers as both are competing for light and growing space. Cover by small understory trees was also included for the same reason. As percent cover was estimated independently for each vegetation layer, the percentage may exceed 100% because of canopy overlap. No error bars were added to the graph, because only one vegetation plot was used per site. While the data show a substantial degree of variability, there was a positive trend with increasing stand age. The best fit trendline ($r^2 = 0.34$, p=0.003) for second-growth sites was an asymptotic function ($Y = a - \dfrac{b}{time}$).

Variability in understory vegetation cover was very high among the old-growth sites. This was likely due to the high degree of light availability (observed, not directly measured) near the shrub level in old-growth sites. Specifically, light levels for minor vegetation appeared to be low in old-growth sites with vigorous growth of understory trees.

It is problematic to employ an old-growth average for understory vegetation cover because of the high degree of variability in this structural attribute. For the purpose of comparison among other structural attributes, the trend line for understory vegetation cover in second-growth stands reaches the low old-growth confidence interval by year 105 and the old-growth average by year 158.
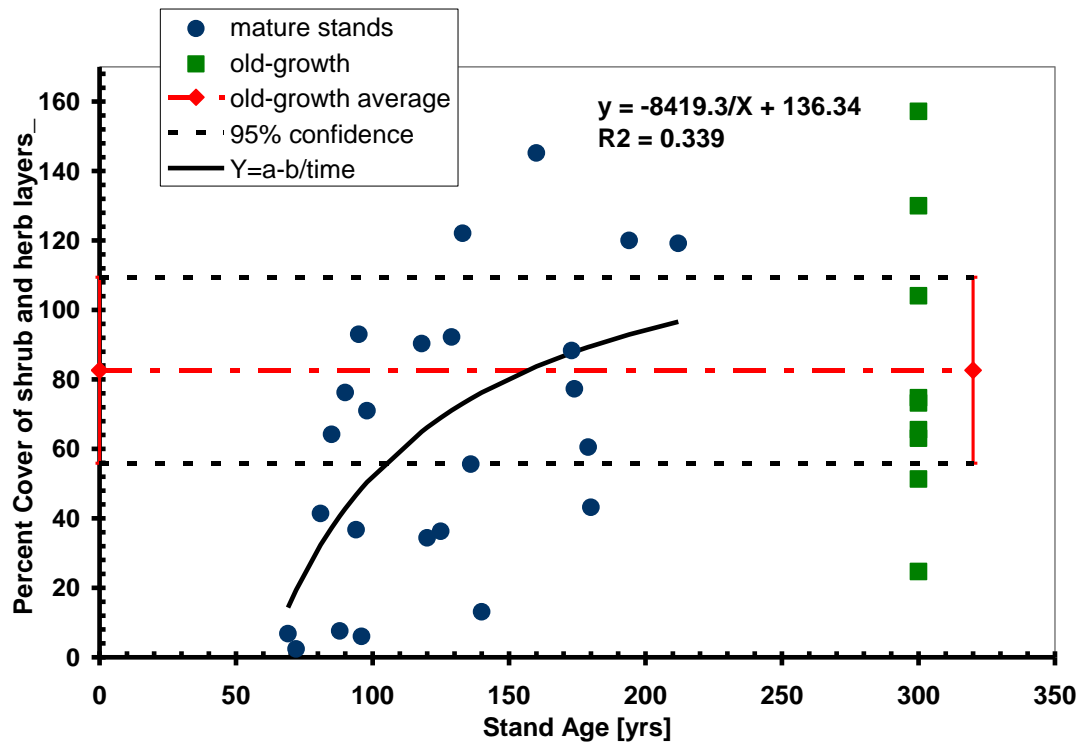
Figure 2.9 Percentage cover of sum of shrub and herb layers. Includes short understory trees. Percentage is higher than 100% due to overlap of plant canopy. A 95% confidence interval threshold is shown for all old-growth sites.

Old-growth averages and timing

A summary of the developmental rate of structural attributes in second-growth stands relative to averages derived from field-measured old-growth stands is shown in Table 2.4 The timing to reach old-growth was determined as the time at which the best fit trend line crosses the old-growth average. Where possible, the error in timing was determined by the time that the line crosses the lower 95% confidence interval. It was not possible to fit trend lines for some variables (e.g. snags > 100 cm DBH) due to their absence in second-growth stands. Additionally, the standard deviation of DBH reached its old-growth average after the age of the oldest second-growth site, and hence the estimation of the age was not precise. In these cases, timing of recovery was estimated as greater than 250 years.

Of the structural variables measured, the recovery of the number of large live structure (> 50 cm DBH) was among the fastest (119-190 years, depending on the measure). Recovery of understory vegetation was also relatively fast (approximately 160 years) but showed a high level of variability among stands. Large diameter snags (>50 cm DBH), CWD and standard deviation in stem size required longer time periods (> 200 years) to recover old-growth conditions.

Table 2.4 Summary of attributes tested for correlation with age. Not applicable R^2 indicates that no correlation was found. Yet, some of these non-correlated attributes do change within longer time scale. Hence, timing to reach old-growth average was estimated also for them.

Attribute	average for old-growth (OG)	95% confidence of the OG average	R^2 for correlation with time	Timing to reach old-growth	Error in timing
Volume/ha of trees with DBH>50cm	1071 m^3/ha	±260 m^3/ha	0.49	190 years	±53 years
Stems/ha of trees with DBH>50cm	113 stems/ha	±22 stems/ha	0.51	112 years	±15 years
Snags/ha with DBH>50cm	23.3 snags/ha	±10 snags/ha	NA	More than 200 years	±50 years
Non-residual CWD mass/ha	120 Mg/ha	±40 Mg/ha	0.27	250 years	±80 years
Non-residual CWD volume/ha	430 m^3/ha	±170 m^3/ha	0.24	240 years	±90 years
% cover of shrub and herb layers	83 %	±27 %	0.34	158 years	±53 years
Vol/ha DBH>=100cm	470 m^3/ha	±260 m^3/ha	NA	Probably more than 250 years	NA
Stems/ha DBH>=100cm	19 stems/ha	±9.6 stems/ha	NA	Probably more than 250 years	NA
Snags/ha DBH>=100cm	8 snags/ha	±5.6 snags/ha	NA	Probably more than 250 years	NA
Standard Deviation of DBH	27.4 cm	6.2cm	0.28	Probably more than 250 years	NA
CV of DBH	75 no units	23 no units	NA	Probably more than 250 years	NA

2.4 Discussion

2.4.1 Recovery of old-growth structural attributes

The chronosequence analysis identified seven practical attributes that can be used to express the rate and state of development of old-growth structural characteristics in second-growth stands in the maritime Coastal Western Hemlock zone of BC following a variety of stand-replacing disturbance events. The hypothesis of correlation between stand attribute and stand age in second-growth stands was supported for all of the evaluated structural attributes with the exception of the coefficient of variation in stem size and the recruitment of very large diameter snags (>100 cm DBH). It should be noted that the stand attributes included in the present analysis were chosen subjectively and focused only on plant-related structures. They, however, do not constitute the whole range of attributes that can be used to describe and identify old-growth forests. Old-growth forest condition also encompasses pedodiversity (Scharenbroch and Bockheim 2007), old-growth dependent organisms such as canopy lichens and bryophytes (e.g. Sillett et al. 2000), and other structural attributes not measured here (e.g. Wells et al. 1998). Attributes associated with these characteristics may reach old-growth averages at different times. Structural properties nevertheless can be indicators of habitat structure, and abundance and diversity of some species (Kremsater et al. 2003). The application of old-growth averages and associated confidence intervals allows forest managers to evaluate the maintenance and recruitment of old-growth features within managed forest landscapes. The fact that one of the attributes has crossed old-growth thresholds does not necessarily imply that the forest reached its old-growth state. Nonetheless, the inclusion of multiple structural attributes as part of an integrated analysis provides a more robust measure. It should be noted that the minimum of old-growth confidence interval represents only 5% of old-growth stands. Hence, management of the stand to the confidence interval as a target will create an old-growth stand that will be less representative of the old-growth forests in the area. Management of the stand to the old-growth average will result in a stand that will on average resemble most of the old-growth stands. Clearly, the target of the management can be set loose enough to allow variation in the old-growth values to resemble the variation in nature presented by the confidence interval.

Live tree volume and frequency of stems by size class

The presence of large live stems (typically defined as having diameters > 50 cm or more depending on the relative productivity ecosystem) is an effective indicator of the old growth

condition for a number of reasons. Large trees provide unique habitat structures including opportunities for nesting and foraging for a variety of species (Bunnell et al. 2003). The crowns of these trees include large branches providing nesting platforms and habitat for plants, lichens and fungi. The presence of large live structure generally facilitates the development of open and diverse understory conditions, which are effective as shelter. Lastly, large live structure is necessary for the continual recruitment of large logs and snags (see below).

In the present analysis, indicators of large live structure (volume and stem density of trees > 50 cm DBH) in developing second-growth stands were well correlated with stand age. This was partly related to the fact that live tree attributes are less sensitive to disturbance events that kill only a small percentage of the stems. Nonetheless, all R^2 values are relatively low (less than 0.51) due to variability of the field data. Variability in these indices was likely related to dissimilarity in disturbance history, differences in regeneration patterns including timing, species and establishment density, and other site factors that influence site productivity. The time required to reach old-growth averages will be dependent on the relatively subjective DBH cut-off used to define large stems. For example, only three second-growth sites had live stems > 100 cm DBH, but these large stems were present in all old-growth stands.

The volume of large live structure tends to level off as canopy dominants gradually decline in vigour and are increasingly subjected to low intensity tree mortality events. The total stem biomass for old growth stands measured in this study (624 ± 96 Mg ha^{-1}; converted from volume using hemlock wood density of 480 kg m^{-3}) is in the range of the data presented by Wells (1996) for similar stands. Spies and Franklin (1988) observed that the volume in older stands tended to approach a steady state where tree mortality will be compensated by new tree growth. It may potentially be that the volume graph will have a hump before the old-growth state and then decline until reaching steady state in old-growth, because the stem density of big trees is higher in the mature state than in old-growth (Wells 1996). The number of large diameter stems ought to stabilize in uneven-aged old-growth stands with the gradual recruitment from new large trees from released understory trees (Spies and Franklin 1988). From a management perspective, there may be opportunities for accelerating the development of large diameter trees through thinning (Omule 1988, Sullivan et al. 2006), but thinning regimes will have to be carefully balanced to not reduce the future population of large trees to an extent that it cannot provide for the future recruitment of large snags and CWD.

Tree size diversity

Stand structural diversity has an influence on future stand growth. For example, regeneration of new trees is dependent on the amount of light that reaches the understory, and hence less diverse young forests with a closed canopy will have little understory regeneration. Additionally, stand structure constitutes habitat for other living creatures, and thus contributes to biodiversity in the area (Tews et al. 2004). Theoretically, the diversity of DBH should increase with time as new trees establish in the understory. Moreover, a forest in its stem exclusion phase has less diverse structure than an older forest, because of the competition for light among neighboring trees (for example (Wells 1996)).

CV can be problematic as an indicator of old-growth conditions because as the stand matures the mean of DBH increases with the SD, and hence the change in CV may not be significant (as in the case of Varga et al. 2005). Alternatively, CV may show a U-shape pattern where CV is higher in younger forest, reaches its minimum in mature forest and rises again in old-growth (Wells 1996). In the present analysis there was a weak positive correlation between SD and stand age but no trend for CV. The fact that the analysis was limited to stems > 12.5 diameter may account for the lack of a trend in DBH. Indeed, if understory trees were included, mean DBH would decline and SD would increase more substantially with increasing stand age. From the perspective of stand dynamics, the appearance of additional young trees during the understory re-initiation phase should increase both measures of tree size diversity (e.g. Fierst et al. 1993, Wells 1996). The result of a weak correlation of SD with time emphasizes the importance of information regarding small tree sizes. It also stresses that tree size diversity can be compared only between sites with large age difference. Otherwise, their SD will be similar.

Frequency of snags

Large snags can be an indicator for old-growth as the density of large trees increases from young to mature forest, and therefore these big trees will eventually die and contribute to an increase in snag density. Large snags are also an important habitat for variety of insects, invertebrates, birds, fungi and epiphytes (e.g. Franklin et al. 1981, Berg et al. 1994) and therefore contribute to the overall biological diversity in older stages of the forest.

The cutoff of 50 cm DBH for snag size is based on a USDA report which identifies diameter threshold of 50 cm as meaningful in terms of habitat use of snags in coastal forests (Bunnell et al. 2002). The report reviews research regarding bird and mammal use of snags. Bunnell et al. (2002) indicate that birds in coastal BC nest only on snags greater than 50 cm DBH and taller

than 5 m. It is worth noting that almost one-half of the snags measured during current field work were less than 5 m tall. Although short snags may be of little value for nesting, they probably can be a valuable habitat for insects, and hence a foraging site for birds.

The chronosequence data showed a high level of variability in the frequency of large diameter snags in both second-growth and old-growth stands (see Table 2.3). Moreover, there were several older second-growth sites in which no large snags were detected. The relative frequency of these large diameter snags may be underestimated by the sampling method employed in this project. The area sampled using the prism plot methodology may be inadequate to accurately detect the presence of these relatively rare structures. Mensuration data from BC Provincial Ecology Program shows an average of 11 large diameter snags·ha^{-1} from 13 measured old-growth sites in CWHvm1 variant (Ministry of Forests 2001). Yet, the data collection methods were identical to current research, and hence could also underestimate the amount of snags in the area. Another reason for substantial variation in the number of large snags is the fact that the sites have different disturbance histories. For example, if frequent wind events uproot trees on the site, it will not have many snags. Since the data collection method can be inappropriate for the snags, the average for old-growth in Figure 2.6 may not be reliable. More work is required to determine the best sampling strategies and more robust threshold for snags as an indicator of old growth condition.

Coarse woody debris mass and volume

Although as a forest ages it has more live tree volume, CWD mass does not necessarily always increase with time. Three trends of biomass change are possible: steady increase with maximum biomass at the old-growth phase; U-shaped trend with maximum biomass at young and old forests; inverse U-shaped trend with maximum CWD mass at mature state of the forest (e.g. Feller 2003, Wells and Trofymow 1997). Such differences in trends appear when residual and newly accumulated CWD are measured together. Therefore, to differentiate old-growth from younger forests it is important to exclude residual debris. When only non-residual logs are included, trends in CWD mass and volume should increase with stand age as the population of large live structure increases and because the decomposition of CWD is quite slow. This trend was evident in our analysis. The degree to which non-stand replacing disturbance events affect a given site will also have a strong influence on the quantity of accumulated CWD present at a particular point in time.

Spies et al. (1988) suggest that coastal old-growth forests in the Pacific Northwest of the US do not necessarily reach a steady state condition regarding woody debris in their first 450 years.

The CWD mass in their study increased with stand age without stabilization on older sites. Even if the forest does not reach a steady state for CWD, it is still possible to establish some minimal threshold that will be sufficient for old-growth. It should be noted that the CWD mass and volume, suggested as old-growth averages in this project, were within the range of CWD reported for other old-growth forests in CWHvm1 and vh1 variants in BC (Feller 2003).

The trends in CWD accumulation observed here provide insight for management. When residual CWD is excluded or removed during logging operations, the best-fit trend line suggests it can take more than 240 years to reach the old-growth average for CWD. Although current research concentrates on the volume/biomass of woody debris, it is also important to pay attention to the decay condition of the logs. Different decay classes provide different habitats and hence their increased variety increase biodiversity in the stand (e.g. Stokland 2001, Vanderwel et al. 2006). Therefore, for habitat conservation it would be important to check how abundance of logs in each decay class recovers with time.

Plant percentage cover

Understory vegetation cover is dependent on the light availability under the main canopy. As the stand closes its canopy in the stem exclusion phase, many understory plants die without sufficient light and only shade tolerant species survive (Spies 1991). Once canopy gaps start to appear later on, understory growth reinitiates. Based on research data from coastal BC plant cover should increase with stand age after the stem exclusion phase (e.g. Banner and LePage 2008, Wells 1996). Hence, understory percent cover can be an indicator of old-growth recovery.

The nature of understory vegetation data can vary from project to project depending on objectives. For example, Banner and LePage (2008) presented average plant cover by stand age classes, whereas Wells (1996) presented detailed and highly variable vegetation cover data. Both studies found that old-growth sites can have as low as almost 0% cover and up to 100%. Similar variability in understory vegetation cover was observed in the present study (see Figure 2.9). Some of this variation in understory cover derives from the variability in the density of the sub-dominant tree canopy that effectively captures much of the light penetrating beneath the main canopy, and thus suppresses the development of understory vegetation. The presence of sub-dominant trees is typically associated with canopy gaps and is spatially variable. Some gaps can remain relatively open for extended periods of time allowing light to reach the shrub layer, whereas other gaps can fill quite quickly depending on a number of site and species factors. The vegetation plots used in this study were only 20 by 20 meters and thus may have been insufficient to capture the spatial variability of the old-growth canopy on a per hectare basis.

However, even if several plots were established, it does not change the fact that the light reaching the shrub layer in an old-growth forest can be less intense than the light reaching the shrub layer during the understory reinitiation phase.

Another reason for variability of understory cover data is the fact that plant percentage cover has limited correlation with light availability, because it does not always correlate with plant biomass. For example, some dominant shrubs on the field sites were *Vaccinium* species. For red huckleberry *Vaccinium parvifolium* it was found that there is only poor linear correlation between its percentage cover and biomass (Nyberg 1985). While light levels increase and the plant increases its biomass, the canopy cover may stay the same. Despite those limitations, percentage cover was used in the current project, because it is the typical information that is collected by other surveys in BC.

An additional important aspect that may influence current understory measurements is that mule deer *Odocoileus hemionus* are common in the area of the field project. These ungulates feed on several understory species (shrubs and conifer seedlings) that constitute a large part of the percentage cover on our sites (Serrouya and D'Eon 2008).

2.4.2 Limitations of the study

One of the key limitations of the study is the relatively small number of sites included in the analysis (24 second-growth sites and 9 old-growth sites). It may have been possible to achieve more robust trend lines and thresholds if more sites had been included in the chronosequence analysis. Nonetheless, the variability of the data would still be high due to other individual parameters of each site (Wells 1996). The sites in the current study were not limited to specific slopes and aspects, and thus varied in their susceptibility to windthrow and possibly other disturbance agents (Scott and Mitchell 2005). Moreover, differences in timing and impact of low intensity disturbance regimes led to differences in snags and CWD accumulation among chronosequence sites that were similar in stand age.

Another limitation of the study stems from the fact that selected sites were not randomly located within the larger study area. Preference was given to sites with closer location to the road for better site access. Stands that were located close to each other could have similar disturbance regime. Additionally, subjective selection of the sites could selectively prefer some structural attributes. For example, the sites were chosen to be relatively uniform to comply with the definition of a stand. However, forests, especially old-growth, have natural horizontal diversity (Franklin 2009). Examples include canopy gaps, dense patches of trees, accumulation of dead wood, patches with different soil attributes and difference in slope gradient within a stand. Due

to that fact non-uniform sites that could potentially show other results were avoided. This is not entirely a limitation, because the choice regarding the stands was made to simplify the study to uniformly grown stands.

Care should also be taken in terms of interpreting and extrapolating from the old-growth averages identified for specific indicators defined here. The time required for a specific attribute to reach the old-growth condition is dependent both on specific stem size cut-offs (where applicable), as well as the functional shape of the fitted trend line. In general, an effort was made to select trend line functions that made sense from a biological perspective.

2.5 Conclusions.

The analysis presented here demonstrates a methodology for evaluating the relative recovery of old-growth characteristics in second-growth stands within a managed forest landscape. The use of indices based on structural characteristics rather than, or in addition to, traditional age-based thresholds provides more information with respect to the degree to which a given managed landscape has recovered towards an old-growth condition and should facilitate better planning. In addition, the use of quantified attributes eliminates the duality in forest state description as being only old-growth or not and suggests a continuous scale of reference.

Further research is needed to support the analysis done in the current study. Increase in the number of captured second-growth sites might increase the R^2 of the trendlines. In addition, more old-growth sites should be measured to insure the accuracy of the old-growth averages for structural attributes. Live tree, understory vegetation and CWD attributes chosen in present study showed significant dependence on time, whereas data collected for snags was questionable and their data collection methods should be revised.

Collected quantified information allows computerized assessment regarding old-growthness of the stand. Such ability will allow forest growth models to be involved in a decision making process. Models are capable of simulating structural changes, and hence representing the recovery of the old-growth forest. Therefore, models can facilitate the use of information regarding stand structure for stand and landscape-scale forest planning.

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Chapter 3. Simulating the development of old-growth structural attributes in second-growth coastal western hemlock forests: Evaluation of the mechanistic forest growth model FORECAST[2]

3.1 Introduction

Coastal western hemlock (CWH) forest covers much of the coastal region of British Columbia (BC), and since stand replacing disturbances are rare, the majority of the unlogged CWH forest is in an old-growth condition (Price and Daust 2003). Old-growth forests in the CWH zone are characterized by high structural complexity (Wells et al. 1998, Franklin et al. 2002) which has been shown to be important for ecosystem functioning and maintenance of biological diversity (Franklin and Spies 1991a , Carey 2009). Managed forests in coastal BC have historically been logged using clearcutting methods (D'Anjou 2003), typically resulting in the development of second-growth stands with more homogeneous structure including a narrower distributions of tree sizes and reduced amounts of deadwood relative to old-growth stands. As forest management in BC and elsewhere moves increasingly towards multi-objective systems, the conservation and recruitment of old-growth forest has been identified as a key component of sustainable forest management plans (Ministry of Forests and Range 2004).

The ability to develop and apply multi-objective forest management plans that include the conservation and continued recruitment of old-growth forest requires the ability to predict the recovery of forest ecosystems following both traditional logging activities and alternative silviculture systems (Kimmins 2008). Yet, with the lack of long-term experience in coastal BC, particularly with alternative silviculture systems, extended trajectories of forest structural development are difficult to forecast. One approach for evaluating long-term stand development patterns is through chronosequence analysis (e.g., Trofymow et al. 1997, Wells 1996, Van Pelt and Nadkarni 2004). While valuable, chronosequence analysis is limited in its application as target sites must be similar in terms of site productivity and disturbance/management history. As management systems become more complex it becomes more difficult to predict ecosystem recovery using chronosequence analysis. Another method for predicting development patterns is to utilize knowledge gained from long-term field trials of different harvesting methods on the same site (e.g., Thompson 2007, Arnott and Beese 1997). While this type of experience is highly useful, such studies are usually limited to several decades and the variability of available

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management options and site types is high relative to the amount of long-term studies that can be feasibly established.

A third option for prediction of management outcomes is to use forest growth models (e.g., Kimmins et al. 1999, Pacala et al. 1996, Choi et al. 2001). Relative to chronosequence analysis and field trials, models are far more flexible in their application and can be parameterized to represent many site conditions and a variety of silviculture systems. While empirical models will be limited by the availability of historical growth data, mechanistic models can simulate forest development based on representations of well-understood growth processes. Hence, such models can be used to project the outcome of alternative silviculture systems for which we have limited field experience, and in situations where management activities change the properties of the site (Kimmins et al. 2008).

To be effective for evaluating the development of old growth characteristics in second-growth stands, a model must include explicit representations of the structural features that can be used to distinguish old growth conditions (e.g., Choi et al. 2007). Such features include individual tree size measures, characteristics of coarse woody debris including log sizes and state of decay, and characteristics of standing dead trees including, species and dimensions (Franklin and Spies 1991b, Tyrrell and Crow 1994). It is also helpful if a model is capable of adequately representing the ecosystem processes that lead to the formation, accumulation and loss of these features. Such processes include density dependent mortality (stand self-thinning), minor (non-stand-replacing) disturbance events such as insect mortality and windthrow, harvesting events, snag fall rates, and organic matter decomposition rates (including snags and logs of different species and size classes).

One model that meets these criteria is the mechanistic forest growth model FORECAST (Kimmins et al. 1999). FORECAST was designed to accommodate a wide variety of harvesting and silvicultural systems in order to compare and contrast their effect upon forest productivity, stand dynamics, and various biophysical and social indicators of non-timber values. The model has been applied to a variety of forest types: mixed Douglas-fir and paper birch forest (Sachs 1996), mixed aspen and white spruce forest (Welham et al. 2002, Seely et al. 2002), Chinese-fir plantations (Bi et al. 2007), coastal Douglas-fir forest (Blanco et al. 2007). FORECAST has been validated against field data for a range of growth and yield and structural variables in: coastal Douglas-fir forests (Blanco et al. 2007, Boldor 2007), and interior mixedwood forests (Seely et al. 2008) in British Columbia.

To be effective for guiding management decisions, it is essential to establish a level of confidence with respect to the reliability of model predictions. Regional chronosequence studies can provide data that is suitable for model evaluation (e.g. Bugmann et al. 2001). However, comparisons between model results and field observations must be done carefully to account for inconsistencies between simulated model conditions and field conditions in chronosequence sites including disturbance histories and regeneration patterns. An evaluation of the performance of forest growth and development models can be divided into a few key components or perspectives (after Vanclay and Skovsgaard 1997 and Huang et al. 2003):

1. Assessment of biological consistency
2. Graphical (visual) inspection of predicted versus observed values.
3. Statistical tests for goodness-of-fit
4. Analysis of model sensitivity and bias.

Assessing the biological consistency of a specific model is important as it helps to assure that the model will predict reasonable responses to initial conditions and planned management operations. It also helps to assure that model output does not contradict well-understood patterns and processes of forest growth (Soares et al. 1995). Graphical or visual analysis of model output can be useful for evaluation of biological consistency as it allows the user to easily compare projected trends in stand development to observed trends in time series data (e.g. Leary 1997). While such visual comparisons are ultimately subjective and sometimes prone to false impression, it is considered to be among the most effective methods for evaluation of forest growth models; especially when combined with statistical tests (Huang et al. 2003). Statistical tests of goodness-of- fit, provide a quantifiable measure of model performance. However, when used in isolation, they may generate misleading results. For example, a modeled curve may have high goodness-of-fit, but an abrupt and illogical shape. Further, Yang et al (2004) suggested that statistical tests should be selected based upon the unique circumstances of each situation rather than generally.

Sensitivity analyses provide an additional method for evaluating model behavior. In a sensitivity analysis model parameters are incrementally changed to determine their relative influence on model output and general performance. Comparisons of the model output can be made against the field data or against default model run. Either way the same visual and statistical tests discussed above are used for sensitivity estimation, and hence sensitivity analysis is also potentially subjective and biased (Loehle 1997).

To date, FORECAST evaluations have been limited to stands less than 60 years old. The current application of the model to assess temporal patterns in the development of old growth characteristics requires an evaluation over longer time periods. The present study evaluates the ability of FORECAST to project the development of old growth structural characteristics as measured in a chronosequence study of second growth coastal western hemlock stands along the west coast of Vancouver Island, BC (Chapter 2). Here, model performance is assessed in terms of its consistency with ecological theory and by means of graphical inspection and statistical analysis. In addition, a limited sensitivity analysis is conducted to explore the response of the model to varying regeneration and disturbance parameters.

3.2 Methods

3.2.1 Field data description

A chronosequence study was established including 33 sites varying in age from 60 to over 300 years in an area on western Vancouver Island spanning 380 km in length (See Chapter 2 for a detailed description). Field measurements within the sites included stand structural attributes, vegetation and soil properties. In addition, tree ages were measured and disturbance history was estimated. A set of attributes were developed that showed clear trends in the development of stand structure and old-growth characteristics with increasing stand age. An emphasis was placed on indicators that could be calculated from FORECAST model output and that would be practical to work with from a forest management perspective.

3.2.2 Model description

FORECAST is a management-oriented, stand-level forest growth and ecosystem dynamics simulator. A detailed description of FORECAST is provided in Kimmins et al. (1999) and Seely et al. (1999); only a summary is provided here. The model was designed to accommodate a wide variety of harvesting and silvicultural systems and natural disturbance events (e.g., fire, wind, insect epidemics) in order to compare and contrast their effect on forest productivity, stand dynamics and a series of biophysical indicators of non-timber values. Projection of stand growth and ecosystem dynamics is based upon a representation of the rates of key ecological processes regulating the availability of, and competition for, light and nutrient resources (a representation of moisture competition is being completed but was not included in this study). The rates of these processes are calculated from a combination of historical bioassay data (biomass

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accumulation in component pools, stand density, etc.) and measures of certain ecosystem variables (decomposition rates, photosynthetic saturation curves, for example) by relating 'biologically active' biomass components (foliage and small roots) with calculations of nutrient uptake, the capture of light energy, and net primary production. Using this 'internal calibration' or hybrid approach, the model generates a suite of growth properties for each tree and understory plant species that is to be represented. These growth properties are subsequently used to model growth as a function of resource availability and competition. They include (but are not limited to): (1) photosynthetic efficiency per unit foliage biomass and its nitrogen content based on relationships between foliage nitrogen, simulated self-shading, and net primary productivity after accounting for litterfall and mortality; (2) nutrient uptake requirements based on rates of biomass accumulation and literature- or field-based measures of nutrient concentrations in different biomass components on different site qualities; (3) light-related measures of tree and branch mortality derived from stand density input data in combination with simulated light profiles. Light levels at which foliage and tree mortality occur are estimated for each species. FORECAST performs many calculations at the stand level, but it includes a sub-model that disaggregates stand-level productivity into the growth of individual stems with user-supplied information on stem size distributions at different stand ages. Top height and DBH are calculated for each stem and used in a taper function to calculate total and individual gross and merchantable volumes. Snags and logs are created in the model from natural stand self-thinning and from different types of user-defined disturbance events such as insect/disease-induced mortality, windthrow, and non-commercial thinning. Snag fall rates and log-decomposition are simulated using species-specific and tree-size-specific decay parameters derived from literature reviews and expert opinion.

FORECAST has four stages in its application (after Blanco et al. 2007): 1) data assembly and input verification; 2) establishing the ecosystem condition for the beginning of a simulation run (by simulating the known or assumed history of the site); 3) defining a management and/or natural disturbance regime; and 4) simulating this regime and analyzing model output. The first two stages represent model calibration. Calibration data are assembled that describe the accumulation of biomass (above and below-ground components) in trees and minor vegetation for three chronosequences of stands, each one developed on homogeneous conditions, representing three different nutritional qualities. Tree biomass and stand self-thinning rate data are often generated from the height, DBH and stand density output of traditional growth and yield models in conjunction with species-specific component biomass allometric equations. To

calibrate the nutritional aspects of the model, data describing the concentration of nutrients in the various biomass components are required. FORECAST also requires data on the degree of shading produced by different quantities of foliage and the photosynthetic response of foliage to different light levels. A comparable but simpler set of data for minor vegetation must be provided if the user wishes to represent this ecosystem component. Lastly, data describing the rates of decomposition of various litter types and soil organic matter are required for the model to simulate nutrient cycling. The second aspect of calibration requires running the model in "set-up" mode to establish initial site conditions. The detailed representation of many different litter types and soil organic matter conditions makes it impractical to measure initial litter and soil conditions directly in the field; consequently, the model is used to generate starting conditions.

3.2.3 Model Application

Establishing initial conditions

The calibration dataset used for this project was developed as part of a previous modelling project in the coastal western hemlock zone on Vancouver Island, BC. (Seely 2004). The model was run in set-up mode to generate initial ecosystem conditions (soil organic matter, litter and coarse woody debris levels) that were consistent with an old-growth forest immediately following a stand-replacing disturbance. A starting site productivity level (Site index at breast-height-age-50 = 32) was selected based on field measurements made as part of the chronosequence study (Chapter 2). The set-up run consisted of 10 successive cycles western hemlock grown for 250 years, each with a stand-replacing fire at the end the cycle. By the end of the 2500-year set-up period, soil organic matter and litter levels had stabilized. A final set-up run was simulated with nutrient feedback turned on to allow the model to stabilize with respect to the effect of nutrient availability on tree growth. The final set-up run consisted of a western hemlock stand regenerated at 2700 stems ha^{-1} and clearcut harvested at age 250 with no trees retained.

Evaluation run

The set-up runs resulted in a starting condition (for the evaluation run) with a relative small amount of residual dead wood and no veteran trees. Since most of the trees on measured chronosequence field sites were western hemlock (Chapter 2), it was decided to simulate only this tree species in the evaluation run to simplify the modelling process. The shrub species simulated in the model was based on a general Vaccinium shrub (see Seely 2004).

Western hemlock, a shade tolerant species, will often establish several age cohorts through natural regeneration following a disturbance event until the overhead canopy becomes dense enough to inhibit further regeneration (Boldor 2007). Cohorts that are established earlier typically have a growth advantage over subsequent cohorts, and thus trees within different cohorts will tend to diverge in size more quickly than those within a single age cohort. Therefore, the establishment of multiple cohorts can significantly influence stand structural development. FORECAST was designed to represent multiple age cohorts in the user interface and the number of established trees and the timing of establishment can be defined by the user.

Model regeneration and disturbance parameters for the evaluation run were initially estimated from field data and literature descriptions. Regeneration parameter estimates were subsequently refined based on measured variation in tree ages within the chronosequence sites (Chapter 2). The younger, second-growth chronosequence sites showed an average age difference of 20 years among canopy dominants. Further, preliminary model runs with only one cohort did not produce the expected diversity of DBH sizes of living trees observed in the field data. For these reasons, we decided to simulate multiple cohorts (within a 20-year establishment window) until sufficient stem sizes diversity would be achieved. It was found that three cohorts were enough to attain the level of diversity that was equal to the one measured in the field. When more cohorts were added, the later established trees became suppressed and did not grow. The final set of regeneration parameters used in the evaluation run is shown in Table 3.1.

While FORECAST will automatically simulate density-dependent mortality through stand self-thinning, it is often necessary to represent additional low-intensity (non-stand-replacing) disturbance events including windthrow and pest or disease related mortality using the management user interface in FORECAST. The relative abundance of large snags and coarse woody debris observed in the chronosequence sites indicates the presence of such disturbance events in these coastal western hemlock dominated forests. The frequency and intensity of windthrow and snag-creating disturbance included in the evaluation and sensitivity analysis simulations were based on literature reports (e.g., Lertzman et al. 1996) and expert opinion (personal communication, Dr. Steve Mitchell). A description of low-intensity disturbance regimes implemented in the evaluation run is provided in Table 3.1

FORECAST, like many other forest growth models, does not automatically simulate natural regeneration of trees on the site. Thus, there was a need to introduce additional two natural regeneration cohorts in later stages of the simulation (Table 3.1) following windthrow events that

temporarily opened the overstory canopy, and hence created favorable conditions for understory regeneration. The total simulation time of the evaluation run was set to 300 years.

Table 3.1 Model parameters values describing assumptions for natural regeneration patterns, and disturbance events simulated in the evaluation run.

Model parameter	Value	Remarks
Total evaluation time	300 years	
Vegetation simulated	western hemlock, vaccinium shrub	
Shrub regeneration at first years: percent of maximum occupation	20%	
Number of cohorts	5	Three cohorts regenerate in stand-initiation phase, one in understory-reinitiation and one in old-growth phase
Stems density regenerated	600, 400, 400, 400,400	For cohorts 1-5, respectively
Year of cohort establishment	1, 11, 21, 171*, 211*	For cohorts 1-5, respectively
Windthrow	The disturbance is applied once in every 40 years and affects 15% of the trees. The first windthrow event is applied at year 50 of the simulation	Impacts trees older than 40 years
Disease related mortality	The disturbance occurs continuously within 20 years interval. During this interval 3% of the trees are being killed.	Impacts trees older than 40 years.

* The last 2 regeneration cohorts were included to account for regeneration that typically occurs when forest-floor light levels increase following the reduction of overstory canopy from windthrow events in mature stands. The dates correspond with simulated windthrow events.

Sensitivity Analysis

The sensitivity analysis was designed to explore the effect of varying key model assumptions related to initial regeneration patterns and simulated disturbance regimes. The value of each parameter was systematically adjusted around the value used for the evaluation run of the model (Table 3.2). Model output was graphically compared both to the field data and to model output from the evaluation run.

Table 3.2 A description of model parameters evaluated in the sensitivity analysis. Simulated values for each parameter are shown.

Parameter	Simulated values
Number of cohorts	4 instead of 3 during stand-initiation stage
Total number of seedlings in stand initiation phase	±50% of the seedling in evaluation run
Timing between successive cohort regeneration in stand-initiation stage	±5 years
Percentage of trees killed by disturbance	±5% mortality during 40 years
Length of wind disturbance period	±10 years

3.2.4 Model Evaluation

Graphical Analysis

Model output was evaluated for biological consistency, and a set of indicator variables derived from the chronosequence study was used to assess the capability of the model to project temporal trends in structural development in second growth stands (Table 3.3). The specific diameter thresholds were selected for two reasons. First, the thresholds were found to show clear temporal patterns with stand age. Second, the 50 cm DBH threshold was found to be biologically significant for these forest types (see Chapter 2). Since the field data from the chronosequence study was derived from many sites with differences in regeneration patterns and disturbance histories, model output was compared primarily to trendlines fitted to chronosequence data. Trendline functions were selected to be consistent with existing biological understanding for each attribute.

Table 3.3 Model output for structural variables used in model evaluation. Criteria for inclusion in specific indicator are shown.

Test Variables	Criteria	Units
Cumulative volume in large stems	≥50 cm DBH	$m^3 \cdot ha^{-1}$
Frequency of large stems	≥50 cm DBH	$stems \cdot ha^{-1}$
Cumulative volume in medium stems	25-50 cm DBH	$m^3 \cdot ha^{-1}$
Frequency of medium stems	25-50 cm DBH	$stems \cdot ha^{-1}$
Standard deviation of stem sizes	≥12.5 cm DBH	cm
Accumulation of CWD mass	Non-residual CWD*	$T \cdot ha^{-1}$
Frequency of large snags	≥50 cm DBH, non-residual snags*	$stems \cdot ha^{-1}$

*In the case of second-growth stands, non-residual CWD and snags refers to dead wood derived from the current stand as opposed to the previous stand.

Statistical Analysis

The goodness-of-fit of model output to field data trendlines was quantified for the structural variables described in Table 3.3 using a series of commonly used statistics (after Vanclay and Skovsgaard 1997). Mean bias (Eq. 3.1) measures the averaged difference between the model and the field data, the smaller the number, the closer the output of the model to the field data. The Root Mean Square Error (RMSE) statistic is an estimator of model accuracy which measures the average error associated with single prediction point of the model (Eq. 3.2). In contrast, the modelling efficiency (ME) statistic provides an index of model performance on a relative scale where 1 indicates the best performance, 0 reveals that the model is not better than the average of field data and negative values indicate poor performance (Eq. 3.3).

$$\text{Mean Bias} = \frac{1}{n} \sum_{i=1}^{n} \left(Y_i^{field} - Y_i^{model} \right) \qquad (3.1)$$

$$\text{Root mean square error (RMSE)} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(Y_i^{field} - Y_i^{model} \right)^2} \qquad (3.2)$$

$$\text{Modeling Efficiency (ME)} = 1 - \frac{\sum_{i=1}^{n} \left(Y_i^{field} - Y_i^{model} \right)^2}{\sum_{i=1}^{n} \left(Y_i^{field} - Y_{average}^{field} \right)^2} \qquad (3.3)$$

3.3 Results

Overall, the model was able to simulate the trajectories of development of the selected structural variables from the chronosequence reasonably well. Graphical and statistical evaluations of model performance are shown for each structural variable below. Figures 3.1−3.5 depict the comparison between the model and the fitted curves of the field data. Table 3.4 summarizes the statistical evaluation.

3.3.1 Live tree volume and stem density by size class

Model projections of cumulative volume in large stems and frequency of large stems showed a good fit (ME = 0.95 and 0.83, respectively) with the associated chronosequence data trend lines (Figure 3.1 and Table 3.4). The periodic dips in the model projections of these variables are associated with the simulated low-intensity disturbance events (see Table 3.1). The mean bias and RMSE were of comparable size to the amount of volume lost from these simulated disturbances. Model projections for both large stem variables reached the average for old-growth stands by age 195 and 110 years, respectively. The largest tree diameter simulated by the model after 300 years was 126 cm. In contrast, the old-growth sites from chronosequence had, on average, 7 trees ha^{-1} with diameters ≥130 cm, and 3 trees ha^{-1} with diameters > 200 cm. These very large trees, mostly western redcedars (*Thuja plicata*), are likely considerably older than the 300 years simulated in the model.
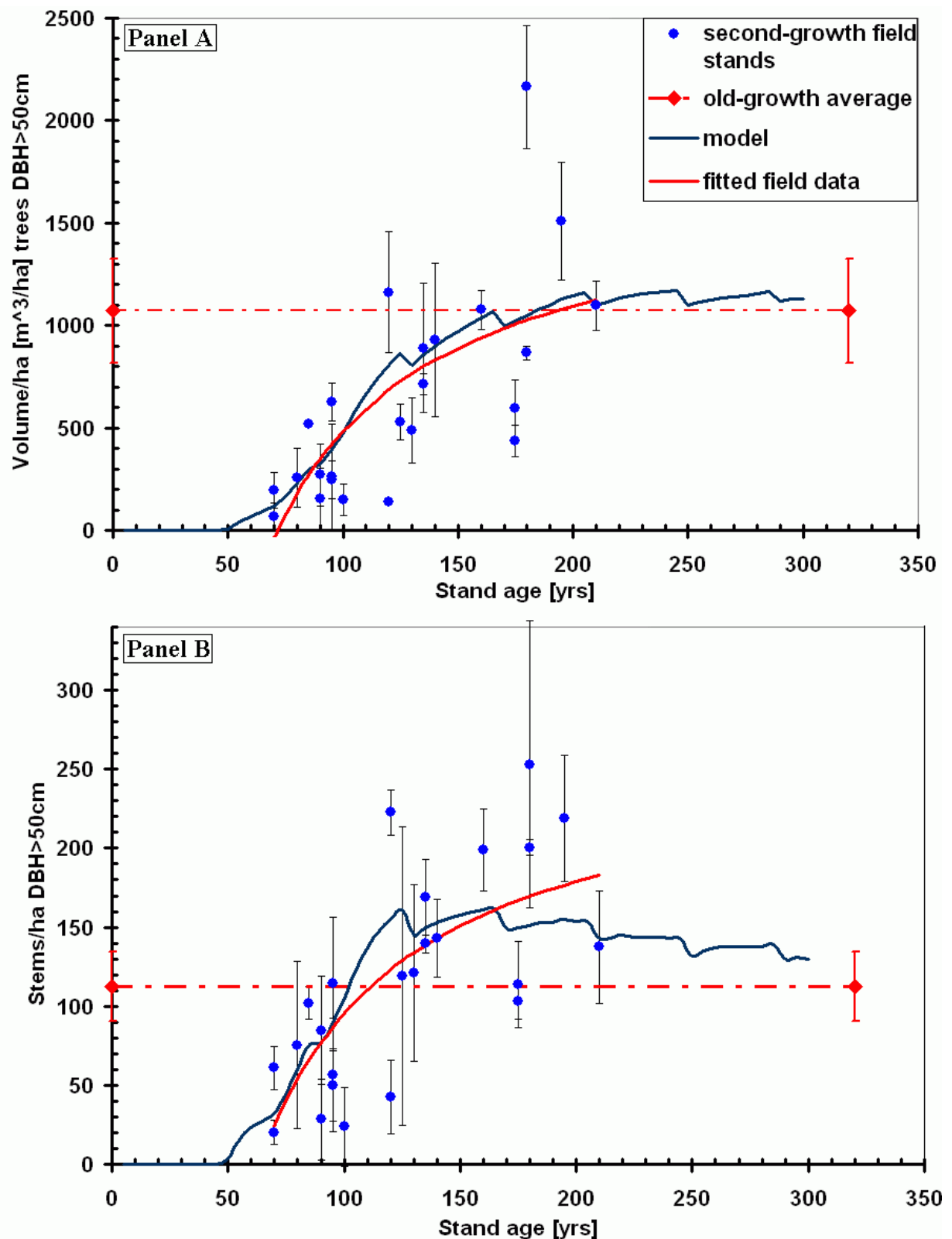
Figure 3.1 Comparison of model output for A) cumulative volume in large stems (≥50cm DBH) and B) frequency of large stems against trend lines fitted to chronosequence field data. The average for old-growth stands measured in the field study is also shown with the 95% confidence interval represented by the error bar. Error bars for the second-growth sites represent standard error.

The fit of model projections for cumulative volume in medium stems (DBH 25-50 cm) and frequency of medium stems was not as good as those for large stems (ME= 0.54 and 0.9 respectively), but temporal trends were similar to those observed in the fitted chronosequence data (Figure 3.2 and Table 3.4). As would be expected, the model showed an increase in medium stems abundance and volume until year 80 when many trees transitioned into larger size classes. Following the simulated windthrow events at years 170 and 210, the establishment of new cohorts led to a gradual increase in the volume and frequency of medium-sized trees. The field data did not include sites younger than 70 years, and hence it was not possible to evaluate model output during this period.
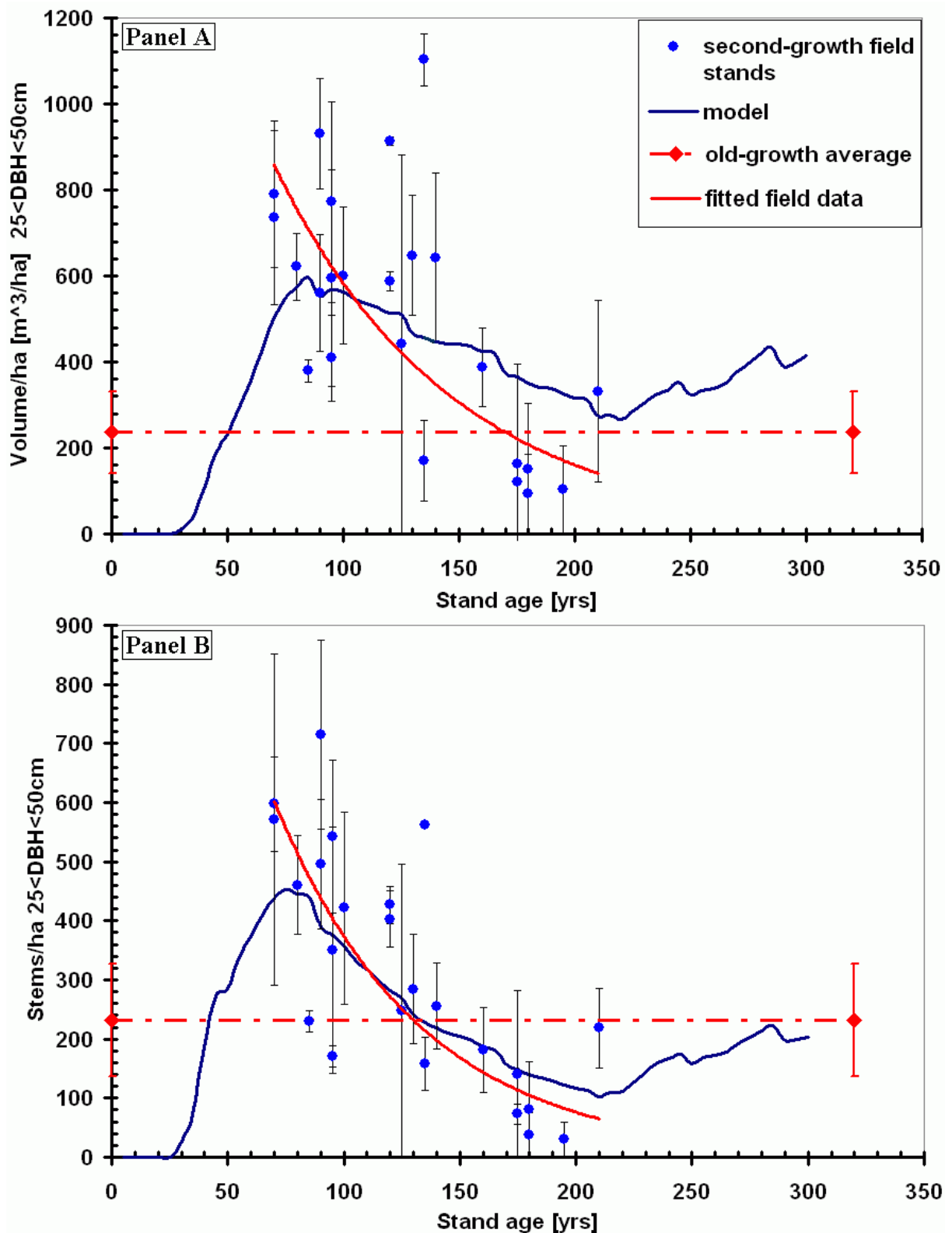
Figure 3.2 Comparison of model output for A) cumulative volume in medium-sized stems (25-50cm DBH) and B) frequency of medium-sized stems against trend lines fitted to chronosequence field data. The average for old-growth stands measured in the field study is also shown with the 95% confidence interval represented by the error bar. Error bars for the second-growth sites represent standard error.

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3.3.2 Standard deviation of stem sizes

FORECAST output for standard deviation of DBH showed a good fit (ME = 0.98) with the trend line of the chronosequence data (Fig. 3.3 and Table 3.4). Statistical estimators of goodness-of-fit were calculated for a period of years 70-180 only. This was due to the fact that after year 180, there was a sharp raise in simulated standard deviation due to regeneration of new cohort following the windthrow disturbance in year 171. Yet, the fitted line of the field data represented second-growth stands without the regenerated cohort. The simulated standard deviation in stem size increased steadily with stand age. This was related to both an increase in the average stem diameter and a continued divergence in size between the smallest and largest stems. Modeled standard deviation approached the confidence interval of field measured old-growth stands at year 200 of the simulation.
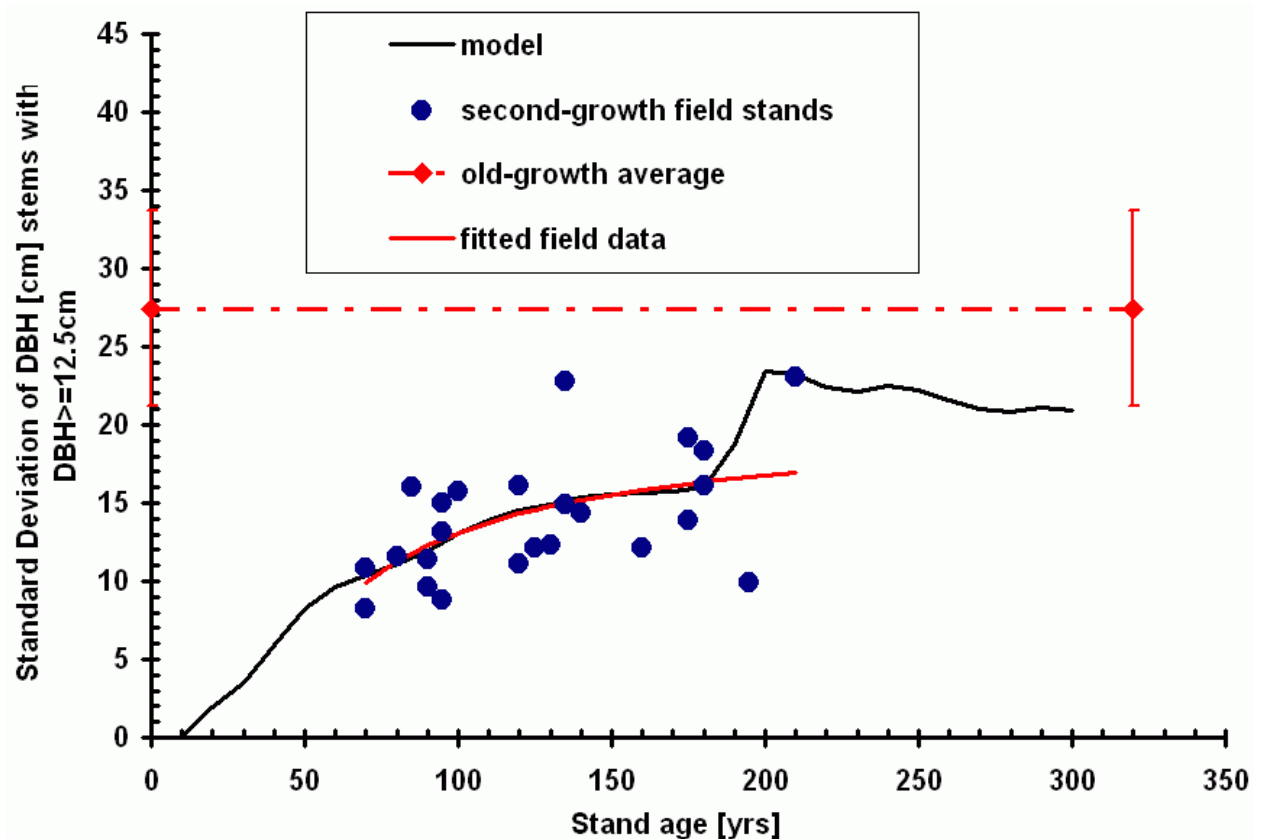
Figure 3.3 Comparison of model output for tree size diversity as measured by standard deviation of DBH for trees with DBH>12.5cm against the chronosequence field data and fitted trend line.

3.3.3 Accumulation of CWD mass

Since the evaluation run simulated in FORECAST represented a single stand, model output for CWD was highly sensitive to the low-intensity disturbance regime represented in the model (see Table 3.1), with peaks in CWD resulting from each disturbance event (Figure 3.4). The pulse of new CWD mass generated from each disturbance slowly declined due to decomposition until the next windthrow event occurred. Given the sensitivity of the model to a specific low-intensity disturbance regime, an asymptotic trend line was fitted to the model output ($R^2 = 0.76$, p<0.001) to show trends in the accumulation of CWD mass and to facilitate a more fair comparison of modeled CWD mass to field measurements. The fit of an asymptotic trend line to the chronosequence data was relatively poor ($R^2=0.21$, p=0.02), most likely because of the differences in disturbance histories among chronosequence sites.

A final comparison of the two trend lines showing the general rate of accumulation of CWD mass (model output and field data) showed reasonably good model performance (ME=0.72) for this variable (Figure 3.4 and Table 3.4).
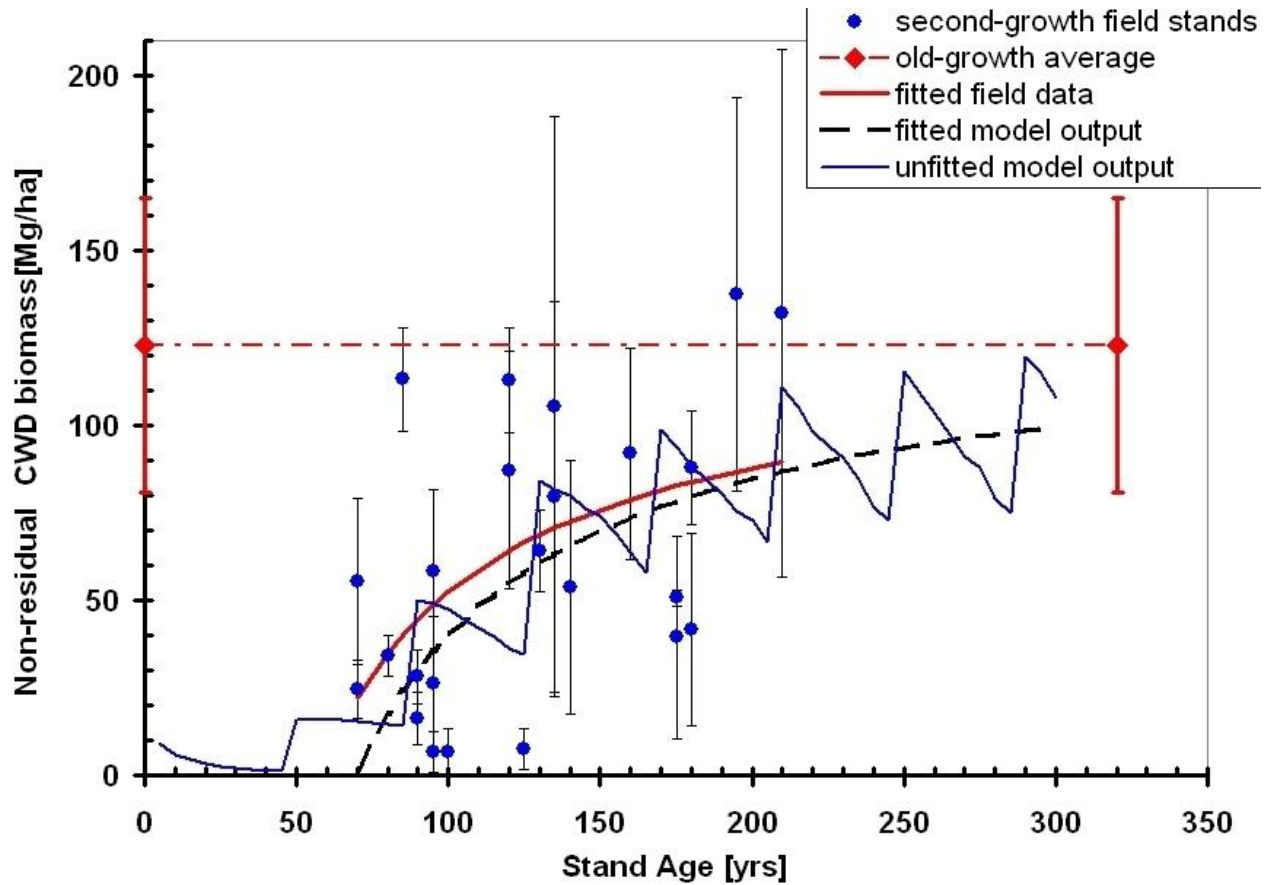
Figure 3.4 Comparison between the CWD mass of the field data and the model output. Asymptotic trend lines are shown for both model output and field data. The error bar of old-growth average represents the 95% confidence interval. Error bars for the second-growth sites represent standard error. Residual logs in chronosequence sites were excluded from CWD mass totals using the criteria described in the text.

Table 3.4 Results from statistical comparisons of model output to trend lines fit to chronosequence field data. The form of the trend line fit to the chronosequence data and the goodness of fit are shown for each evaluation variable.

Variable	Units	Trend line equation	R^2 field fitting	Mean Bias	RMSE	ME
Cumulative volume in large stems (≥50cm DBH)	$m^3\ ha^{-1}$	asymptotic $Y = \dfrac{a}{X} + b$	0.48	-54 m^3/ha	70 m^3/ha	0.95
Frequency of large stems (≥50cm DBH)	stems ha^{-1}	asymptotic $Y = \dfrac{a}{X} + b$	0.5	-1.16 stems/ha	18.5 Stems/ha	0.83
Cumulative volume in medium stems (25-50cm DBH)	$m^3\ ha^{-1}$	exponential decline $Y = \dfrac{a}{Exp(-bX)}$	0.59	-49 m^3/ha	143 m^3/ha	0.54
Frequency of medium stems (25-50cm DBH)	stems ha^{-1}	exponential decline $Y = \dfrac{a}{Exp(-bX)}$	0.7	-4.7 Stems/ha	49 Stems/ha	0.9
Standard Deviation of DBH*	cm	asymptotic $Y = \dfrac{a}{X} + b$	0.28	0.063 Cm	0.275 cm	0.98
CWD mass**	$Mg\ ha^{-1}$	asymptotic $Y = \dfrac{a}{X} + b$	0.21	8.47 Mg/ha	9.9 Mg/ha	0.72

*Model fit analysis was limited to year 180, prior to the establishment of additional cohorts following windthrow events.

** In this case model data was represented by a trend line fit to model output to smooth the abrupt changes due to disturbance regimes.

3.3.4 Frequency of large snags

The high degree of variability in large diameter snags (≥ 50 cm DBH) observed in the chronosequence field data (see Chapter 2) made direct comparisons of model output to field data trends difficult. As an alternative, chronosequence sites were grouped into discrete age classes for which average large snag frequency could be easily calculated and compared against model output. Error bars were calculated for chronosequence data using the equation Error=$\dfrac{\sigma}{\sqrt{N}}$, where σ is the standard deviation and N is the number of sites in age class. In the case of the old-growth age class, the error was calculated as a 95% confidence interval to be consistent with

presentation of other structural attributes. While the model showed an increase in the frequency of large snags with time (Figure 3.5), simulated values were consistently lower than field averages. In most cases the model was within the error of the field data.
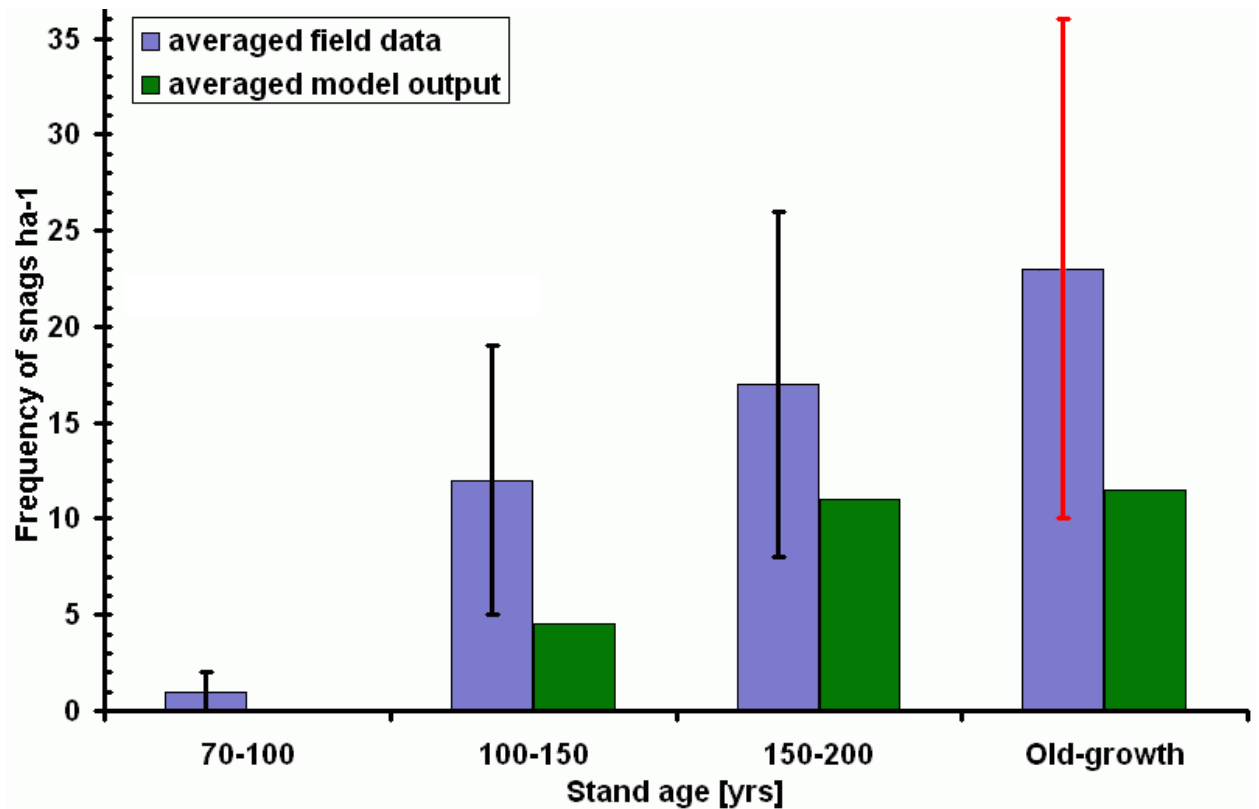
Figure 3.5 Average frequency of large snags ($\geq$50 cm DBH) in field sites grouped into age classes compared to model output. Residual snags were excluded as explained in the text. Old-growth has 95% confidence interval as an error bar, whereas other age classes have standard error of the mean bars. Simulated stand age class 200-300 were compared to old-growth field data.

3.3.5 Sensitivity analysis

Results from the sensitivity analysis are summarized for each variable examined.

1. Number of cohorts

During the model parameterization process it was determined that at least three cohorts in the stand initiation phase were required to achieve the range in stems sizes observed in the field data. The addition of a 4th cohort, as indicated in Table 3.1, had only a minimal impact on model evaluation variables.

2. Total number of seedlings regenerated

Changing the density at which seedlings regenerated had a significant impact on the long-term accumulation of volume in large diameter (>50 cm DBH) stems (Fig 3.6). As would be expected, the higher the stem density, the less volume accumulated in large live stems as the stand-level production was distributed over fewer larger stems. The opposite trend occurred for medium-sized stems. Quantities of CWD mass and the frequency of large diameter snags also declined with increases in regeneration density, but the changes were less pronounced. Nonetheless, the shapes of the graphs followed similar trajectories.
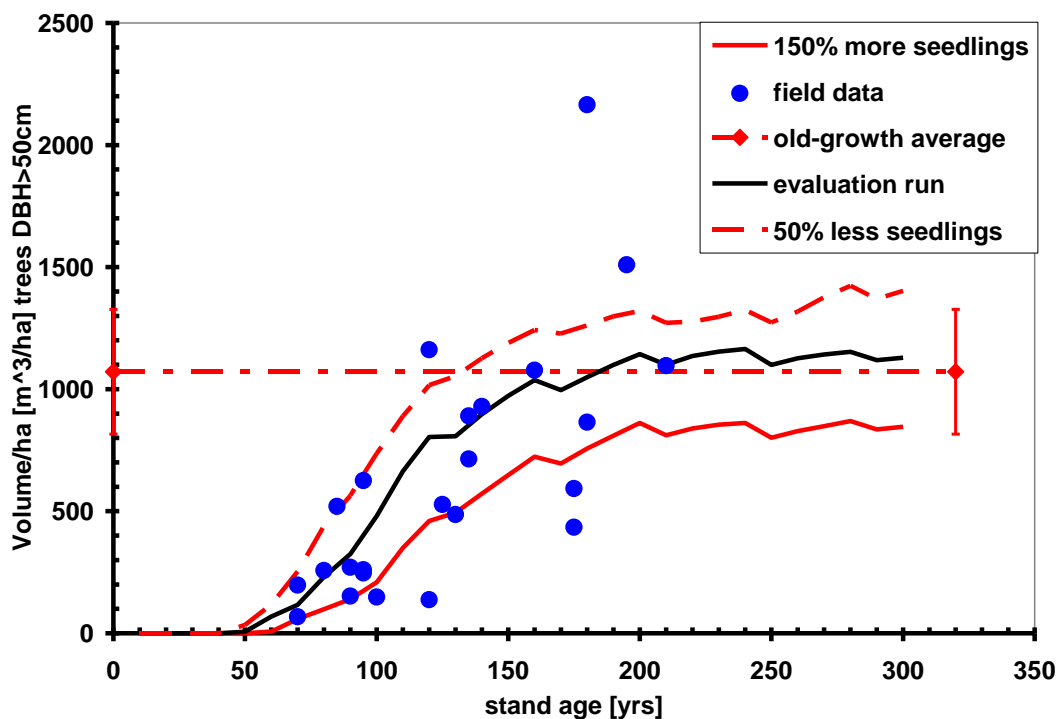
Figure 3.6 Comparison of model runs for different initial density of seedlings. Error bars for field data are omitted. The average for old-growth stands measured in the field study is also shown with the 95% confidence interval represented by the error bar.

3. *Timing of regeneration*

The evaluation of changes in the time between regeneration cohorts revealed that it had only minor to negligible impacts on all evaluation variables.

4. **Intensity of windthrow events.**

Results show that the model was quite sensitive to changes in the intensity (% of stems affected) of simulated windthrow events. Figure 3.7 demonstrates the effect of changing windthrow intensity on the relative accumulation of volume in large stems. Changes in windthrow intensity had a strong impact on the accumulation of CWD mass (e.g., increased intensity led to increased CWD, data not shown).
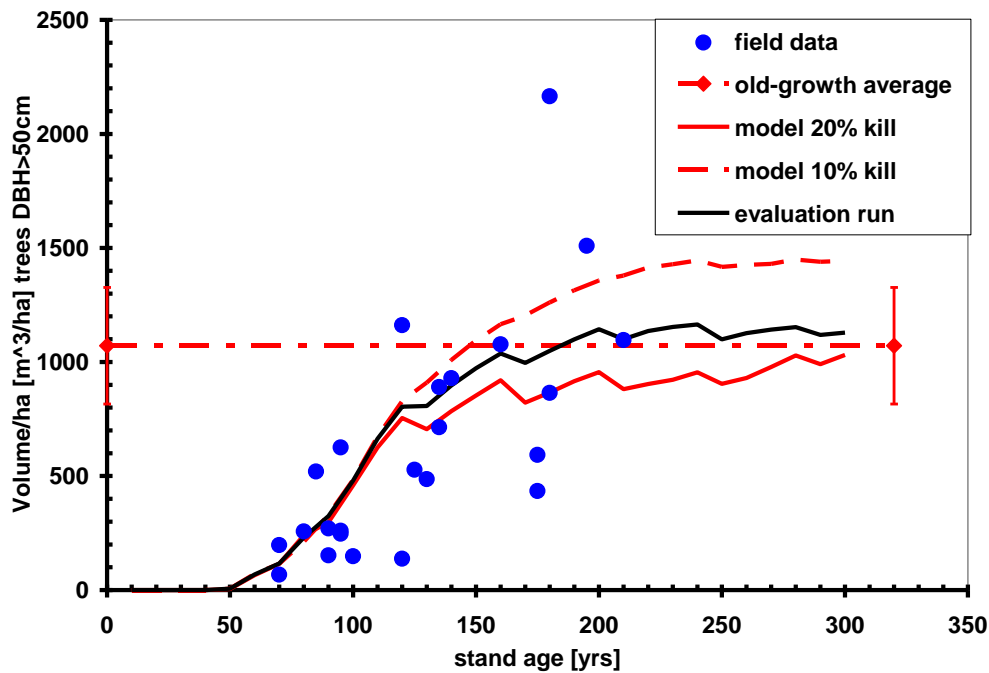
Figure 3.7 Comparison of large tree volume with different percentage of tree mortality. Error bars for field data are omitted. The average for old-growth stands measured in the field study is also shown with the 95% confidence interval represented by the error bar.

5. **Frequency of windthrow events**

Changes in the frequency of windthrow events by ±10 years had only a small impact on the cumulative volume and stem frequency by size class variables. Figure 3.8 illustrates the impact of changing the frequency of wind disturbance events on the total accumulation of CWD mass. Increasing the frequency of wind disturbance events led to increase of approximately 10 Mg ha^{-1}, on average, relative to the 40-year period used in the evaluation run. A similar but opposite pattern was found for CWD mass when the frequency was reduced to 50 years.
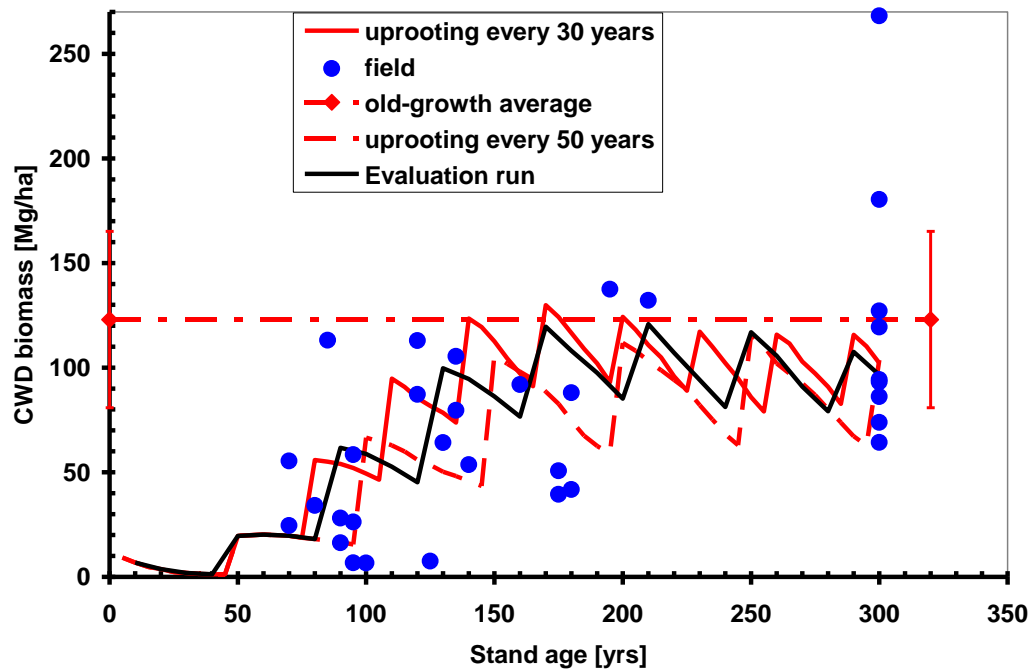
Figure 3.8 Comparison between 30 years and 50 years disturbance cycle length. Error bars for field data are omitted. The average for old-growth stands measured in the field study is also shown with the 95% confidence interval represented by the error bar.

3.4 Discussion

3.4.1 Model evaluation using chronosequence data

The two main types of data used for the evaluation of forest growth models are long-term data sets with repeated measures (e.g., Blanco et al. 2007, Pabst et al. 2008) and chronosequence data sets in which multiple sites spanning a range of ages are measured and used to construct a temporal growth sequence for a general site type (e.g., Purvesa et al. 2008). While the former provides the most robust evaluation of model performance for a specific site type and management/disturbance conditions, the use of chronosequence data for model evaluation provides a good measure of model performance for a general forest type at a local to regional scale. The evaluation of model output against data from a chronosequence study with multiple stands may use a different approach than the direct model-to-field-data comparison employed when using long-term datasets with repeated measures. Rather, the site-to-site variability associated with chronosequence data sets can involve the fitting of a functional curve to the field data with time as the predictor variable. The fitted curve then becomes the standard against which model output can be evaluated using statistical measures of goodness of fit.

With respect to this study, the considerable variability in the chronosequence field data was derived mainly from differences in regeneration patterns (timing and density of cohort establishment), and differences in disturbance histories (frequency and intensity of windthrow and other mortality agents) among chronosequence sites (see Chapter 2). The functional curves fit to the chronosequence data (see Table 3.4) were selected for evaluated variables using two criteria. The first and most important test was whether the curve made sense biologically based upon knowledge of how forest structure develops. The second test was the degree to which the age-dependent functional curve explained the variance in the data (indicated by an R^2 value). While most of the variables fit had a reasonably good R^2 values (near or >0.5), two variables, accumulation of CWD mass and standard deviation of DBH, showed relatively poor relationships with age (R^2 = 0.21 and 0.28, respectively). The causes and implications of these relationships are discussed in the context of the evaluation of model performance for specific structural variables presented below (section 3.4.2).

In contrast to the high variability observed in the chronosequence data, the model was set up to provide a single evaluation run that represents the 'average' regeneration and disturbance conditions that occurred within the chronosequence sites. Despite efforts to use field-based information to guide this process, the establishment of model parameters is always subjective to a certain degree. A sensitivity analysis can help to address the effect of changing model parameters on model behavior (see Section 3.3.5). We believe the approach used in this study of comparing the model results against functional curves fit to the chronosequence data provides a good measure of the capability of FORECAST to project the long-term development of structural attributes in second-growth coastal western hemlock stands.

3.4.2 Projection of the development of stand structure

FORECAST was able to project the long-term development patterns of most of the evaluated structural variables quite well as indicated by the predominantly high (>0.7) values for the ME statistic (Table 3.4). Moreover, the simulated temporal patterns in structural attribute development were biologically consistent.

Live tree volume and stem density by size class

With respect to measures of live-stem stand structure, the model performed well for large diameter stems (ME = 0.95 and 0.83 for cumulative volume and stem frequency, respectively) but not as well for medium diameter stems (ME = 0.54, and 0.9 for cumulative volume and stem frequency, respectively). The long-term temporal patterns of volume accumulation and stem

density by size class for live trees were consistent with other studies reported in the literature. Spies and Franklin (1988), for example, found that the cumulative volume and frequency of large trees in coastal Douglas-fir forests in the US Pacific Northwest increased with the age of the stand and stabilized when stands reached an old-growth condition. In the case of medium-sized (25-50 cm) trees, the model indicated a more complex pattern of an initial increase in cumulative volume and stem frequency followed by an exponential decline which began around age 70 and stabilized at a lower level as new trees began to grow in diameter during the understory re-initiation phase. The exponential decline in stem frequency of medium-sized trees was due to two distinct processes: tree mortality in stem exclusion phase and the increase of DBH size in living trees beyond 50 cm. The absence of stands younger than 70 years of age in the chronosequence prevented an evaluation of the long-term shape of the simulated trend for medium trees. However, the trend of an initial increase followed by a decline, as trees grow in diameter, was consistent with observations of medium-sized trees made by Wells (1996) in a broader chronosequence analysis in the CWH zone on Vancouver Island.

Standard deviation of stem sizes

The projected trend in the standard deviation of stem DBH (stems > 12.5 cm DBH) was highly consistent with the asymptotic curve fit to the chronosequence field data (ME = 0.98). However, as mentioned above, the field data showed a high degree of variability and only a weak relationship with stand age ($R^2 = 0.28$). The high degree variation in the chronosequence data was predominantly related to differences in regeneration timing and density among the chronosequence sites. Despite this variability, the comparison did provide a level of confidence in the model's ability to simulate a trend in tree size distributions that was consistent with field observations, at least in terms of slope and the width of the frequency distribution DBH size classes as indicated by the standard deviations. Further, the asymptotic shape of the simulated model output for standard deviation of DBH was consistent with trends reported in the literature (Van Pelt and Nadkarni 2004, Wells 1996).

Model output after year 170 showed that the introduction of new cohorts following simulated disturbance events can substantially increase the standard deviation of DBH (see Figure 3.3).

Quantity of CWD mass

The rate at which CWD accumulates in these coastal forests depends, to a large degree, on the history of wind disturbance in the area. As the chronosequence sites included in the analysis presented here were distributed across a wide geographic range in coastal Vancouver Island,

differences in local wind patterns would likely lead to differences in the frequency and intensity of windthrow events (see Chapter 2). These differences would ultimately translate into differences in CWD accumulation rates. While the fit of the asymptotic curve applied to the CWD field chronosequence data was relatively low ($R^2 = 0.21$), it still provided a reasonable estimate of an average trend in CWD mass accumulation as second-growth stands develop towards an old-growth condition.

Simulated patterns of CWD mass accumulation were also sensitive to changes in the frequency and intensity of simulated windthrow disturbances. The relatively good fit between the simulated CWD accumulation rate and the curve fit to the chronosequence data suggested that the assumptions regarding the wind disturbance parameters (see Table 3.1) were reasonably accurate.

From the multi-step shape of the simulated CWD curve (Figure 3.4) we can conclude that in real stands the amount of CWD mass fluctuates around a base accumulation rate that plateaus as the stand reaches an old-growth condition.

Frequency of large snags

Although the model simulated an increased abundance of large snags, projected frequencies were low in comparison to field data. Potential causes of the lower simulated snag numbers could include an over-estimation of snag decomposition and fall rates and/or an under-estimation of snag-creating mortality events. However, further sensitivity analysis showed that increasing mortality rates had only a short-term effect. Another explanation for the reduced numbers may be related to the relatively simple representation of snag fall in FORECAST. The model tracks the loss of hard mass in snags and triggers the transfer to a downed log when the hard mass remaining reaches a specified threshold (30% of stem mass at the time of tree mortality). The estimated threshold may be too high. The chronosequence data include snags as short as 1.3 m. As was noted in Chapter 2, half of the snags that were measured in the field had heights lower than 5 m. Thus, if shorter snags had been excluded, model output would be closer to field-measured values.

3.4.3 Limitations of the model evaluation

The model evaluation was limited to a relatively small set of structural variables. They represent only some of the aspects of the old-growth condition in forest ecosystems. Yet similar attributes have been used effectively in other studies (DeLong et al. 2004, Morgantini and Kansas 2003). It could be argued that the variables were chosen subjectively and that a different

set of cutoffs/variables would produce other results. Nevertheless, the set used in the current study was successful in representing continuous recovery of old-growth structure (see Chapter 2). While some stand attributes and structural variables may be helpful in differentiating between mature and old-growth stands, they are often less useful to quantify the transition period between these two stages of the forest (e.g., Spies and Franklin 1991, Franklin and Spies 1991b). The sensitivity analysis presented here was limited to narrow changes around optimal values of the simulation to provide an insight into precision of model performance. Wider analysis could have shown additional uncommon stand development trajectories. However, the focus of the research was to evaluate the model against development of an average stand.

A limitation of the field data (discussed in chapter 2) is the relatively small number of sites included in the analysis. It may have been possible to attain better results for the trend lines if more sites had been included. However, the variability of the data would still be high because of other individual parameters of each stand (Wells 1996). The sites in current study were not limited to specific slopes and aspects and thus varied in their susceptibility to disturbance agents such as windthrow (Scott and Mitchell 2005). Moreover, variation in timing and impact of low intensity disturbance regimes led to differences in deadwood accumulation among chronosequence sites that were similar in stand age.

While the results shown here provide confidence in the capability of the model to project the development of multi-cohort stands regenerated following a clearcut, the degree to which the model will be able to represent variable retention harvesting remains untested. The retention of live structure has been shown to influence stand growth dynamics. Remnant trees increase seed availability (Keeton 2000), cast shade and compete for water and nutrients (Aubry et al. 2009). Consequently, residual trees have positive and negative effects on regeneration of new cohorts. Although each of these processes is simulated in the model, the current evaluation did not address these conditions. It is generally difficult to obtain chronosequence data from partially harvested stands due to variability of harvest techniques used and the short history of such logging practices in North America. In the absence of such long-term data, mechanistic models can be used to explore alternatives, but their results should be interpreted with caution (Korzukhin et al. 1996).

3.5 Conclusions

This research presents a first attempt to evaluate FORECAST model for a period as long as 300 years for the coastal region of BC. It evaluated the capability of the model to project the development of old-growth structural characteristics as measured in a chronosequence study of

second growth coastal western hemlock sites along the west coast of Vancouver Island, BC (Chapter 2). Model performance was assessed by means of graphical inspection, statistical analysis and in terms of model consistency with ecological theory. The model followed theoretical trends and the field data with reasonable accuracy and model efficiency. The evaluation supports the use of the model to project and examine the recovery of old-growth structural attributes in second-growth forests. Additionally, it provides a level of confidence for the application of FORECAST to explore alternative variable retention scenarios (Chapter 4).

Collection of additional field data can improve model evaluation and add clarity to simulation of snags and tree mortality. For the time being, the lack of long-term studies of low-intensity disturbance events limits the ability of the model to properly simulate such disturbances. Further research is needed to clarify the subject and to improve model performance.

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Chapter 4. Exploring the implications of variable retention harvesting on the recovery of old-growth attributes in the context of multiple-objective management[3]

4.1 Introduction

In recent years variable retention (VR) harvesting has gained momentum and credibility in British Columbia (BC) and the Pacific Northwest of the US as a harvesting approach designed to meet the diverse goals of multi-objective forest management (e.g. Franklin et al. 1997, Clayoquot Sound Scientific Panel 1995, Arnott and Beese 1997). While traditional silviculture systems such as clearcut, shelterwood, etc. have generally focused on maximizing timber production and assuring future regeneration with target species, the fundamental objective of VR harvesting is to retain forest structural elements at the stand or harvest block level for at least one rotation to conserve environmental values associated with structurally complex forests (e.g. Mitchell and Beese 2002, Franklin et al. 2002). Benefits claimed for VR systems include greater connectivity of forest cover in managed landscapes, improved habitat suitability through the maintenance of key structural elements such as large-diameter live and dead trees and logs, enhanced carbon storage in managed forests, improved soil stabilization, and reduced visual impact from harvesting activities (e.g. Franklin et al. 1997, Bunnell et al. 2003).

Despite evidence of the short-term benefits of VR management, uncertainty remains with respect to the long-term impacts of VR on stand growth dynamics and ecological interactions. Past studies suggest that selective harvesting may alter regeneration patterns, change competitive interactions between species, and influence growth rates (e.g. Sullivan et al. 2009, Bowden-Dunham 1998, Thysell and Carey 2000). More recently, the short-term ecological effects (4-7 years after harvest) of VR harvesting were examined in mature Douglas-fir *(Pseudotsuga menziesii)* forests in Washington state as part of the Demonstration of Ecosystem Management Options - DEMO project (Aubry et al. 2009). Results from this study show significant differences in the amount of transmitted light, and soil and air temperatures between stands with varying levels of dispersed and aggregate retention. Higher levels of dispersed retention (40%) resulted in substantial declines in seedling growth rates (~50%) relative to areas with 15% or less retention. Survival rates of shade intolerant species were also reduced under retention. In general, residual trees gradually expanded their crowns into new openings reducing short-term gains in

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light penetration to the forest floor. VR harvesting may also increase the susceptibility of the residual trees to disturbance agents. Aubry et al. (2009) found that mortality of residual trees was higher in the 15% retention area due to wind disturbance and snow damage. Similar findings with respect to the influence of VR on residual mortality rates were reported by D'Anjou (2002).

Retained forest structure can be left in patches (aggregate retention) or can be left evenly distributed in the stand (dispersed retention). In the case of aggregate retention, entries into retention patches can be avoided, thereby reducing harvesting impact to the soil, coarse woody debris (CWD) and snags within these areas. Moreover, trees retained within aggregate groups tend to be less susceptible to windthrow than dispersed trees (Scott and Mitchell 2005), and due to aggregation tend to cast less shade on the newly regenerated trees in the openings (Battaglia et al. 2002). Conversely, dispersed retention generally provides greater connectivity of forest habitat important for species with low dispersal capabilities (e.g. epiphytes – Sillett et al. 2000), provides more evenly distributed refugia habitats for below-ground ecosystem components (e.g. mycorrhizal associations - Luoma et al. 2006), and serves as distributed source of deadwood.

In the coastal western hemlock zone (CWH) of BC, there are many factors ranging from pre-harvest conditions, to species interactions and specific management objectives, which must be carefully considered when designing and implementing VR management systems. With respect to pre-harvest conditions, forests in this region can generally be divided into two distinct groups: 1) old-growth forests with high levels of structural diversity and lower levels of net primary productivity, and 2) second-growth stands derived from clear-cut harvesting with high levels of net primary productivity, but lower structural diversity (see Chapter-2). Target retention levels under these initial stand conditions will vary depending on management objectives. For example, in a modelling study, Fraser et al. (2007) found that lower levels of dispersed retention (≤15%) were required in second-growth stands to achieve reasonable survival and growth of regenerated trees. In contrast, when starting from an old-growth condition, reasonably high levels of production could be achieved from regenerating trees established under dispersed retention levels up to 40%. The difference between the two conditions was the greater vigour of the younger retained stems in the second-growth stands, which allowed them to expand crowns and close canopy quickly thereby limiting light availability for regenerating trees. The opposite trend was observed when the objective of retention was to maintain a supply of large diameter snags and coarse woody debris. In this case the larger trees and greater CWD loads in the old-growth stands, allowed for higher levels of structural diversity relative to the VR stands originating from a second-growth condition.

The gradual transition to VR harvesting in coastal BC has implications for the conservation and recruitment of old-growth forest, which has been identified as a key management objective in the region (Ministry of Forests and Range 2004). Currently, the province defines old growth in the coastal region as stands that are greater than 250 years in age. As discussed in chapter 2, this age-based definition of the old-growth condition is not compatible with the multi-aged conditions generated through the application of VR harvesting. Alternatively, a set of structural attributes was identified and evaluated in the context of chronosequence data for use as indicators of the degree of recovery of old-growth structural conditions in managed stands (Chapter 2). In this chapter we employ these indicators to evaluate the implications of alternative dispersed retention scenarios on the recovery of old-growth structural conditions using the mechanistic forest growth model FORECAST (Kimmins et al. 1999). FORECAST was designed to explore the ecological and economic implications of a wide variety of stand management scenarios. The model has been calibrated for the CWH zone and verified with respect to its ability to project the temporal trends in structural development in western hemlock dominated forests using chronosequence data from a series of second-growth and old-growth stands distributed throughout the coastal region of BC (Chapter 3). To ensure a more realistic evaluation with potential for providing useful insight for forest managers, the modelling exercise includes a trade-off analysis with a range of indicators of sustainable forest management.

4.2 Methods

4.2.1 Ecosystem description

The focal forest ecosystem for the modelling exercise is the CWH biogeoclimatic zone on Vancouver Island, BC, Canada. Specifically, the model was calibrated to represent the very wet maritime (vm1) and very wet hypermaritime (vh1) variants as described by Green and Klinka (1994). The elevation range of the CWHvh1 variant is 0-200 m above sea level. It has a cool climate with low snowfall. Mean annual precipitation is 3120 mm; mean May to September precipitation is 617 mm/year; total mean annual snowfall is 450 mm; mean annual temperature is 9.1ºC with a frost free period of 229 days/year. The CWHvm1 variant generally occurs above the CWHvh1 variant at 200-650 m above sea level. It has a very wet, humid climate. Mean annual precipitation is 2682 mm; mean May to September precipitation of 611 mm/year; total mean annual snowfall of 1950 mm; mean annual temperature of 8.3 ºC with a frost free period of 199 days/year. Soil types in both variants are primarily Humo-Ferric or Ferro-Humic Podzols originated from morainal parent material (Soil Classification Working Group 1998). Major

stand-replacing disturbances are rather rare (every 1400-20,000 years). Thus, much of the area undisturbed by human activities in these variants is in the old-growth phase (Price and Karen 2003).

The predominant species in these forests is western hemlock (*Tsuga heterophylla*) with a lesser amount of western redcedar (*Thuja plicata*) and amabilis fir (*Abies amabilis*). Some sites also include Douglas-fir (*Pseudotsuga menziesii*), Sitka spruce (*Picea sitchensis*), shore pine (*Pinus contorta var. contorta*) and red alder (*Alnus rubra*). Saplings of western hemlock, amabilis fir and western redcedar are commonly found in the understory with hemlock and amabilis being more numerous. Other minor species of vegetation are listed in the Field Guide for Vancouver Forest Region (Green and Klinka 1994) and in MacKinnon (2003).

4.2.2 Model description

FORECAST is a management-oriented, stand-level forest growth and ecosystem dynamics simulator. A detailed description of the FORECAST model is provided in Kimmins et al. (1999) and Seely et al. (1999). Therefore, only a summary is provided here. The model was designed to accommodate a wide variety of harvesting and silvicultural systems and natural disturbance events (e.g. fire, wind, insect epidemics) in order to compare and contrast their effect on forest productivity, stand dynamics and a series of biophysical indicators of non-timber values. Projection of stand growth and ecosystem dynamics is based upon a representation of the rates of key ecological processes regulating the availability of, and competition for, light and nutrient resources (Figure 4.1) (a representation of moisture competition is being completed but was not included in this study; since soil moisture is generally not a significant limiting factor on zonal sites in the study area this is not thought to invalidate the simulations). The rates of these processes are calculated from a combination of historical bioassay data (biomass accumulation in component pools, stand density, etc.) and measures of certain ecosystem variables (decomposition rates, photosynthetic saturation curves, for example) by relating 'biologically active' biomass components (foliage and small roots) with calculations of nutrient uptake, the capture of light energy, and net primary production. Using this 'internal calibration' or hybrid approach, the model generates a suite of growth properties for each tree and understory plant species that is to be represented. These growth properties are subsequently used to model growth as a function of resource availability and competition. They include (but are not limited to): (1) photosynthetic efficiency per unit foliage biomass and its nitrogen content based on relationships between foliage nitrogen, simulated self-shading, and net primary productivity after accounting for litterfall and mortality; (2) nutrient uptake requirements based on rates of biomass

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accumulation and literature- or field-based measures of nutrient concentrations in different biomass components on different site qualities; (3) light-related measures of tree and branch mortality derived from stand density input data in combination with simulated light profiles. Light levels at which foliage, branch and tree mortality occur are estimated for each species from this internal calibration. FORECAST performs many calculations at the stand level but it includes a sub-model that disaggregates stand-level productivity into the growth of individual stems with user-supplied information on stem size distributions in even-age stands at different stand ages. Top height and DBH are calculated for each stem and used in a taper function to calculate total and individual gross and merchantable volumes. Snags and logs are created in the model from natural stand self-thinning and from different types of user-defined disturbance events such as insect or disease-induced mortality, windthrow, and non-commercial thinning. Snag fall rates and log-decomposition are simulated using species-specific and tree-size-specific decay parameters derived from literature reviews and expert opinion.

FORECAST has four stages in its application (Blanco et al. 2007): 1) data assembly and input verification; 2) establishing the ecosystem condition for the beginning of a simulation run (by simulating the known or assumed history of the site); 3) defining a management and/or natural disturbance regime; and 4) simulating this regime and analyzing model output. The first two stages represent model calibration. Calibration data are assembled that describe the accumulation of biomass (above and below-ground components) in trees and minor vegetation for three chronosequences of even-aged, single-species stands, representing three different nutritional qualities. Tree biomass and stand self-thinning rate data are often generated from the height, DBH and stand density output of traditional growth and yield models in conjunction with species-specific component biomass allometric equations. To calibrate the nutritional aspects of the model, data describing the concentration of nutrients in the various biomass components are required. FORECAST also requires data on the degree of shading produced by different quantities of foliage and the photosynthetic response of foliage to different light levels. A comparable but simpler set of data for minor vegetation must be provided if the user wishes to represent this ecosystem component. Lastly, data describing the rates of decomposition of various litter types and soil organic matter are required for the model to simulate nutrient cycling. The second aspect of calibration requires running the model in "set-up" mode to establish initial site conditions. The detailed representation of many different litter types and soil organic matter conditions makes it impractical to measure initial litter and soil conditions directly in the field; consequently, the model is used to generate starting conditions.

Figure 4.1. Illustration of key processes simulated in FORECAST.

4.2.3 Model application

In Chapter 3, FORECAST was calibrated for the CWH zone on Vancouver Island and successfully evaluated with respect to its ability to project the development of old-growth structural attributes in second-growth stands derived from clearcut harvesting. The objective the modelling exercise presented here is to use the calibrated model to explore the long-term implications of VR harvesting with varying levels of dispersed retention on the maintenance and recovery of old-growth structural attributes and indicators of other forest values in the context of multi-objective forest management. To examine the influence of starting condition on model results, the dispersed retention scenarios were simulated for two representative starting conditions including a productive second-growth stand derived from clearcut harvesting and an old-growth stand with multiple age cohorts and lower levels of productivity (Figure 4.2). The second-growth starting condition was generated by simulating the regeneration and growth of a

western hemlock stand for 80 years following a clearcut harvest. The old-growth stand was simulated starting with natural regeneration following a clearcut and was grown for 250 years. Each of the simulations to generate starting conditions included a representation of a minor (non-stand-replacing) disturbance regime including mortality events from pests, disease and windthrow events (see Table 4.1). This disturbance regime, important for the recruitment of snags and coarse woody debris, was the same as that represented in the model evaluation demonstrated in Chapter 3.
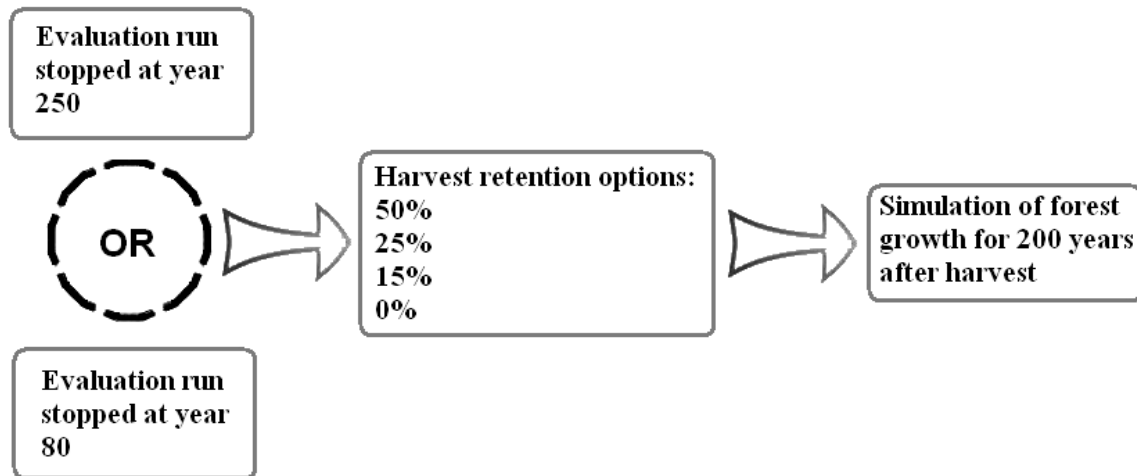
Figure 4.2. Flowchart of the simulation. First, two different initial conditions were generated by stopping the Evaluation run at 80 years and 250 years. Then a series of simulations were conducted for each starting condition in which the stands were harvested at four levels of retention, and subsequent stand development simulated for a 200-year post-harvest period.

The dispersed retention scenarios simulated for both starting conditions included four different levels of retention (% of stems·ha^{-1}): 50%, 25%, 15%, and 0% (clearcut) with the harvest occurring in year 1 of the simulation. Each simulated harvest removed an equal percentage of trees in every simulated cohort and in every size class of trees. Hence, the retention defined using stems per hectare should be relatively equivalent to retention defined as percentage of volume or basal area. Logs and other CWD were be retained on site during all harvest events. All snags were felled during clearcut harvest, but all were retained on the site in the case of dispersed retention harvests. Post-harvest tree regeneration was represented as natural regeneration as defined in Table 4.1. Establishment densities for natural regeneration simulated in the model were within the range of the BC provincial stocking standards for these forest types (BC Ministry of Forests and Range 2000). To limit model artifacts associated with different assumptions of regeneration density, simulated natural regeneration rates were kept the same for all scenarios. The mortality rate of regenerated seedlings is simulated in FORECAST as a

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function of light availability and nutrient competition. In the dispersed retention scenarios, suppressed understory trees left from the harvest represented advanced regeneration.

The disturbance regime applied for the establishment of initial conditions (Table 4.1) was also applied for the dispersed retention and clearcut simulations. The frequency and intensity of these disturbances were based on literature reports (e.g. Lertzman et al. 1996) and expert opinion (personal communication, Dr. Steve Mitchell). Windthrow events were simulated with a frequency of 40 years and a blow-down rate of 10%. Disease and insect related mortality was applied to all cohorts and tree size classes with a frequency of 20 years and 3% mortality rates.

Table 4.1. Model parameters describing assumptions for natural regeneration and simulated natural disturbance events.

Model variable	Value	Remarks
Total simulation time	200 years	
Vegetation simulated	Western hemlock, Vaccinium shrub	
Shrub regeneration at first years: percent of maximum occupation	20%	
Number of cohorts	8	Five cohorts are left from post-harvest forest and additional three new cohorts represent natural regeneration after harvest. (Clearcut simulation is represented by three regenerated cohorts only.)
Stem·ha^{-1} regenerated	600, 400, 400	For new cohorts 1-3 respectively
Year of cohort establishment	1, 11, 21	For new cohorts 1-3 respectively
Windthrow	The disturbance is applied once in every 40 years and affects 10% of the trees.	Impacts trees older than 40 years
Disease and insect related mortality	The disturbance occurs with a frequency of 20 years. During this interval 3% of the trees are being killed.	Impacts trees older than 40 years.

4.2.4 Evaluation of model output

FORECAST output from the dispersed retention scenarios was evaluated using the old-growth structural indicators defined as part of the chronosequence study presented in Chapter 2. Old-growth thresholds were defined for each indicator based upon its average value in old-

growth sites with a 95% confidence interval. These indicators included: cumulative volume of large stems (DBH > 50 cm), frequency of large stems (DBH>50cm), standard deviation of stem sizes (only for stems with DBH > 12.5 cm), accumulation of CWD mass and frequency of large snags (DBH > 50 cm) (Table 4.2). In addition, model output for volume harvested and ecosystem carbon storage were examined as economic indicators to facilitate a broader trade-off analysis.

Graphs from model output were produced to show the temporal trends in the recovery of specific structural attributes under the alternative retention scenarios and the general effect of starting condition. Additional graphs with multiple indicators were generated for a series of time steps following harvest (10, 40, and 80 years) for both starting conditions to illustrate the potential value trade-offs associated with the varying levels of dispersed retention.

Table 4.2. Model output for structural variables used in model simulation. Criteria for inclusion in specific indicator are shown.

Test Variables	Criteria	Indicator type	Units
Cumulative volume in large stems	≥50 cm DBH	OG structure/habitat diversity	$m^3 \cdot ha^{-1}$
Frequency of large stems	≥50 cm DBH	OG structure/habitat diversity	$stems \cdot ha^{-1}$
Standard deviation of stem diameters (SD of DBH)	≥12.5 cm DBH	OG structure/habitat diversity	cm
CWD mass	The entire CWD	OG structure/habitat diversity	$T \cdot ha^{-1}$
Frequency of large snags	≥50 cm DBH	OG structure/habitat diversity	$stems \cdot ha^{-1}$
Volume harvested	Merchantable volume (includes an age-based correction for waste and breakage, 5% loss per 100 years)	Economic value	$m^3 \cdot ha^{-1}$
Ecosystem carbon storage	Total carbon in live and dead structure including soil	Economic value	$T \cdot ha^{-1}$

4.3 Results

4.3.1 Long-term effects of dispersed retention harvesting on structural attributes

Large live structure

As would be expected, for the first 50-60 years following harvest, greater levels of retention led to increases in large live stems for both starting conditions (Fig 4.3). Interestingly, the rate at which the indicators of large live structure recovered towards the old-growth thresholds was greater when starting from the second-growth condition. The reason for this was a combination of the fact that there were more stems in total in the second-growth starting condition and that the younger retained trees within the second-growth condition responded more vigorously to release from competition. In the case of the old-growth starting condition, the indicators of large live structure begin to recover more quickly after approximately 50 years when the regenerated trees began to reach diameters of 50 cm.

The length of time required to reach the old-growth threshold (as defined by the minimum old-growth confidence interval) was similar for all dispersed retention scenarios when starting from the old-growth condition (approximately 90 years for frequency of large stems, and 120 years for volume of large stems), although the 50% retention stand took longer than other retention levels to recover to the old-growth average (135 years comparing to 100). When starting from the second-growth condition, the time required for recovery of indicators of large-live structure to the minimum of old-growth confidence interval varied from 90 to 140 years.

Although the higher retention scenarios tended to recover towards the old-growth thresholds more quickly, over the long-term the indicators of large live structure reached higher levels in the lower retention and clearcut scenarios (Fig. 4.3). The main reason for this was the increased suppression of regenerated trees in the higher retention scenarios caused by higher levels of shading from retained trees. This effect was more pronounced when starting from the second-growth condition as the younger, more vigorous trees closed canopy more quickly following the harvest events relative to the old-growth starting condition.
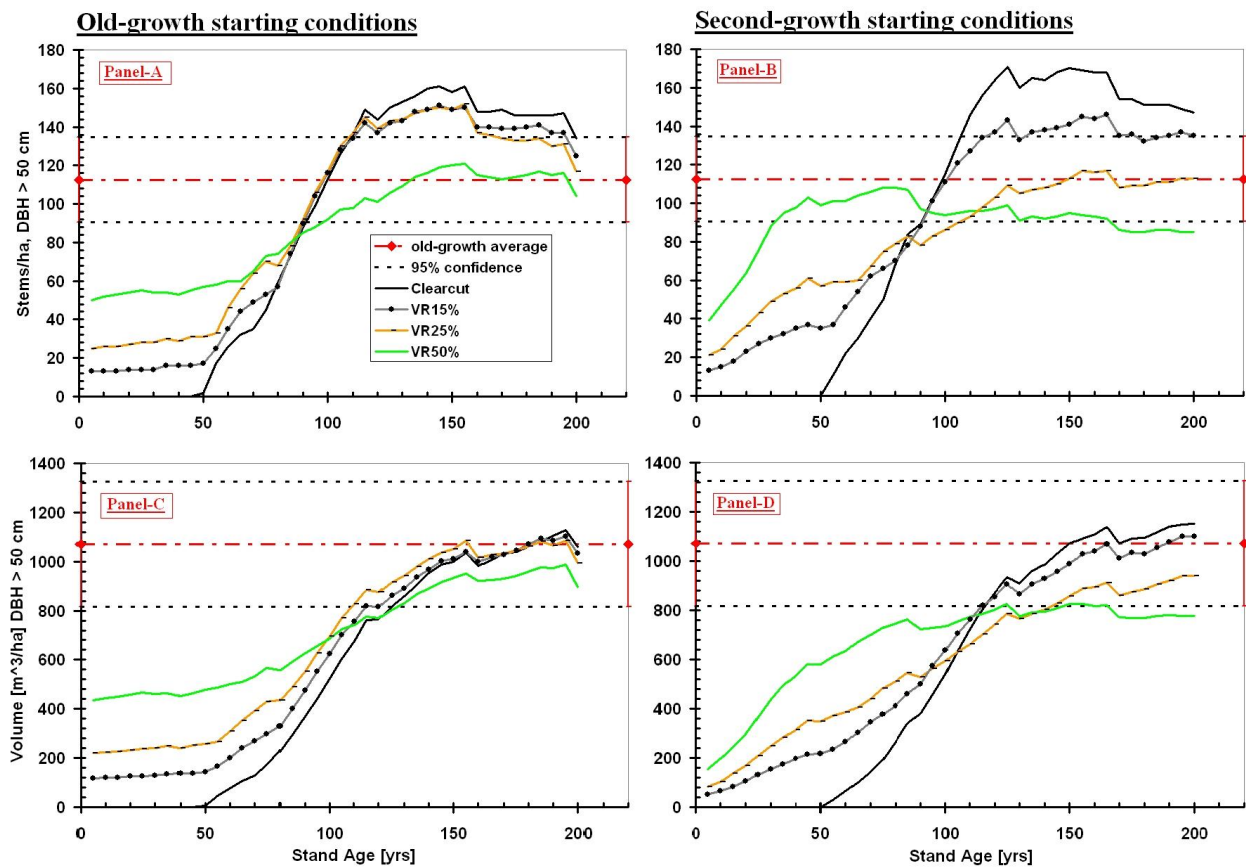
Figure 4.3 Long-term trends in large live structure under alternative dispersed retention levels for two different starting conditions. Panels A and B show the frequency of large live stems (>50 cm DBH) for the old-growth, and second-growth starting conditions, respectively. Panels C and D show the cumulative volume in large live stems (>50 cm DBH) for the old-growth, and second-growth starting conditions, respectively.

Large snags and CWD

For the first 90 to 100 years following harvesting, the frequency of large diameter snags (>50 cm DBH) was highest by far in the 50% retention scenario with the old-growth starting condition showing a declining trend and the second-growth condition showing an increasing trend (Fig 4.4, Panels C & D). The clearcut scenarios required approximately 80 years before any significant accumulation of large diameter snags occurred. In all harvesting scenarios, it took more than 150 years for the frequency of large diameter snags to reach the old growth threshold and none reached the average level for old-growth stands during the 200-year simulation period.

Coarse woody debris levels were strongly influenced by starting condition, with the old-growth starting condition showing levels of CWD that were within or near the old-growth threshold for much of the simulation period (Figure 4.4, Panel A). The saw-tooth-shape of the CWD graphs was the result of the wind disturbance regime imposed for each simulation (see

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Table 4.1). When starting from the second-growth condition, it took more than 100 years for CWD levels to reach the old-growth threshold (Fig. 4.4, Panel B). In both starting conditions, higher retention levels generally led to small increases in CWD mass.
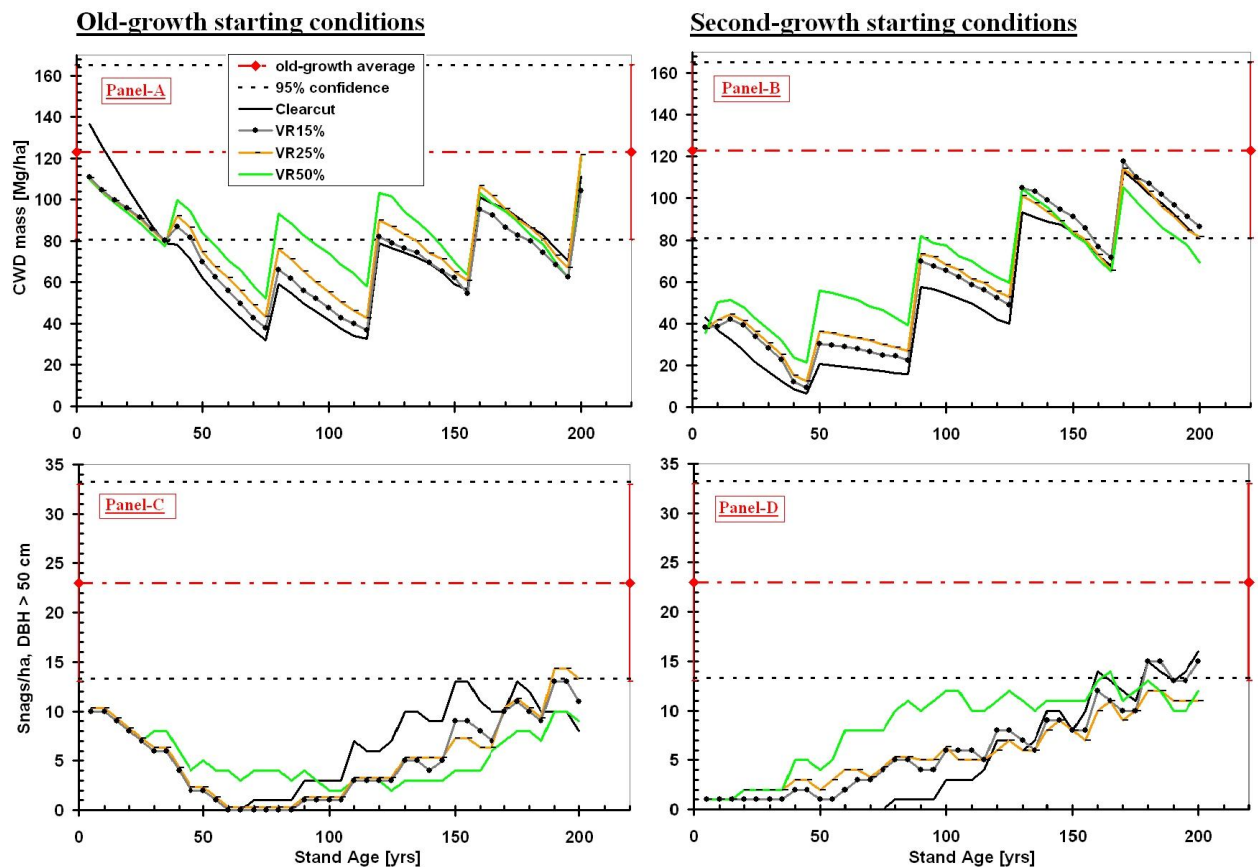
Figure 4.4. Long-term trends in dead wood for 200 years post-harvest under alternative dispersed retention levels for two different starting conditions. Panels A and B show the cumulative CWD mass for the old-growth, and second-growth starting conditions, respectively. Panels C and D show the frequency of large snags (>50 cm DBH) for the old-growth and second-growth starting conditions, respectively.

Stem size diversity

The retention of trees in the dispersed retention scenarios led to substantially higher levels of stem size diversity relative to the clearcut scenarios in both starting conditions (Fig. 4.5). However, the level of retention had only a minor impact on stem size diversity as measured by the SD of DBH (stems > 12.5 cm DBH). When starting from an old-growth condition, SD of stem DBH remained close to the old-growth minimum of confidence interval for approximately 20 years following harvest after which it declined steeply as large numbers of regenerated trees

began to reach the 12.5cm DBH limit effectively reducing this measure of diversity. A similar decline occurred around year 30 in the second-growth starting condition. In both starting conditions, it took approximately 200 years for this measure of stem size diversity to recover to the old-growth threshold.
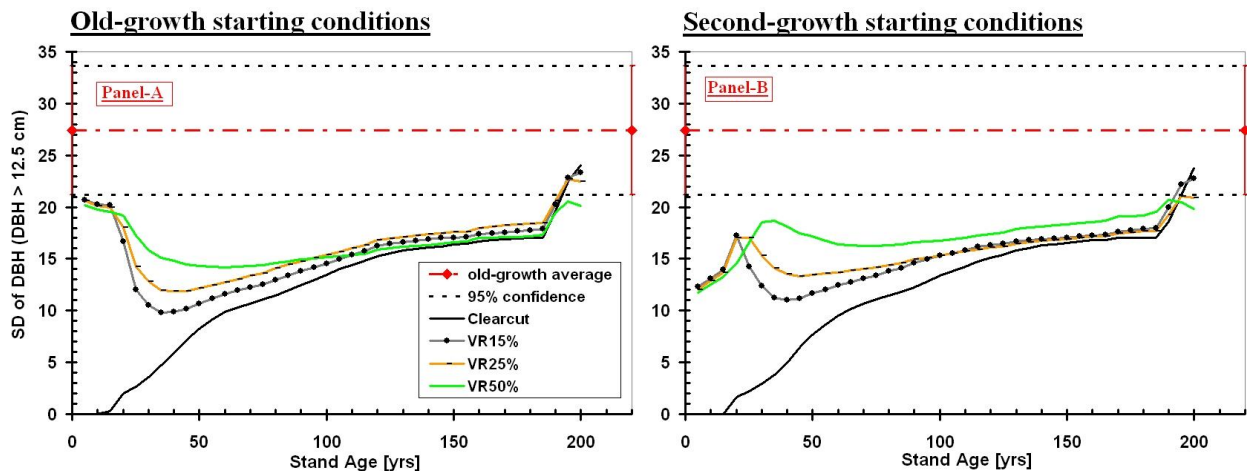
Figure 4.5. Long-term trends in stem size diversity under alternative dispersed retention levels for two different starting conditions. Panels A and B show the SD of stem DBH (trees > 12.5 cm DBH) for the old-growth, and second-growth starting conditions, respectively.

4.3.2 Trade-off analysis

To facilitate the value tradeoff analysis, each of the simulated indicator variables was converted to a relative value (between 0 and 1) by dividing the values by the maximum value for that variable for all time steps, starting conditions, and retention level combinations. Figure 4.6 shows the relative effect of retention level on each of the indicator variables for three points in time (10, 40, and 80 years) following the initial harvest event. A positive slope indicates a benefit of increasing retention on a specific indicator while negative slope indicates the opposite.

By definition, the amount of volume harvested decreased linearly with retention level. As described above, the level of retention had only a minor positive impact on the maintenance of CWD levels, particularly when starting from old-growth conditions. Like CWD mass, the frequency of large diameter snags consistently increased with the level of retention.

Increases in retention level showed a strong positive relationship with ecosystem carbon storage in the first 40 years following harvest regardless of starting condition. However, the difference in total ecosystem carbon storage among different retention levels had declined

substantially by year 80 as the biomass of regenerating stems began to offset that stored in retained stems. This result indicates that while high retention has a positive influence on total ecosystem carbon storage in the short to mid term, net ecosystem carbon uptake rates (sequestration) are higher in the long-term for lower retention systems.

Stem size diversity was perhaps the least responsive of the variables examined to changes in the level of retention. While any level of retention had a substantial positive influence on the SD of stem diameter relative to clearcuts, there was little or no positive effect of increased retention.
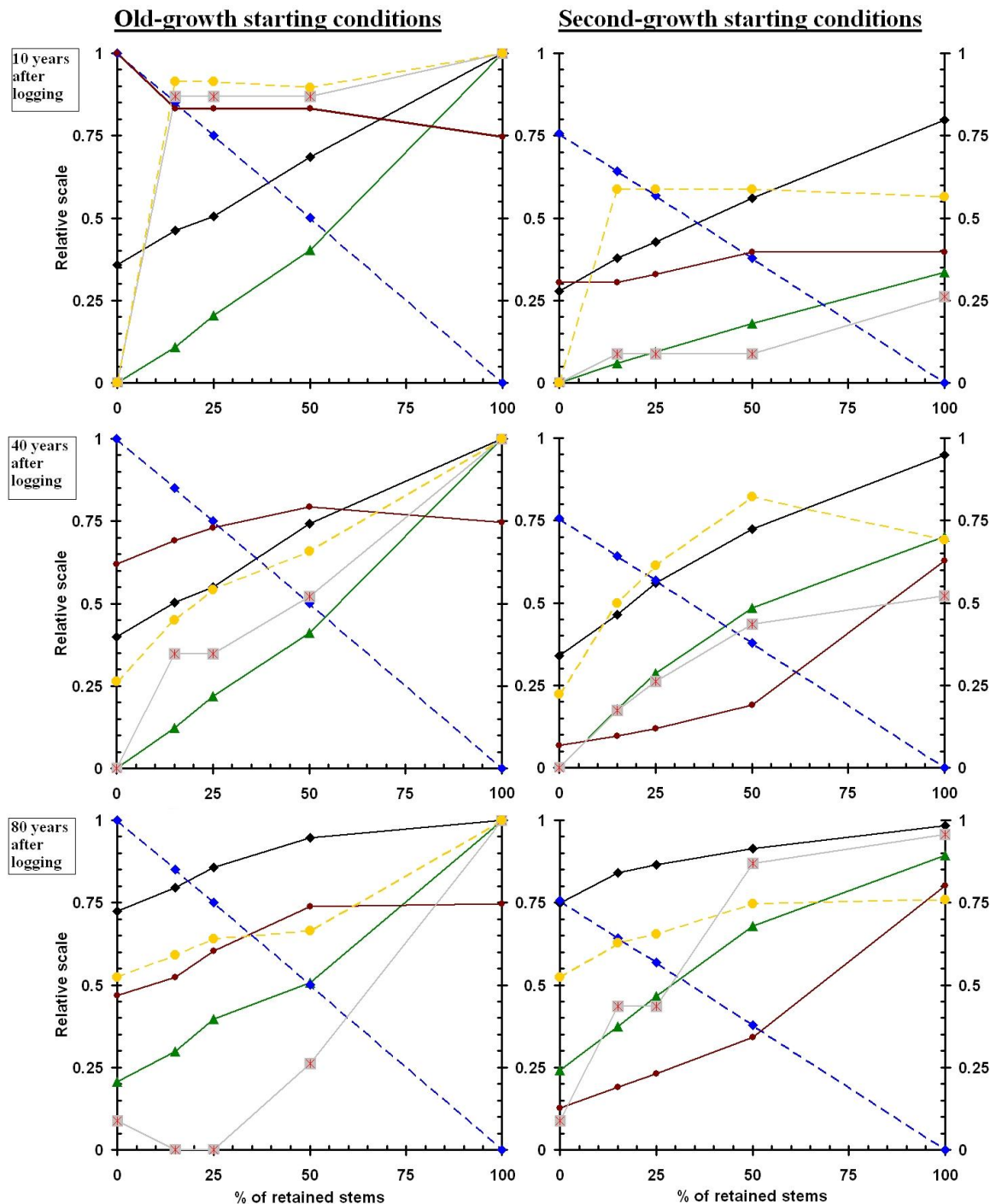
Figure 4.6. Trade-off analysis showing the effects of increasing levels of dispersed retention on relative values for total harvested volume, large live structure, coarse woody debris mass, frequency of large live snags and total ecosystem carbon storage. Panels on the left show the trends when starting from an old-growth condition (age = 250 years) and those on the right show trends when starting from a second-growth condition (age = 80). Data are shown for three time periods following harvest (10, 40 and 80 years). The Y-scale on each graph is relative to the maximum value of the attribute. Hence, values from all the graphs can be compared among them.

4.4 Discussion

The primary objective of this chapter is to evaluate the degree to which different levels of dispersed retention could potentially mitigate the impacts of harvesting on the maintenance and development of a suite of old-growth structural attributes in coastal western hemlock forests. We also set out to explore the effect of ecosystem starting condition on these impacts and their temporal trends. Finally, we sought to consider the results in the context of indicators of other forest values to facilitate a tradeoff analysis. While the focus of forest management in coastal BC has shifted away from a focus solely on timber production to accommodate other forest values, it is clear that economic viability remains a key factor for the survival of the coastal forest industry and the social benefits derived from its existence. Thus, the maintenance of the production of round wood and high quality timber and non-timber products from these forests is critical. More recently, with the threat of climate change and efforts to reduce and offset greenhouse gas emissions, the value of forests as carbon sinks has been recognized. As policy and markets develop there is the increasing potential for the use of forest ecosystems to generate marketable carbon offsets through conservation and improved forest management (e.g. Greig and Bull 2009). This prospect of generating income from carbon offsets has the potential to provide a complimentary or alternative source of revenue over and above timber products (e.g. Depro et al. 2008; Seidl et al. 2007). All of these factors have made the management of coastal forest ecosystems from stands to landscapes increasingly complex. Models such as FORECAST can help to provide insight for such tradeoff analyses.

4.4.1 Use of dispersed retention to maintain and accelerate the development of structure in harvested stands

Dispersed retention harvesting has been developed and implemented primarily as a method for maintaining structural complexity within a harvest block to provide habitat for wildlife and to reduce the negative aesthetic impact of timber harvesting (Burton et al., 1999, Mitchell et al., 2001). The simulation results presented here suggest that it is possible to maintain and recruit structural elements for prolonged time periods using dispersed retention. However, the degree to which such structural elements are maintained depends both on the condition of the pre-harvest stand and on the level of retention. It should also be noted that even the highest levels of retention led to declines in structural indicators relative to thresholds based on measurements in regional old-growth stands (See chapter 2).

Simulation results show that increased levels of retention provide the most benefit with respect to structural variables during the first 50 to 90 years following harvest after which differences declined and in some cases the lower retention levels began to exceed those for higher initial retention levels. As described above the reason for these increased levels in the lower retention scenarios in the long-term was related to reduced competition for regenerating stems. The potential benefits of dispersed retention for the maintenance of large diameter snags are likely overstated in these simulation scenarios as we assumed that all existing snags at the time of harvest would maintained within the cutblock. In reality, current safety regulations in BC stipulate that standing snags must be felled prior to harvesting to avoid injury. The use of aggregate retention patches could reduce the loss of standing snags as workers would not have to enter these areas.

Starting condition appeared to have the largest impact on patterns of CWD and the frequency of large diameter snags. The old-growth starting condition had a much more pronounced biological legacy for these two variables which tended to begin high but slowly decline for several decades. In contrast, CWD started much lower in second-growth stands but climbed steadily for all retention levels. Interestingly, for the majority of the structural variables examined, the total time required to recover to the old-growth threshold based on the 95% confidence interval was not reduced in the dispersed retention scenarios relative to the clearcut scenario. The only exception for this was in the case of CWD (50% retention and old-growth starting condition) and in the case of the frequency of large live stems (%50 retention and second-growth starting condition). These results suggest that the main value of the dispersed retention is to reduce the impact of harvesting on stand structure in the short to mid-term as opposed to accelerating the long-term recovery of stands to reach an old-growth structural condition.

4.4.2 Management Implications

The goal of multi-objective forest management is to provide a wide range of forest values including timber production, habitat availability, old-growth representation, carbon storage, recreation, etc. from a single landbase. This is not to suggest that each of these values should be represented in every stand unit all of the time, but rather that the stands that make up the landbase should account for the full range of values. A zonation approach in which specific parts of a landbase are managed to meet specific resource objectives can work well in some regions (e.g. Seymour and Hunter 1999), particularly when intensive forest management for timber

production is included. However, in coastal BC and other similar regions with large areas of publicly owned forest land, an extensive forest management model has been adopted. This extensive management model in combination with public pressure to reduce clearcut harvesting, has gradually forced the regional forest industry towards the use of harvesting systems such as variable retention that address multiple objectives within a single stand or cutblock.

If we assume that once harvested with specific retention level the stand will be left for an entire rotation, the higher levels of retention will likely have a significant impact on harvest yields. While the harvest of additional areas could offset these losses, there are other issues that emerge from expanded harvest areas including higher road densities, increased landscape fragmentation, increased transportation costs, and greater green house gas emissions from logging activities (Seely et al 2004, Crow and Gustafson 1997). Another factor that must be considered is the availability of volume for harvest in subsequent rotations. If the retained structure is assumed to be 'hard retention' that will be left indefinitely, future harvests must come from trees regenerated following the initial harvest. Fraser et al. (2007) showed that higher levels of dispersed retention, particularly in second-growth stands, can substantially inhibit the growth of regenerating stems such that there would be insufficient volume available for harvest at the next rotation. The use of aggregate retention systems may reduce the impacts of retained structure on the growth of regenerating stems but its relative impact will depend on several factors including patch size, spatial arrangement and light requirements of regenerating species (e.g. Aubry et al 2009). The probability of post harvest windthrow is another factor that must be considered in determining retention levels and patterns (Scott and Mitchell 2005).

The inclusion of forest carbon management as an alternative or complementary source of income may influence the relative weighting of dispersed retention scenarios from an economic perspective. Based on the simulations ecosystem carbon storage, particularly in the first 40 to 80 years following harvest, showed a strong positive correlation with retention level. This increase in carbon storage, if maintained at a landscape scale, could be used as the foundation for a forest carbon project aimed at generating saleable carbon offsets. To meet the standards required for eligibility, the proponents of such a project would have to prove additionality (that the proposed management is different than what would have been done without the carbon project) and that leakage (transfer of avoided volume harvest to other areas and/or increased emissions from product substitution) would be accounted for (Voluntary carbon standard 2008). This type of management for multiple revenue streams has the potential to enhance the overall profitability from the forest resource while also providing for greater retention of structural attributes. The

lost value from volume in retained trees can be compensated by income generated through the production of carbon offsets. The degree to which carbon offsets and timber are emphasized will depend on market prices and other economic and ecological factors.

The results of this study suggest that use of variable retention harvesting can help to mitigate the effects of harvesting on the maintenance of old-growth structural attributes including large live trees, large-diameter snags, CWD and stem size diversity. While all levels of simulated harvesting led to reductions in structural attributes to below threshold levels based on measurements in old-growth sites, most of the structural variables evaluated increased with increasing retention for 50 to 90 years following harvest. The effect of increasing retention levels was greatest for the maintenance of large live stems, followed by large diameter snags, stem size diversity and CWD. As described above, the simulations show that the time required for the evaluated structural elements to recover to levels measured in old-growth stands was generally not reduced with increasing levels of dispersed retention. This result suggests that the recruitment of second-growth stands towards old-growth conditions will be more dependent on time since harvest. Thus, rotation length will likely be the primary consideration for the recruitment of new old-growth stands within managed landscapes. Results from the modelling study presented here and the field study presented in Chapter 2 suggest that the development of old-growth structural conditions in these CWH forests may take anywhere from 100 to greater than 250 years depending on the structural attribute.

4.4.3 Limitations of the Study

The simulation study presented here only considered dispersed retention due to the spatial limitations of the FORECAST model. It is clear that more work needs to be done to explore aggregate retention systems in a similar context. Spatially explicit models such as LLEMS (e.g. Seely 2005, Fraser et al. 2007) would be useful to examine the long-term implications of different levels and spatial patterns of aggregate retention in these forest types. Another limitation of the simulations presented here is that they only consider the first rotation. Many of the structural variables considered were strongly influenced by the biological legacy (starting condition) of the previous stand. This was particularly true when starting from an old-growth condition. This biological legacy will inevitably decline through subsequent rotations. Additional work needs to be done to explore the impacts of variable retention systems over multiple rotations.

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Chapter 5. Concluding remarks

5.1 Research overview and discussion

The fundamental goal of the research conducted here was to quantify the recovery of old-growth characteristics in coastal western hemlock forests following disturbance and to evaluate the implications of alternative dispersed retention harvest scenarios. Towards this end the following specific objectives were addressed:

1. Develop a set of structural attributes which are indicative of the old-growth condition and correlate with stand age.
2. Evaluate forest growth model FORECAST against chronosequence data with the use of developed structural attributes.
3. Employ FORECAST to assess the implications of alternative dispersed retention scenarios on the recovery of old-growth structural conditions.

With respect to the first objective, a set of practical structural attributes was identified through the use of chronosequence analysis in chapter-2. The chronosequence analysis demonstrated the effectiveness of these attributes as indicators to quantify the rate of ecosystem recovery with respect to the development of old-growth structural characteristics in forests of CWH zone in BC. The following attributes were found to be correlated with stand age and showed clear temporal trends as the stands developed towards old-growth conditions:

- Frequency of large live trees (stem DBH> 50 cm)
- Cumulative volume of large live trees (stem DBH> 50 cm)
- Non-residual CWD mass
- Frequency of large snags (stem DBH > 50 cm),
- Stem size diversity (standard deviation of DBH for stems with DBH > 12.5 cm).
- Percent cover of shrub and herb layers.

It should be noted that the stand attributes included in the present analysis were chosen subjectively and focused only on plant-related structures including deadwood. Yet, the chosen attributes do not constitute the whole range of possible traits that can be used to describe an old-

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growth forest. Old-growth condition encompasses wide variety of traits including pedodiversity (Scharenbroch and Bockheim 2007), old-growth dependent organisms such as canopy lichens and bryophytes (Sillett et al. 2000), and other structural attributes that were not used in this research (Wells et al. 1998). These characteristics can be described by additional attributes which, however, may reach old-growth thresholds in different timing from the one described in present study. Structural properties, nevertheless, can be indicators of habitat structure, and abundance and diversity of some species (Kremsater et al. 2003). The application of old-growth averages and associated confidence intervals allows forest managers to evaluate the maintenance and recruitment of old-growth features within managed forest landscapes. The fact that one of the attributes has crossed old-growth thresholds does not necessarily imply that the forest reached its old-growth state. Nonetheless, the inclusion of multiple structural attributes as part of an integrated analysis provides a more robust measure (e.g. Franklin and Spies 1991). It should be noted that the minimum of old-growth confidence interval represents only 5% of old-growth stands. Hence, management of the stand to the confidence interval as a target will create an old-growth stand that will be less representative of the old-growth forests in the area. Management of the stand to the old-growth average will result in a stand that will on average resemble most of the old-growth stands. Clearly, the target of the management can be set loose enough to allow variation in the old-growth values to resemble the variation in nature presented by the confidence interval.

Second objective of the thesis was achieved using the field data from chapter-2 to evaluate the capability of the FORECAST model to project the development of old-growth structural characteristics. This comparison between the model and the chronosequence data was the first attempt to evaluate FORECAST results against a long-term field data set (300 years) for the coastal region of BC. Model performance was assessed by means of graphical inspection, statistical analysis and in terms of model consistency with ecological theory. The model followed the trends in the field data with reasonable accuracy as measured by the model efficiency statistic. The evaluation supported the use of the model to project the recovery of old-growth structural attributes in second-growth forests. In addition, it provided a level of confidence for the application of FORECAST to explore alternative dispersed retention scenarios done in chapter-4.

The simulation in chapter-4 used the developed set of structural attributes from chapter-2 to accomplish the third objective of the thesis: to evaluate structural development and the recovery of old-growth traits following dispersed retention harvest. The study results demonstrate that it is

possible to conserve residual structure for prolonged period of time by using dispersed retention. However, after the harvest the forest entered degradation period in terms of its old-growth structure for deadwood and stem size diversity, because the amount of trees was initially reduced by logging. The frequency of large stems recovered to old-growth threshold within 100 years, but the recovery of deadwood related attributes required more time. These results suggest that it may be difficult to sustain similar amount of residual structure during the second rotation, especially if the rotation is shorter than 100 years. The post-harvest condition of the stand after second rotation would be degraded comparing to the post-harvest condition after the first rotation.

A trade-off analysis conducted for the dispersed retention scenarios illustrated the tradeoffs associated with leaving different amounts of volume behind. The effect of increasing retention levels was greatest for the maintenance of large live stems, followed by large diameter snags, stem size diversity and CWD. As described in chapter-4, the simulations show that the time required for the evaluated structural elements to recover to levels measured in old-growth stands was generally not reduced with increasing levels of dispersed retention. This result suggests that the recruitment of second-growth stands towards old-growth conditions will be more dependent on time since harvest. Thus, rotation length will likely be the primary consideration for the recruitment of new old-growth stands within managed landscapes.

The inclusion of forest carbon management as an alternative or complementary source of income may influence the relative weighting of dispersed retention scenarios from an economic perspective. Based on the simulations ecosystem carbon storage, particularly in the first 40 to 60 years following harvest, showed a strong positive correlation with retention level. This increase in carbon storage, if maintained at a landscape scale, could be used as the foundation for a forest carbon project aimed at generating saleable carbon offsets. To meet the standards required for eligibility, the proponents of such a project would have to prove additionality (that the proposed management is different than what would have been done without the carbon project) and that leakage (transfer of avoided volume harvest to other areas and/or increased emissions from product substitution) would be accounted for (Voluntary carbon standard 2008). This type of management for multiple revenue streams has the potential to enhance the overall profitability from the forest resource while also providing for greater retention of structural attributes. The lost value from volume in retained trees can be compensated by income generated through the production of carbon offsets. The degree to which carbon offsets and timber are emphasized will depend on market prices and other economic and ecological factors.

5.2 Significance of the research

The analysis presented in the study demonstrated a methodology for evaluating the relative recovery of old-growth characteristics for a subsequent use in modeling or other potential analysis. In addition, the research provides a foundation for the use of forest growth models such as FORECAST as decision support tools to help guide management decisions that will influence the conservation of stand structure and the recruitment and conservation of old-growth forest in managed forest landscapes. The use of indices based on structural characteristics rather than, or in addition to, traditional age-based thresholds provides more information with respect to the degree to which a given managed landscape will recover towards an old-growth condition and should facilitate better planning. The study also removed the duality in treatment of the forest as either old-growth or not and provided tools to examine continuous recovery of old-growth characteristics.

While the use of VR harvesting including dispersed and aggregate retention systems has been gaining momentum throughout coastal BC as method for addressing multi-objective forest management, there is little long-term data available to evaluate the long-term impacts of these management practices on the maintenance and development of stand structural characteristics and other associated values. .The analysis of alternative dispersed retention scenarios presented here demonstrates that the FORECAST model can be used as a tool to help understand management tradeoffs and stand growth dynamics following dispersed retention harvests. The work also illustrated the importance of starting condition when developing and applying VR management.

5.3 Limitations of the study.

The chronosequence analysis presented in this thesis was limited by the relatively small number of sites (n=33) included in the analysis. This limitation had an influence on all the three parts of the research. In chapter-2 it may have been possible to achieve more robust trend lines and old-growth thresholds if more sites had been included in the chronosequence analysis. Yet, the variability of the data would still be high due to other individual parameters of each site (Wells 1996). In chapter-3, as the model was evaluated against field-data-based trendlines, the low amount of the sites influenced the evaluation process. In chapter-4 the conclusions regarding the old-growth state of the attributes in the simulations of dispersed retention were dependent on the old-growth thresholds. Sampling more old-growth sites will no doubt improve the accuracy of the old-growth average for each discussed structural attribute.

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The research was restricted to a relatively small set of structural variables. They represented only some of the aspects of the old-growth state in the forest. Yet, similar attributes have been used effectively in other studies (DeLong et al. 2004, Morgantini and Kansas 2003). It could be argued that the variables were chosen subjectively and that a different set of cutoffs/variables would produce other results. Nevertheless, the set used in the current study was successful in representing continuous recovery of old-growth structure (chapter-2).

Although the results shown here provided confidence in the capability of the model to project stand development following a clearcut, the degree to which the model was able to represent dispersed retention logging remains untested. This is due to the fact that retention of residual structure has been shown to influence stand growth dynamics. For example, remnant trees increase seed availability (Keeton 2000), cast shade and compete for water and nutrients (Aubry et al. 2009). Although each of these processes was simulated in the model, they were not addressed during model evaluation. It is generally difficult to obtain chronosequence data from partially harvested stands due to variability of harvest techniques used and the short historical record of such logging practices in North America (chapter 4). In the absence of such long-term data, models can be used to explore alternatives, but their results should be interpreted with caution (Korzukhin et al. 1996).

5.4 Suggestions for future research

FORECAST is a non-spatial model (Kimmins et al. 1999), and hence can simulate only dispersed retention. Yet, the non-spatial simulation process done in the study provides the background for future simulations of aggregated retention with spatially explicit models. The study also introduced basic concepts of continuous recovery of old-growth traits with the old-growth thresholds. Therefore, any spatially-explicit model that is capable of simulating the same stand attributes can be evaluated against the proposed set of structural attributes and clearly also against the chronosequence data in general. The spatially explicit simulations should be the next logical step in projecting old-growth characteristics recovery. These simulations are especially important for deriving management conclusions due to the fact that the majority of VR harvest in coastal BC is done using aggregate retention or using a mix of aggregate and dispersed retention.

Some limitations of the simulation in the study were outcomes of poor scientific knowledge with regard to percentage of tree mortality due to non-stand-replacing disturbances and scarcity of the data regarding the decay rates of hemlock logs and snags. Both of these elements are crucial to improve the capabilities of forest growth models. For example, simulation in chapter-3

had shown that model output was highly sensitive to changes in wind related mortality. In addition, improved decay rates of western hemlock will promote greater reliability of model representation of CWD and snags. Therefore, further research in the specified areas is needed to promote forest growth modeling.

Only structural attributes were used in present research to describe old-growth forest. Availability of habitat and biological diversity can be linked to specific structural attributes. For example, Huggard et al. (2009) indicates that large live trees provide foraging sites for canopy gleaners, nesting platforms, and substrates for epiphytes; CWD is used by rodents, small carnivores, and amphibians; and large snags provide dens for carnivores, nest sites for birds, and encourage persistence of wood-inhabiting organisms. Therefore, as FORECAST employs the mentioned structural attributes, it can be used to project the recovery of habitat availability and changes in biodiversity. In order to be credible in such predictions the model should be evaluated against related field data.

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Appendix A. Chronosequence sites - information summary

Table 1. Summary of site information for chapter-2. Brackets indicate that the site is under influence of the site series or variant in the brackets. Species are abbreviated as follows: Ba - Abies amabilis, Fd - Pseudotsuga menziesii, Dr - Alnus rubra, Hw - Tsuga heterophylla, Cw - Thuja plicata, Ss - Picea sitchensis. Variants and site series follow the BC BEC system.

Chronosequence age [yrs]	Site I.D.	Variant	Site Series	Stand initiating disturbance	% of residual trees from total by Volume/ha	Species composition in % Stems/ha by species	GPS coordinates (Using NAD83 datum)
69	SG-1	vh1	1	Logging	0	Fd:Hw:Ba 46:39:15	Lat 49º3'25" Long 125º28'42"
72	SG-2	vm1	1	Wind	0	Hw:Ba 97:3	Lat 49º45'21.4 Long 126º22'53.8"
81	SG-3	vh1	11(1)	Logging	0	Cw:Hw 64:36	Lat 48º56'19.2" Long 125º27'43.3"
85	SG-4	vh1	1	Wind	0	Hw 100	Lat 49º5'39.5" Long 125º35'46.8"
88	SG-5	vm1	1	Logging	0	Hw:Ba:Ss 93:6:1	Lat 50º34'0.2" Long 127º7'25.3"
90	SG-6	vm1	1	Logging	0	Hw:Ba:Dr: 85:13:2	Lat 50º39'36.4" Long 128º1'2.5"
94	SG-7	vm1	1	Logging	0	Hw:Cw 96:4	Lat 48º48'17.3" Long 124º39'37"
95	SG-8	vh1	6	Wind	0	Hw:Ba 98:2	Lat 50º40'22.3" Long 128º10'50.3"
96	SG-9	vm1	1	Insects	11%	Hw:Cw 99.5:0.5	Lat 48º47'43.3" Long 124º38'46.8"
98	SG-10	vm1	1	Fire	5%	Hw:Cw 81:19	Lat 49º45'10" Long 126º24'19.6"
118	SG-11	vm1	01(5)	Fire	17%	Hw:Cw:Fd 71:24:5	Lat 49º46'24.8" Long 126º29'5.9"
120	SG-12	vm1(vh1)	1	Logging	0	Hw 100	Lat 48º35'42.4" Long 124º25'15.9"
125	SG-13	vm1	1	Logging	0	Hw:Ba 86:14	Lat 48º52'46.4" Long 124º41'47.7"
129	SG-14	vm1	1	Wind	0	Hw 100	Lat 49º48'51.2" Long 126º30'47.8"
133	SG-15	vm1	05,07	Wind	0	Hw:Ss 95:5	Lat 50º40'24.6" Long 128º5'58.6"
136	SG-16	vm1	01(3)	Wind	0	Ba:Hw 99:1	Lat 49º12'18.5" Long 125º19'6"

Chronosequence age [yrs]	Site I.D.	Variant	Site Series	Stand initiating disturbance	% of residual trees from total by Volume/ha	Species composition in % Stems/ha by species	GPS coordinates (Using NAD83 datum)
140	SG-17	vm1	01(5)	Wind	15%	Hw:Ba:Cw 73:25:2	Lat 48º37'30.4" Long 124º25'59.7"
160	SG-18	vm1	1	Wind	0	Ba:Hw 56:44	Lat 50º41'59.1" Long 127º41'15"
173	SG-19	vm1	5	Wind	31%	Hw:Ba 99:1	Lat 49º48'55.1" Long 126º30'49.5"
174	SG-20	vm1	5	Wind	36%	Hw:Ba 73:27	Lat 50º40'49" Long 128º6'15"
179	SG-21	vm1	1	Probably Wind	0	Hw 100	Lat 48º48'14.8" Long 124º39'36.7"
180	SG-22	vm1	1	Fire	0	Hw:Fd 97:3	Lat 49º46'36.5" Long 126º21'45.5"
194	SG-23	vm1	1	Wind	0	Hw:Fd 96:4	Lat 49º45'23.2" Long 126º22'59.2"
212	SG-24	vh1	6	Wind	0	Ba 100	Lat 50º40'11.3" Long 128º8'41.5"
Old-growth	OG-1	vh1	11,01	Unknown	0	Hw:Ba:Cw 80:10:10	Lat 50º41'55.1" Long 127º48'52.8"
Old-growth	OG-2	vm1	1	Unknown	0	Hw:Ba:Cw 94:3:3	Lat 50º21'10.9" Long 126º9'51.1"
Old-growth	OG-3	vh1	1	Unknown	0	Hw:Ba 99:1	Lat 50º40'22.6" Long 128º10'31.9"
Old-growth	OG-4	vm1	1	Unknown	0	Ba:Hw 84:16	Lat 49º12'2.2" Long 125º19'13.3"
Old-growth	OG-5	vm1	01(3)	Unknown	0	Hw:Cw:Ba 97:2:1	Lat 48º49'1.8" Long 124º46'13.6"
Old-growth	OG-6	vm1	1	Unknown	0	Ba:Hw:Cw 76.5:23:0.5	Lat 48º48'20.1" Long 124º47'18.1"
Old-growth	OG-7	vm1	1	Unknown	0	Hw:Ba:Cw:Fd 81:9:8:2	Lat 48º52'1.8" Long 124º40'7.4"
Old-growth	OG-8	vm1	05(1)	Unknown	0	Hw:Ba 75:25	Lat 49º44'47" Long 126º32'0.4"
Old-growth	OG-9	vm1	03(1)	Unknown	0	Hw:Cw:Ba:Fd 78:11:9:2	Lat 49º45'15.5" Long 126º31'1.7"