

**A FIELD AND SIMULATION STUDY OF THE
INITIATION PHASE IN DOUGLAS-FIR
PLANTATIONS**

by

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Abstract

The stand initiation phase of stand dynamics has important implications for subsequent stand development, yet it is generally not addressed in growth and yield models. Planted trees may or may not grow as expected if there is significant recruitment of natural regeneration and/or herb and shrub competition and if the interactions between the planted trees and other vegetation is not managed. Two experiments initiated at Malcolm Knapp Research Forest (MKRF) in the early 1980's were re-measured to produce extended data sets that describe stand development in the face of invasion by non-crop trees and the competitive effects of shrubs. These data sets were then used to test the predictive ability of the ecosystem management model FORECAST (a stand level hybrid simulation model) to represent early stand development.

The Blaney Lake experiment was established to examine the vegetation development in a chronosequence of young Douglas-fir plantations on four adjacent small clearcuts that incorporated a local topographic sequence of soil moisture regimes - xeric, mesic and hygric. The data showed that there is a relatively short temporal window (up to 10 years) for non-crop tree recruitment, that this varies from year to year, and that the outcomes pose a difficulty for predicting future stand development. The data also suggest that unmanaged recruitment may invalidate early stand development predictions of models that ignore non-crop recruitment and interactions with planted trees. FORECAST was capable to capture the effects of these complex interactions.

The Vegetation Competition experiment was initiated to study the effect of different levels of non-crop vegetation on growth of two conifer species and the results were compared with output from FORECAST to assess its ability to represent the competitive interactions. Again, for most of the variables FORECAST made predictions that mimicked the field data.

The results presented here provide evidence of the utility of the ecosystem model FORECAST in projecting the development and growth of young conifer plantations in the CWHdm biogeoclimatical subzone. This study increases confidence in the FORECAST model for application in young stands. However, it must be emphasized again that the accuracy of model performances will reflect the availability of appropriate calibration data sets.

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Chapter 1 Introduction

1.1 Thesis overview

The period of plantation establishment and early stand development presents considerable challenges to forest managers. It is during this period the most silviculture investment is required to assure that plantations develop as expected. Biotic factors that can influence early stand dynamics and the potential long-term development of harvestable resources include the ingress of non-crop tree species through natural regeneration, and the development of minor vegetation communities that can suppress initial growth rates and, in extreme cases, cause mortality of crop trees. Field trials designed to assess the influence of competing vegetation of conifer growth in BC suggest the impacts vary from minor to substantial depending on ecosystem type and initial conditions (Messier and Kimmins 1991; Rose et al. 2006; Simard and Vyse 2006). These results, in turn, have implications for the degree of silviculture interventions required to maintain satisfactory growth of crop trees. Ecosystem-based models provide a method for evaluating the long-term impacts of early stand dynamics as influenced by the aforementioned biotic factors and associated silviculture systems. To be useful, ecosystem models must be evaluated, where possible, against long-term data sets to build confidence in their ability to project patterns of stand development. The overall goal of this thesis is to examine early stand dynamics in Douglas-fir plantations and to evaluate the ability of the ecosystem-based forest management model FORECAST to represent the impacts of biotic factors including ingress and competition from minor vegetation on survival and growth rates of crop trees.

1.1.1 Thesis objectives

The overall objective of the thesis is to test outputs of the FORECAST ecosystem management model (calibrated using a general CWHdm data, set) against data collected from two experiments at Malcolm Knapp Research Forest in the Coastal Western Hemlock dry maritime (CWHdm) biogeoclimatic subzone, Maple Ridge, B.C.

The specific objectives for the study are to:

1. Examine previously established and monitored vegetation development plots (post-harvesting succession and conifer growth) in Douglas-fir plantations along topographical sequence on four cutblock ages to create a 23 year chronosequence data set with repeated measurements.
2. Test the ability of FORECAST to simulate the effect on the growth of the planted Douglas-fir in these plantations accounting for competition with naturally regenerated western hemlock and other species
3. Re-measure an existing set of experimental vegetation plots that documented shrub and deciduous tree competition on early Douglas-fir growth and use the data to test the simulated conifer/shrub/deciduous tree interactions in FORECAST.

1.1.2 Thesis outline

Thesis is structured in five chapters:

Chapter 1

This chapter introduces the reader to the main aspects of forest modeling, presents several criteria of model classification and has discussed the most important issues concerning the testing of forests models. Since the thesis is describing two experiments on Douglas-fir plantations, an overview of the most important management problems in Douglas-fir plantations is presented here.

Chapter 2 –Site and model description

The second chapter deals with the description of the research area, represented by the CWHdm biogeoclimatic subzone and that of the FORECAST model. The most important aspects of the calibration and simulation processes in FORECAST are described as related with the thesis objectives.

Chapter 3 – The Blaney Chronosequence: Assessment of early stand development and evaluation of model performance

Chapter 3 describes the Blaney Chronosequence experiment which was initiated by John Karakatsoulis in early 1980's and re-measured in 2003. The experiment was initially developed to study the vegetation development and growth of Douglas-fir seedlings along a topographic sequence. Data obtained from the field were then compared with FORECAST model outputs to evaluate the model capabilities of representing complex natural regeneration conditions in Douglas-fir plantations. A factorial experiment was also conducted using FORECAST model to

determine the effects on planted Douglas-fir growth of different hemlock densities natural regenerated at various stand ages.

Chapter 4 –Vegetation Competition plots

In this chapter, another experiment initiated by John Karakatsoulis was partially remeasured and the results are compared with FORECAST simulations. The vegetation competition plots experiment was initiated to study the effect of understory vegetation on conifer species in eight different treatments, and differs from the previous described experiment as the soil organic material was heavily removed.

Chapter 5 - Synthesis

The last chapter concludes the thesis with a summary of the important results and findings and recommendations for future research.

1.2 The prediction of stand dynamics

There is an ethical responsibility for resource managers to consider the implications of today's actions for the forest values that will be available to our grandchildren and their grandchildren. This involves predictions of the possible outcomes of alternative ways of managing forests. Experience has been the most dependable basis for such prediction in the past (Kimmins 2004). However, most foresters in western Canada have reliable records dating back only 50 years or less, and even in European countries with a long history of forestry the reliable record may be limited to one or two centuries. This experience generally relates to climatic, management and natural risks (e.g. storms, fire, diseases, introduced plants and pests) situations than are likely different than those that will occur in the future for which forecasts of management outcomes must be made. As a consequence, experience on its own is no longer a sufficient basis for planning in forest management. As we face climatic change and social demands for a much wider range of forest values, what type of forecasting tools do we need in order to develop and apply new and untested management plans with confidence?

Even-aged timber-based forestry has traditionally been concerned with the establishment and management of single species populations of crop trees. Simple empirical or competition-based population models often sufficed for prediction of development and dynamics in such stands because populations were established by planting or natural regeneration, competition from non-crop trees, shrubs and herbs was regulated through weeding, and stand density and composition

were regulated by pre-commercial thinning. This reduced the need to represent these processes explicitly in prediction systems. However, changes in the economics of stand tending, economic and environmental limitations on weed control, wildlife habitat and biodiversity considerations, and the declining availability of forest workers have resulted in a steady reduction in the intensity of early stand management. Under these circumstances, simple tree population models no longer suffice. Crop trees exist as a component of complex biotic communities, the “founder effect” of which has important implications for stand development and the growth and yield of crop trees. This added complexity requires prediction systems – models – that can explicitly account for those key determinants that cannot be regulated through management (Kimmins 2007, Pers. Comm.).

Stand development has been described as having four main phases: stand initiation, stem exclusion, understory re-initiation and old growth (Oliver and Larson 1990). Each phase is associated with a set of key determinants (Figure 1.1). Most even-aged timber stands have been managed for only the first two of these phases, and clearly the complexity of determinants over this period is greatest for the stand initiation phase. Most growth and yield models commence at the beginning of the stem exclusion phase, omitting the stand initiation phase and thereby avoiding this complexity. However, with the requirement for multi-value management and the limitations on intensive forestry, models that cover all phases of stand development are needed. Such models should be as simple as possible but as complex as necessary to provide reliable prediction (Kimmins, 2006 Pers. Comm.).

Models¹ of forest ecosystems are abstractions of reality. By definition, a model can never exactly duplicate reality, because if it did it would be reality and not a model. Furthermore, a model can never provide perfect predictions of the future. There will always be uncertainty. However, despite these limitations, models at the appropriate spatial, temporal and complexity scales can provide one of the best ways to forecast forest futures (Kimmins et al. 2001). Models cannot be based solely on experience. They should combine available relevant experience with our growing understanding of forest ecosystems.

¹ What is a model? The word model derives from the Latin “modus” meaning the way in which things are done, and is explained by The New Oxford Dictionary as a “simplified description of a system, etc., to assist in calculations and predictions”. In Hilborn and Mangel (1997), a model is considered “a stylized representation or a generalized description used in analyzing or explaining something”.

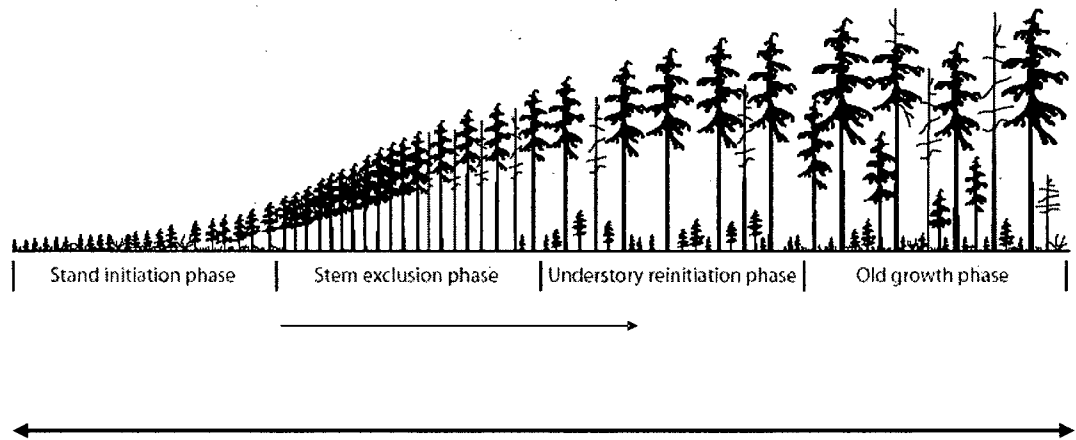


Figure 1.1 The four phases of stand dynamics showing some key determinants of each phase. Where these processes cannot be managed and are variable in time and space, acceptably accurate prediction of stand development will require their representation in predictive models. Where biologically-significant climate change is anticipated over the period of the prediction, climate change effects on these determinants will be required (After Kimmins 2004).

Prediction based on models has developed in all fields of human endeavor including forestry, but the question always remains as to whether a model's forecasts are sufficiently accurate to be useful? Forestry is the art, practice, science and business of managing forested landscapes to sustain an ecologically possible and socially desired balance of values across appropriate temporal and spatial scales (Kimmins 2004). Single value models at only one spatial scale are unlikely to serve the needs of contemporary sustainable forest management which must address the multiplicity of components, processes and values of the forest over spatial scales from hectares to hundreds of thousands of hectares, and time scales long enough to assess sustainability as well as resource inventories. Simple population models of timber or wildlife are

easier to develop and use than the more complex ecosystem-level models, but are unlikely to provide accurate forecasts in ecosystems that are implicitly complex.

Forest models are becoming one of the tools that every forester should use in the process of designing new management systems and in developing management plans. Using ecologically-based, ecosystem management forecasting systems, foresters should be able to make more credible analyses of the range of possible outcomes of their management plans than is possible in the absence of such decision support tools. Rapid expansion of knowledge, especially in the last century, has made it difficult to comprehend and integrate existing knowledge about forests and for forest managers to harness this diverse knowledge in their management. Appropriate models can help to evaluate which is the best way to manage such a complex system such as a forest in new and untested ways to achieve a new set of objectives. Suitable models can help us to create viable future forests, but the question remains: how accurately does a particular model represent the reality one is managing? Until models are tested against reality, it is difficult to establish our level of confidence in them.

Representing the results of almost 30 years of research and model development, FORECAST (Kimmins 1993, 2001 ; Kimmins et al. 1999), LLEMS (Local Landscape Ecosystem Management Simulator) (Kimmins et al. 2001) and POSSIBLE FOREST FUTURES (PFF) (Kimmins et al. 2001; Kimmins 2004) are ecologically-based forest management models that are receiving increasing attention from companies and government agencies in Canada and internationally. However, use of these models as both management and educational tools requires further software development, calibration and testing. FORECAST, the driving “engine” of PFF and LLEMS, has been subjected to several tests and found to perform well (Binkley 1986; Yarie 1986; Sachs and Trofymow 1991; Comeau and Sachs 1992; Sachs 1996; Morris et al. 1997; Seely et al. 1999; Wei et al. 2000; Seely et al. 2002; Welham et al. 2002; Wei et al. 2003; Blanco et al. 2007; Seely et al. 2007). However, it has not yet been tested against data sets that describe early plantation establishment and performance under conditions of natural regeneration of other tree species, or against data sets that define different levels of non-crop vegetation under coastal B.C. conditions. These two tests are the focus of this thesis. Establishing the performance of FORECAST in situations of unmanaged competition from herbs, shrubs and other trees that recruit into the plantation by natural regeneration is a necessary pre-requisite to testing PFF.

The complexity of natural phenomena is one of the most challenging issues in science (Kimmins et al. 2005), and there is increasing use of models that incorporate much of the natural complexity of ecosystems as a compliment to the necessary but insufficient traditional disciplinary scientific reductionism (Kimmins 2004). Maintaining a wide variety of measures of biodiversity and other non-timber forest values within their “natural” range of variation (NRV), where this is known, has become a major objective in forest management systems in Canada and elsewhere around the world. As a result, the relatively simple forest management systems of the past are being replaced by ecosystem-based management systems (EBM) and occasionally by the next step in the evolution of forestry: ecosystem management (EM). The complexity of the new forest management paradigms calls for more advanced decision support systems, amongst which hybrid simulation models at various spatial scales are attracting increasing attention and application (Oliver et al. 2001; Welham et al. 2002).

Ecological modeling is undergoing rapid development all over the world. A literature survey regarding the articles published in three prestigious forestry journals between 1973 and 1999 indicates that while in the early 1970’s only 5% of the published papers were directly related to modeling and simulation models, by 2000 the percentage had increased to more than 15% (Messier et al. 2003). Ecological models in combination with experience and empirical data provide powerful tools for use by researchers and managers. However, as with any human-made tool, there is continuing need to test the accuracy of ecological models and evaluate their utility, and there is the continuing question as to how complex such tools should be (Kimmins 2004).

1.3 Classification of models

There are many ways to classify the models available today. Referring only to ecosystem and forestry-related models, they can be compared based on their origin, purpose, structure and, functionality. Models can be deterministic or stochastic; mechanistic or statistical; static or dynamic; quantitative or qualitative; large scale or small-scale (Hilborn and Mangel 1997; Messier et al. 2003). Models can be used for understanding, prediction or decision-support.

Conceptual (internally represented) models are the precursors of externally-represented models (Kimmins 2004). Conceptual models are basically collections of thoughts or ideas without any material (real, observable) representations. Such conceptual models become “real” or “externally-represented” when converted to word models, pictorial models or computer models based thereon.

Kimmins (Kimmins et al. 1990; Kimmins 2004) describes three major approaches to modeling in forestry: historical bioassay (HB), process simulation (PS) and hybrid simulation (HS). In HB models, data describing the past growth pattern and historical patterns of variation in other ecosystem parameters are used as the basis for deriving predictions of the future. This approach is the basis for most biometrical tree and stand growth and yield models. The most notable disadvantage of this type of model is the assumption that the ecological and management conditions that occurred over the period from which the historical data were obtained will not change in the future. The model's simulations can be considered reliable only if ecosystem and management conditions of the past are repeated in the future. When this assumption is met, this family of models can provide reliable results, at least for the single values that such models generally address.

Process simulation (PS) models, also called mechanistic models, are considered to be the "ultimate scientific approach to ecosystem modeling" (Messier et al. 2003). These models simulate key ecosystem processes, adding time dependent parameters to the simulation and overcoming the inability of HB models to represent the ecosystem in situations of changed conditions. Process-based models provide a more comprehensive description of ecosystem development than HB models. Their explanatory and descriptive capabilities can increase our understanding of the system being modeled, but only if sufficient key determinants are included. The complexity of forest ecosystems requires that many determinants be represented in PS models, and this acts as an important limitation in purely process modeling. Although the more complex the models are the higher the expected accuracy of the outputs, the added complexity increases the difficulty and cost of model calibration and limits model portability. As a consequence of this complexity issue, most mechanistic models omit one or more important ecosystem processes or structures whose variation in time has important ecosystem implications. Many process models are too simple to be used to answer complex ecological and forest management questions (Korzukhin et al. 1996; Kimmins 2004). However, as our knowledge of forest ecosystems dynamics and mechanisms increases, more complex and accurate process simulation tools will undoubtedly be developed (Messier et al. 2003).

Hybrid simulation (HS) models represent a combination of the two previous approaches - historical bioassay and process-based modeling - to produce predictions based on both experience and knowledge (Kimmins 1993; Kimmins 2004). Hybrid models employ output from, or the empirical data associated with HB models, the predicted growth then being

modified according to process-based simulations. HS models take advantage of the positive aspects of both historical bioassay and process-based models, thereby overcoming some of the limitations of the two component approaches (inability to make accurate forecasts under changed conditions, and excessive calibration data requirements, respectively). This type of model has a solid foundation in empirical data but also has flexibility in terms of reacting to future ecosystem change. This accounts for the increasing use and development of hybrid models (Kimmins 1993; Kimmins 2004). Hybrid models can be grouped in three main categories: “gap” models of ecological succession, stand level ecosystem management models, and individual tree growth models (Kimmins 2004).

A fourth approach, environmental correlation, is a general methodology mostly used for spatial predictions and modeling genetic parameters. It consists of exploring the relationships between different ecosystem variables and selected environmental parameters (McKenzie and Ryan 1999). Models based on environmental correlation are able to make predictions under environmental change but do not represent the processes involved.

1.4 Testing models. Why should models be tested?

Modeling can provide ecologists with the possibility to examine complex systems and to synthesize our rapidly advancing knowledge about forest ecosystems. Model use is equally important in forecasting the possible consequences of long term management strategies and in exploring important sustainability-related questions. Modeling can offer alternative solutions to these issues and forecasts concerning the tradeoffs between the many values over different time and space scales. Computer models, the most advanced expression of modeling, is a vitally important tool in all fields of forest ecology (Kimmins 2004).

No model will ever be capable of simulating the ecosystem phenomena accurately enough to exactly mimic nature, but well-designed and calibrated models can and should be successfully used in forest ecology. Most scientist recommend caution and skepticism in interpreting model results (Oreskes et al. 1994; Parysow and Gertner 1997; Messier et al. 2003; Kimmins 2004). “All models must fundamentally be considered to be to some degree wrong”, but this not mean that models have no predictive value (Kimmins 2004). Forest policies and management decisions inevitably depend on the use of models no matter how imperfect they are (Rykiel 1996).

There will always be a need to test a model, as for any other entity that humans produce. The ultimate goal of any modeler is eventually to have their model used in research, education and/or practical application, but generally this cannot be done without having an estimate of how “good” or “bad” the model is. With the increasing use of complex forest ecosystem models, the need to establish a level of confidence in their ability to represent ecosystem-level problems is becoming a key issue, but also one of the most difficult tasks involved in the model development process (Brown and Kulasiri 1996). Validation is a controversial issue for both the modeler and users alike, and no general accepted methodology is available. The debate over model assessment extends from the definition of words like *validation* and *verification* to the procedures that should be used in the validation process. Model validation is considered an essential procedure by numerous authors like Gentil and Blake(1981), Mayer and Butler(1993), Power (1993) as cited in Rykiel (1996), while many others maintain that the validation and verification of models is impossible, or at least not a task that can be successfully completed given our present research and industrial capabilities (Oreskes et al. 1994; Parysow and Gertner 1997). Terms such as “validation” and “verification” that have been used widely until recently are increasingly being considered inappropriate. Terms like “evaluation” and “testing” seem to be preferred

Ambiguity in both the conceptualization and application of model evaluation leads to the conclusion that model usefulness is an equally important criterion in the assessment of a model. Models are only approximations of reality, so it will always be possible to challenge them against unattainable criteria. A model should be evaluated or tested only in the context of the application for which it is intended (Cale Jr. et al. 1983; Rykiel 1996). The acceptance of a model by resource managers or the public may depend on many factors (e.g. subjective evaluations, possibility of implementation, political and economic factors) other than the evaluation of model performance (Vanclay and Skovsgaard 1997), but the ultimate criterion appears to be the overall model usefulness. If a model is not useful why bother evaluating it?

1.5 Issues concerning growth and management of Douglas-fir in the CWHdm subzone

Douglas-fir (Df), also called red-fir, Oregon-pine and Douglas-spruce in the past, is one of the world's most important and valuable timber trees. There are two recognized varieties: *Pseudotsuga. menziesii* (Mirb.) Franco var. *menziesii*, called coastal Douglas-fir, and *P.*

menziesii var. *glauca* (Beissn.) Franco, called interior, Rocky Mountain or blue Douglas-fir (Hermann and Lavender 1990). In British Columbia coastal forests, Douglas-fir is considered to be a seral species, found in both pure and mixed stands and attaining high levels of growth performance. It grows best on well aerated soils and does not do well on compacted or waterlogged soils. Extensive, almost pure stands of coastal Douglas-fir were created and maintained in the past by periodic wildfires. Logging in the last century eliminated most of the original old-growth Douglas-fir forests, but clearcutting combined with slash burning and planting helped maintain this species as the dominant component in many second-growth coastal stands (Minore 1979). In the Coastal Western Hemlock dry medium biogeoclimatic subzone (Meidinger et al. 1991), Douglas-fir is mainly associated with western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and redcedar (*Thuja plicata* Donn.) (Klinka 1976). When Douglas-fir regeneration is not successful and when mineral soil is exposed, red alder (*Alnus rubra* Bong.) often forms early seral stands. Naturally regenerated Douglas-fir seedlings normally establish best on moist mineral soil with thin litter layers; they establish and survive poorly on heavy accumulations of organic debris, although planted vigorous seedlings may succeed. Especially on southerly aspects, low summer moisture and high summer temperature can become limiting factors for seedling establishment (Hermann and Lavender 1990).

Coastal Douglas-fir is generally classified as being an intermediate shade tolerance species (Carter and Klinka 1992), but with seedlings that can survive relatively low light intensities (Minore 1979) while other authors, like Mailly (1998; 2003) found that coastal Douglas-fir is intolerant of shade. Its growth in the early years gradually accelerates, so that by 10 years old, an average of 1 m height increment per year is common on good sites (Hermann and Lavender 1968). However, there is a need for vegetation management, especially on fertile, moist sites where juvenile Douglas-fir is easily overtopped by deciduous species (Wang 1997). While it may grow at low light levels the resultant high height/diameter ratio makes it susceptible to mortality by wind or snow. How well Douglas-fir can compete with other conifer and broadleaf species cannot be generalized as it depends on many factors related to particular site conditions. As opposed to western redcedar and western hemlock, Douglas-fir does not usually regenerate under its own canopy, and because of infrequent seed years, planting is generally required after clearcutting to achieve stocking standards (see Mailly and Kimmins (1997); Mailly (1998)).

As an economically important species on the coast of B.C., Douglas-fir is typically planted on appropriate sites and subzones because of a history of inadequate regeneration, especially in large clearcuts (Arnott 1986). Because of the public antipathy towards clearcutting, the use of

alternative silvicultural practices is on the rise (Welham et al. 2002; Kimmins 2004), although the long term consequences of using these alternative systems are not known (Franklin 1992). Even-aged forest stands follow a sequence of developmental stages from small seedlings and saplings to dense, closed-canopy stands of pole-sized trees with much competition mortality, and then to mature stands with canopy gaps and understory re-establishment, and eventually to complex, multistoried, overmature or “old growth” stands (Oliver and Larson 1990).

Traditionally, plantations have only represented the first three of these five stages, and competition from non-crop tree species has been controlled by early stand management (spacing, herbicides (for competing hardwoods) or pre-commercial thinning). However, the public desire for mixed species and multi-layered stands has led to the development of silviculture systems that allow naturally-regenerated companion species to persist in the stand and features of the later phases of stand development to develop. Success in managing for these features requires knowledge of the physiology and ecology of the tree species involved (Klinka et al. 1992), especially with respect to the competitive effects on crop trees of natural regeneration of other tree species.

Knowledge of intra and inter-species interactions is becoming necessary for the success of mixed-species stands. Stocking a site with the right tree species and in the right proportions is the ultimate aim of any successful plantation (Radosevich and Osteryoung 1987). However, the stand management decision support tools used by foresters have generally lacked the ability to represent the recruitment of non-crop tree species, their competitive effects for light and soil resources (nutrients and moisture), or the later phases of stand development (Welham et al. 2001).

Among the most important issues in the development of a Douglas-fir plantation that need to be incorporated into stand management decision support tools are:

- Initial (pre-disturbance) site conditions, the type and severity of the disturbance (if any), and the site conditions at the time of planting;
- Site preparation and the type and age of seedlings,;
- Intraspecific competition for light, water and nutrients, and the vigor of the planted seedlings (Carter and Klinka 1992);
- Competition generated by herbs and shrubs, and herbivore-caused damage;
- Diseases and damage from wind, snow, drought and freezing temperatures;
- Interspecific competition generated by advance regeneration or recruitment of other tree species.

Chapter 2 Site and model description

2.1 Description of the study area

2.1.1 Location of the field study sites

To achieve the objectives listed in Chapter 1, data were collected from study sites located in the dry maritime subzone of the Coastal Western Hemlock biogeoclimatic zone of Malcolm Knapp Research Forest (MKRF; latitude 49°15' - 49°22' N; longitude 122°31' - 122°36' W) in the Fraser Valley, approximately 60 km west of Vancouver, British Columbia (Fig 2.1).

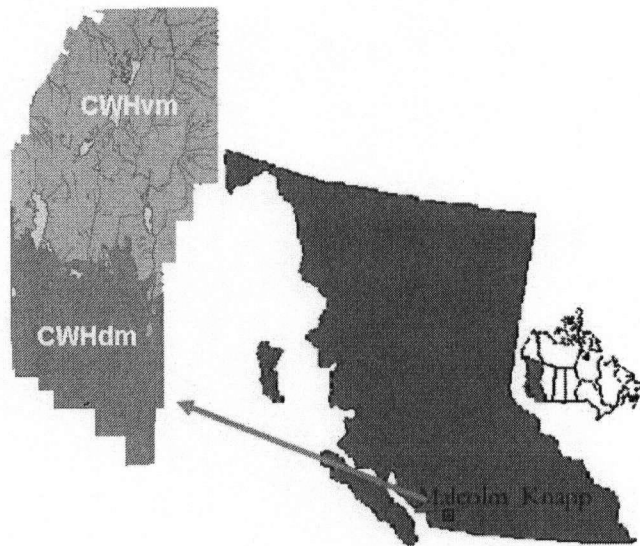


Fig 2.1 Location of Malcolm Knapp Research Forest

The research forest covers an area of 5,157 hectares between Pitt Lake to the West, Golden Ears Provincial Park to the North and East and the urban area of Maple Ridge to the south. It spans an elevation range from about 1000m in the north-east corner near Golden Ears Mountain, to nearly sea level at the border with Pitt Lake to the west. The Research Forest was established in 1949 when it was crown-granted to UBC, and has been administrated by staff from the UBC Faculty of Forestry since then (Klinka 1976). The variety of soils and vegetation associations in

MKRF, which is about 4 km wide (East-West) and 15 km long (North-South), combined with a well developed road system creates a good research environment.

2.1.2 Climate

The climate of the Malcolm Knapp Research Forest is described as wet to very wet, cool mesothermal. It is characterized by mild temperatures, relatively dry and cool summers, wet, mild winters, with heavy precipitation occurring in the winter season. The temperature range is quite narrow, with an annual mean of 9.2°C, a mean temperature of the warmest month of 16.8°C, and that of the coldest month of 1.4°C. It is also characterized by frequent cloudiness and annual precipitation averaging 2140mm. The summer growing season receives an average of 606mm. The average precipitation of the driest month is 66mm (Eis 1962; Klinka and Krajina 1986).

2.1.3 Geomorphology

Geologically, MKRF is part of the Coast Crystalline Belt, an extensive plutonic and metamorphic complex of rocks that lies beneath and makes up the majority of the Coast Mountains. The bedrock consists mostly of quartzdiorite in the central and western part of the research forest and gabbro and diorite on the east (Klinka 1976).

Glacial tills and related colluviums are the dominant parent materials in the forest and their chemical and physical properties reflect the mineralogical properties of the quartz-diorite bedrock. The dominant soils that have developed in these unconsolidated surficial deposits are sandy ferro-humic podzols. Generally, the soil organic material has decomposed enough to be considered humus (Klinka and Krajina 1986). Gleyed hydromorphic soils can be found in the lower-lying sites. On granite knolls there are skeletal soils with thin organic layers. Generally, the soils are coarse textured, acidic and have a low base status; their nutrient status is submesotrophic to mesotrophic (Klinka 1976).

2.1.4 Vegetation and Ecology

Based on the biogeoclimatic classification of B.C. (Pojar et al. 1991), MKRF is situated in the Coastal Western Hemlock (CWH) biogeoclimatic zone, with the southern (lower in elevation) half of the forest falling into the dry maritime (dm) subzone, and the northern (upper)

half into the very wet maritime (vm) subzone (Fig 2.1). The research reported in this thesis was conducted in the southern part of the Malcolm Knapp Research Forest, in the CWH dm subzone. This subzone has a climate described as wet, cool mesothermal with mild winters and dry summers. Mean annual precipitation is 2140 mm, with approximately 600 mm falling between April and September (Klinka and Krajina 1986).

Vegetation and ecosystem associations have been described by Klinka (1976) and Klinka and Krajina (1986). Spatial representation of the ecological and biogeoclimatic units used in this thesis are based on the synecological map produced by Klinka (Klinka 1976) and updated by Klinka and Varga (2004). The forest is dominated by large and fast-growing evergreen coniferous trees, the most common of which are Douglas-fir (*Pseudotsuga menziesii*. (Mirb.) Franco), western redcedar (*Thuja plicata* Donn.) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). Red alder (*Alnus rubra* Bong.) is the most common deciduous species along with black cottonwood (*Populus trichocarpa* Torr.&Gray.), western white birch (*Betula papyfera* Marsh.), bitter cherry (*Prunus emarginata* (Dougl.) D.Dietr.) and bigleaf maple (*Acer macrophyllum* Pursh.).

The names of the CWH biogeoclimatic zone imply that western hemlock is the most frequently occurring species in climax forests, being capable of regenerating under the forest canopy; hemlock regeneration occurs on all sites but there may be a requirement for accumulations of acid forest floor materials or decaying wood on rich sites (Klinka and Krajina 1986). Douglas-fir generally dominates the drier sites with western hemlock and western red cedar as secondary species, while wetter sites are usually dominated by western red cedar and western hemlock (Fig 2.2)

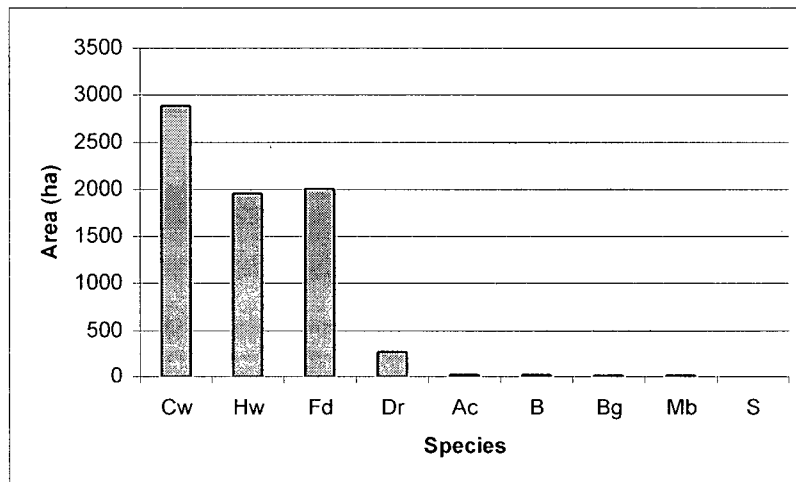


Fig 2.2 Species distribution in the CWHdm subzone at MKRF (where Cw-redcedar, Hw-western hemlock, Fd- Douglas-fir, Dr-red alder, Ac-poplar (*Populus* sp.), B- fir (*Abies* sp.), Bg-grand fir, Mb-bigleaf maple, S- spruce (*Picea* sp.)).

Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), also called Pacific hemlock and west coast hemlock, is occupying an extended area along the Pacific Coast and northern Rocky Mountains being the dominant species on British Columbia and Alaska. Its potential for management as an efficient producer of fiber has long been recognized. It is a pioneer on many sites, but can be found as climax dominant on many sites (Packee 1976; Burns and Honkala 1990). Western hemlock is highly productive on soils with a broad range of available nutrients and is relatively tolerant to extreme temperatures (Minore and Smith. 1971). In conditions of adequate moisture availability, seed germination and germinant survival are excellent on a wide range of materials.

Western hemlock is considered to be very tolerant of shade. Only Pacific yew and Pacific silver fir are considered to have equal or greater tolerance of shade than western hemlock. Western hemlock is considered a climax species either alone or in combination with its shade-tolerant associates (Klinka and Krajina 1986; Burns and Honkala 1990).

Western redcedar (*Thuja plicata* Donn ex D. Don), also called Pacific redcedar, giant-cedar, arborvitae, canoe-cedar, and shinglewood, is the only *Thuja* species native to western North America (Minore 1979; Burns and Honkala 1990) and is the most dominant species at MKRF (Fig 2.2). The natural habitat is extended along the Pacific Coast between 40° and 56° lat N.

When moisture is sufficient, the most limiting factor redcedar growth is low temperature. It grows well on a wide range of soils, and when water and nutrients are sufficient, redcedar

seedlings would outgrowth seedlings of Douglas-fir or western hemlock (Burns and Honkala 1990). It rarely forms pure stands as is usually found in association with other species. In the CWHdm biogeoclimatic subzone is a minor component on sites dominated by Douglas-fir or western hemlock (Minore 1979; Burns and Honkala 1990). Redcedar seedlings are more susceptible to extreme temperature than Douglas-fir, but on productive sites, coastal redcedar growth can compete with Douglas-fir or hemlock during the first 5 years of development. After that, however, Douglas-fir and hemlock would eventually outgrow redcedar (Curran and Dunsworth. 1988).

Red alder (*Alnus rubra* Bong.) occurs on a variety of low to middle elevation forest sites in the Pacific Northwest region of North America. Red alder is found throughout the Coastal Western Hemlock biogeoclimatic zone and is the most abundant broad-leaved species in coastal British Columbia (Klinka and Krajina 1986; Burns and Honkala 1990).

Red alder is a major competitor with young conifer plantations throughout its range in B.C. Seedlings that establish in disturbed areas following logging form the primary source of competition (Haeussler and Coates 1986). Juvenile growth of red alder is much more rapid than that of most conifers. Three-year- old red alder can grow 2 - 3 m/yr in height, and can rapidly overtop neighboring conifers. Red alder can remain dominant in a stand for up to 40 years. When it overtops conifers, it can substantially reduce light availability, and can cause physical damage to crop trees. The degree of light reduction and the amount of damage to conifers depends largely on the density and size of the red alder component of the stand (Comeau and Sachs 1992).

Red alder litter influences nutrient cycling in the forest and can also contribute to site nitrogen capital and long-term productivity through the process of symbiotic nitrogen fixation. Most studies on the effect of red alder competition on crop trees have involved Douglas-fir. Alder competition reduces height, diameter, and biomass of Douglas-fir (Cole and Newton 1986), and can cause significant mortality (Miller and Murray 1978). On the other hand, red alder interplanted with Douglas-fir clearly increased height and diameter growth of the associated dominant conifers on a nitrogen-deficient site in southwestern Washington (Miller and Murray 1978). Red alder also increases soil organic matter content (Bormann and Debell 1981).

Dominance of understory species varies with site moisture and nutrient regime, but the most common understory species are salal (*Gaultheria shallon*), dull Oregon grape (*Mahonia*

nervosa), and red huckleberry (*Vaccinium parviflorum*), and salmonberry (*Rubus spectabilis*) on the richer moister sites. The moss layer is dominated by Oregon beaked-moss (*Kindbergia oregana*), step moss (*Hylocomium splendens*), lanky moss (*Rhytidiadelphus loreus*), and flat moss (*Plagiothecium undulatum*) (Pojar et al. 1991).

2.1.5 Disturbance history

Several major disturbances have affected the Research Forest since the beginning of the nineteenth century. Prior to the initiation of forest management by the University of BC, MKRF area was affected both by human and natural disturbances. Among the natural factors, fire was the predominant disturbance agent despite the fact that climate of the forest is quite wet. A major fire in 1868 was the result of agricultural land clearance and burning in the Fraser valley adjacent to the forest during an extreme dry summer. The fire burned most the western side of the forest except the wettest pockets around lakes and stream gulleys (Klinka 1976). This area is now covered with a mature, 120 to 130-year-old forest made up of a mixture of Douglas-fir, western red cedar and western hemlock. In some areas where the fire did not burn, old-growth remains intact (MKRF 2006). Earlier extensive fires occurred in 1550, 1660, and 1780. Records also show that in 1800 and 1840 two smaller scale fires affected the Research Forest (Eis 1962).

In September 1925, a fire started in a cut-over near Alouette Lake and extended through the eastern part of the Research Forest, consuming much of the soil organic layers. A small fire occurred also in 1926 generated by the same logging activities (Eis 1962). In July 1931, a large fire that started outside of the forest near Raven Creek burned out of control for more than a month, consuming the slash and humus layers on exposed sites with shallow soils in the eastern valley of the forest, and extending over the area that was burned six years before. It appears that the fire eliminated most of the advanced regeneration of amabilis fir (*Abies amabilis* Douglas ex Forbes) except for the very wet areas around Marion Lake (Klinka 1976). Following this fire, logging was abandoned in the area creating conditions for second growth stands to establish by natural regeneration. These stands were 65-75 years of age in 2004 and are today composed mainly of western hemlock and red cedar with small amounts of Douglas-fir (MKRF 2006).

Although not as historically important as fire, windstorms are also quite frequent in the area, the last major event occurring on October 12th, 1962. This storm, locally called Typhoon Frieda affected mostly the wetter (northern) part of the forest but small openings were created in the lower elevation, southern, drier subzone (CWHdm) as well. A total area of 77 ha was affected

creating fairly large openings in the CWHvm subzone (Kinnear 1969). In December 2006, the storm that destroyed hectares of trees in Vancouver's Stanley Park, has affected the MKRF as well. The affected area consists on scattered patches totaling about one hectare in the CWHdm subzone. The damage produced in the northern part (vm subzone) is not yet known (I. Aron, Jan 2007, Pers. Comm.).

Logging activities have also played an important role in the development of the ecosystems at MKRF. Between 1920 and 1931, logging in the Research Forest increased significantly, with about 2800 hectares of high volume, old-growth stands in the eastern part of the Forest being clearcut (Klinka and Krajina 1986). Most of the timber was harvested by Abernathy & Lougheed (A & L) logging company. Their principal method was railway logging using steam donkeys and high-lead systems to yard larger trees. Much evidence of this history could still be found in the early 2000's on the eastern side of the Forest, including large cedar stumps, old railway grades, and metal cabling used in railway logging. Most of the roads in this part of the Research Forest have been built on old railway grades used for hauling timber in the 1920's (MKRF 2006).

Until recently, most of the post World War II harvesting was done in stands created by the 1868 fire. After clearcutting, most sites were slash-burned and then planted with Douglas-fir (Klinka 1976). More recently, as the management policies changed, harvesting has been less extensive and various trials have been installed to test the feasibility of different silvicultural methods such as shelterwood, group selection, and variable retention.

Harvesting in the Research Forest since 1949 has led to a range of younger age classes from 40-year-old second growth to 1-year-old second or third growth scattered throughout the area. At the upper end of the age range, some small patches of 400-year+ old growth forests remain intact at higher elevation (not in the dm subzone). The next oldest age class is the 120-130 year-old stands, which represent about half of the western side of the forest. Another age gap exists between these stands and the 70-year-old stands dating from the A&L logging that cover most of the eastern half of the forest. In the southern part (dm subzone), younger stands (1-40years old) cover about a third of the forested area, but the most extensive age class in 2004 was 61-80 years (class 4), which represents second-growth stands regenerated following 1920-1940 logging.

2.2 Description of the stand-level ecosystem management model FORECAST

This thesis tests the ability of the FORECAST model to simulate the development of Douglas-fir plantations that have been invaded by several other tree species, and the performance of planted Douglas-fir when faced with competition from a community of shrubs, shrubs plus hardwood tree species, or from pure alder. It is necessary to present some details of this model as background to the test of its efficacy.

FORECAST (**FOR**est and **En**vironment **C**hange **A**ssessment**T**) is a decision support software package developed for the evaluation of long-term sustainability and value tradeoffs related to stand-level management in forest ecosystems (Kimmins et al. 1999; Seely et al. 1999). Developed as an advanced Windows®-based interface version of the FORCYTE 11 model (**FOR**est nutrient **C**ycling and **Y**ield **T**rend **E**valuator), FORECAST represents the outcome of 29 years of ecological modeling research at UBC. The models of the FORCYTE series are described by the authors as hybrid, stand level simulation models capable of making predictions of the effects of management on biomass and nutrient accumulation in trees and minor vegetation (Kimmins et al. 1990; Kimmins 1993).

The development of FORECAST was driven by concerns over maintaining long term tree growth and yield under changing nutrient and soil organic matter levels. Its development started in the early 1970s as pressure on oil supplies from the threatened Arab oil embargo led to interest in bioenergy as an alternative energy source. There was a need to assess the sustainability of short-rotation bioenergy plantations (Kimmins 2004). FORECAST employs the hybrid simulation approach in which prediction is based on a combination of experience and knowledge of ecosystem processes (Kimmins et al. 1990; Kimmins 1993). A more detailed description of the hybrid simulation approach and references to other modeling approaches can be found in Kimmins et al. (1990), Kimmins et al. (1999), Kimmins (2004), Messier et al. (2003).

FORECAST uses empirical historical bioassay data to develop estimates of the rates of key growth and other ecosystem processes. This “back-casting” methodology creates a relational bridge between empirical field data and process simulation. The estimated process and transfer rates are used in the ecosystem simulation together with data describing those processes that cannot be calibrated by the back-casting approach (Kimmins 2004). The use of process-based simulation increases the flexibility of the historical bioassay, and the constraints imposed by the

empirical data improve the reality of the process simulation. FORECAST can be calibrated for any biogeoclimatic association and, based on the extent and quality of the calibration data, can produce representations of the ecosystem processes on a yearly time step. The model was designed to simulate ecosystems at different levels of representations of ecosystem complexity. The lower the level of representation needed, the lower the requirement for input data (Kimmins et al. 1999). The possibility of using the model at different complexity levels make FORECAST a useful teaching tool.

2.2.1 User interface

The FORECAST user interface (FORECAST Navigator) reflects the modular structure of the model which enables the user to access individual submodels for trees, plants (herbs, shrubs), bryophytes and soils/climate (Fig 2.3).

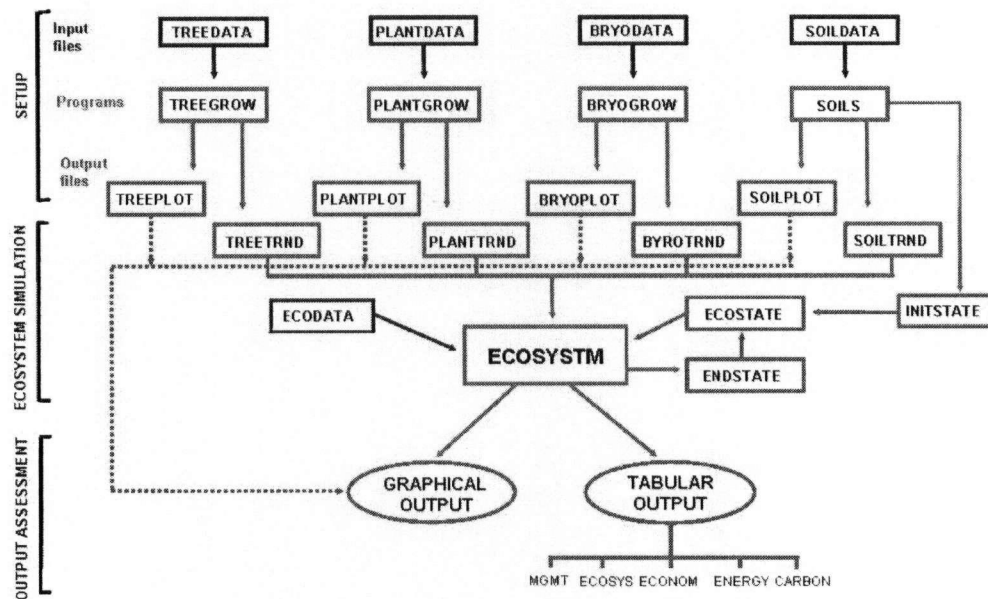


Fig 2.3 FORECAST files structure

Navigator represents the individual input file/subroutine/output file modules as boxes and data flow processes as a system of pipes, allowing the user to follow the information flow visually. FORECAST Navigator facilitates calibration data entry, editing and testing; setting up the model to represent particular ecosystems with particular disturbance histories; establishing the management and natural disturbance regime to be simulated; running the model; output analysis and archiving the results of particular simulation runs for later analysis; and comparison of different runs through graphical and tabular utilities. The user can access any of the four main

sections of the model: input data files, “setup” programs, the ecosystem simulation module and the output analysis module (graphical and tabular utilities) (Fig 2.4).

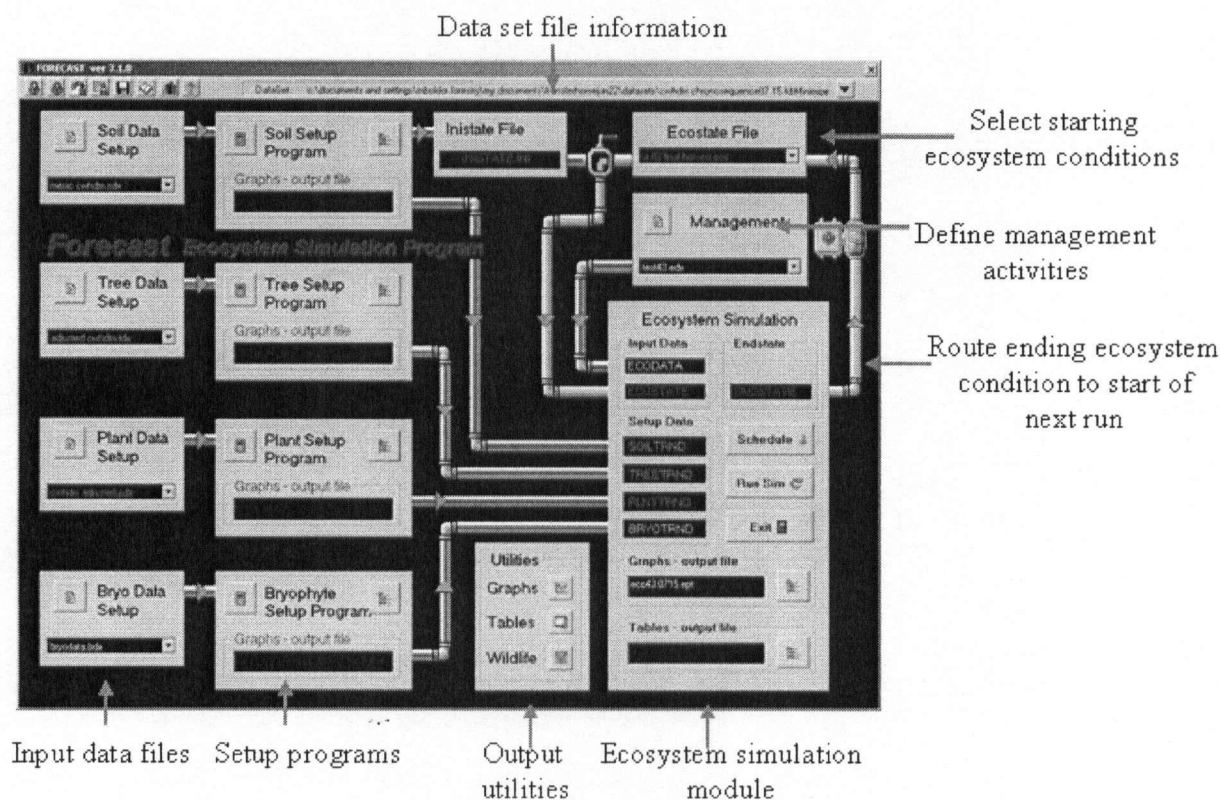


Fig 2.4 FORECAST version 7.0 user interface

The input data module consists of four sub-models: soil, trees, “plants” (herbs and shrubs) and bryophytes. Another two sections representing wildlife and climate change are under development and will be added to the model. As their names imply, the four sub-models contain information related to soil, trees, plants and mosses, respectively, with the requirement that the botanical input data should come from single species populations, or from a characteristic mixture of species for the site in the case of herbs, shrubs and bryophytes. The data contained in each sub-model can be accessed and modified by the user.

The setup module provides for calibration data entry, data quality assessment, the estimation of key ecosystem process rates to be used in the ecosystem simulation module, and a graphical check on the performance of these estimates in the simulation using the graphical utility.

The ecosystem simulation module is the core of the FORECAST model. In this module the simulation rules established in the setup module are used to simulate ecosystem structures and

key functions. The management scenarios (e.g. harvesting schedule, planting, thinning, pruning) and/or natural disturbances (i.e. fire, wind and insects) that are to be simulated are also contained in this module in an interactive tabular form named Management Data (Figs 2.4 and 2.5). The FORECAST user interacts with this part of the model in the process of creating the ecostate file – the initial conditions at the start of a simulation (a “run”) – as well as in the simulation of management or disturbance outcomes.

The screenshot displays the 'Management Data' window in the FORECAST software. It features a menu bar with 'Block Select', 'Close Page', 'Save', 'Cut', 'Copy', and 'Paste'. Below the menu is a grid with 13 columns representing simulation cycles. The data is organized into several sections:

- General Management:**
 - Nutrient status of site:** Nitrogen (2) and Phosphorus (0).
 - Nutrient feedback:** 0 (No control), 1 (Limitation), 2 (Limitation and site change).
 - Nutrient status:** 13.00.
 - Management Cycles:**
 - Number of cycles to be simulated: 1
 - Number of time steps per cycle: 30
 - Rotation length (for graphing purposes only): 100
- Fertilization (broadcast):**
 - Time of application (999-No test): 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999.
 - Mass of fertilizer (kg/ha): 600, 500, 400, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.
 - Amount of Nutrient #1 Nitrogen (kg/ha): 1000, 100, 100, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.
 - Amount of Nutrient #2 Phosphorus (kg/ha): 200, 50, 100, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.
 - Volatilization loss (% loss to atmosphere): 0.00, 0.00.
- Burning (wild or broadcast):**
 - Time of burning (999-No burn): 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999.
 - Burn code: 1, 2, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.
- Logging (wild or broadcast):**
 - Time of logging (999-No logging): 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999.
 - Logging code: 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.
 - Fate of material (fate code: 1-market, 2-compost, 3-burnpile): 1, 3, 2, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0.
- Compost spreading (broadcast):**
 - Compost Mode (1-run Compost, 2-imported Compost): 2, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1.
 - Time of application (999-No application): 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999.
 - Mode 1: Mass applied from compost pile (t/ha): 10.0, 20.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0.
 - Mode 2: Mass applied from imported compost (t/ha): 50.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0.
 - Amount imported of nutrient #1 Nitrogen (kg/ha): 10.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0.
 - Amount imported of nutrient #2 Phosphorus (kg/ha): 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0.
- Ash spreading (broadcast):**
 - Time of application (999-No ash): 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999, 999.
 - Mass applied (t/ha): 3.0, 5.0, 5.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0, 0.0.

Fig 2.5 Example of a FORECAST data management tabular input file

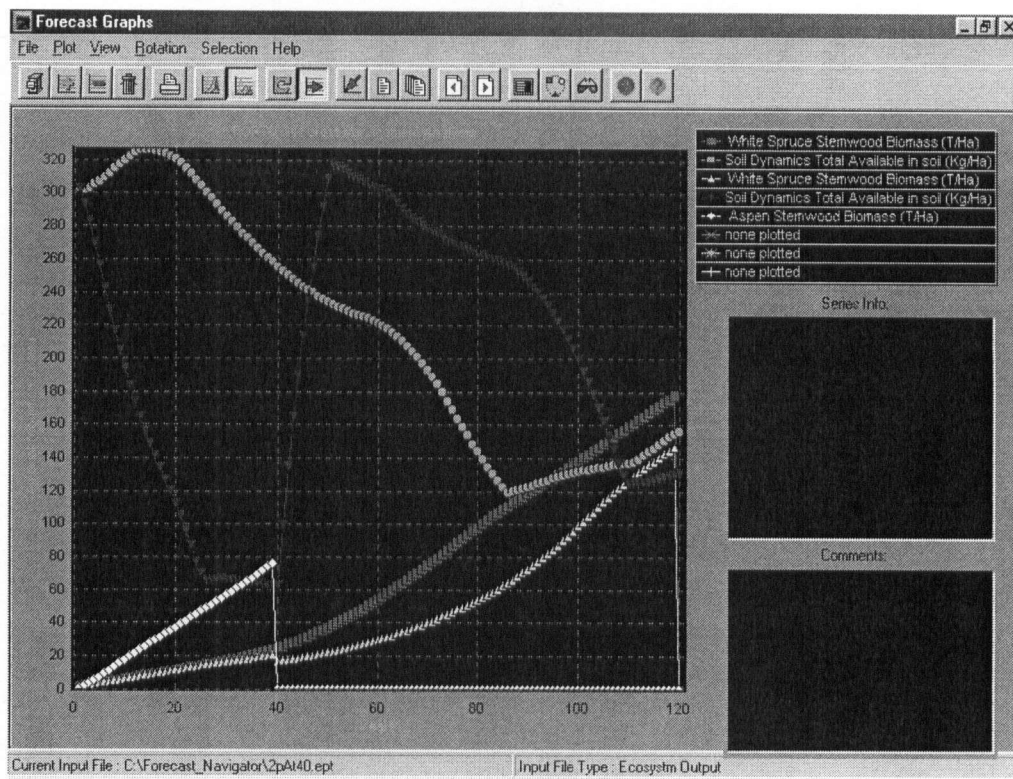


Fig 2.6 Example of a graphical FORECAST output

The output analysis module produces a comprehensive set of graphs and tables that represents the model outputs (Fig 2.6). The temporal patterns of a large number of ecosystem variables can be examined graphically, and any set of variables from any run can be compared with those from other runs. Summary statistics of the different forest resources values, including economics, employment, energy consumption, carbon and nutrient budgets, are presented in a tabular form (Seely et al. 1999).

2.2.2 Processes represented in FORECAST

This section describes the algorithms and relationships between the different FORECAST components. For a more detailed description of FORECAST and its scientific foundation see Kimmins et al. (1990; 1999), Kimmins (1993), Seely et al. (1999).

FORECAST calibration data requirements include variables such as: height, stand density, stem size frequency, biomass accumulation, nutrient concentrations, atmospheric nutrient inputs, rates of biomass transfer through litter-fall, photosynthetic adaptations of foliage, and various other stand and soil variables. The information should be obtained preferably from re-

measurements of individual stands growing on a variety of sites over time output from empirical models based on such data (see Kimmins et al. 1999). FORECAST was designed as a flexible tool to be used at different level of complexity. The model can be run with trees and/or minor vegetation with or without nutrient cycling and nutritional regulation of growth. The minimum level of complexity possible is light regulation of growth, and light competition.

The algorithms that are used in FORECAST are based on a curve-fitting procedure employing linear interpolations between input data points followed by a smoothing routine through the data points. The user is required to examine the consequences of input data quality for this smoothing; bad input data will result in poor model performance. Because the model requires input of empirical data rather than published coefficients based on data that the user cannot inspect, FORECAST ensures that the user is responsible for data quality and thus model reliability.

Among the most important indicators calculated in FORECAST are: total net primary production, annual potential growth, various measures of nutrient cycling, and site quality change. These indicators are detailed described in Kimmins (1993) and Kimmins et al. (1999), but a brief description is provided below.

FORECAST simulates annual growth based on the combination of light availability and foliar nitrogen content (based on foliage biomass and foliage N concentration). For each tree species represented in the model total net primary production (TNPP_t) is calculated for annual time steps as a function of biomass increment, litterfall and mortality as follows:

$$\text{TNPP}_t = \Delta\text{biomass}_t + \text{ephemeral litterfall}_t + \text{mortality}_t, \quad [3.1]$$

where:

$\Delta\text{biomass}_t$ is the sum of change in biomass in time step t (Fig 2.7);

$\text{ephemeral litterfall}_t$ is the sum of the mass of ephemeral tissues that are lost in time step t ;

mortality_t is the total mass of the plants that die in time t .

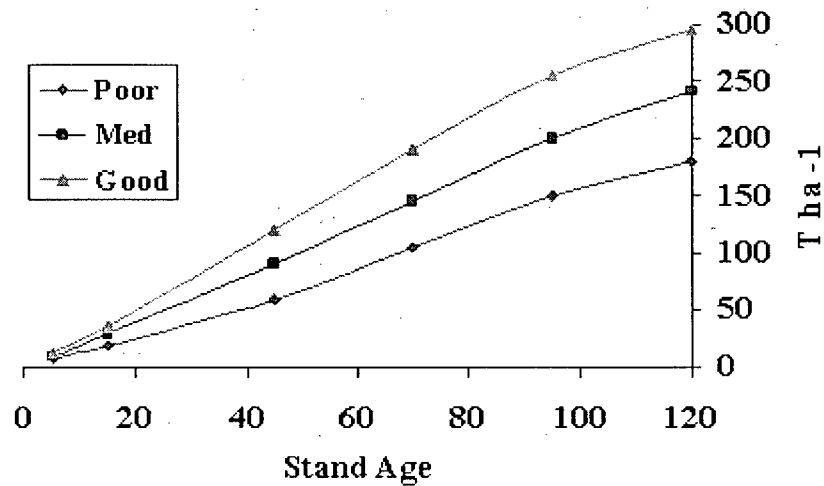


Fig 2.7 Example of biomass derivation in FORECAST

For the other vegetation components (shrubs, herbs and mosses) the net primary production is calculated based only on biomass increment and ephemeral litterfall, the understory plants being represented as continuous cover not as individuals. Mortality of individual stems is not simulated.

Photosynthetic production based on the foliage nitrogen content is the driving function of the vegetation potential growth in FORECAST. The model assumes that the foliage nitrogen content is a better estimator of the photosynthetic function than foliage biomass (Kimmins et al. 1999). The total amount of nitrogen in the foliage at a particular time step t (FN_t) is given by:

$$FN_t = \text{foliage biomass} \times \text{foliar N concentration.} \quad [3.2]$$

The model needs an estimate of the efficiency of photosynthetic activity, expressed as foliage nitrogen efficiency (FNE):

$$FNE_t = TNPP_t / FN_t, \quad [3.3]$$

Foliage nitrogen efficiency is not independent of light availability, which in turn is related to foliar biomass. Consequently, the model uses “shade corrected” foliar nitrogen efficiency rather than unaltered FNE. It also depends on species light adaptations and their ability to modify the

morphological and physiological characteristics of the foliage under different light intensities (i.e. sun and shade foliage adaptations).

FORECAST represents the canopy as an “opaque blanket”, the foliage being uniformly distributed horizontally over an area of one hectare, and uniformly vertically between the top and the bottom of the canopy (Fig 2.8).

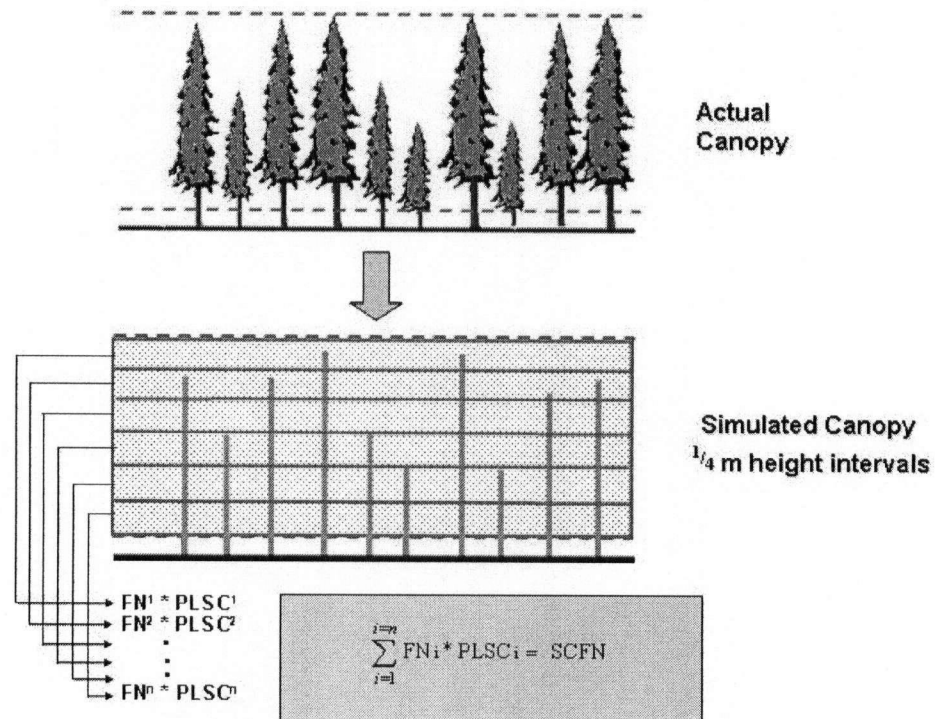


Fig 2.8 Simulation of canopy in FORECAST (adapted from Kimmins et al.(1999))

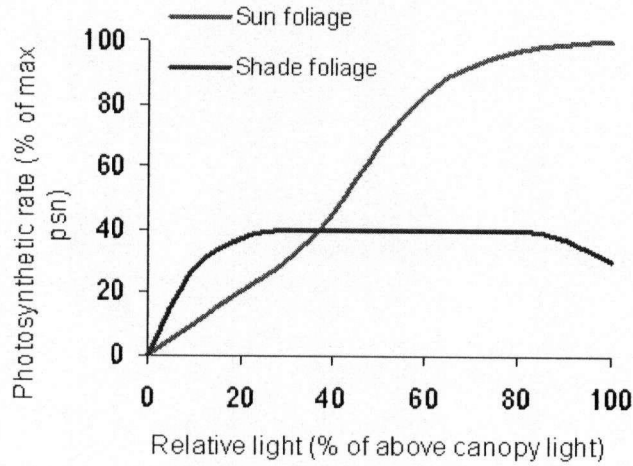


Fig 2.9 Example of sun foliage and shade foliage photosynthetic light saturation curves in FORECAST (after Kimmins et al.1999)

The model uses this vertical distribution of the foliage biomass to calculate the degree of self-shading and the percentage of the above canopy light reaching each level within the simulated canopy. A photosynthetic light saturation curve (PLSC) is generated for each quarter meter of the canopy by interpolating between input data on PLSCs for sun and shade foliage (Fig 2.9). Based on this, the model calculates the shade-corrected foliar nitrogen content for the entire stand as a sum of the foliage nitrogen biomass adjusted for the light saturation curve:

$$SCFN_t = \sum_{i=1}^n (FN_i \times PLSC_i), \quad [3.4]$$

where:

FN_i – foliage nitrogen mass for the i^{th} quarter meter of the canopy (kg/ha),

$PLSC_i$ – the photosynthetic light saturation value for the associated light level for the i^{th} quarter meter of the canopy,

n - represents the number of canopy levels (quarter meters),

$SCFN_t$ is the shade corrected foliar nitrogen content at time step t (kg/ha).

Extending the simulations over t time steps (from $t = 1$ to $t = \text{max tree age}$) and for all n canopy levels, the model creates for each species a time series curve of SCFN values.

Thus, adding the shade correction into the equation [3.3] we have:

$$SCFNE_t = TNPP_t / SCFN_t, \quad [3.5]$$

where,

$SCFNE_t$ is the shade corrected foliar nitrogen efficiency at time step t .

As with $SCFN_t$, the model generates a species-specific time series curve of $SCFNE_t$ values. Curves are produced for each site quality for which input data are provided.

The model driving function is then:

$$AGP_{(t+1)} = SCFN_t \times SCFNE_t, \quad [3.6]$$

where:

$AGP_{(t+1)}$ is the annual potential growth for a given species at the next time step (time = $t+1$) (Kimmins et al. 1999).

If FORECAST is run as a light-only model, AGP is the growth driver. If the model is run with both light and nutrient limitation, AGP is reduced to the level at which there are sufficient nutrients available by uptake from the soil and internal cycling within the plant to achieve the expected tissue concentrations for the current site quality.

2.2.3 Simulation of nutrient cycling

Availability of nutrients can be invoked as a major growth determining factor in FORECAST. The actual annual growth (AAG) is simulated in the model based on the availability of nutrients to sustain the potential growth (APG) established by the SCFNE (Fig 2.10).

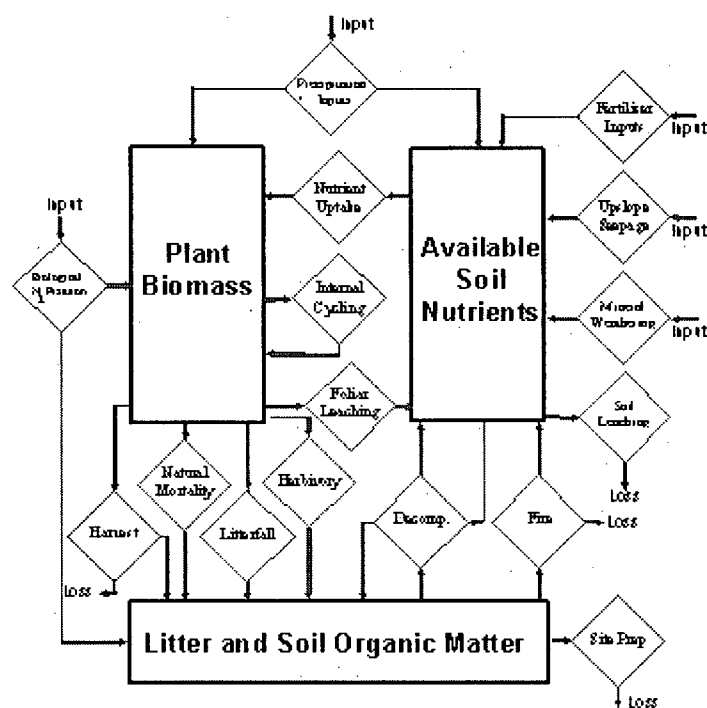


Fig 2.10 Diagram of nutrient cycles in FORECAST (after Kimmins 1993)

For many users at temperate and northern latitudes, FORECAST will be used with nitrogen as the limiting nutrient because it is the major growth-limiting nutrient in most forests at these latitudes (Kimmins et al. 1990). However, FORECAST can simulate the limiting effects of up to five nutrients (Seely et al. 1999). For each time step, the model simulates nutrient availability, nutrient demand and uptake to support new growth, and soil nutrient retention capacities. Nutrients in excess of these are assumed to be lost to leaching, semi-permeant sorption (P) or denitrification (N).

Three distinct pools of nutrients are represented in FORECAST: the plant biomass pool, the soil available nutrient pool and the soil organic matter pool (Kimmins et al. 1999).

Nutrients Inputs

Nutrient inputs that can be simulated in FORECAST include precipitation, weathering, biological N-fixation, and seepage from upslope. The rates of the physical inputs depend on the site characteristics (climate, atmospheric chemistry, slope position, soil properties) and these remain unchanged throughout the run even if simulated site quality changes. Biological N-

fixation is simulated as symbiotic, which changes as the N-fixing species change, and a-symbiotic fixation, which does not change during a run. The user can simulate fertilizer additions – either inorganic or organic forms (Kimmins et al. 1999).

Nutrients Outputs

The model simulates volatilization of the fertilizer N before the plants can access the N. Leaching losses are simulated as the excess of nutrients not taken up by plants and not held on soil exchange sites. There is no detailed simulation of ion exchange processes in the soil other than sorption/desorption of P. Denitrification is not simulated as a loss of NO₃ separate from leaching loss of unutilized nitrate. Thus, leaching of nitrate-N really simulates leaching + denitrification combined. The soil organic matter pool loses nutrients to fires (wildfires or slashburns), litter raking, and mechanical removal of the logging slash. Nutrients are lost from the biomass nutrient pool as a result of the simulated harvest operations.

Decomposition

Decomposing material is separated in the model into as many as 40 decomposition classes (or as few as one), the user deciding how many classes to use and which litterfall materials should be put into each class (e.g slow, medium and fast decomposition classes, or individual classes for every litter type). Input data define the mass loss rate and shape of the nutrient concentration change curve for each class on each site quality for which input data area provided. Microbial mineralization or immobilization is represented as increases and decreases in nutrients content of litter classes over time, respectively.

Plant nutrient uptake

The nutrient uptake by plants is simulated in FORECAST as the uptake demand to support the potential new growth, interacting with the availability of nutrients in the soil and in internal translocation processes. The nutrient uptake demand for each species is determined as:

$$UD_i = (APG_i \times EC_i) - (IC_i + CU_i) + Li, \quad [3.7]$$

Where:

UD_i – the annual uptake demand for species i (kg/ha);

APG_i - annual potential growth for species i (kg/ha);

EC_i - the average of expected nutrient concentration for new biomass of species i (%);

IC_i - the annual net nutrient gain from internal cycling for species i (kg/ha);

CU_i - the annual direct canopy uptake from precipitation or throughfall, for species i (kg/ha);

L_i - total annual foliar leaching from species i (kg/ha) (Kimmins et al. 1999);

After the calculation of each species' nutrient demand, the model represents the accessibility of soil nutrients as:

$$NAP_i = TAN \times RO_i, \quad [3.8]$$

Where,

NAP_i – available nutrients accessible by species i (kg/ha);

TAN – total size of the available nutrient pool in the current time step (kg/ha);

RO_i – the root occupancy of soil by species i.

The root occupancy is in turn determined as:

$$RO_i = FRB_i / MFRB_i, \quad [3.9]$$

Where:

FRB_i – is the fine root biomass for species i at the specified site quality (kg/ha);

MFRB_i – is the maximum fine root biomass for species i at the specified site quality (kg/ha).

The uptake demand is satisfied in the model based on the available resources. Thus, when the species nutrient demand is less than the total available quantity, then the species will be provided with the demanded quantities as:

$$AU_i = \min (UD_i, NAP_i) \quad [3.10]$$

where,

AU_i – represents the actual annual nutrient uptake for species i (kg/ha).

When the available nutrients do not satisfy the ecosystem demand, then the available supply is divided between the species as a function of their uptake demand and root occupancy:

$$AU_i = \min (UD_i / UD_{total}, NAP_i) \quad [3.11]$$

UD_{total} – represents the annual total uptake for all species from the ecosystem (kg/ha).

The nutrient limited growth for a species is then defined as:

$$\text{Nutrient limited growth } i = \text{APGi} \times \text{AU}_i / \text{UD}_i \quad [3.12] \quad (\text{Kimmins et al. 1999}).$$

Where the total uptake demand for all species exceeds the available pool, the uptake is allocated between species in proportion to each species demand (Kimmins et al. 1990). Within plants, nutrients are allocated to different biomass components based on the input data ratios.

2.2.4 Nutritional site quality

Site quality change is empirically represented in FORECAST in terms of the most limiting nutrient. An internal function (a bioassay) compares the annual nutrient uptake demands of the vegetation with the simulated total available for the most limiting nutrient. When the demand based on the expected growth at the present site quality exceeds the available nutrients, site quality is decreased, and vice-versa (Seely et al. 1999). Input calibration data should be collected from at least two chronosequences of stands of different site quality (or from multiple measurements studies) providing the basis for establishing a range of nutritional site qualities within the simulation. Most of the simulated processes are controlled by the site quality (e.g. carbon allocation and decomposition) but some are not (e.g. nutrient inputs from mineral weathering).

There are two site quality components in FORECAST: nutritional site quality, perceived by plants, and site quality based on soil processes. The plant site quality is simulated to change as nutrient availability changes. Soil site quality is based on plant site quality and changes in the same direction as plants site quality changes but with an “inertial delay” determined by the much slower soil processes. The relationship between change in the two types of site quality is user-determined in the form of a damping function (Kimmins et al. 1999).

2.2.5 Key assumptions in FORECAST

Most models have a set of assumptions that must be met if the model output is to be reliable. The following are the assumptions used in this thesis: 1) the historical bioassay input data provide an accurate indicator of the growth potential of the simulated species on the sites being simulated; 2) the input data come from the same range of site qualities that are expected to be encountered in the simulations; 3) the initial conditions for the ecosystem (plants, soil) can be

accurately defined; 4) the estimates of rates of change for processes that are calculated internally in the model are an accurate reflection of real ecosystem process rates (Kimmins 1993).

2.2.6 Creating an ECOSTATE file in FORECAST

Every simulation in FORECAST must start from the description of the initial conditions; this is contained in a *state of the ecosystem* or ECOSTATE file. An ECOSTATE file represents the “working sheet” for each simulation run in which the ecosystem condition at a given time is described in terms of levels of organic matter resources and vegetation characteristics. Over the runs, the ECOSTATE file is modified according to the treatments applied and the simulated process rates.

At the commencement of a simulation activity, a blank file (INISTATE) is created by the Soil Setup program with a format that reflects the decisions the user has made concerning what species and what decomposition classes are to be included in the simulation. INISTATE is then populated with data that describe the desired starting condition for the future runs by switching off the nutritional feedback on growth, and running FORECAST to simulate the known or assumed history of ecosystem disturbance. Having nutrient feedback switched off forces the simulation to duplicate the historical bioassay input data and use the ecosystem process rates that have been calculated there from. The model builds the ecosystem from scratch based on the historical data. It may be necessary for the user to run the model several times to generate the length of time over which the present ecosystem condition developed. There are some indicators (e.g. total humus mass, humus nutrient accumulation) that the user should check at the end of each simulation to determine whether the ECOSTATE has reached the desired starting condition for subsequent runs. Experience with FORECAST shows that the ECOSTATE file preparation has almost the same importance as the calibration of the model (Kimmins et al. 1999).

2.2.7 Some limitations of FORECAST

No model is perfect. Among the limitations of the model are: the simplistic representation of soil processes, which currently prevents the simulation of compaction and erosion; the simplified representation of the canopy (the “opaque blanket”); the fact that seasonality is not well represented (Kimmins et al. 1999). Seasonality and soil moisture are being added to the model, as is wildlife habitat representation and climate change effects. The fire section of the

model will also be improved by adding a fire risk assessment. The model is deterministic, and depends on the user to add stochastic events like fire or insect attack according to empirically-determined probabilities.

2.2.8 Background of FORECAST testing

FORECAST and its predecessors FORCYTE-10 and FORCYTE -11 have been subjected to several tests (Sachs and Trofymow 1991; Comeau and Sachs 1992; Sachs 1996; Morris et al. 1997; Seely et al. 1999; Wei et al. 2000; Seely et al. 2002; Welham et al. 2002; Wei et al. 2003; Bi et al. 2007; Blanco et al. 2007; Seely et al. 2007). As a management tool, the model was used in several projects in Canada, Europe and China (Table 2.1).

Table 2.1 FORECAST model major projects (adapted from <http://www.forestry.ubc.ca/forestmodels/>, accessed Mar 2006)

Location		Project	Applications
Canada	British Columbia		
	Arrow TSA	Arrow IFPA Project	Growth & Yield projection in complex stands, long-term site productivity, indicators of non-timber values
	Canfor TFL 48	Development of SFM plan, Certification	Growth & Yield projection in complex stands, long-term site productivity, indicators of non-timber values, carbon sequestration
	Alberta	Oil sands reclamation	Ecosystem recovery, long-term site productivity
	Saskatchewan	Boreal mixed wood management	G&Y projection in aspen / spruce mixed woods, economic analyses, decision support tool
International	Scotland	Plantation forestry	Projection of treatment response in Sitka spruce stands, long-term site productivity
	Norway	Plantation forestry	Projection of treatment response in Norway spruce stands, long-term site productivity
	China	Plantation forestry	Projection of treatment response in Chinese fir stands, long-term site productivity

FORECAST has been tested against other models and against field data. Yarie (1986) compared one of the FORECAST predecessors, FORCYTE-10 with another ecosystem model, LINKAGES, by simulating the development of an old growth white spruce stand. The development of aboveground standing crop and the biomass dynamics of the forest floor and humus layers were adequately portrayed by both models. However, when compared to existing data, only FORCYTE-10 satisfactorily portrayed stand density dynamics and nitrogen mineralization.

In another trial, Binkley (1986) tested FORCYTE-10 against FORNUTS, a simple model, designed for educational use, which is also based on nutrient cycling. A variety of stand treatments (stem-only harvesting, whole-tree harvesting, and fertilization) were simulated over three rotations and the results were similar for both models. Binkley's study explored the aspect of complexity in modeling and the difficulty of validating complex models. This test was not very comprehensive and the full potential of FORCYTE-10 was not explored.

Sachs and Trofymow (1991) conducted a more elaborated evaluation of the capabilities of FORCYTE-11. The model results were tested against experimental data obtained from a long-term trial. The model did not perform well when calibrated with a generalized data set for the CWHxm (very dry maritime Coastal Western Hemlock) biogeoclimatic subzone. However, model performance improved with a dataset that was calibrated to the specific site being simulated; a well-calibrated data set was necessary for the model to provide good results.

Blanco et al (2007) have re-tested FORECAST against an extended Shawnigan Lake data set. They compared model performance using the original Sachs and Trofymow (1991) data set and also with an improved data set. Results highlighted again the dependence between the model outputs and the quality of the data set. The model generally produced good predictions but the performances clearly improved when a better data set was used.

Bi et al (2007) used FORECAST to examine a conceptual model of Chinese-fir (*Cunninghamia lanceolata* (Lamb.) Hook) decline. The conceptual declining model tested was focused on the effect of shorter rotations which generate excessive nutrient depletion and soil erosion. A FORECAST data set was calibrated using data from Chinese-fir related publications. Several scenarios were tested and the results confirmed the validity of the conceptual model. The validity of FORECAST outputs was then tested using an independent data set obtained from a similar study and the results were confirming FORECAST's capabilities to simulate this complex issue of Chinese-fir decline. The study results emphasize the utility of using ecosystem-level models like FORECAST which explicitly can represent all major ecosystem components. These types of models, when properly calibrated, are fully capable to emulate complex ecosystem issues and provide reliable results.

Seely et al (2007) have evaluated the FORECAST capability to project patterns of stand growth and dynamics in two mixewood forests from two different biogeoclimatic subzones: Sub Boreal Spruce (SBS) and Interior Cedar Hemlock (ICH). Different stand management

treatments were simulated and the model outputs were compared with the field measurements. The results showed that FORECAST is capable to project stand growth and management activities with reasonable accuracy (Seely et al. 2007).

The general usefulness of the FORECAST model was explored in Wei et al (2000; 2003) who used visual estimations of the model outputs and sensitivity tests that challenged the model performance against real designed experiments. The results showed the efficacy of using well calibrated models for testing management decisions (Wei et al. 2003).

Chapter 3 – The Blaney Chronosequence: Assessment of early stand development and evaluation of model performance

3.1 Introduction

Any model user needs to be able to decide, based on an evaluation of performance, whether a particular model is adequate for a particular application (Soares et al. 1995). The choice of evaluation technique is restricted in many situations by the characteristics of the model and the particular conditions under which it is being tested. Not many attempts to evaluate complex ecosystem models have been made, but several approaches for testing forest growth models have been presented (Soares et al. 1995; Vanclay and Skovsgaard 1997). A five-step methodology has been suggested, emphasizing the importance of evaluating a model from both qualitative and quantitative perspectives, including theoretical and empirical aspects. While the qualitative testing should evaluate the internal structure of the model from logical and biological perspectives, the quantitative examination refers mostly to error evaluation, statistical tests, sensitivity analysis and comparisons between model outputs and real observations. No single methodology provides a complete basis for evaluation. Some authors suggest that an ongoing process of testing that starts with model design, continues through code development and ends with testing the application of the model is a more cost-effective alternative than efforts to apply the entire range of tests when model development is complete (Vanclay and Skovsgaard 1997). However, many of the quantitative evaluations (statistical tests, error interpretation and sensitivity analysis) can only be done after a model has been developed. Testing during model development is limited to qualitative tests (Oreskes et al. 1994; Vanclay and Skovsgaard 1997).

One of the main objectives of this thesis is to compare some selected output values produced by FORECAST with empirical data obtained from field measurements (qualitative assessment), and to compliment this with a quantitative test of model performance. Comparison between model outputs and an independent data set, preferably from controlled and replicated trials measured over extended periods, has been suggested as one of the most rigorous tests of a model (Vanclay and Skovsgaard 1997).

To evaluate the performance of FORECAST, data obtained from two experiments established at MKRF in the early 1980's by Karakatsoulis (1993; 2004) and data from re-measurements of

these installations were used. In the first of these, the Blaney Lake Chronosequence, this resulted in a 23-year data set. In this chapter these data are compared against the model's predictions obtained using a general calibration data set for the CWHdm biogeoclimatic subzone. Because the field data only spanned 23 years, they do not provide a validation of FORECAST predictions over a full management rotation. Consequently, the scope of this thesis is limited to evaluation of model performance over the period of stand establishment to canopy closure and the onset of competition-induced mortality. This is a critical phase because it sets up the species composition, stocking, and timing to full site occupancy by trees – the main factors that determine future stand condition and yield. This is also a critical period because most growth models only start at about the end of this phase of stand dynamics; a phase that is also poorly represented in many ecosystem models which only simulate tree growth after some minimum diameter has been reached.

Most models fail to address recruitment of non-crop trees during the stand initiation phase of stand dynamics, and fail to represent the consequences of herb and shrub competition in stand initiation and early tree growth, and the combined consequences of non-crop tree and herb and shrub recruitment on growth and survival of planted crop trees. This thesis focuses on these issues.

Most recent models give height estimates only for either juvenile (up to 15 to 25-year-old stands) or for older stands. However, there is a need for models that provide continuous growth forecasts from germination to the old growth phase of stand development (Nigh and Polsson 2002). Analytical methods such as splicing, fitting, interpolation and data manipulation have been developed to bridge the age gap, but there is a cost to all of these methods in terms of either lack of accuracy or lack of model portability.

This chapter and the following one address the question as to how well FORECAST predictions emulate real data. Some quantitative tests are used in order to provide some confidence regarding the model behavior.

Specific objectives include the following:

- 1) Continue the study initiated by Karakatsoulis et al (1993) on vegetation development and Douglas-fir growth in the face of non-crop tree recruitment and minor vegetation.
- 2) Test the ability of FORECAST to duplicate the empirical results of real experiments by simulating the Blaney Lake Chronosequence stand development and comparing model output with the field data;

- 3) Explore the effects of natural regeneration of mixed species in a cutblock planted with only Douglas-fir, with a focus on the effects of western hemlock recruitment;
- 4) Examine the “window of opportunity” for recruitment of regeneration of hemlock and other species, and examine the consequences for stand development of the timing of this recruitment.

3.2 Methods

3.2.1 The chronosequence approach

The chronosequence approach, though controversial, is still used in many natural sciences, including forestry. The main advantage of this approach is the opportunity to study ecological processes over time periods that are longer than direct observation would permit – it is space for time substitution. The chronosequence approach assumes that all the sites that make up the chronosequence are ecologically similar, have had the same histories, and that the only difference between them is time. Of course this is rarely the case. Opinion continues to be split on whether or not the benefits of the chronosequence outweigh its limitations. However, the extended periods of time involved in stand and ecosystem development generally make direct empirical observation of these processes and their products impractical, and, consequently, despite the problems in the method (Yarie et al. 1989), chronosequence research is often the only choice available in model evaluation and in understanding long term ecosystem dynamics (Bardgett et al. 2005). To assess whether or not the chronosequence is valid, the component stands of the chronosequence can be re-measured over time. If re-measurements of stands of the different ages in the sequence show the same temporal development patterns as implied by the original chronosequence data, confidence in the method is increased. However, chronosequence studies should be complimented wherever possible by long-term studies that track the respective ecosystem over time (Martin et al. 2002; Bardgett et al. 2005).

In the Blaney Lake Chronosequence Project the topography, soils, elevation, aspect, vegetation, disturbance history (all four stands developed in small clearcuts in a uniform stand that developed after an 1868 fire) and climatic conditions are the same or very similar for the four stands in the chronosequence. The veracity of this conclusion was tested through re-

measurement and confirmation that the four stands have all tracked the same stand development pathway (Karakatsoulis and Kimmins 1993).

3.2.2 Description of the Blaney Lake Chronosequence Sites

The Blaney Lake Experiment was initiated by John Karakatsoulis in the early 1980's and was originally designed as a chronosequence study of the early vegetation development following clearcutting (Karakatsoulis and Kimmins 1993). The experiment is situated in the CWHdm biogeoclimatic subzone of the MKRF south of Blaney Lake. The study consists of a series of four adjacent sites, which were clearcut harvested in 1980, 1982, 1984, and 1986. The high-lead harvesting produced very little forest floor disturbance and minimal soil exposure. Each cutblock in the sequence is approximately 10 ha in size, the average elevation is 350 m, and all have a south-southwest aspect (Karakatsoulis and Kimmins 1993) (Fig3.1F).

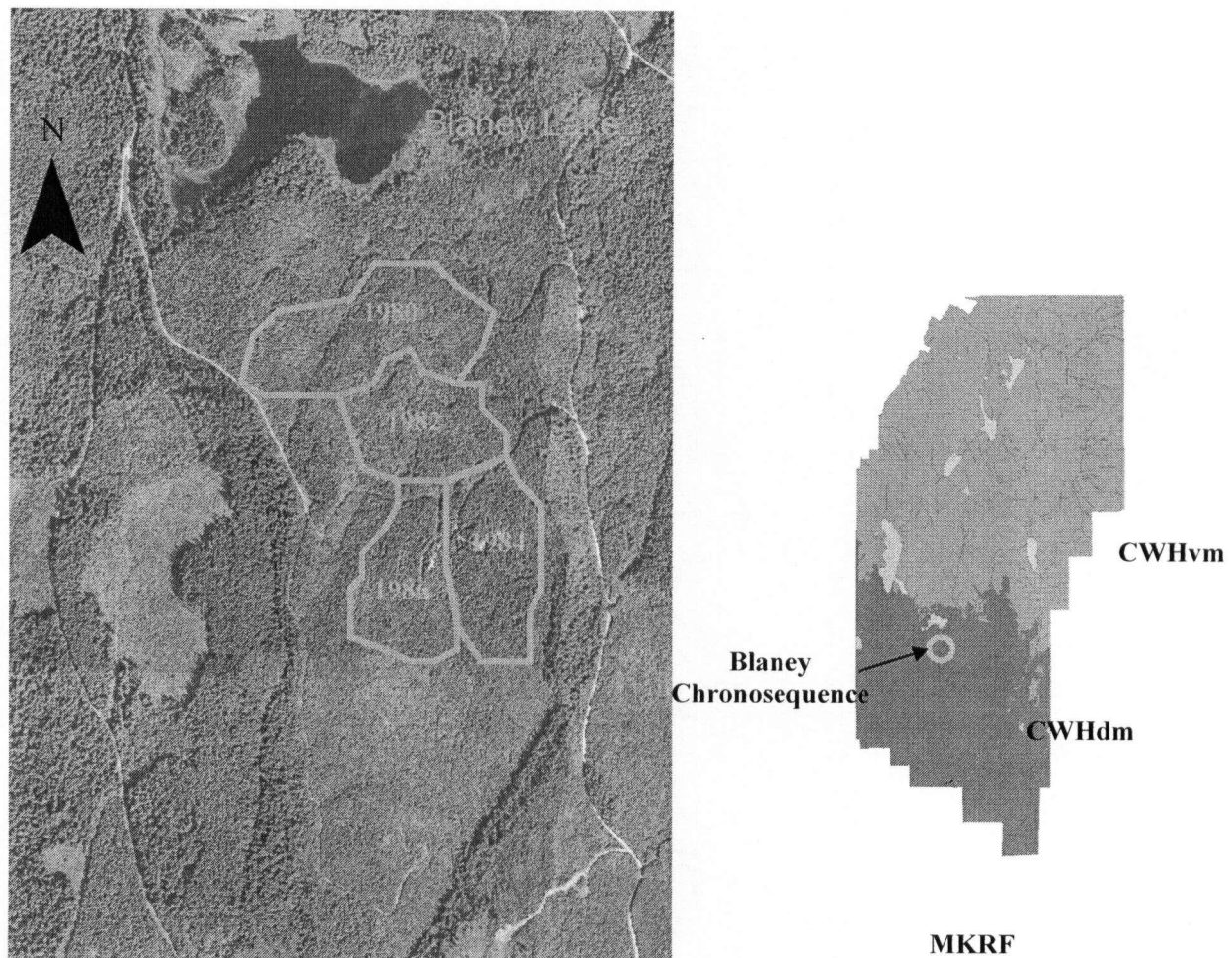


Fig 3.1 Site location

The entire chronosequence area was classified by Klinka (1976) as predominantly a Gaultheria-WH-DF plant association with inclusions of other vegetation on mesic and moister microsites, with till-derived, loamy sand soil texture, and Lithic Mini Humo-ferric and Lithic Podzol soils. The study sites were arranged along a topographic sequence formed by a SW-facing low ridge, varying from relatively dry (xeric) and nutrient poor, at the top (the Gaultheria association identified by Klinka) to moist and nutritionally medium to rich and moist at the bottom (hygric), and mesic, nutrient medium at midslope positions. Humus varied from mor at the top to moder at the bottom of the topographic sequence. The elevation difference from top to bottom of the slope varied between 65 and 95m. The upper site was characterized by the ericaceous shrub *Gaultheria shallon* (salal) while the lower part of the slope supported the rosaceous shrub *Rubus spectabilis* and the fern *Polystichum munitum* (swordfern). In mature stands on the mesic midslope site, the minor vegetation is a mixture of feather mosses. Each cutblock was planted with 2-year-old bare root Douglas-fir seedlings within 1 year of harvesting, at approximately 1200 seedlings per hectare. Two sets of measurements were made in 1987 and 1990 to provide an age sequence of vegetation development and Douglas-fir growth on clearcuts aged 1, 3, **4**, 5, **6**, 7, **8** and **10** years (bold italics years are the 1990 re-measurement). Remeasurements in 2003 provided data for 19, 21, 23 and 25 year old stands.

3.2.3 Measurements

1987 and 1990 measurements

The 1987 and 1990 measurements used sampling methodologies appropriate for the young stands where the maximum age reached was 12 years. Sub-plots were located on hygric, mesic and xeric points along the topographic moisture gradient. Plots within the 1984 site and the 1980 hygric site were not measured in 1990. In 1987, thirty Douglas-fir seedlings/plot were measured for height and basal diameter and another 45 seedlings (5 per plot) were destructively sampled for stem and foliage biomass calculation (they were separated in branches, foliage and stems, oven dried and then weighted). The same sampling procedure was used in the 1990's measurements, with 30 Douglas-fir seedlings per plot measured for height and basal diameters but only seven seedlings were destructively sampled for biomass measurements.

For the understory vegetation, the methodology adopted in 1987 was a partial random sampling with thirty (30) 1x1 m plots randomly sampled along three 30m transects (10 plots per transect line) (Karakatsoulis and Kimmins 1993). Height was measured and percent cover was estimated for each species present. An additional 5 plots per SMR-clearcut-age combination were used for destructive sampling; the plants were separated into stem and foliage components, oven dried for 48 hours at 70 °C and then weighed and used for biomass estimation. In 1990, the number of plots was reduced to 5 per transect (15 per clearcut-age combination) but the plot size was increased to 5 m² (1.26 m radius plots) (Karakatsoulis and Kimmins 1993).

2003 measurements

In 2003, with the stand ages varying from 19 to 23 years old, a slightly different methodology was used. Fully stocked areas of the four stands were selected for each hygrotpe-age combination (12 in total) using aerial photographs, digital maps of forest cover and field confirmation of the selections; maps were prepared based on information collected from the GIS and MKRF data. The detailed synecological map of the area (Klinka and Varga 2004) was used to select individual site types, again confirmed by field inspection. Aerial photos at a resolution of 1x1m were wrapped with a 10x10m grid and all non-representative grid-cells (non-forested patches - areas excessively occupied by rocks) were removed. A complex map with all the stands and vegetation characteristics was created and used in conjunction with the aerial photographs. ArcGIS 9.x[®] (ESRI 2004) software was used for all the GIS analyses. Because the non-forested patches had been eliminated, the sampling was based on assumed uniform stand conditions for each age-SMR combination. Three randomly selected grid cells were established for each combination (Cochran 1977, Freese 1962). If a selected cell bordered a previously selected location, the cell was not used and the process was repeated (this occurred in three out of thirty six cases). The centers of the selected cells were then field checked and circular 100m² plots were laid out.

The following variables were measured for each plot:

- diameter at breast height (DBH) and root collar, health condition and canopy position for all tree species (Douglas-fir, hemlock, redcedar, and alder);
- height for representative trees from each age cohort of each species
- height and percentage cover for all understory species
- stems position coordinates for all trees

- site characteristics (slope, elevation, aspect and surficial materials)
- stand density.

In addition to the planted Douglas-fir, there were significant numbers of three other tree species and additional Douglas-fir that recruited by natural regeneration. During the first two sampling periods (1987 and 1990) only the planted Douglas-fir were measured and recorded; Mailly (2003), however, noted the recruitment of natural regeneration in the younger clearcuts. Ten years later, during the 2003 field sampling, there was a significant component of naturally regenerated Douglas-fir and western hemlock, a minor component of redcedar, and some red alder on some sites.

3.2.4 Data analysis

Initial measurements on the Blaney Lake Chronosequence examined only minor vegetation and planted Douglas-fir. Although natural regeneration of other tree species had begun to recruit in the younger stands, these trees were not yet a significant stand component. The objective of the 2003 re-measurement, conducted as part of this thesis, was to document all tree species as well as the minor vegetation. The Blaney Lake chronosequence data covers clearcut ages up to 23 years. They were planted with two-year-old seedlings so the oldest trees were 25 years old. In total, each plot was measured three times (in 1987, 1990 and 2003) with slight differences between the earlier two and the final set of measurements as noted above; species density and breast height diameter were measured only at the third measurement. FORECAST produces only DBH values, so regression equations between the collar and breast height diameters were developed for all tree species (Table 3.1). FORECAST's DBH values were then converted into root collar diameter values and compared with the field data. Budget restrictions did not permit any destructive sampling for Douglas-fir biomass, so that stemwood biomass was not measured directly; it was estimated using the regression equations produced by Standish et al (1985) (see table 3.2.). However, these equations are not perfectly fitted for the age range of this study as the range age was for Douglas-fir, for hemlock and for redcedar. Stand density was assessed in 2003 to evaluate Douglas-fir mortality associated with strong competition from the naturally regenerated trees of several species.

Table 3.1 Simple linear regressions fitted between collar diameters (Dbase) and breast height diameters (DBH) of Douglas-fir, western hemlock, redcedar and red alder for the Blaney Lake area.

Species	Equation used	Model fit (R ²)	Range for DBH (cm)	Sample size
Douglas-fir	$Dbase = -0.63459 + 1.231128DBH$	0.99	2.5 - 25	46
Western hemlock	$Dbase = 0.111 + 1.223DBH$	0.98	1.2 - 15.4	31
Western redcedar	$Dbase = 0.696 + 1.066DBH$	0.97	0.8 - 21	63
Red alder	$Dbase = 0.734 + 1.018DBH$	0.92	1.9 - 17.0	21

Table 3.2 Equations used to estimate total stemwood biomass (Bio) for the principal tree species using breast diameter (DBH) and total height (H) adapted from Standish et al. (1985).

Species	Sample size	Age range (average age)	Equations used
Douglas-fir	49	9 - 86 (31)	$Bio = 10.3 + 110.4 \times DBH^2 \times H$
Hemlock	70	11 - 253 (64)	$Bio = 5.5 + 123.3 \times (DBH/100)^2 \times H$
Western redcedar	70	18 - 273 (74)	$Bio = 3 + 68.4 \times (DBH/100)^2 \times H$
Red alder	41	5 - 48 (19)	$Bio = 4.6 + 159.6 \times DBH^2 \times H$

Analysis of variance (ANOVA) was performed for diameter, height, stem density and stemwood biomass using SAS software (SAS 2003) to determine whether there was a SMR influence. For the understory species, only above ground biomass was estimated using equations developed by Karakatsoulis and Kimmins (1993) from data recorded from the Blaney Lake area (Table 3.3).

Table 3.3 Equations used to estimate total biomass (*Bio*) for the principal understory species adapted from Karakatsoulis and Kimmins (1993). Where, *lnCOV* and *lnHT* represent the natural logarithms of the percent cover and height of the specified species.

Species	Equation used
<i>Gaultheria shallon</i>	$Bio = e^{(-0.932 + 0.971(\ln COV) + 0.551(\ln HT))} + e^{(-0.477 + 1.552(\ln COV) - 0.047(\ln HT))}$
<i>Pteridium aquilinum</i> <i>Polystichum munitum</i>	$Bio = e^{(-2.448 + 1.220(\ln COV) + 0.537(\ln HT))} + e^{(-5.208 + 1.079(\ln COV) + 1.061(\ln HT))}$
<i>Rubus spectabilis</i>	$Bio = e^{(-3.949 + 0.960(\ln COV) + 1.083(\ln HT))} + e^{(-6.205 + 0.815(\ln COV) + 1.693(\ln HT))}$
<i>Rubus parviflorum</i>	$Bio = e^{(-6.289 + 0.906(\ln COV) + 1.553(\ln HT * 100))} + e^{(-5.915 + 0.869(\ln COV) + 1.374(\ln HT * 100))}$
<i>Vaccinium parvifolium</i>	$Bio = e^{(-2.869 + 1.776(\ln COV) + 0.258(\ln HT))} + e^{(-4.453 + 2.240(\ln COV) + 0.736(\ln HT))}$

3.2.5 Model calibration

Since an existing calibration data for the Coastal Western Hemlock dry maritime (CWHdm) subzone set was used for the modelling work conducted here, only a brief description of the calibration process is provided. A detailed description of the calibration process is available in Seely (2004). In general, the dataset was developed used regional growth and yield data for Douglas-fir, western redcedar and western hemlock derived from TIPSYS (see www.for.gov.bc.ca/hre/gymodels/TIPSYS). These data were transformed into biomass using species-specific allometric biomass equations (Standish et al. 1985). Other data describing ecosystem, processes including decomposition rates, nutrient concentrations, photosynthetic light response curves, minor vegetation, and canopy light interception were derived from literature sources (see Seely 2004). As described by Blanco et al. (2007), data sets developed for a regional applications (e.g. a biogeoclimatic sub-zone (Meidinger et al. 1991)), while not as accurate as site-specific calibrations, provide a reasonable level of accuracy for most applications.

3.2.6 Model application

The purpose and development of the Ecstate file was described in Chapter 2. It represents the initial conditions of a forest from which growth and development will be simulated.

An ecstate file was prepared for the Blaney Lake area using a general CWHdm data set created for MKRF. An Ecstate file was produced for each of the three SMR classes (xeric, mesic and hygric) by simulating the stand disturbance history as reported by Klinka (1976), Mailly (1998) and Kinnear (1969). The estimated site index for Douglas-fir for each SMR was 36 for xeric, 39 for mesic and 43 for hygric. Based on the literature, the fire frequency (fire is the most important disturbance agent in the region) was estimated at 200 years. Windthrow also occurs at MKRF but has only affected small areas (Kinnear 1969). The starting conditions of the simulations were based on a mixture of Douglas-fir (initial density of 1200 sph) and western hemlock (initial density of 800sph) with an understory component of salal (initial percentage cover of 0.02%). The model was run for five cycles of 400 years with a severe fire simulated every 200 years. Nitrogen feedback was switched off to allow the model to accumulate humus, litter and associated nutrients so that they were similar to current forest floor conditions (see Seely et al. (1999) for more details about the development of starting conditions). By the end of the 2000-years of ecstate preparation period, the rate of humus mass accumulation had leveled off. At this point the simulated forest ecosystem was considered to be representative of the initial conditions of the Blaney Lake Chronosequence experiment.

The 2003 measurements revealed a high degree of variation in the density and species composition of natural regeneration (ingress) between the different ages of a given SMR class, suggesting that similar sites will develop along somewhat different trajectories and result in different stand dynamics. This invalidates the basic assumption of the chronosequence approach and makes it difficult to infer a single development trajectory from the combination of data from all measurements. As a consequence, the design of the simulation experiment was changed. A single site was selected for each hygric, mesic and xeric site, with site index 36, 39 and 43 respectively. The moisture regime and site quality were not the only criteria to differentiate these sites but also the ingress species composition and age. The comparison between field data and model output was restricted to these sites.

The simulation experiment was conducted for each of the three SMR by planting Douglas-fir in the first year of the simulation. The ingress of natural regeneration recorded in the field was simulated as well. Thus the simulated sites vary on site quality and in species composition and at a complexity level similar to that of the real forest (Table 3.4).

Table 3.4 Description of the simulation runs with species, age of regeneration and densities (percent cover for the understory species). Regen year represents the initiation year for a particular species. Species are defined as follows: Fd, FdII –Douglas-fir. Hw, HwII –western hemlock, Dr – red alder. Only Fd was planted, all others established as ingress from natural regeneration. The ‘II’ notation refers to a second age cohort of natural regeneration of a specific species that established after the first cohort. Each age cohort is modeled independently.

Sites	Species	Tree#1	Tree#2	Tree#3	Tree#4	Tree#5	Plant#1	Plant#2
		Fd	Hw	Dr	FdII	HwII	Salal	Salmonberry
		Densities (sph)					Percent cover (%)	
Hygric	Density/cover	1200	350	-	-	550	-	0.02
	Regen year	1	1	-	-	6	-	3
Mesic	Density/cover	1200	780	380	-	-	0.02	-
	Regen year	1	7	6	-	-	3	-
Xeric	Density/cover	1200	1000	-	200	-	0.02	-
	Regen year	1	4	-	3	-	3	-

Perhaps the most easily grasped method by which to assess model performance is a simple graphical comparison between model predictions and field data. Though a widely used trivial technique, this methodology is not a rigorous test but a nonetheless useful criterion in testing time series type models against small data sets, being considered a measure of model adequacy (Haefner 2005). Graphical comparisons between data and model outputs were done for each of the four variables and for all three selected sites.

3.2.7 Statistical tests used to evaluate FORECAST

There is no generally accepted methodology for testing complex ecological models, but the qualitative-quantitative approach proposed by Soares et al.(1995), the validation techniques suggested by Mayer and Butler (1993), and the five step framework of Vanclay and Skovsgaard

(1997) are useful techniques that can be used as guidance. There is an even greater diversity of opinion with respect to statistical methods for model validation-evaluation (Yang et al. 2004). While there are many statistical procedures that can be used, none has been adopted universally because of the specificity of each model. However, error estimation tests and procedures like those proposed by Freese (1960) and Reynolds (1984) are widely used. More recently, Power (1993), Brown and Kulasiri (1996), West (1995) and Hasenauer et al.(1997) have provided useful methodologies and tests for model evaluation. Other widely used techniques include:

- Estimation of the regression between predicted (by the model) and observed (or outputs of an already tested model) and evaluation of the coefficient of determination, R^2 (Sachs and Trofymow 1991; Soares et al. 1995; Ollinger 1998; Kirschbaum 1999; Lucas et al. 2000; Beaudet et al. 2002; Landsberg et al. 2003; Blanco et al. 2007).

- Various tests to evaluate the means equivalence or equality either between two models or from a model and field data (Yang et al. 2004; Blanco et al. 2007).

- Tests that verify the normality of the mean differences; e.g. the Kolmogorow-Smirnoff, Cramer von Misses or Anderson Darling tests (Yang et al. 2004).

- Tests using alternative hypothesis have also been used in evaluating models, exploring the power of the test and the equivalence testing methods (Eis 1962; Robinson 2004;2005; Blanco et al. 2007).

- Nonparametric tests, as presented in Yang et al. (2004) are also broadly used for testing complex models where the simulation does not provide a normally distributed output.

Among other alternative complex evaluation techniques are the “Bakuzis matrix”, that asses all parameters at once in a matrix based approach (Leary 1997), the multi-criteria evaluation presented by Reynolds and Ford (1999) that assess the parameterization of a model, or the so called “ergodic theory”, a multivariate approach that implies a complex all-in-one evaluation (Pietsch and Hasenauer 2005). Most of these techniques are described and analyzed by Haefner (2005).

These statistical tests should be used cautiously (Vancly and Skovsgaard 1997; Yang et al. 2004) as they are mostly adaptations of techniques usually applied to real data. Their limited applicability across the existing range of models is another impediment to their acceptance as a generally applicable method of model evaluation. Ultimately, it is the user who should decide the usefulness of a particular model, starting with the simpler, classical approach of graphical

evaluation. However, for an advanced user or a manager, statistical test should be used to provide a more rigorous approach to model evaluation.

The following sections describe several statistical tests that were used to evaluate the FORECAST model against the field data from the Blaney Lake sites (for more details see Hafner 2005).

Model bias

The bias of a model can be assessed using the predictive bias, the mean error of a prediction series (Power 1993). A summary of measured data and the corresponding model simulation values are prepared for each variable averaged across all three site indices (SI36, SI39 and SI43). The differences between predicted and observed values for each SI and age, for each of the four variables analyzed, were calculated and the overall mean difference, standard error and mean absolute difference were determined. The model bias (the mean error) has been calculated using the following formula as given in Power (1993):

$$Bias = \bar{e} = \frac{\sum_{i=1}^m e_{n+i}}{m}, \text{ where } n \text{ is the number of observed values, } m \text{ the number of predicted}$$

values, e the difference observed – predicted. In our case $n = m$.

The average percent error is also used and calculated with the formula:

$$\bar{e}\% = \frac{100}{m} \sum_{i=1}^m \frac{e_{n+i}}{S_{n+i}}, \text{ where } n \text{ is the number of observed values, } m \text{ the number of}$$

predicted values, e the difference observed – predicted, and S are the observed values.

Normality tests of the errors-accuracy of the predictions

The hypothesis that the differences between the predicted and observed values follow a normal distribution is a frequently used technique to assess the precision of a model relative to a particular data set (Yang et al. 2004). The four most used normality tests (Shapiro-Wilk, Kolmogorow-Smirnoff, Anderson-Darling and Cramer von Misses) were calculated for each variable and all SI strata. These tests can also be used, at a lower level of accuracy, as measures

of goodness of fit. The last three tests are measures of goodness-of-fit based on the empirical distribution function (EDF) (Neter et al. 1996), but this property is not addressed here.

Parametric validation tests

Most of the parametric tests are based on the traditional approach of the null hypothesis. In the case of model testing, the null hypothesis should state that there is no significant difference between the observed and predicted data. An estimation of the accuracy of model predictions was determined by calculating the critical errors e^* using the technique described by Freese (1960) and modified by Reynolds (1984):

$$e^* = \sqrt{\frac{\sum_{i=1}^n D_i^2 \chi_{1-\alpha}^2(1)}{\chi_{1-\alpha}^2(n)}}$$

where $D_i = \text{Observed}_i - \text{Predicted}_i$, n is the number of data pairs observed-predicted, and i^{th} is a particular pair. Use of the χ^2 (chi-square) function establishes the critical errors as maximum absolute differences between the observed and the predicted values that should be accepted under the assumption of a specific α (alpha) level (Sachs and Trofymow 1991; Blanco et al. 2007). In this case, two α levels of 0.05 and 0.20 are considered for calculating the critical errors.

Assessment of goodness-of-fit

One of the most common tests in the literature, goodness-of-fit, can be computed both for continuous and categorical data (Snedecor and Cochran 1980). The goodness-of-fit explores the similarity between observed and predicted data populations, and various methodologies that compute goodness-of-fit have been developed. Three tests have been selected to evaluate the similarity between FORECAST predictions and field values.

As one of the most common goodness-of-fit indices, the coefficient of determination (R^2), was calculated for a linear regression of predicted vs. observed values that was fitted for all the three site index data sets.

Another index used was Theil's inequality coefficient (U), as used in (Power 1993) and (Blanco et al. 2007). This coefficient is calculated as follows:

$$U = \sqrt{\frac{\sum_{i=1}^n D_i}{\sum_{i=1}^n Observed_i^2}},$$

where $D_i = Observed_i - Predicted_i$, n represents the number of data pairs, and i^{th} is a particular pair. The U coefficient is bounded between 0 and ∞ . For values of $U = 0$, the model is assumed to produce perfect predictions. For $U = 1$, the model would produce predictions of a system behaviour that might not be any better (though they can be less cost effective) than a zero change prediction. If $U > 1$, then the predictive power of the model is worse than the no-change prediction (Power 1993; Blanco et al. 2007).

The modelling efficiency index (EF) (Vanclay and Skovsgaard 1997), is another way of estimating the goodness-of-fit, a test somehow equivalent with the coefficient of determination (R^2), and is given by the following formula:

$$EF = 1 - \frac{\sum_{i=1}^n D_i^2}{\sum_{i=1}^n (Observed - (Avgpred))^2}$$

where $D_i = Observed_i - Predicted_i$, n represents the number of data pairs, $Avgpred$ is the average of the predicted value, and i^{th} is a particular pair. This statistic provides a simple index of model performance on a relative scale, partially similar to the R^2 scale (that has only positive values), where $EF = 1$ indicates a perfect fit, $EF = 0$ suggests that the model predictions are no better than a simple average, and a negative value would indicate an eventually poor model performance.

3.2.8 Factorial experiment to assess impacts of hemlock ingress

To evaluate the potential effects of natural regeneration of western hemlock on Douglas-fir growth, a 5 x 6 factorial experiment was set up in FORECAST using the existing calibration data set for the CWHdm. The experiment consisted of simulating the growth of a Douglas-fir plantation with increasing levels of western hemlock ingress is occurring. Douglas-fir was planted at a density of 1200sph, with 2 years old bare root seedlings. Six different hemlock densities (250, 500, 750, 1000, 1250 and 1500 stems per hectares) were simulated initiated at five different moment in time during stand establishment (1, 3, 5, 7, 9 years since disturbance). The model was also run with Douglas-fir only and the parameter values obtained here were considered as control values. The same variables considered in testing the model against field data in the previous sections were considered here (height, diameter, stemwood biomass and stem density). A relative difference index was calculated for each variable to evaluate the impact of the hemlock ingress on Douglas-fir growth using the following formula:

$$\text{Relative difference (\%)} = [(Control - Regeneration_{ij}) / Control] \times 100,$$

where “Control” represents the parameter value in the absence of hemlock natural regeneration, and “Regeneration_{ij}” represents the parameter value with natural regeneration of western hemlock of *i* density and initiated at year *j*. The index is calculated using conditions at year 80 to approximate rotation age effects. A 5x6 matrix of relative difference values is obtained for each of the four parameters and is presented in graphical and tabular outputs in the results section.

3.3 Results

3.3.1. Overstory

Initial (1987 and 1990) measurements

The measurements taken by Karakatsoulis (initially measured 1987 and re-measured 1990) described the understory vegetation development and the early growth of planted Douglas-fir in the Blaney Lake Chronosequence over the age range 1 to 10 years (Karakatsoulis and Kimmins 1993). The data for the first 10 years of development showed that Douglas-fir height and diameter growth did not differ significantly between the hygric and mesic sites, but the trees growing on the xeric sites were significantly smaller. The average height of xeric site trees was 1.5 m less after 8 years, and 2.2 m less after 10 years than on the mesic sites. The mean stem diameter on the xeric sites was 3.8 cm less at year 12 on xeric than on mesic and hygric sites (Table 3.5.).

The total stem biomass of the planted Douglas-fir showed the same between-site relationships as diameter and height. Trees growing on the mesic and hygric sites had significantly higher above-ground biomass (as much as 3 times higher) than those growing on xeric sites after 10 years (Table 3.6).

Table 3.5 Height and diameters of planted Douglas-fir growing on hygric, mesic and xeric sites on the Blaney chronosequence. Numbers in rows followed by the same letters are **not significantly** different at $p < 0.05$ (Tukey test; for the 2003 values both Tukey and Bonferonni tests were performed). Values in brackets represent the standard errors of the mean. Shaded cells represent the 2003 measurements value. Sample numbers ranged from 7- 11 for each mean.

Clear cut Age	Tree Age	Diameters (cm)			Height (meters)		
		Hygric	Mesic	Xeric	Hygric	Mesic	Xeric
1	3	0.79(0.04)a	0.77(0.03)a	0.65(0.04)a	0.48(0.02)a	0.47(0.02)a	0.44(0.02)a
4	6	3.54(0.11)a	3.7(0.15)a	3.16(0.13)b	2.42(0.06)a	2.29(0.06)a	1.73(0.08)b
5	7	3.51(0.15)a	3.59(0.17)a	3.08(0.21)a	2.3(0.08)a	2.3(0.09)a	1.66(0.11)b
6	8	6.92(0.26)a	7.33(0.25)a	6.14(0.28)b	4.18(0.15)a	4.06(0.11)a	3.44(0.14)b
7	9	-*	4.58(0.2)a	3.73(0.16)b	-*	2.74(0.1)a	2.19(0.08)b
8	10	9.46(0.43)a	8.58(0.31)b	6.68(0.39)b	5.22(0.17)a	4.94(0.13)a	3.54(0.16) b
10	12	-*	11.08(0.38)a	7.31(0.34)b	-*	6.86(0.15)a	4.65(0.16)b
17	19	13.96(0.77)a	12.2(0.74)a	14.28(0.91)a	12.41(1.38)a	12.15(0.9)a	13.14(0.3)a
19	21	16.46(0.86)a	18.41(0.72)a	15.17(1.18)a	13.68(0.57)a	13.64(0.29)a	11.25(0.27)b
21	23	25.08(0.75)a	23(0.27)ab	19.4(1.07)b	16.34(0.29)a	14.62(1.81)b	14.87(0.91)ab
23	25	26.07(1.26)a	16.06(0.85)b	19.99(0.49)b	17.63(0.06)a	13.82(1.77)b	14.55(1.36)b

-* not measured

Table 3.6 Stand density and stem biomass of planted Douglas-fir growing on hygric, mesic and xeric sites on the Blaney Lake Chronosequence. Numbers in rows followed by the same letters are **not significantly** different at $p < 0.05$ (Tukey and Bonferonni tests, performed only for the 2003 measurements). Values in brackets represent standard errors of the mean. Shaded cells represent the new measurements values. Sample numbers ranged from 7- 11 for each mean.

Clear cut Age	Tree Age	Density (sph)			Stem biomass (t/ha)		
		Hygric	Mesic	Xeric	Hygric	Mesic	Xeric
1	3	1200*	1200*	1200*	0.01(0.001)	0.006(0.001)	0.004(0.1)
4	6	1200*	1200*	1200*	0.47(0.04)	0.55(0.07)	0.35(0.04)
5	7	1200*	1200*	1200*	0.48(0.06)	0.52(0.06)	0.38(0.07)
6	8	1200*	1200*	1200*	3.13(0.39)	3.65(0.33)	2.36(0.3)
7	9	1200*	1200*	1200*	-**	1.02(0.11)	0.57(0.07)
8	10	1200*	1200*	1200*	7.58(0.96)	5.72(0.53)	2.97(0.49)
10	12	1200*	1200*	1200*	-**	11.67(1.09)	3.85(0.54)
17	19	1100(81.65)a	1067(57.74)a	1067(57.74)a	34.79(16.78)a	26.49(2.62)a	31.89(6.16)a
19	21	1025(95.74)a	1067(57.74)a	1100(0)a	42.69(9.92)a	53.06(5.72)a	39.61(7.09)b
21	23	933(208.17)a	1033(57.74)b	950(70.71)a	96.1(20.66)a	86.65(25.18)a	67.7(12.12)a
23	25	1000(100)a	1050(70.71)a	1100(0)a	110.63(13.29)a	41.22(3.91)b	65.8(25.28)b

*Density values for the first 10 years were not measured and assumed to be 1200sph

** not measured

2003 measurements

Figs 3.2-3.5 present 23 year chronosequences for dbh, height, stand density and stem biomass. The expectation was that the hygric site would have the greatest growth followed by the mesic site, with the xeric site having the lowest growth. As in the previous findings there was no consistent increase in growth from xeric to hygric conditions and there were no significant overall differences for any variable between the three SMR (Tables 3.5, 3.6). However, the differences between plots increase with age with greater differences developing between hygric and xeric sites, as one would expect. All variables on hygric sites differ significantly from those on xeric sites at the older ages. The general patterns observed in the tree measurements for the first 10 years were confirmed by the 2003 measurements. Dbh showed the greatest difference between SMR, reflecting both the effects of site moisture on soil fertility and tree growth, and differences in total stand density (see next section). Surprisingly, the mesic sites had lower values for planted Douglas-fir at age 23 than the other SMR's.

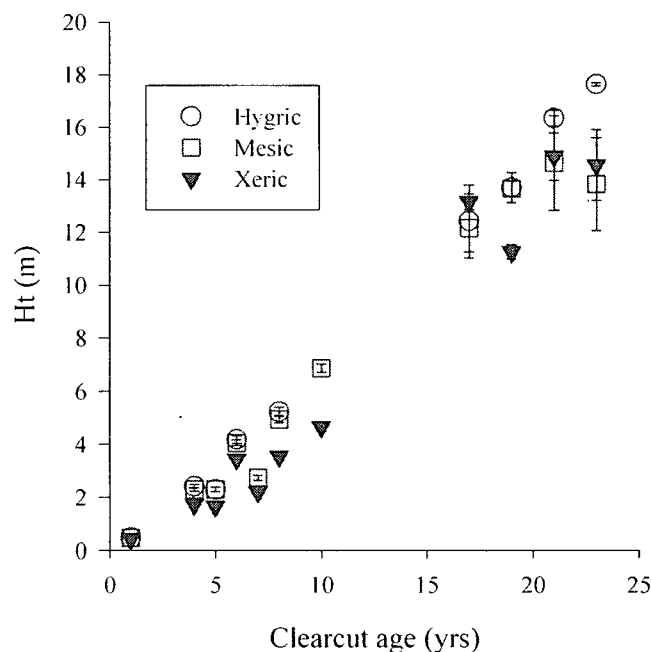


Figure 3.2 Average heights of planted Douglas-fir in the Blaney Chronosequence, stratified by soil moisture regime (SMR). Bars represent standard errors. Missing values represent missing records (see Table 3.5)

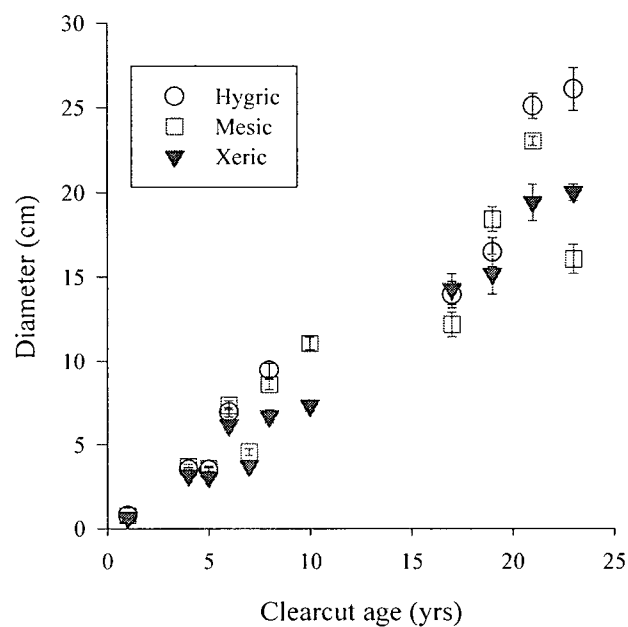


Figure 3.3 Average heights of planted Douglas-fir in the Blaney Chronosequence, stratified by soil moisture regime (SMR). Bars represent standard errors. Missing values represent missing records (see Table 3.6)

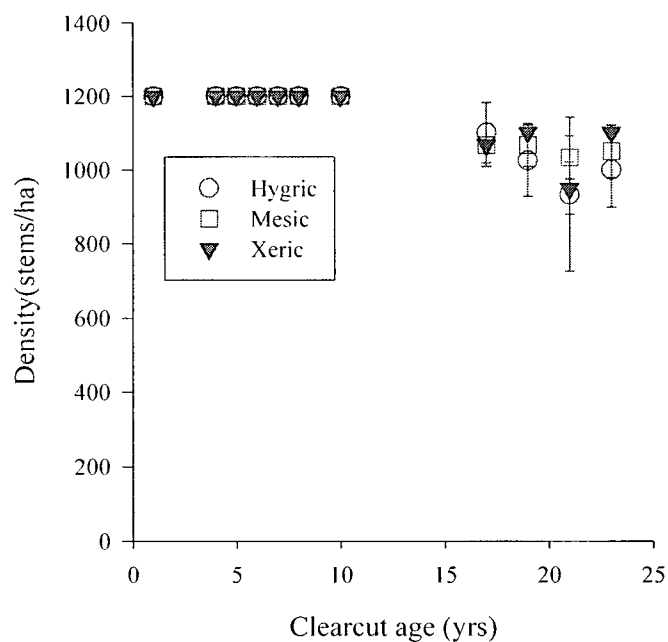


Figure 3.4 Average densities of planted Douglas-fir in the Blaney Chronosequence, stratified by soil moisture regime (SMR). Bars represent standard errors. Missing values represent missing records (see Table 3.6)

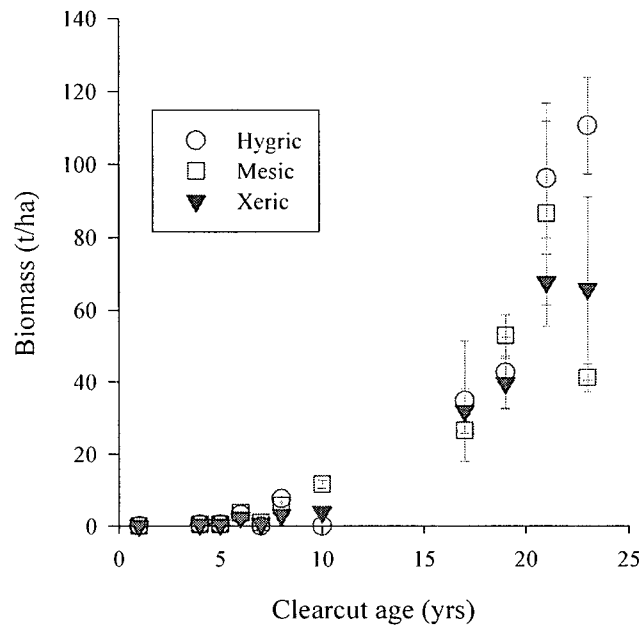


Figure 3.5 Average stemwood biomass of planted Douglas-fir in the Blaney Chronosequence, stratified by soil moisture regime (SMR). Bars represent standard errors. Missing values represent missing records (see Table 3.6)

Natural regeneration

In addition to the planted Douglas-fir, at the 2003 measurements there were three natural regenerated coniferous species (western hemlock, redcedar and Douglas-fir) and two deciduous species (red alder and bitter cherry). Red alder and redcedar were not present on every SMR class and bitter cherry was found only on one site harvested in 1984, and was not included in the study. An examination of the 2003 data shows that there is no clear relationship between the age of the clearcut and the total stemwood biomass of the naturally regenerated trees (Fig 3.6, 3.7).

At the 2003 measurement natural regeneration was most abundant in the youngest stand (harvested in 1986), with no clear trend with age across the three older stands (Fig 3.6). Total stemwood biomass shows a somewhat similar pattern (Fig 3.7). Hemlock had the most abundant natural regeneration on all SMR classes (Fig 3.10), which is reflected in the total stemwood biomass, with hemlock values higher on almost all plots than any of the other species (Fig 3.11). There was relatively less hemlock regeneration on the mesic sites as compared with the hygric and xeric sites, and this correlates with an increased amount of natural regenerated Douglas-fir (Fig 3.10). Height and diameter values for natural regeneration are not higher in the

older stands because the values are averaged for each plot across different aged cohorts of natural regeneration, the size of the younger cohorts reducing the average values (Fig 3.8, 3.9).

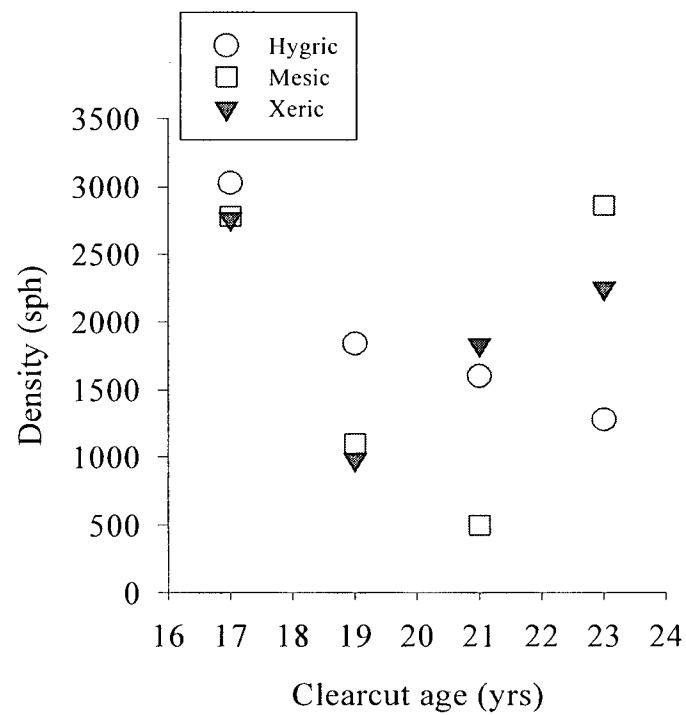


Figure 3.6 Total densities of the naturally regenerated trees (hemlock, redcedar, alder and natural regenerated Douglas-fir) summarized by SMR and age at Blaney Chronosequence.

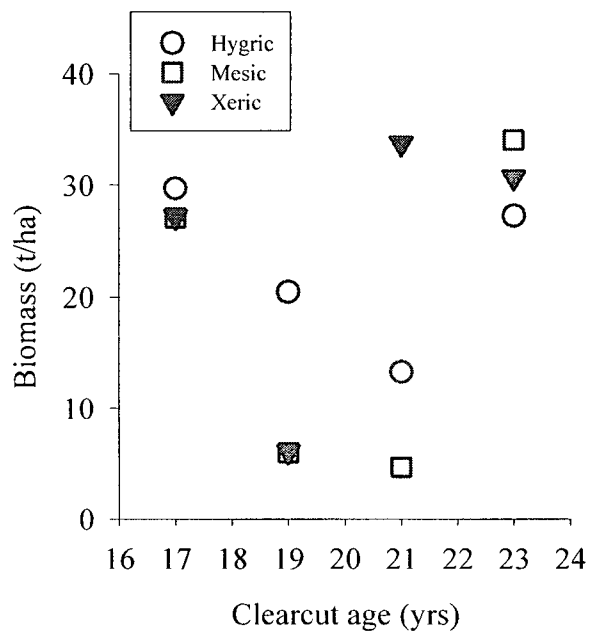


Figure 3.7 Total stemwood biomass of the naturally regenerated trees (hemlock, redcedar, alder and natural regenerated Douglas-fir) summarized by SMR and age at Blaney Chronosequence.

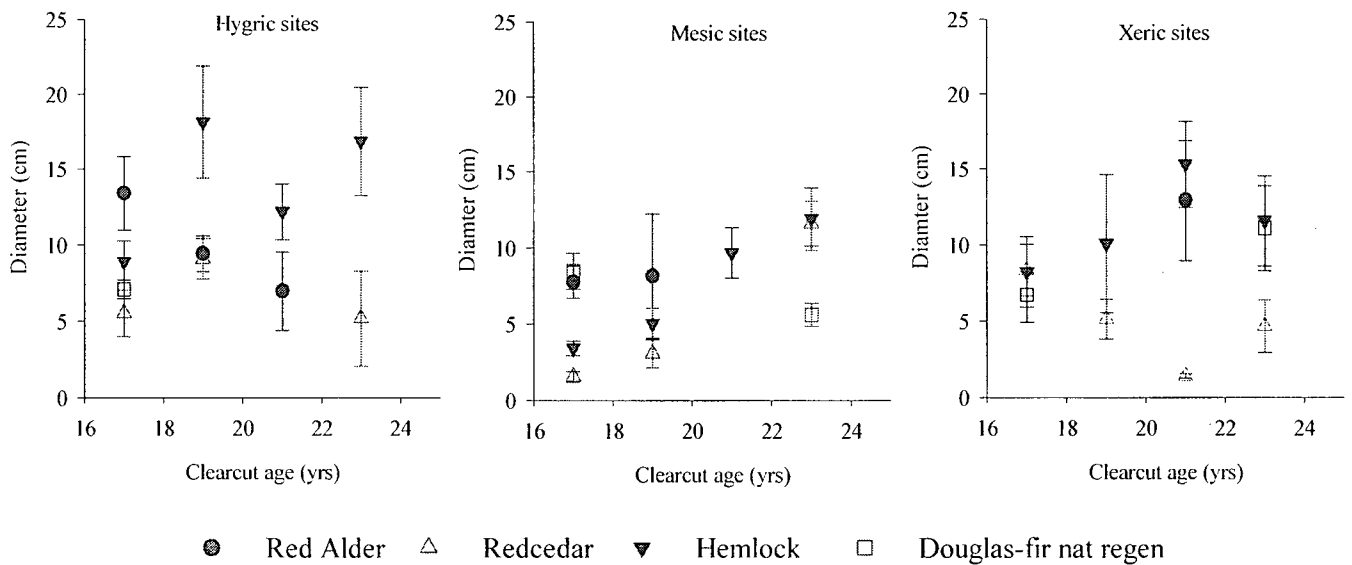


Figure 3.8 Average diameters of the naturally regenerated species (hemlock, redcedar, alder and Douglas-fir) on the Blaney Chronosequence. Data points represent averages per plots and clearcut age (obtained by averaging different cohorts data), and not real temporal trends. Bars represent standard error of the mean.

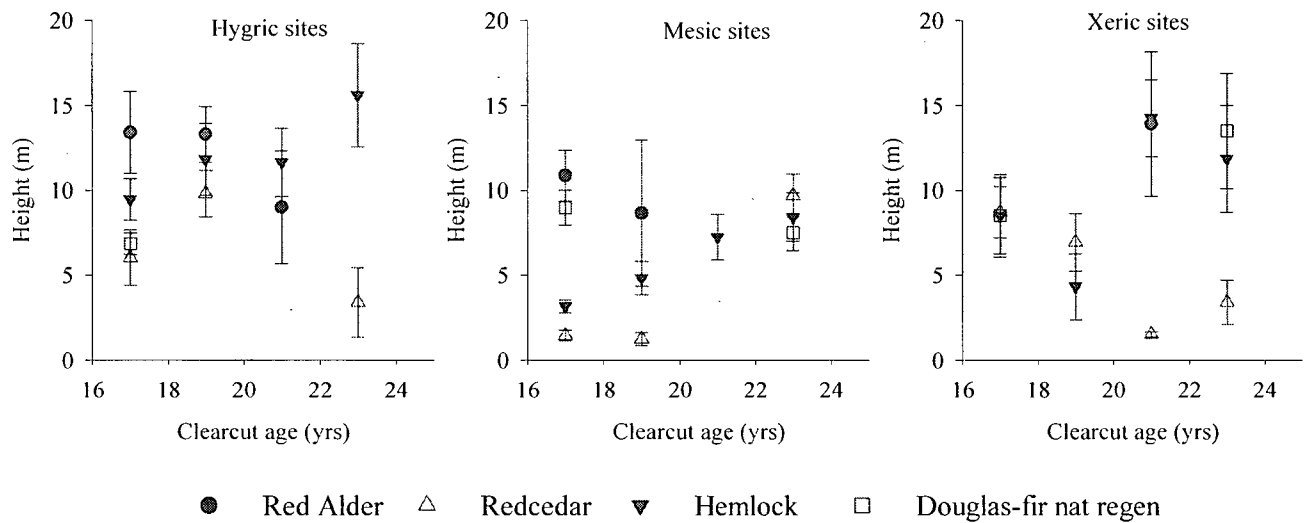


Figure 3.9 Average maximum heights of the naturally regenerated species (hemlock, redcedar, alder and Douglas-fir) on the Blaney Chronosequence. Data points represent averages per plots (obtained by averaging different cohorts' data) and clearcut age, and not real temporal trends. Bars represent standard error of the mean.

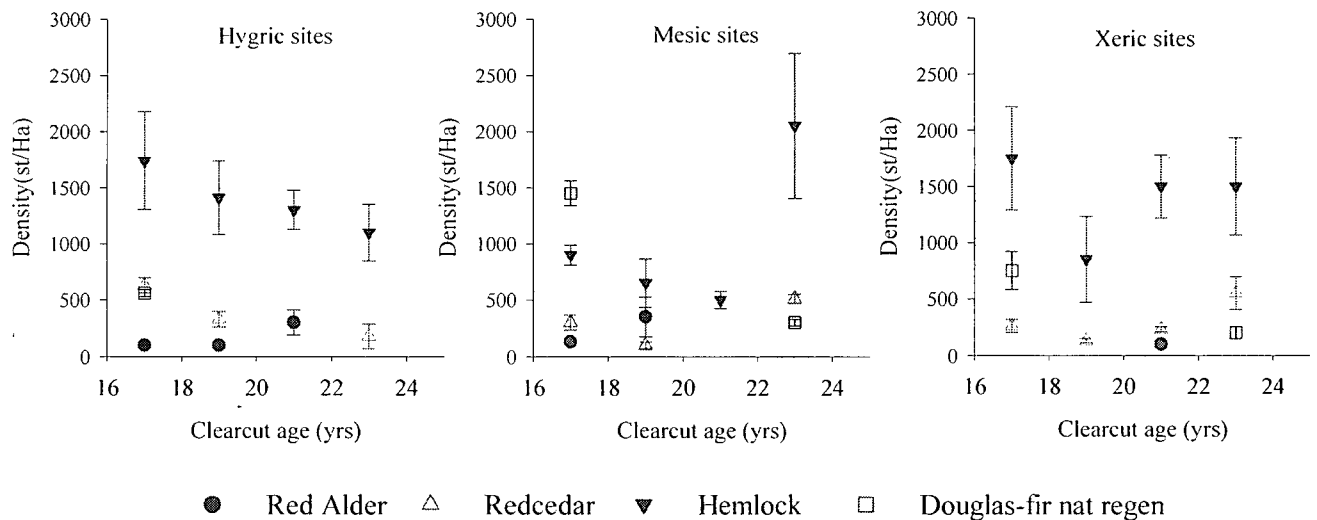


Figure 3.10 Total densities of the natural regenerated species (hemlock, redcedar, alder and natural regenerated Douglas-fir) at Blaney Chronosequence. Data points represent averages per plots and clearcut age (obtained by averaging different cohorts data), and not real trends. Bars represent standard error of the mean.

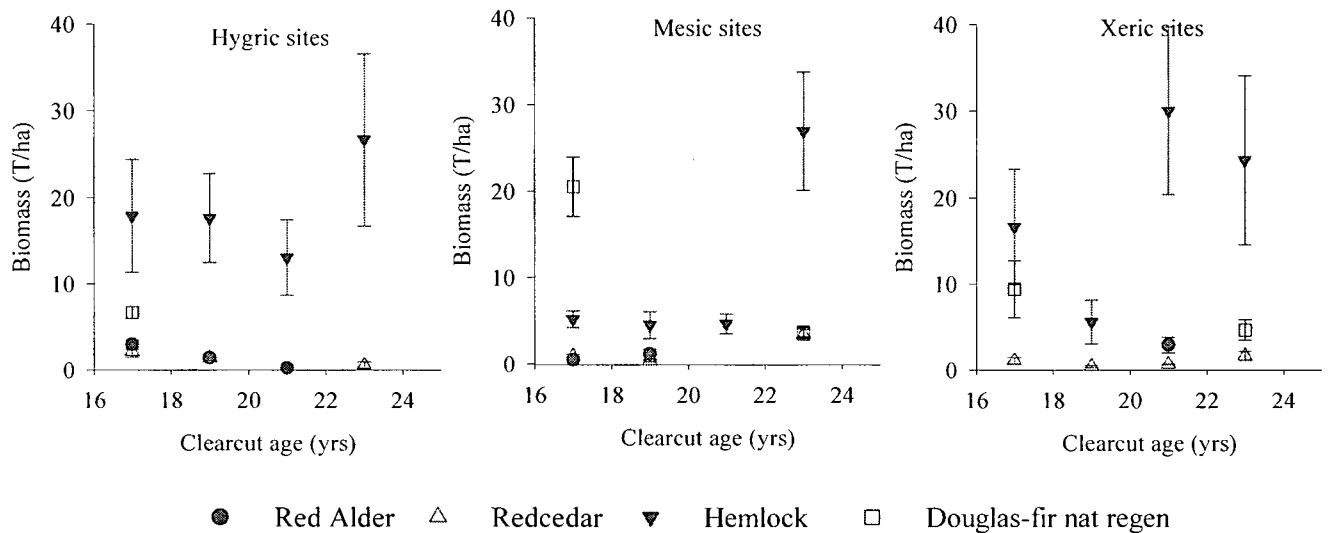


Figure 3.11 Total stemwood biomass of the natural regenerated species (hemlock, redcedar, alder and natural regenerated Douglas-fir) at Blaney Chronosequence. Data points represent averages per plots and clearcut age (obtained by averaging different cohorts data), and not real temporal trends. Bars represent standard error of the mean.

Western hemlock was the most abundant, being present in all plots and competing with planted Douglas-fir (Fig 3.10 and Table 3.6). There are no clear differences between the three SMR in terms of natural regeneration establishment, with all three SMR exhibiting declining recruitment with time. For more details see Appendix 1.

Figures 3.12 -3.15 represent the plotted densities of the natural regenerated species against the establishment year on the three SMR. Being the most abundant natural regenerated species, hemlock stemwood biomass is represented as percentage of the total plot biomass (Fig 3.16).

Natural regeneration of Douglas-fir was only present on the hygric site on the youngest plot, and only on the youngest and oldest plots on the mesic and xeric sites. No natural regenerated Douglas-fir seedlings were recorded later than 8 years after the disturbance and the abundance of established seedlings decreased with the time since harvesting on all three SMR (Fig 3.12-3.14).

Redcedar seedlings were recruited for up to 12 years post-harvest on hygric sites (Fig 3.12) and for 16 years for mesic and xeric sites (Fig 3.13, 3.14). In contrast to the general trend, redcedar seedlings exhibited a slight increase in the establishment rate on all hygric sites (Fig 3.12-3.14). Red alder regeneration was sporadic (Fig 3.12-3.14) and was limited to the first nine year post harvest on all SMR.

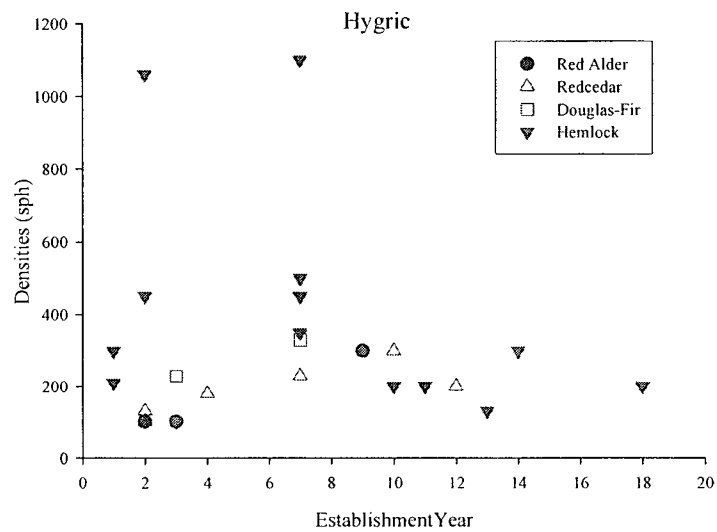


Fig 3.12 Actual densities of the natural regenerated species at Blaney Chronosequence represented by establishment year* for the hygric sites

*The year of regeneration for a specific species

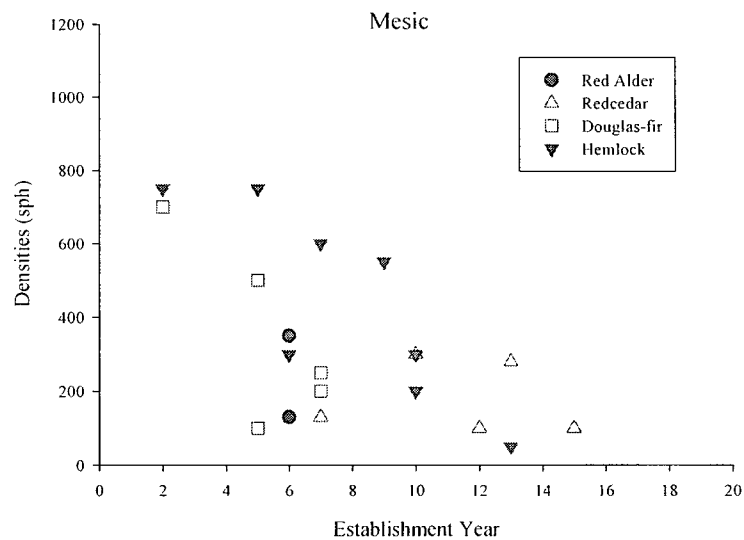


Fig 3.13 Actual densities of the natural regenerated species at Blaney Chronosequence represented by establishment* year for the mesic sites

*The year of regeneration for a specific species

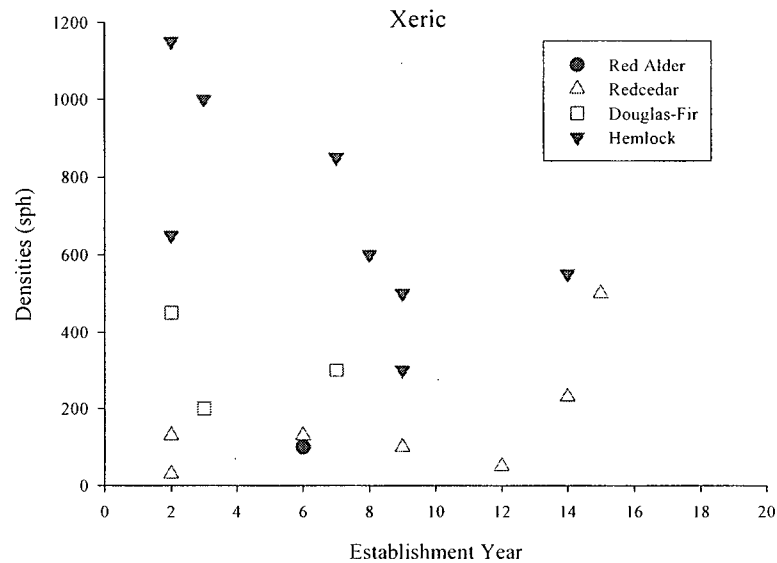


Fig 3.14 Actual densities of the natural regenerated species at Blaney Chronosequence represented by establishment year*, for the xeric sites

*The year of regeneration for a specific species

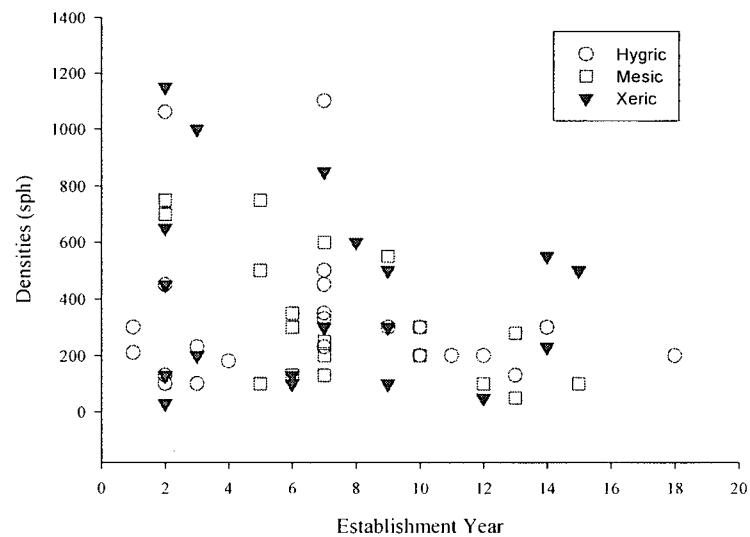


Fig 3.15 Actual densities of all natural regenerated species at Blaney Chronosequence represented by establishment year* and SMR

*The year of regeneration for a specific species

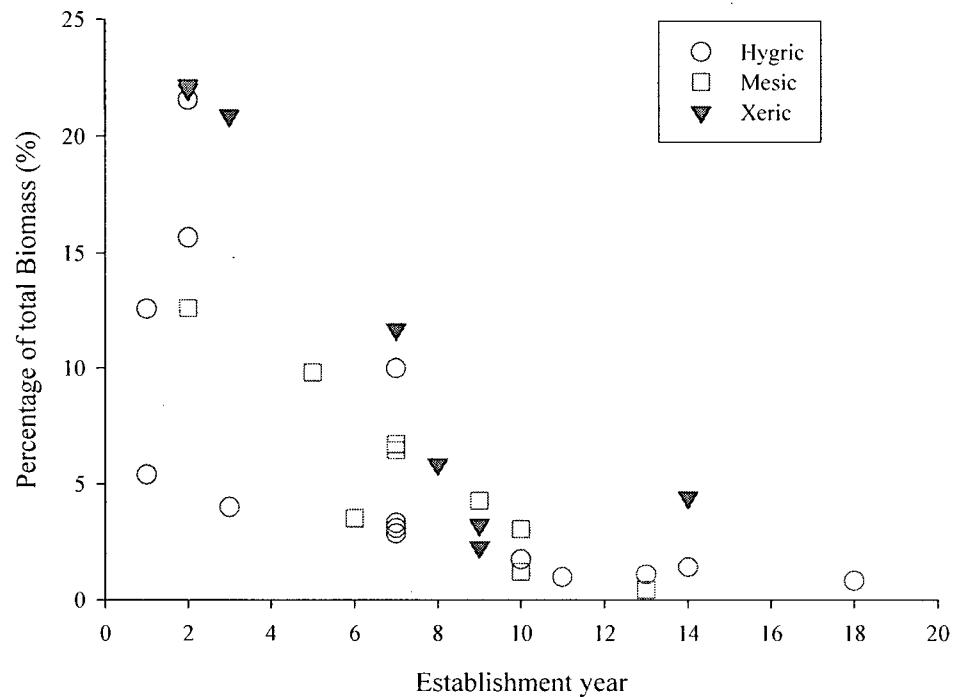


Fig 3.16 Hemlock total stemwood biomass represented as percentages of the total plot stemwood biomass, represented by establishment year and SMR as measured in 2003. Data points are obtained for each combination SMR/age by summarizing all seedlings established in the same year.

More than one cohort of hemlock got established on most sites (Fig 3.12-3.14) although a lot of hemlock got established within the first years after the clearcut (Fig 3.12-3.14). On average, hemlock regenerated with the same abundance on all three SMRs, (Fig 3.12-3.14). By 10 years after harvesting, the opportunity for hemlock to germinate under the developing canopy was much reduced. The hemlock cohorts regenerated in the first 7 years represented 10-15 % of the total stand stemwood biomass; in three sites, hemlock that emerged in years 2-4 accounted for as much as 20 % of total stemwood (Fig 3.16).

3.3.3 Understory

Species composition and percent cover

Karakatsoulis and Kimmins (1993) provided a very detailed description of the understory vegetation development for the first ten years after the disturbance. Twenty eight non-crop species were recorded on the site and a comprehensive analysis of the cover, height and biomass of the understory was reported. There was a decrease in species abundance, biomass and diversity between years 10 and 23 as a number of non-crop species declined to only 6 species 2003 (Appendix 2). The overall pattern of the vegetation percent cover after 10 years and the species involved varied between xeric, mesic and hygric sites (Karakatsoulis and Kimmins 1993) (Fig 3.17). Measurements made in 2003 reveal that the total percent cover of the understory species peaked some time between 10 and 17 years and then declined as the overstory canopy closed (Fig 3.17). The decline was greatest on the xeric site. Variation in the pattern of percent cover appear to reflect the density of the overstory; for example, the low value for the 23 year old mesic site echoes the lower biomass of planted Douglas-fir at that site, which in turn reflects the high density of natural regeneration trees (Fig 3.4, 3.10, 3.17). The individual species percent cover values differ between the three SMR, but ten years after harvesting, the species abundance diminished, with salal (*Gaultheria shallon*) remaining the dominant species on xeric and mesic sites (Fig 3.20). However, salal is becoming more dominant in the hygric sites (Fig 3.20), and exceeding the performances of *Rubus* species and *Epilobium angustifolium* that were reported as dominant in the hygric sites by Karakatsoulis and Kimmins (1993).

Height

The height of the understory showed a similar trend for the three SMR, increasing to somewhere between age 10 and age 17, with the SMR rankings generally hygric>mesic>xeric with the sigmoidal pattern, observed by Karakatsoulis and Kimmins (1993) maintained for several years after year 10 since the clearcut before the all understory species declined (Fig 3.18). There was no only one dominant species in terms of average height per species as some isolated patches of *Acer circinatum* increased the averaged in the mesic sites and *Rubus* species in the hygric ones. Salal, the most dominant as percent cover, was in the very low level of height in the first ten years since the clearcut, albeit becoming one of the tallest components later in time under the fully closed overstory canopy (Fig 3.21). This contrasts with Messier and Kimmins (1991) who reported greater salal heights under closed canopies.

The above-ground biomass of the non-crop vegetation developed following different trends on xeric, mesic and hygric sites but still reflecting the cover dominance of salal, especially in the mesic and xeric sites, while *Rubus* sp. was still an important biomass component on hygric sites, confirming what the authors of the first study (Karakatsoulis and Kimmins 1993) suggested (Fig 3. 20, 3.22). Maximum values for biomass and as well for the percent cover were recorded around age 17 (Fig 3.19), but it is not known if the peak for these variables occurred earlier. The highest value of understory biomass was recorded for the mesic sites but it was because of some isolated patches of vine maple (*Acer circinatum*) that determined a higher average value (Fig 3.22).

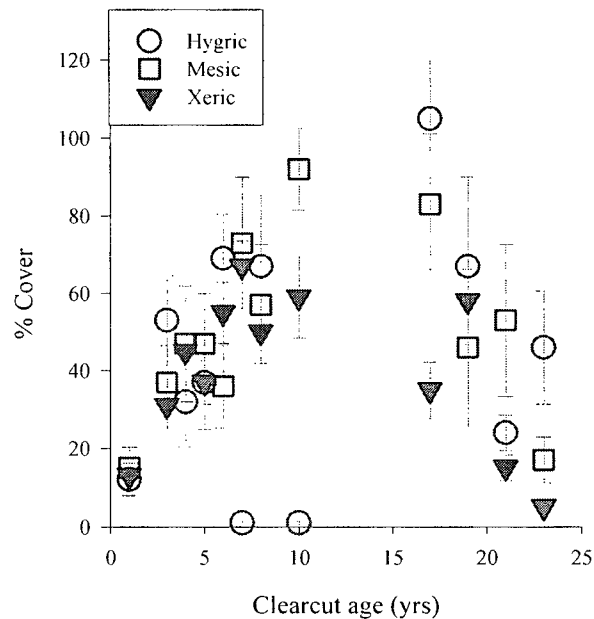


Figure 3.17 Total percent cover of the understory species by SMR (soil moisture regime) at Blaney Chronosequence. Bars represent standard error of the mean.

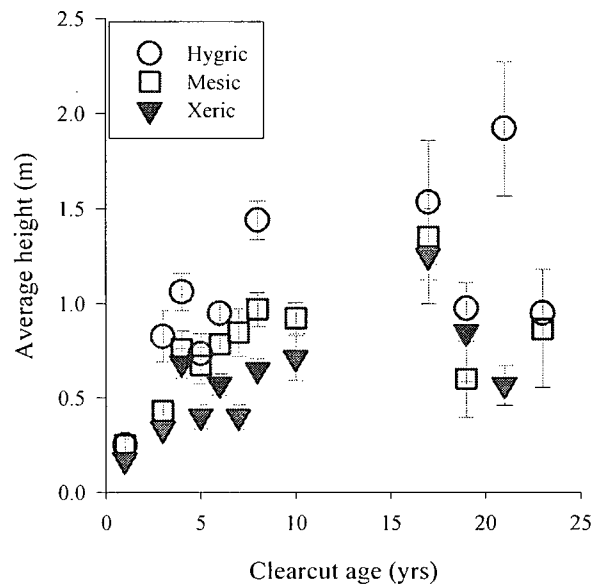


Figure 3.18 Average heights of the understory species by SMR (soil moisture regime) at Blaney Chronosequence. Bars represent standard error of the mean.

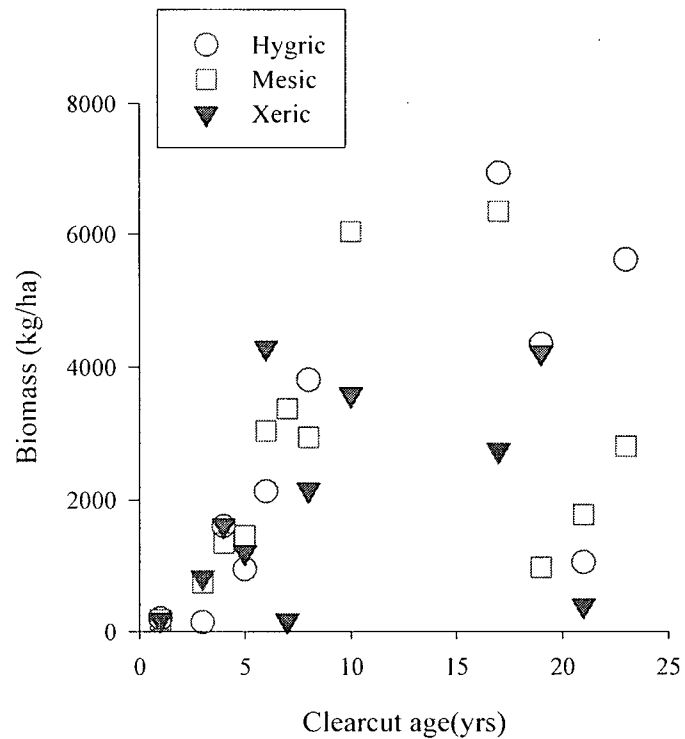


Figure 3.19 Total aboveground biomass of the understory species by SMR at Blaney Chronosequence

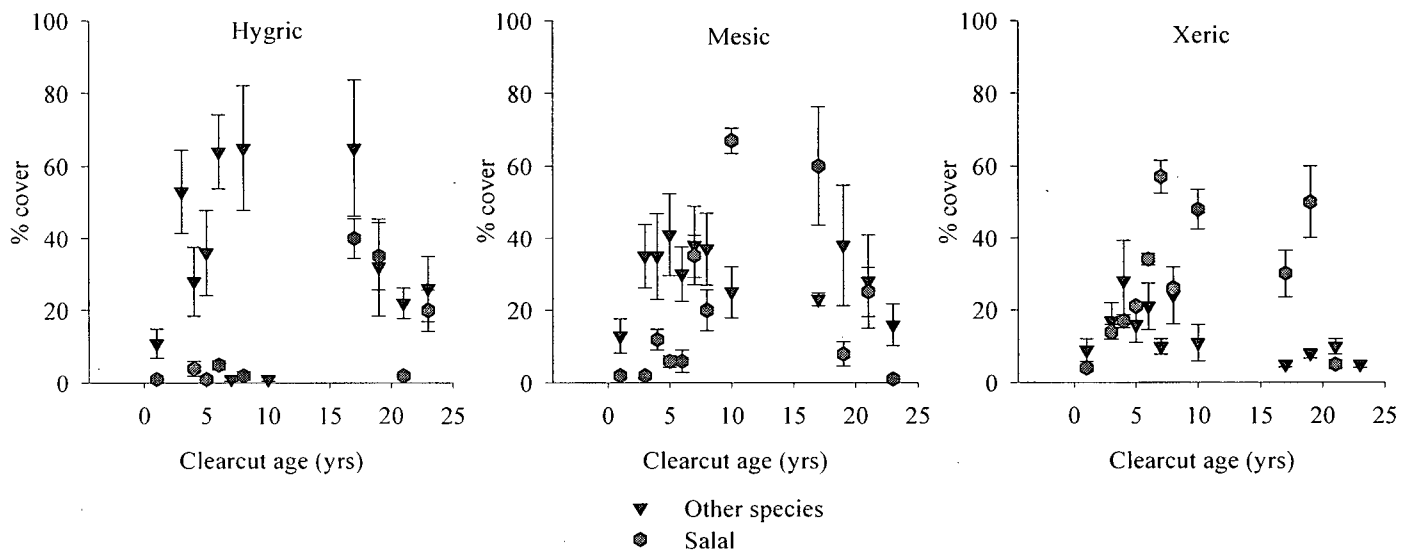


Figure 3.20 Comparison of percent cover between salal and all other species by SMR at Blaney Chronosequence. Bars represent standard error of the mean.

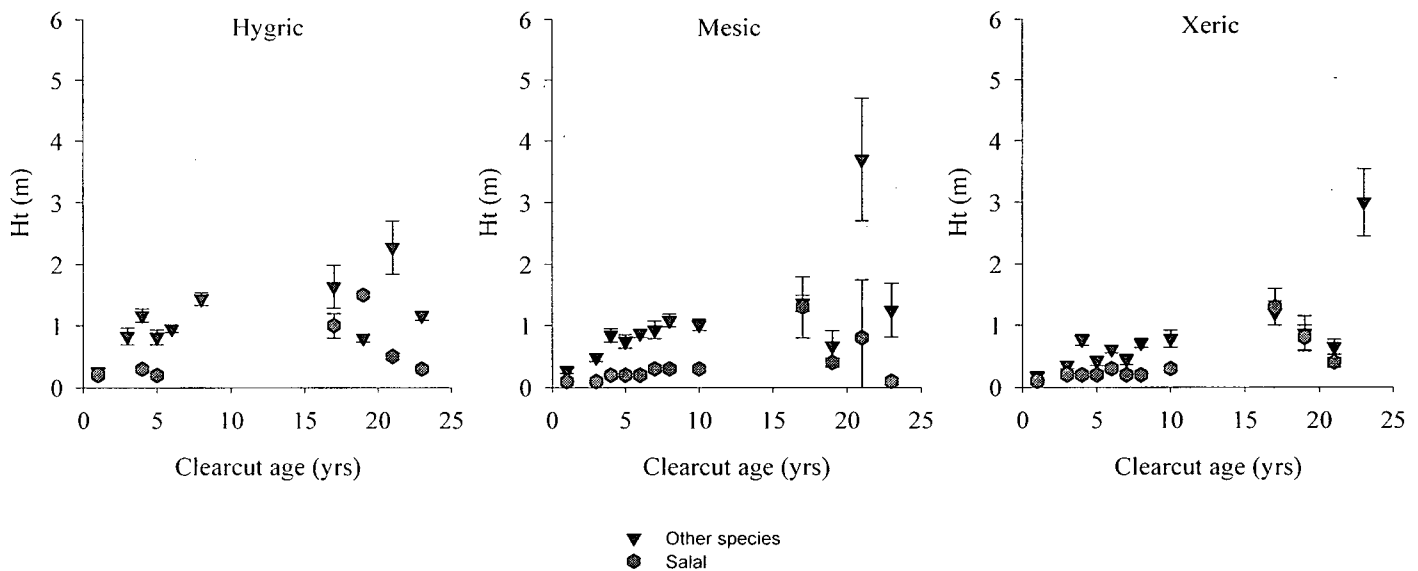


Figure 3.21 Comparison of average height between salal and all other species according by SMR at Blaney Chronosequence. Bars represent standard error of the mean.

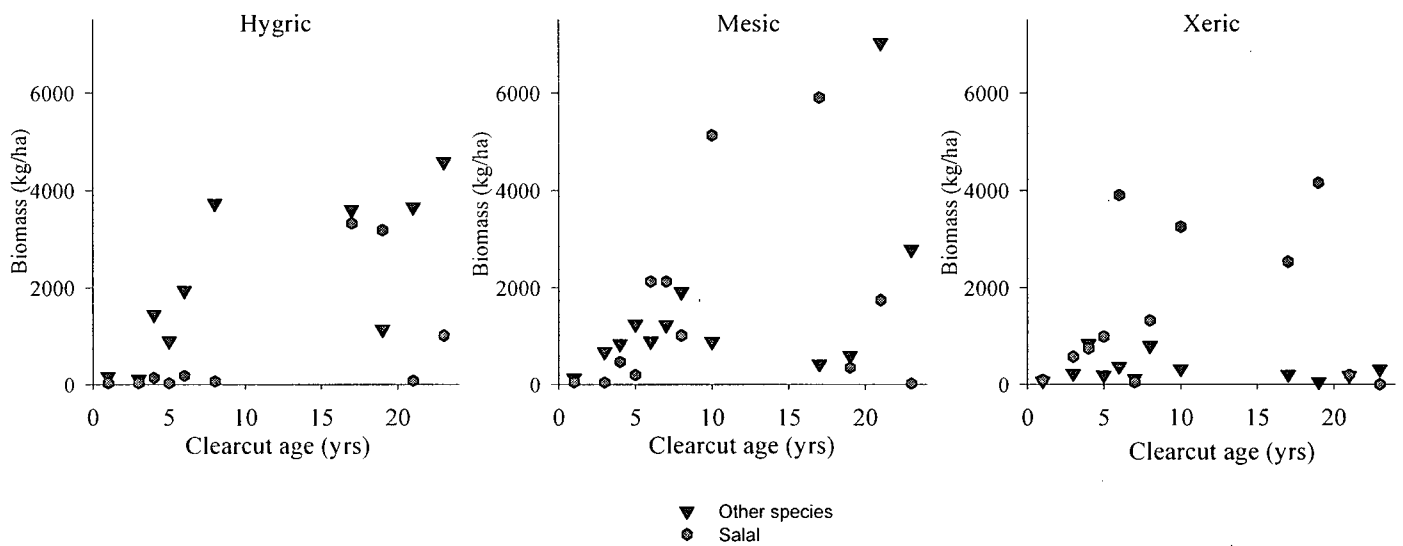


Figure 3.22 Comparison between aboveground biomass of salal and all other species by SMR at Blaney Chronosequence

3.3.4 Comparison of field measurements and model predictions

Graphical outputs were obtained from the FORECAST model for each variable of interest, for planted Douglas-fir and for the natural regenerated species, and field and simulated data were plotted together (Fig 3.23- 2.25).

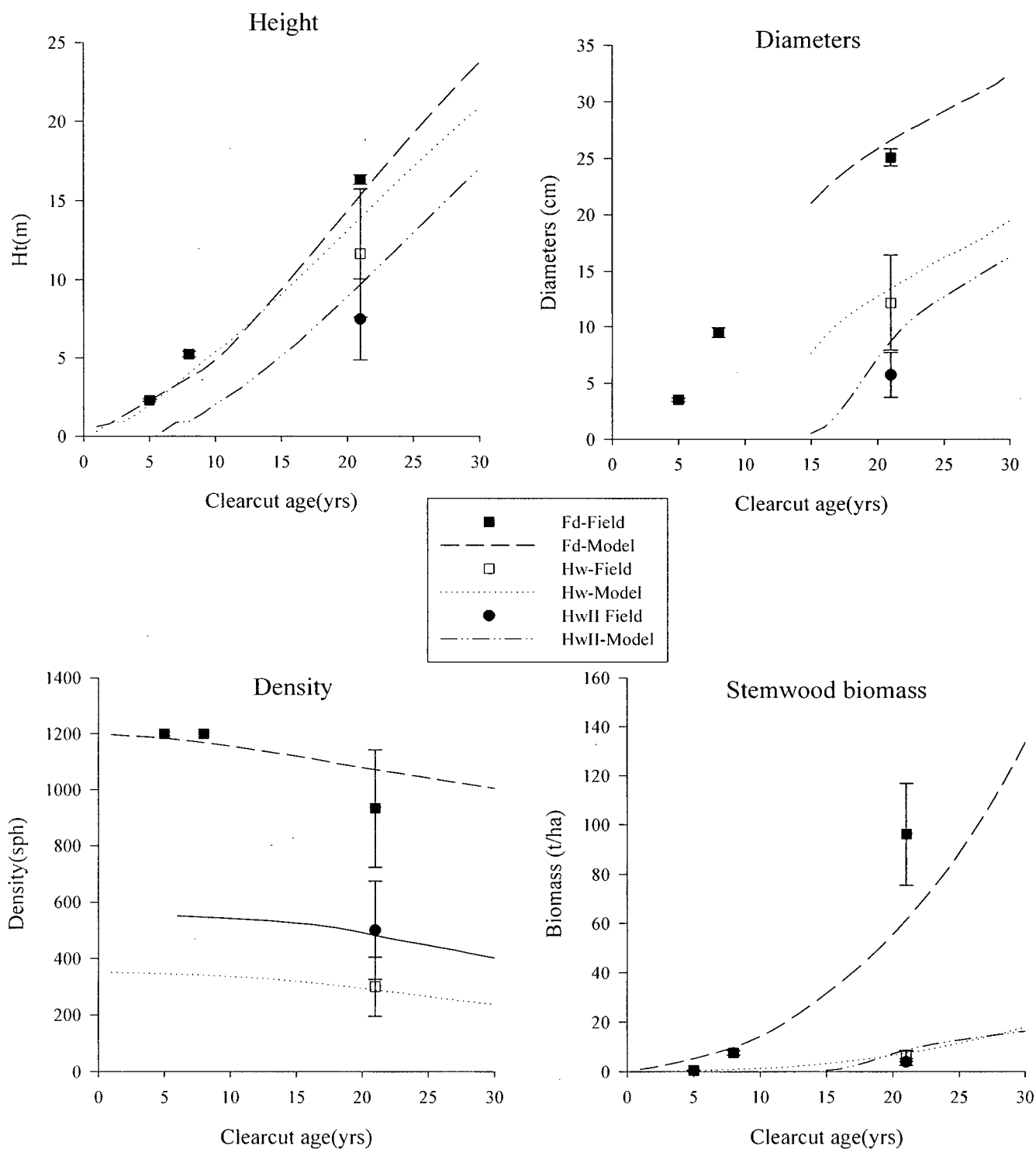


Figure 3.23 Comparisons between field data (points) and model predictions (continuous lines) for planted Douglas-fir(Fd), and two cohorts of natural regenerated western hemlock (Hw and HwII) for heights, diameters, densities and stemwood biomass in a selected **hygric** site at Blaney Chronosequence. Bars represent standard error of the mean.

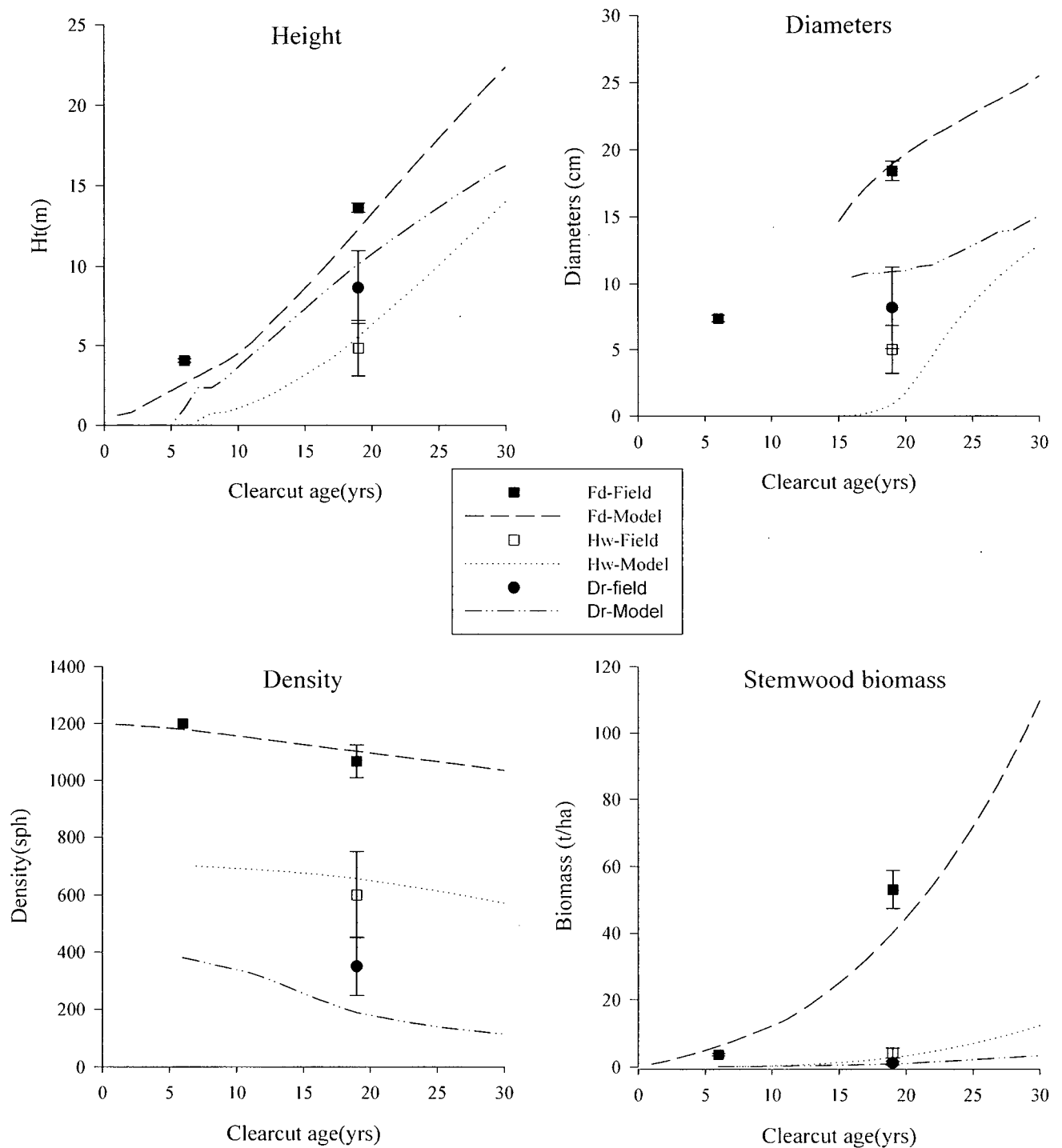


Figure 3.24 Comparisons between field data (points) and model predictions (continuous lines) for planted Douglas-fir (Fd) and naturally regenerated western hemlock (Hw) and red alder (Dr) for heights, diameters, densities and stemwood biomass in a selected **mesic site** at Blaney Chronosequence. Bars represent standard error of the mean.

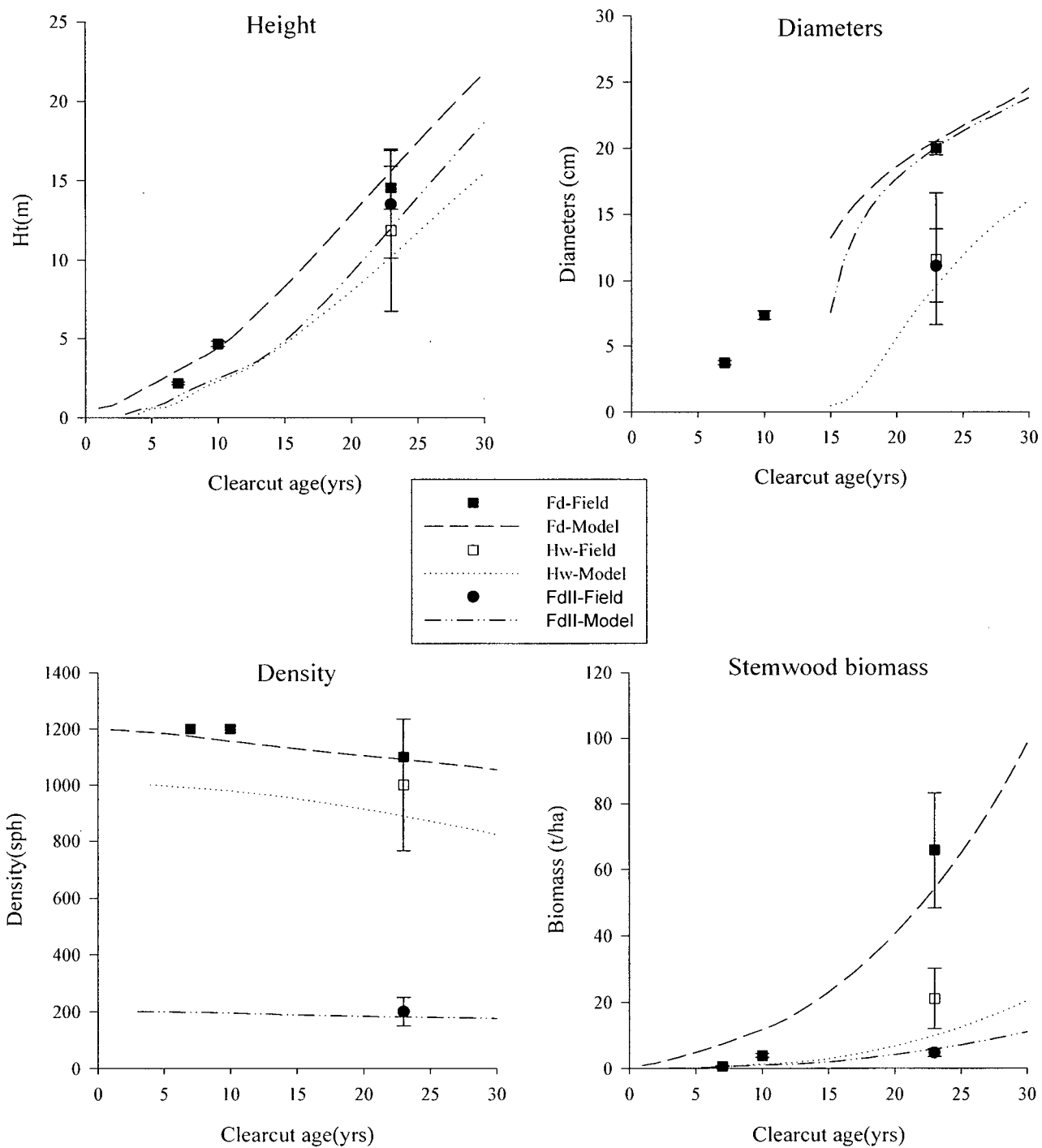


Figure 3.25 Comparisons between field data (points) and model predictions (continuous lines) for planted Douglas-fir (Fd) and naturally regenerated western hemlock (Hw) and Douglas-fir (FdII) for heights, diameters, densities and stemwood biomass in a selected **xeric site** at Blaney Chronosequence. Bars represent standard error of the mean.

As observed from Figures 3.23 - 3.25, model predictions of height and diameters for Douglas-fir were consistent with field measured values, and the results are consistent among the three SMR. Simulated stand densities were also similar to field measurements with the best fit for mesic and xeric sites. The model also performed reasonably well in predicting patterns of stemwood biomass accumulation for planted Douglas-fir but tended to overestimate at younger ages and underestimate at older ages. With respect to natural regeneration, the model performed best in representing hemlock growth, either one or two cohorts, followed by red alder and natural regenerated Douglas-fir.

3.3.5 Statistical evaluation of model performance

The results of the statistical test that were performed to compare the model prediction with the associated field data are presented in Table 3.7.

Table 3.7 Statistics and tests that were used to compare the field results from Blaney data with the FORECAST model outputs'. Where: e^* - Reynolds errors comparing the overall fit; R^2 – coefficient of determination; U – Theil's inequality coefficient; EF -modeling efficiency.

Statistic(Test)	Variables			
	Height	Diameter	Density	Biomass
<i>Bias indicators</i>				
Mean diff-Bias	0.5	-0.8	-2.2	4.4
StDev	1.0	0.6	59.5	14.6
StError	0.4	0.2	21.0	5.2
MeanAbsolute Bias	0.9	2.5	326.0	83.2
%AvgBias	5.72	-2.9	-0.63	-297.9
<i>Normality tests</i>				
Shapiro-Wilk	0.104	**	0.16	0.0292
Decision	Accept, normal		Accept, normal	Reject, non-normal
Kolmogorov-Smirnov	0.128	**	0.15	0.0564
Decision	Accept, normal		Accept, normal	Accept, normal
Cramer-von Mises (p)	0.112	**	0.2162	0.042
Decision	Accept, normal		Accept, normal	Reject, non-normal
Anderson-Darling (p)	0.1056	**	0.1644	0.0346
Decision	Accept, normal		Accept, normal	Reject, non-normal
<i>Accuracy estimators</i>				
e^* at $\alpha=0.05$	1.49	1.16	78.45	20.20
Accuracy	Acceptable	Acceptable	Acceptable	Acceptable
e^* at $\alpha=0.20$	1.15	1.80	60.83	15.66
Accuracy	Acceptable	Acceptable	Acceptable	Acceptable
<i>Goodness of fit</i>				
R^2	0.97	1.00	0.98	0.85
Conclusion-prediction	Good	Good	Good	Good
U	0.11	0.04	0.44	0.05
Conclusion-prediction	Good	Good	Average	Good
EF	0.96	0.88	0.83	0.55
Conclusion-prediction	Good	Good	Good	Average

** -not calculated

Model bias

The three indices of the model biasness used here, mean error (bias), absolute mean error (absolute bias) and average percentage bias were compared with the basic descriptive statistics of the errors (mean, standard deviation, standard error). These indices of bias have the same range of values as the standard deviation and standard error. However, as a general trend, the

bias indices showed a general overestimation of height and biomass by FORECAST and an underestimation diameter and density relative to the field observations (Table 3.7).

Normality tests of the errors

The results of the normality tests computed here failed to reject the null hypothesis of error normality for $\alpha = 0.05$ on all cases but for the biomass (Table 3.7). However, Kolmogorov-Smirnoff test for the stemwood biomass did not reject the null hypothesis. After some authors this might be sufficient to consider differences as normal (Yang et al. 2004). These tests also can be considered a low-accuracy goodness of fit tests. The results obtained from the normality tests entitled the use of parametric tests for the errors of differences.

Accuracy of model predictions

Model accuracy was evaluated using the Reynolds's errors criteria. The evaluation is based upon whether or not the differences are smaller than the critical error e^* , for two level of alpha corresponding to a liberal ($\alpha = 0.05$) and strict ($\alpha = 0.20$) levels of accuracy (Sachs and Trofymow 1991). The obtained critical errors were in the range of standard deviation of data and higher than the errors (Mean diff Bias in the Table 3.7) especially for the smaller α values, indicating an acceptable level of model accuracy.

Goodness-of-fit

The results produced by the goodness of fit tests used here are relatively consistent for all four variables considered. Only "good" estimations were obtained for height and diameters and mostly "good" for the densities and the estimated total stemwood biomass (Table 3.7). The customized three levels of prediction ratings "poor", "average" and "good" were customized for each test (e.g. a value of $U = 0.674$ of the Theil's test is considered as representative for an average prediction level on a scale from 0 = "perfect match" to 1 = "poor prediction").

3.3.6 Factorial simulation experiment

Results of the factorial simulation experiment concerning the relative impacts of hemlock ingress on plantation performance indicate that both the timing and density of hemlock ingress influence the impact on Douglas-fir growth (Figs 3.26, 3.27 & Tables 3.8-3.10). This impact was most pronounced for stemwood biomass (maximum decline of 34%) followed by average

diameter (maximum decline of 17%) and height (maximum decline of 3%). While the timing of recruitment (earlier recruitment = greater impact) had the greatest effect, the impact of hemlock always increased with increasing density. The impact of hemlock competition on Douglas fir height growth was quite small in all cases (< 3%).

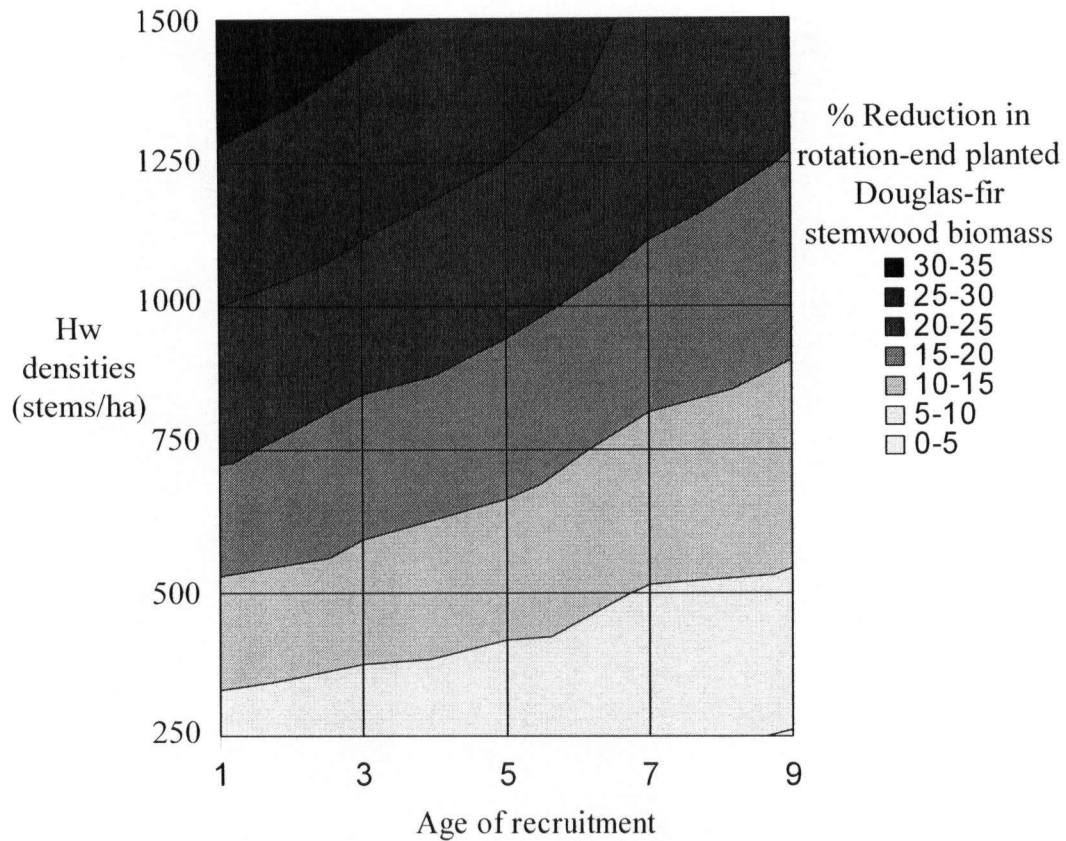


Figure 3.26 Simulated percent reduction in stemwood biomass of the planted Douglas-fir at age 80 as a result of various densities of western hemlock recruitment in years 1 to 9 following planting on a mesic site. The darker the color the greater the reduction.

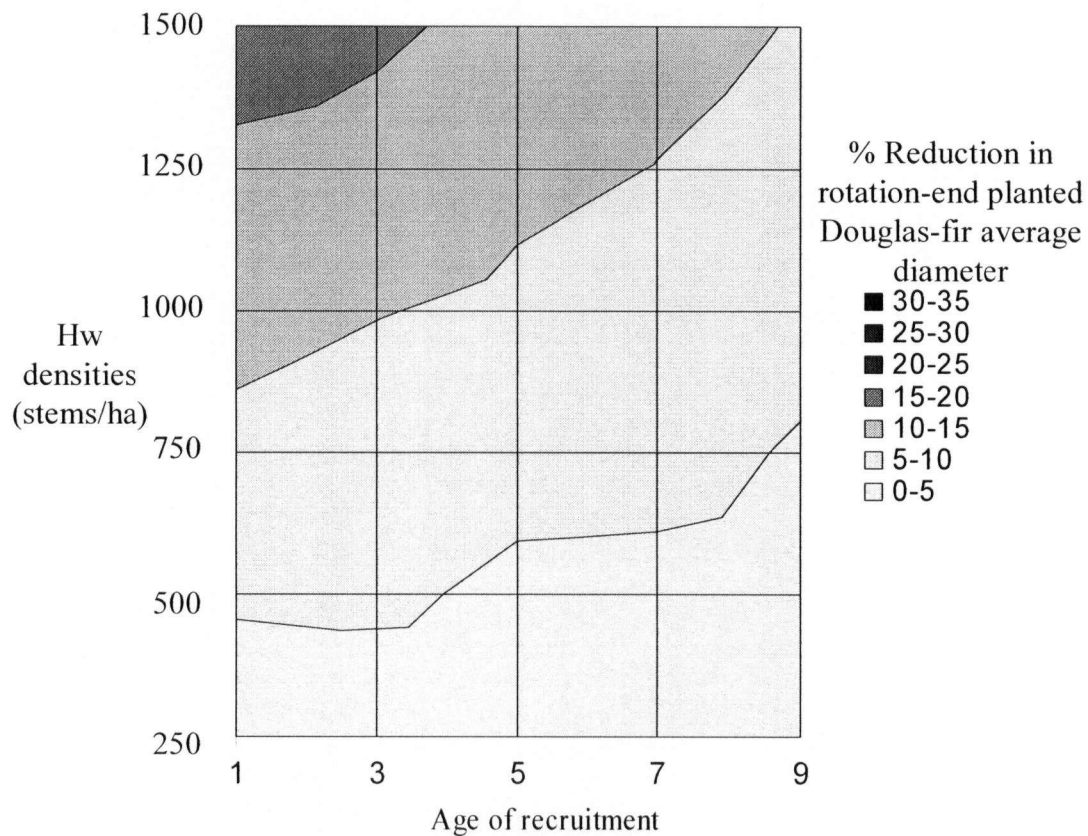


Figure 3.27 Simulated percent reduction in average diameter of the planted Douglas-fir at age 80 as a result of various densities of western hemlock recruitment in years 1 to 9 following planting on a mesic site. The darker the color the greater the reduction.

Table 3.8 Simulated percent reduction in stemwood biomass of the planted Douglas-fir at age 80 as a result of various densities of western hemlock recruitment in years 1 to 9 following planting on a mesic site.

Year of recruitment	Hw densities					
	250	500	750	1000	1250	1500
Age1	8	14	21	25	30	34
Age3	7	13	18	23	27	31
Age5	6	12	17	21	25	29
Age7	6	10	14	18	22	24
Age9	5	9	13	16	20	23

Table 3.9 Simulated percent reduction in average diameter of the planted Douglas-fir at age 80 as a result of various densities of western hemlock recruitment in years 1 to 9 following planting on a mesic site.

Year of recruitment	Hw densities					
	250	500	750	1000	1250	1500
Age1	3	5	9	12	14	17
Age3	2	6	7	10	13	16
Age5	2	4	6	9	11	14
Age7	2	4	6	8	10	12
Age9	2	3	5	6	8	10

Table 3.10 Simulated percent reduction in height of the planted Douglas-fir at age 80 as a result of various densities of western hemlock recruitment in years 1 to 9 following planting on a mesic site.

Year of recruitment	Hw densities					
	250	500	750	1000	1250	1500
Age1	0	1	1	2	2	3
Age3	0	1	1	1	2	2
Age5	0	0	1	1	2	2
Age7	0	0	1	1	1	2
Age9	0	0	0	1	1	1

3.4 Discussion

3.4.1 Overstory

The variation in tree growth, site productivity and moisture for most of the measured variables did not reflect the variation in characteristics of mature stands growing in the different ecosystem types along the local topographic sequence on the study sites. The variation in site was not clearly expressed in the early stand development. This is interpreted to reflect the post-clearcutting assart period and the initial low level of between-tree competition (Kimmins 2004).

This is thought to be due in part to the ending of the assart period of increased soil nutrient availability, which occurs on all sites, but it results in a greater reduction in nutrient availability on the xeric sites. It also reflects soil resource competition on the xeric site that would have

become more acute after the first two decades (Kimmins 2004). The lower tree leaf area on the xeric site results in more shrub competition than on mesic and hygric sites where the higher leaf area results in the shrubs being shaded out.

These results should be interpreted cautiously since the data are from a chronosequence and do not necessarily represent the pattern for a single stand over time. Differences in between-site relationships are certain to vary between different ages of the chronosequence as not all the chronosequence sites are physically identical nor do they have identical histories (Karakatsoulis and Kimmins 1993). Another issue, also discussed in the following section, is that the growth of the planted Douglas-fir cannot be explained without considering the density of other species – which vary greatly on the different aged sites as well as between different SMR. However, with the exception of the mesic sites, data generally indicate that the four sites and their re-measurements do constitute a reasonable chronosequence.

The 2003 measurements confirmed the general trends reported by Karakatsoulis (1993). However, while the shortcomings of using a chronosequence approach were diminished by adding this third set of measurements, the recruitment of natural regeneration increased the variability of stand development between the four components of the chronosequence. Although from a physical site perspective, the chronosequence appear valid, the recruitment challenges the assumption that biologically the four stand ages constitute a chronosequence. The most dominant ingress species, western hemlock, was found on all sites, but at varying densities and time of recruitment. The understory cover was mostly dominated by salal and shrubs from *Rubus* genus.

The hygric sites recruited significant densities of hemlock in two or three cohorts. The hygric site understory was dominated by *Rubus spectabilis*. Some redcedar, red alder and natural regenerated Douglas-fir also established on the hygric sites (Figures 3.6-3.11).

The mesic sites recruited more naturally regenerated Douglas-fir than the hygric sites along with the presence of salal in the shrub strata. A significant amount of red alder also recruited (Figures 3.6-3.11). The mesic sites generally represent the best sites for alder regeneration (Karakatsoulis and Kimmins 1993; Mailly 2003; Karakatsoulis 2004) (Figures 3.6-3.11). Surprisingly, the mesic sites had lower values for planted Douglas-fir at age 23 than the other SMR, which is attributed to differences in the recruitment of natural regeneration and therefore differences in stand density and inter-tree competition.

The xeric sites were less productive than the previous two sites. There was more hemlock regeneration than on the mesic sites as well as several cohorts of Douglas-fir. The amount of red alder and redcedar was less than on the other two sites. Perhaps due to the lower soil disturbance (Karakatsoulis and Kimmins 1993). Salal was most abundant on the xeric site (Figure 3.20) and may have suppressed red alder and redcedar regeneration.

These differences between the three SMR may reflect differences in establishment date of the natural regeneration which has an important influence on the natural regeneration at Blaney Lake Chronosequence.

3.4.2 Understory

The early understory development was reported in Karakatsoulis and Kimmins (1993). This thesis did not provide the same level of detail of the subsequent understory development but the data collected were used in the modeling (ECOSTATE development process). The trends in the later measurements confirmed those described in the early measurements. There was an expected peak in understory development 13 years after the clearcut and the 2003 data set confirmed this (Figures 3.17-3.19).

Salal dominated the understory vegetation on xeric and mesic sites, and was present to a lesser degree on the hygric site, increasing its presence, on this site, with stand age until canopy closure. *Rubus* species were dominant on the hygric site in the early years reflecting the higher nutrient and moisture status of the hygric sites (Karakatsoulis and Kimmins 1993),

3.4.3 Comparison between FORECAST outputs and field data

As mentioned in the results section, the FORECAST model outputs generally provided good estimates of the measured variables. The model predictions for height, diameter, stand density and stemwood biomass have values and temporal patterns very similar to the measured values. The *sine qua non* condition for a better estimation is a good calibration data set and also a carefully constructed ECOSTATE (Kimmins et al. 1999; Seely et al. 1999; Blanco et al. 2007). The data set was calibrated for a general CWDdm subzone and the ECOSTATES represent natural stand conditions, although these are simplified replicas of the natural stands in terms of natural regeneration and understory. The number of data points collected does not allow a detailed statistical analysis of the model performance, but the conclusions obtained from field data-simulated data comparisons imply good prediction capabilities for FORECAST.

Among the variables compared, the best predictions were for the total height of Douglas-fir, where the graphical model results were almost identical with the field results. The statistical tests confirm this. The simulated diameter values are in the range of the data points, but model outputs diameters were considered only for stands older than 15 years. The reason for this is that diameter is not modelled directly in FORECAST. Rather, it is calculated for individual stems from modeled height and stemwood biomass based on the species-specific biomass equations published by Standish et al. (1985). The fact that these equations were parameterized for trees greater than 7.5 diameter means that they do not work well for small trees (< 7.5 cm dbh).

The relationship between DBH and root collar diameter probably changes over time and will be a function of foliage distribution down the stem. The stand density predictions appear acceptable. Since the data variability was higher in this case, the model produced curves that fit the field data range. Statistical tests showed a higher bias and less accuracy for this variable, but the trend of the simulations is comparable with the field data (Table 3.7). Stemwood biomass predictions were some of the most accurate among all variables albeit this parameter was not measured directly but estimated for the last set of data points (2003 measurements) and this can be an extra source of errors.

3.4.4 Window of opportunity for the natural regeneration

One of the most interesting aspects of the 2003 measurements is the variation in abundance and species composition of the natural regeneration between stand ages and SMRs and the effects that this regeneration has had on the planted Douglas-fir. The relatively small size of the cutblocks (up to 10 ha each with a width equal to about four to five times the height of trees in the adjacent mature stands that originated after the 1868 wildfire) created conditions favorable to natural regeneration. This recruited over several years, creating two or three main age cohorts of hemlock and Douglas-fir on most of the sites. Presence of redcedar and alder was noted as well. However, there was high variability in terms of natural regeneration between sites with the same SMR class. Possible causes could be the periodicity of seed years and the year-to-year variation in climatic conditions that would affect regeneration establishment. The differences in ingress among the different plantations within the chronosequence, in effect, violate the conditions of similarity necessary for a valid chronosequence. In addition, it illustrates the difficulty of using data derived from a chronosequence to validate model performance. Such

problems can be avoided by using data from a single or multiple stands with repeated measures over a time sequence for model evaluation, but such data sets are rarely available.

To predict the success of a plantation in the face of abundant natural regeneration it is important to have a better understanding of the key determinants of the ingress and how it affects the community dynamics. The causes and mechanisms that regulate the establishment and survival of the natural regeneration are complex and multiple (Wright et al. 1998) but perhaps the most fundamental is the presence of a seed source or bud bank (Karakatsoulis and Kimmins 1993; Kimmins 2004). Other important factors are the seedbed, the presence of seed consumers and dispersers, and climatic and microclimatic conditions (Wright et al. 1998). These factors have been addressed in studies of natural regeneration under mature forests, both under closed canopy and in canopy gaps (Christy and Mack 1983; Wright et al. 1998; George and Bazzaz 1999; Catovsky and Bazzaz 2002). In contrast, the competitive consequences of ingress regeneration on the development of Douglas-fir plantations in clearcut areas is not well documented, partly because in the past such competition was removed mechanically or by herbicides (Oliver and Larson 1990).

The success of natural regeneration is closely related to the time of recruitment following disturbance – whether or not it can take advantage of the window of reduced competition for light, space and soil resources created by disturbance. The competition for light and nutrients in a plantation increases over time, and there is only a short period at the start of the stand initiation phase of stand dynamics when recruitment can occur (Oliver and Larson 1990; Kimmins 2004).

In the Blaney Chronosequence, the planted Douglas-fir stand would develop into a Douglas-fir–hemlock stand, with smaller components of western redcedar and alder. The objective of this part of the study was to assess how well FORECAST can represent the inter-species competitive effects when the timing of ingress recorded in the empirical field data are represented in the model. As mentioned above, four species recruited in significant amounts: western hemlock, red alder, redcedar and Douglas-fir.

Because there was little disturbance of the organic forest floor and little mineral soil exposure, the seed bed was generally not suitable for Douglas-fir (Karakatsoulis and Kimmins 1993); this might explain the relative lack of regeneration of Douglas-fir (Fig 3.10) despite the dominance of Douglas-fir in the adjacent mature stands. It is questionable whether the later

recruitment of Douglas-fir will contribute to the future stand because of its shade intolerance in this climate. The species can grow in considerable shade (Carter and Klinka 1992; Mailly 1998), but the resultant high height/diameter ratio makes saplings very susceptible to mortality from heavy wet snow fall that occur quite regularly at the study site.

Western Redcedar

Western redcedar is a more shade tolerant species than Douglas-fir once it has mature foliage (Carter and Klinka 1992), but its germinants are relatively shade intolerant until they develop secondary foliage. This means that regeneration from seed is as limited as it is for relatively shade intolerant species like Douglas-fir and red alder (Weber et al. 2003; Karakatsoulis 2004) whereas regeneration from broken twigs and branches (which already have secondary foliage) can occur in the shade. Redcedar is able to grow in height and photosynthesis well in the winter in deciduous stands and under salmonberry, which accounts for its superior recruitment and early growth on hygric sites in comparison with other conifer and deciduous tree species (Weber et al. 2003; Karakatsoulis 2004). Once equipped with secondary foliage, redcedar is very shade tolerant, but its growth in the shade is very slow and it will form a lower slow growing canopy stratum in these stands in the presence of hemlock and Douglas-fir, as is seen in the adjacent mature stands (Figure 3.28). The higher ability of redcedar equipped with mature foliage to survive under a closed canopy (Carter and Klinka 1992) combined with reduced browsing by deer (Karakatsoulis 2002 Pers. Comm.) might explain this sustained establishment rate in comparison with mesic and xeric sites.

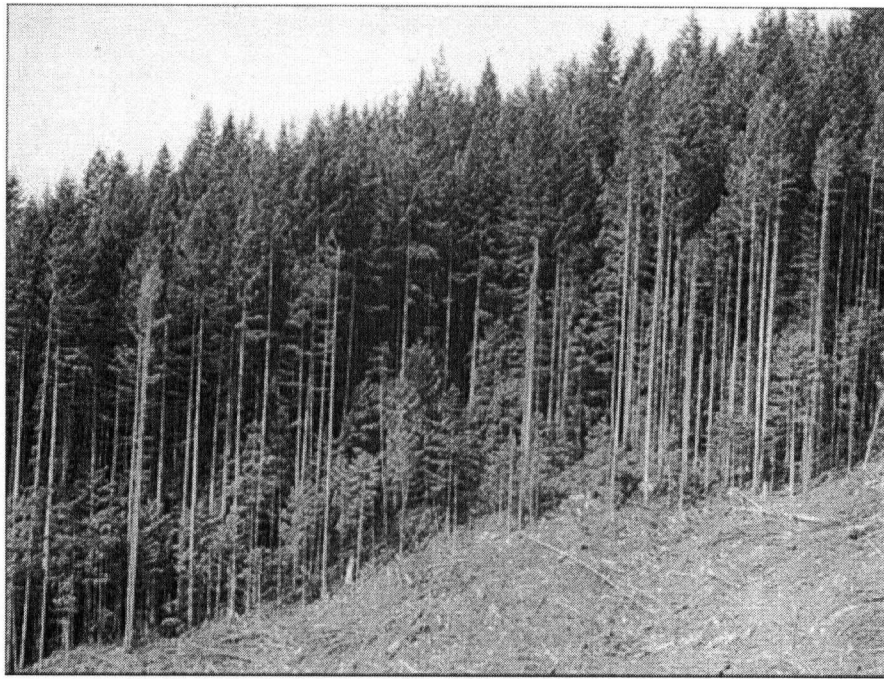


Figure 3.28 Redcedar growing under a Douglas-fir – hemlock canopy.

Photo courtesy of Dr. J.P. Kimmins

Red alder

Red alder, the dominant deciduous species in coastal Douglas-fir mixtures (Klinka 1976; Klinka and Krajina 1986), did not recruit abundantly because of the lack of a suitable exposed mineral seedbed (Karakatsoulis and Kimmins 1993; Maily 1998). The health of the red alder that did recruit was poor, with small crowns due to competition from the evergreen conifers. Douglas-fir and hemlock overtopped alder after about 17 years, and it is expected that red alder will eventually be eliminated from these stands in the absence of any canopy disturbances.

Western Hemlock

The most ubiquitous naturally regenerated species, present on all sites, was western hemlock. The dominance of hemlock seedlings reflects the strong seed source in the surrounding mature CWHdm stands. Hemlock is the climatic climax dominant species on mesic sites in this subzone. Dominance by Douglas-fir is generally reflecting past wildfires, or clearcutting, slashburning and planting of Douglas-fir. Before harvesting, the stand was a second growth Douglas-fir - hemlock mixture, in an area with a known active fire history (Eis 1962; 1962; Maily 1998). The harvesting methodology adopted for the Blaney study area generated a very

little disturbance of soil and minor vegetation, with practically no exposure of the mineral soil, so red alder did not have a suitable seedbed (Karakatsoulis and Kimmins 1993; Karakatsoulis 2004). The initial density of planted Douglas-fir was relatively low (see section 3.2.3) and this permitted abundant hemlock recruitment

Data for the less abundant naturally regenerated species (Douglas-fir, redcedar and red alder) allow only preliminary conclusions regarding the factors determining the successfulness of the natural regeneration. The success of the natural regeneration of these species appears to be related to the availability of seed, but the graphs show a major deterministic role for time of recruitment with a decrease in establishment densities over time (Fig 3.15).

For hemlock seedlings, there is an obvious relationship, for all three SMR classes, between the establishment year and the success of the regeneration, represented here as total stand density (Fig 3.12-3.14). Hemlock densities, together with natural regenerated Douglas-fir, follow the general trend represented in Figure 3.15. Data represent more than a singular site but the declining trend of the hemlock biomass with increasing year of recruitment is noticeable. This provides evidence that the success of hemlock natural regeneration in a Douglas-fir plantation depends on how early it begins. It can be said that the first 10 years after the clearcut are the most important for recruitments. The earlier the seedlings establish on site, the greater the chance for them to compete with planted Douglas-fir and also with the herbs and shrubs that have established (Karakatsoulis and Kimmins 1993).

3.4.5 Factorial simulation experiment

The hemlock ingress factorial experiment simulated here was a continuation of the model testing against field data. This experiment was undertaken to test the ability of FORECAST to replicate the effects of naturally regenerated hemlock in a Douglas-fir plantation. It was found that the establishment year has the greatest single impacts on Douglas-fir growth parameters - greater than the density of hemlock that is getting established. The model's output illustrates this aspect very well, Figure 3.26 proving the usefulness of such models that allow users to produce and compare in a short period of time treatments and processes that would otherwise need decades to occur in natural conditions.

Chapter 4-Vegetation Competition plots

4.1 Introduction

The early phases of plantation establishment and early stand development present considerable challenges to forest managers as they require substantial investments to guarantee the survival and adequate growth of conifers (Ritchie and Hamann 2006). One of the most challenging biotic factors that effect the early stand growth is the rapid development of non-crop natural regenerated trees and minor vegetation species. Since the effects of minor vegetation species are mostly inhibitive, the effects of non-crop broadleaf natural regenerated species can be both inhibitive and facilitative for the planted conifers (Simard and Vyse 2006). However, since the most silvicultural investments are necessary to be applied in the initial phases of the stand development, the usefulness of complex ecosystem models that can successfully examine all these multifaceted issues is becoming evident.

This chapter discusses my extension of the second of the two field experiments established by Karakatsoulis (2004), - the Vegetation Competition (VC) plots. This installation differs in several respects from the Blaney Lake installation that was the focus in Chapter 2. The starting conditions at the time of planting were different for the two experiments: at the Blaney Lake site there was practically no soil disturbance, whereas at the Vegetation Competition installation the forest floor and upper mineral soil were either moved off site or thoroughly mixed on site. There was no management of the non-crop vegetation at the Blaney Lake site, whereas several different vegetation management treatments were applied at the VC site because this site was moist and had a history of severe shrub and pioneer hardwood tree competition. The soil materials were substantially different being coarse textured fluvial outwash over till at the VC site and till at the Blaney Lake site (Klinka 1976; Karakatsoulis 2004). The VC site differed in topography from the Blaney site as the slope was only 5%.

Objectives

The primary objectives of this chapter are:

- 1) to examine the long-term (15-year) impact of minor vegetation and red alder competition on the survival and growth of planted Douglas-fir and western hemlock, and

2) to evaluate the ability of FORECAST to simulate the empirical results of the several vegetation management treatments applied in 1987 (see Karakatsoulis (2004)) to vary the level of competition imposed by non-crop vegetation on planted conifer seedlings. This evaluation is based on repeated measurements (1988, 1989, 1990, 1991, 2002) of the impact of non-crop vegetation development on the growth of Douglas-fir, western hemlock and red alder over a 15-year time period.

4.2 Methods

4.2.1 Description of site and measurements of Vegetation Competition plots

The study site is situated at an elevation of 140m and has a 5% slope with a western aspect. The climate is typical for the CWHdm subzone (Pojar et al. 1991) and prior to mechanical disturbance the soil was a humo-ferric podzol developed in a gravely loam outwash over an underlying layer of till and lacustrine materials 1-2 m deep (Karakatsoulis 2004). Prior to 1920, the site was occupied by a mature mixed conifer stand of natural origin that was exploitatively logged in association with railway development in the 1920's. The stand that developed subsequently by natural regeneration was poorly stocked primarily with western redcedar and with lesser amounts of Douglas-fir and western hemlock most likely because of the intense shrub competition on this site. Karakatsoulis (2004) suggested that the redcedar was able to establish as it is relatively well adapted to tolerate such competition. This second-growth stand was harvested in 1984-85 and heavy shrub competition led to several failures to establish a Douglas-fir plantation. In an effort to rehabilitate the stand, all the remaining stumps, slash, debris and large rocks were removed mechanically in 1985, and the entire area leveled creating a relatively uniform, gently sloping surface (Karakatsoulis 2004). However, there was rapid invasion of non-crop vegetation following the intensive site mechanical preparation.

In the spring of 1987, sixteen, 20m x 25m, plots were established on the site in a randomized complete block split plot design with eight treatments and two replicates per treatment. Four conifer species (Douglas-fir, western hemlock, western redcedar and grand fir) were planted at 2x2m spacing in each plot in three rows, with the position of rows in the plots randomly selected. Deer browsing severely damaged the redcedar and slow early growth of the grand fir resulted in the limitation of my measurements and the analysis in this chapter to Douglas-fir and

hemlock. The age of the seedlings at time of planting was 2 years for Douglas-fir and 1 year for western hemlock.

The following eight treatments were randomly assigned to each of the sixteen plots with two replications each (Karakatsoulis 2004):

1. No vegetation (Noveg) – Manual removal of all non-crop vegetation.
2. No vegetation and fertilizer (NoVegF) – The same as above but the conifers were also fertilized with 40 grams of 14-14-14 (NPK) slow release fertilizer (Osmocote®, Sierra Chemical Co., CA) at time of planting to see how this affected their competitive status.
3. Shrubs (Shrub) – All deciduous trees were removed, but the shrub and herb layers that developed naturally were not managed. The fertilizer treatment was equivalent to about 80 kg/ha.
4. Shrubs plus fertilizer (ShrubF) – The same as #3 but the above-mentioned fertilization treatment was applied.
5. Alder (AR) – A two year old red alder seedling was planted besides each conifer.
6. Alder + fertilizer (ARF) - red alder seedlings planted besides each fertilized conifer.
7. Full competition (Full) – all the naturally-regenerated deciduous tree and minor vegetation was allowed to grow. This treatment was considered as the control.
8. Full competition + fertilizer (FullF) – the same as control but conifer seedlings were fertilized at the time of planting.

The fertilizer used in all treatments was 14-14-14 (NPK) slow release fertilizer (Osmocote®, Sierra Chemical Co., CA) which was applied by mixing 40 grams into the soil around each conifer seedling soon after it was planted.

Stem diameter at root collar and total height were measured mid-summer of 1987, 1989, 1990 and 1991. In the summer of 1998 (a 10 year re-measurement) a reduced set of measurements was taken on three of the treatments (AR, NoVeg and Full) as a partial re-measurement, damage to other installations by wind and snow rendering them unavailable for comparative measurements. Competition from non-crop vegetation renders planted conifers in this coastal area very susceptible to such damage which is therefore an important outcome of non-crop competition. However, quantification of this damage was not a part of this study. Understory vegetation, soil temperature and seedling photosynthesis were also investigated by Karakatsoulis (2004) but they are not discussed in this thesis which focused on the treatment effects on the crop trees.

4.2.2 The 2002 measurements

The Vegetation Competition plots were re-measured in the summer of 2002 (a 15 year re-measurement). The height and root collar diameters for both conifers (Douglas-fir and hemlock) and planted red alder were recorded. Because the plots were not subject to treatments after the 1991 measurements, some of the treatments were not re-measured (the planted conifers had succumbed to non-crop vegetation) and so were not used in this thesis (ARF, NoVegF, Shrub, ShruF, FullF). Also, as noted above, some conifers were damaged during several heavy snowfalls in the late 1990's (Karakatsoulis 2002 Pers. Comm.). The most affected treatments were FullF and ShrubF as they are situated in the western part and the snowfall damage was mostly produced by bigger trees from adjacent trees that fell down in the VC plots. Consequently, only the following three treatments were re-measured: AR (red alder planted beside each conifer), Noveg (all understory vegetation removed), and Full (no vegetation management applied to the plots – maximum competition). Average height and percent cover were also estimated for the understory vegetation.

4.2.3 Model Setup and Application

The FORECAST model (see Chapter 2 for descriptions) was setup and applied to represent the vegetation control plots with the planted Douglas-fir and hemlock growing in competition with naturally regenerated minor vegetation and red alder, and planted red alder in the AR treatment. A general ECOSTATE file was prepared to represent the basic soil and forest floor conditions for all treatments. The preparation of the ECOSTATE file for the VC plots was very similar to that described in Chapter 2 for the Blaney Lake installation, except that for the VC plots the ECOSTATE file was only prepared for one site quality (SI = 36), reflecting the moist and nutrient rich site (Karakatsoulis 2004). Also, at the end of the last run of the ECOSTATE preparation, a mechanical site preparation was simulated to emulate the treatment that was actually applied to the site. The site preparation treatment was simulated using a litter raking option that allows for the removal of the organic material from the forest floor.

A detailed description of the simulation of the three selected treatments, in FORECAST is provided in Table 4.1. Unlike the simulations for the Blaney Lake site, the Douglas-fir and western hemlock on the VC site were simulated separately as they were not intimately mixed in the field plots (Table 4.1). Planting densities for all treatments were the same for both crop trees

examined – 1980 sph. The Noveg plots were represented by simulating the growth and development of the Douglas-fir or hemlock plantation with a substantially reduced regeneration of red alder and salmonberry delayed until year 6 to account for the effect of the treatment. The Full plots were simulated by representing salmonberry establishment at 20% cover in year 1 and red alder natural regeneration (1500 sph) in year 1. While there was other non-crop vegetation on the plots, salmonberry and red alder were the most important from a competition perspective based on the 2002 field measurements. The AR treatment was represented by planting 1 red alder for every crop tree planted for a total of 1980 sph of alder at year 1. The AR treatment also included salmonberry regeneration at 10% initial cover in year 1.

Table 4.1 Simulation parameters for the selected three treatments in the Vegetation Competition plots. Crop trees (Fd 2-year-old seedlings, Hw 1-year-old seedling) and red alder (2-year old seedlings) in the AR treatment were planted in year 1; alder naturally regenerated in the other treatments. Salmonberry (shown as Rubus) regenerated in all treatments but was delayed in the NoVeg treatment.

Treatment	Planted Crop Trees		Non-crop vegetation			
			Tree		Minor vegetation (initial cover%)	
	Douglas-fir (sph)	Hemlock (sph)	Red alder (sph)	Regen year	Rubus (% cover)	Regen year
Noveg	1980	1980	500	6	1	6
Full	1980	1980	1500	1	20	1
AR	1980	1980	1980	1	10	1

4.2.4 Model evaluation

The methodology used to evaluate the FORECAST simulations for the Vegetation Competition plots is very similar to that used for the Blaney Lake area simulations. Both experiments address the development of young plantations and in both cases other species, either planted and naturally regenerated, interfered with conifer growth. The ability of FORECAST to emulate different vegetation competition management treatments was evaluated using the statistical tests described in Chapter 3, Section 3.2.7. These were performed for both Douglas-fir and hemlock simulations. Since more data points are available this case, the

confidence interval comparison (Haefner 2005) was used for visual comparisons between the model and field data. For the VC plots, the 95% confidence intervals were calculated as:

$$\bar{X} \pm \left[t_{(0.05, n-1)} \right] s_{\bar{X}},$$

where \bar{X} is the observed mean, $t_{(0.05, n-1)}$ is the Student's t distribution value for $\alpha=0.05$ and $n-1$ degrees of freedom, and $s_{\bar{X}}$ is the sample standard deviation.

For direct comparison to the field measurements, the breast height diameters produced by FORECAST were transformed into root collar diameters using simple linear regression equations produced using field data obtained from Blaney Lake Chronosequence (see Table 4.2).

Table 4.2 Simple linear regressions fitted between collar diameters (*Dbase*) and breast height diameters (DBH) of Douglas-fir and western hemlock in the Vegetation Competition plots.

Species	Equation used	Model fit (R^2)
Douglas-fir	$Dbase = -0.63459 + 1.231128DBH$	0.99
Western hemlock	$Dbase = 0.274623 + 1.12024DBH$	0.96

4.3 Results

4.3.1 Treatment effects

Karakatsoulis (2004) provides a description of the effects of early competition on conifer based upon the full set of treatments outlined in Section 4.2.1. However, only the three treatments re-measured in 2002 are reported here and details of the early measurements are restricted to these treatments.

There were no significant differences among treatments after the first year of growth. Starting in year 2, diameter growth for both Douglas-fir and hemlock was significantly greater in the Noveg sites compared to the other treatments (Tables 4.3, 4.4). The trend in conifer height growth was different from that observed for diameter. Early (through year 4) conifer height growth was greater or similar in the Full and AR treatments relative to that in the NoVeg

treatment (Tables 4.3, 4.4). By year 10 the trend had reversed and both species were significantly taller in the NoVeg treatments relative to the high competition (AR and Full) treatments.

The 2002 results show significant differences for the diameter and height between the Noveg plots and the other two treatments for both Douglas-fir and western hemlock (Tables 4.3, 4.4). Neither Douglas-fir nor hemlock performed very well when competing with red alder or with the natural regenerated shrubs. In the case of Douglas-fir, the greatest difference in growth rates (diameter & height) was measured between the Noveg and Full plots (Table 4.3). As the shrubs overtopped the Douglas-fir, the seedlings' growth rate was significantly reduced. The same was true for hemlock but the differences between treatments were smaller.

The height/diameter's (H/D) ratios of Douglas-fir and hemlock were in the same range for the first 10 years after planting. H/D values for hemlock were slightly higher in the first four years (Table 4.5) but after 10 years Douglas-fir had slightly higher H/D ratios. As expected, the height/diameter ratios were higher after 15 years for Douglas-fir than for hemlock (Table 4.5). The H/D ratio was highest for Douglas-fir in the "Full" (Full competition) treatment (Table 4.5). For hemlock, the highest H/D ratios at 10 and 15 years were recorded on the Noveg sites.

Douglas-fir seedlings were taller after four and ten years than the hemlock for the selected treatments (Karakatsoulis 2002 Pers. Comm.). This was expected to happen as the shaded Douglas-fir would have greater height growth than the hemlock since the former is assumed to behave like a pioneer species with lower shade tolerance (Carter and Klinka 1992; Karakatsoulis 2004).

Table 4.3 Average collar diameters and total height of the **Douglas-fir seedlings** in three selected treatments in the Vegetation Competition plots. Variable's means within rows followed by the same letters are **not** significantly different from each other at $p < 0.05$ (Tukey test; for the 2002 values both Tukey and Bonferonni tests were performed). Bold numbers are the 2002 measurements values. Sample numbers for each mean ranged from 69-75 for year 1-4 and 10 measurements; sample numbers for each mean in year 15 ranged from 20 – 45.

Year	Diameters (mm)			Height (m)		
	Treatments					
	NoVeg	AR	Full	NoVeg	AR	Full
1	7.40 <i>a</i>	7.40 <i>a</i>	7.30 <i>a</i>	0.48 <i>a</i>	0.55 <i>a</i>	0.51 <i>a</i>
2	13.80 <i>b</i>	15.60 <i>a</i>	12.10 <i>b</i>	0.75 <i>b</i>	0.96 <i>a</i>	0.80 <i>b</i>
3	17.60 <i>a</i>	19.30 <i>a</i>	14.30 <i>b</i>	1.03 <i>b</i>	1.41 <i>a</i>	1.13 <i>b</i>
4	23.40 <i>a</i>	23.00 <i>a</i>	15.80 <i>b</i>	0.80 <i>b</i>	1.07 <i>a</i>	0.93 <i>b</i>
10	86.30 <i>a</i>	41.50 <i>b</i>	29.00 <i>c</i>	8.20 <i>a</i>	4.00 <i>a</i>	3.00 <i>c</i>
15	93.58 <i>a</i>	40.47 <i>b</i>	26.35 <i>c</i>	12.77 <i>a</i>	4.73 <i>b</i>	3.71 <i>b</i>

Table 4.4 Average collar diameters and total height of the **hemlock seedlings** in three selected treatments in the Vegetation Competition plots. Variable's means within rows followed by the same letters are **not** significantly different from each other at $p < 0.05$ (Tukey test; for the 2002 values both Tukey and Bonferonni tests were performed). Bold numbers are the 2002 measurements values. Sample number for each mean ranged from 69-75 for year 1-4 and 10 measurements; sample numbers for each mean in year 15 ranged from 19 – 67.

Year	Average Diameter (mm)			Average Height (m)		
	Treatments					
	NoVeg	AR	Full	NoVeg	AR	Full
1	6.40 <i>a</i>	6.90 <i>a</i>	6.00 <i>b</i>	0.46 <i>b</i>	0.53 <i>a</i>	0.51 <i>ab</i>
2	9.20 <i>a</i>	10.40 <i>a</i>	7.70 <i>b</i>	0.59 <i>b</i>	0.75 <i>a</i>	0.66 <i>a</i>
3	10.00 <i>a</i>	11.30 <i>a</i>	8.60 <i>b</i>	0.72 <i>b</i>	0.89 <i>a</i>	0.79 <i>b</i>
4	11.10 <i>a</i>	12.50 <i>a</i>	9.40 <i>b</i>	0.80 <i>b</i>	1.09 <i>a</i>	0.95 <i>b</i>
10	71.00 <i>a</i>	28.50 <i>b</i>	15.50 <i>c</i>	6.75 <i>a</i>	2.30 <i>b</i>	1.35 <i>b</i>
15	77.70 <i>a</i>	33.22 <i>a</i>	26.69 <i>c</i>	9.38 <i>a</i>	3.03 <i>b</i>	2.69 <i>b</i>

Table 4.5 Average height: colar diameter ratios for **Douglas-Fir** and **hemlock** in the selected treatments in the Vegetation Competition plots. Bold numbers are the 2002 measurement values. Sample numbers for each mean ranged from 69-75 for year 1-4 and 10 measurements; sample numbers for each mean in year 15 ranged from 20 – 45 for Douglas-fir and 19-67 for hemlock.

Year	Douglas-fir			Western hemlock		
	NoVeg	AR	Full	NoVeg	AR	Full
1	0.65	0.74	0.70	0.72	0.77	0.85
2	0.54	0.62	0.66	0.64	0.72	0.86
3	0.59	0.73	0.79	0.72	0.79	0.92
4	0.34	0.47	0.60	0.72	0.87	1.01
10	0.95	0.96	1.03	0.95	0.81	0.87
15	1.36	1.17	1.41	1.21	0.91	1.01

4.3.2 Graphical evaluation of model performance

Comparisons between FORECAST predictions and treatment field data are presented graphically in Figures 4.1-4.6. Modelled average diameter is only considered from year 10 onward (See Section 3.43). Modelled average diameter for Douglas-fir was substantially greater than field measured average diameter in all treatments (Fig 4.1). As, described above, this is largely due the limitations of the diameter calculation method for small trees in FORECAST. The difference between modelled and field measured diameter was less in the hemlock plantations with simulated diameters predominantly within the expected range (Fig 4.2). Average height growth predicted by the model was similar to field measured values for both species (Fig 4.3 and 4.4). The model tended to underestimate Douglas-fir height in the Noveg treatment and over estimate it in the Full competition treatment (Fig 4.3). Simulated hemlock heights are within the range of field data (Fig 4.4) for the NoVeg treatment but slightly over-predicted in AR and Full treatments.

Since density was only measured during the 2002 sampling period, comparisons of stemwood biomass and stem densities are limited to year 10 for each treatment. Modeled stemwood biomass, for both Douglas-fir and hemlock, was similar to the values estimated from the field data (Fig 4.5). Modeled stem density, a measure of competition-related mortality was similar to that measured for Douglas-fir for all treatments (Fig 4.6). In the case of hemlock the model underestimated the effect of shrub competition on mortality and thus simulated stem density was much higher in the Full treatment relative to the field measured value in year 15. The opposite was true in the case of the AR treatment in which case the model under-predicted mortality (Fig 4.6).

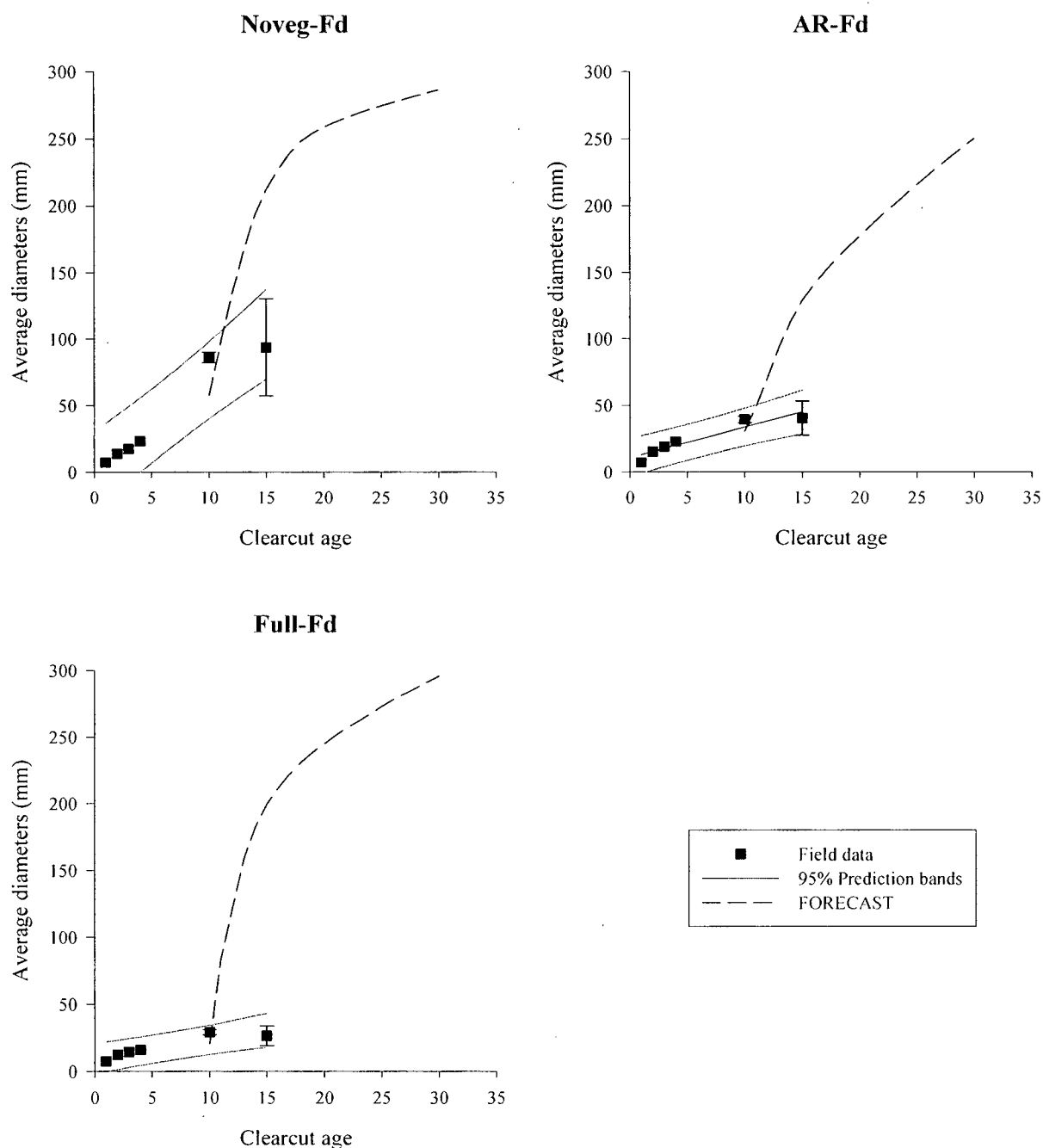


Fig 4.1 Comparisons between the **Douglas-fir** simulated and measured average **collar diameter** for the three selected treatments in the Vegetation Competition plots. 95% prediction bands (obtained through regression) were constructed for the field data (red lines).

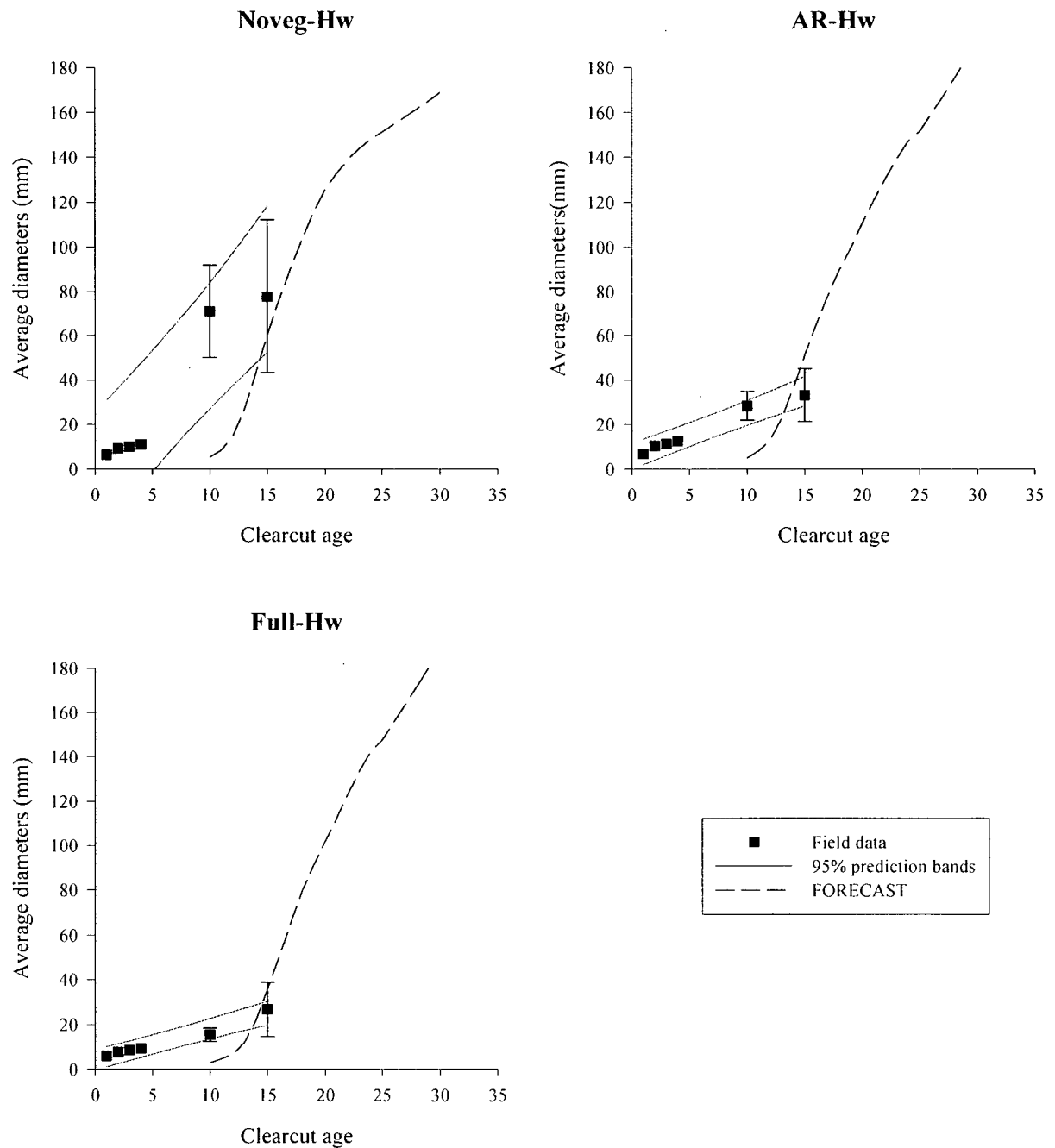


Fig 4.2 Comparisons between the western hemlocks's simulated and measured collar diameters for the selected treatments in the Vegetation Competition plots. 95% prediction bands (obtained through regression) were constructed for the field data (red lines).

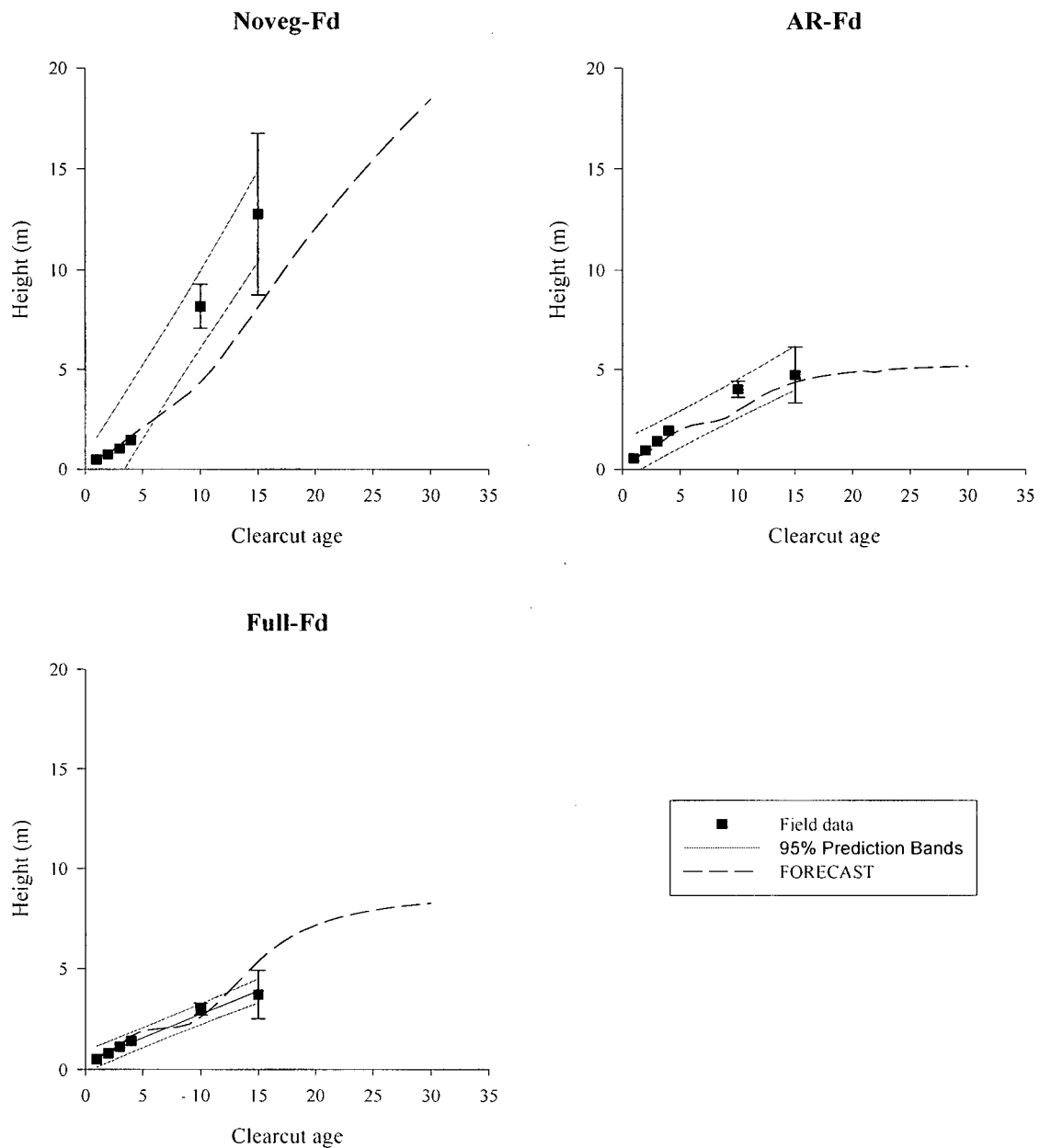


Fig 4.3 Comparisons between the **Douglas-fir** simulated and measured **heights** for the selected treatments in the Vegetation Competition plots. 95% prediction bands (obtained through regression) were constructed for the field data (red lines).

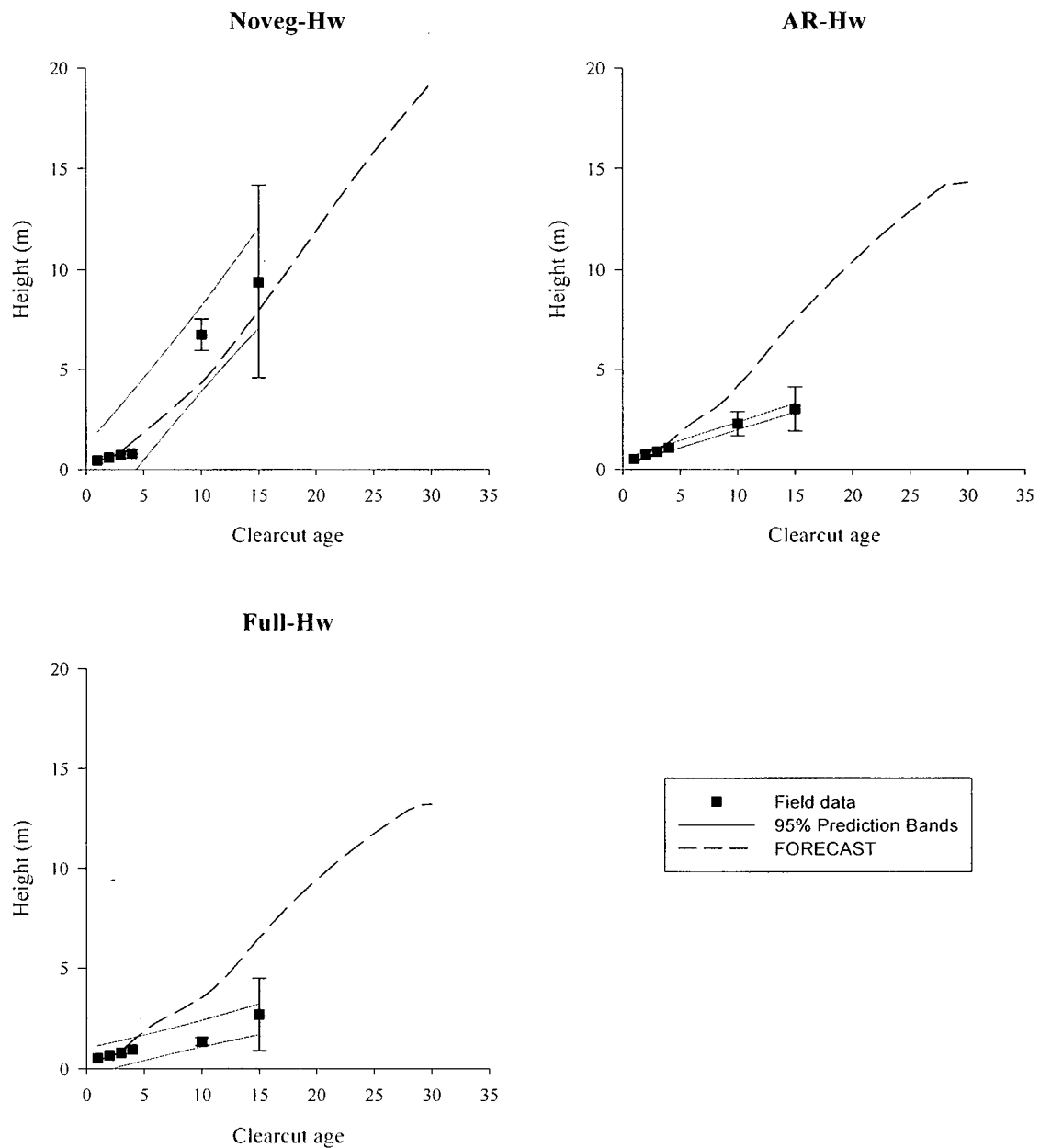


Fig 4.4 Comparisons between the **hemlock** simulated and measured **heights** for the selected treatments in the Vegetation Competition plots. 95% prediction bands (obtained through regression) were constructed for the field data (red lines).

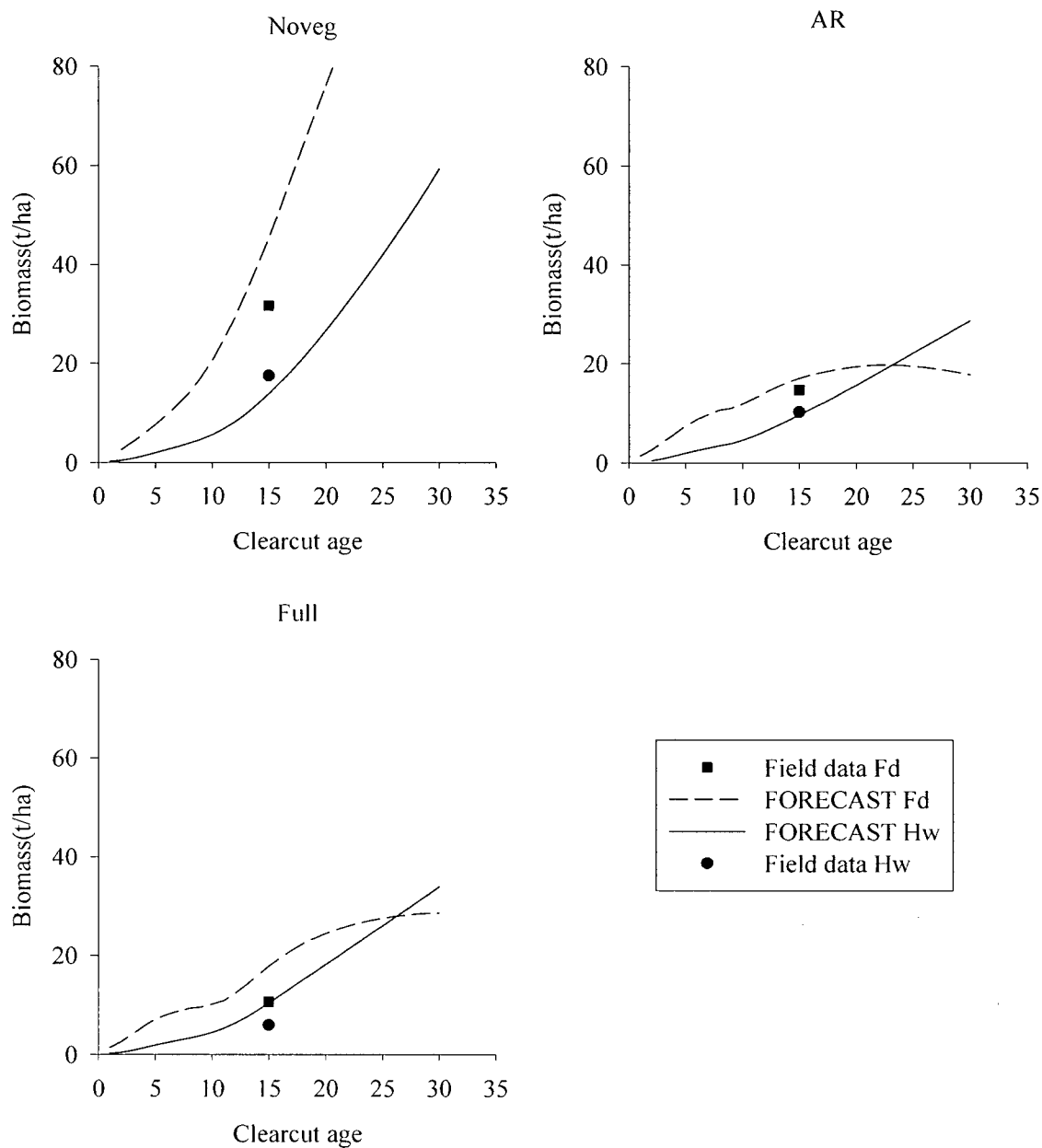


Fig 4.5 Comparison between the **Douglas-fir and hemlock** simulated and measured **stemwood biomass** (only for year 15) for the selected treatments in the VC plots.

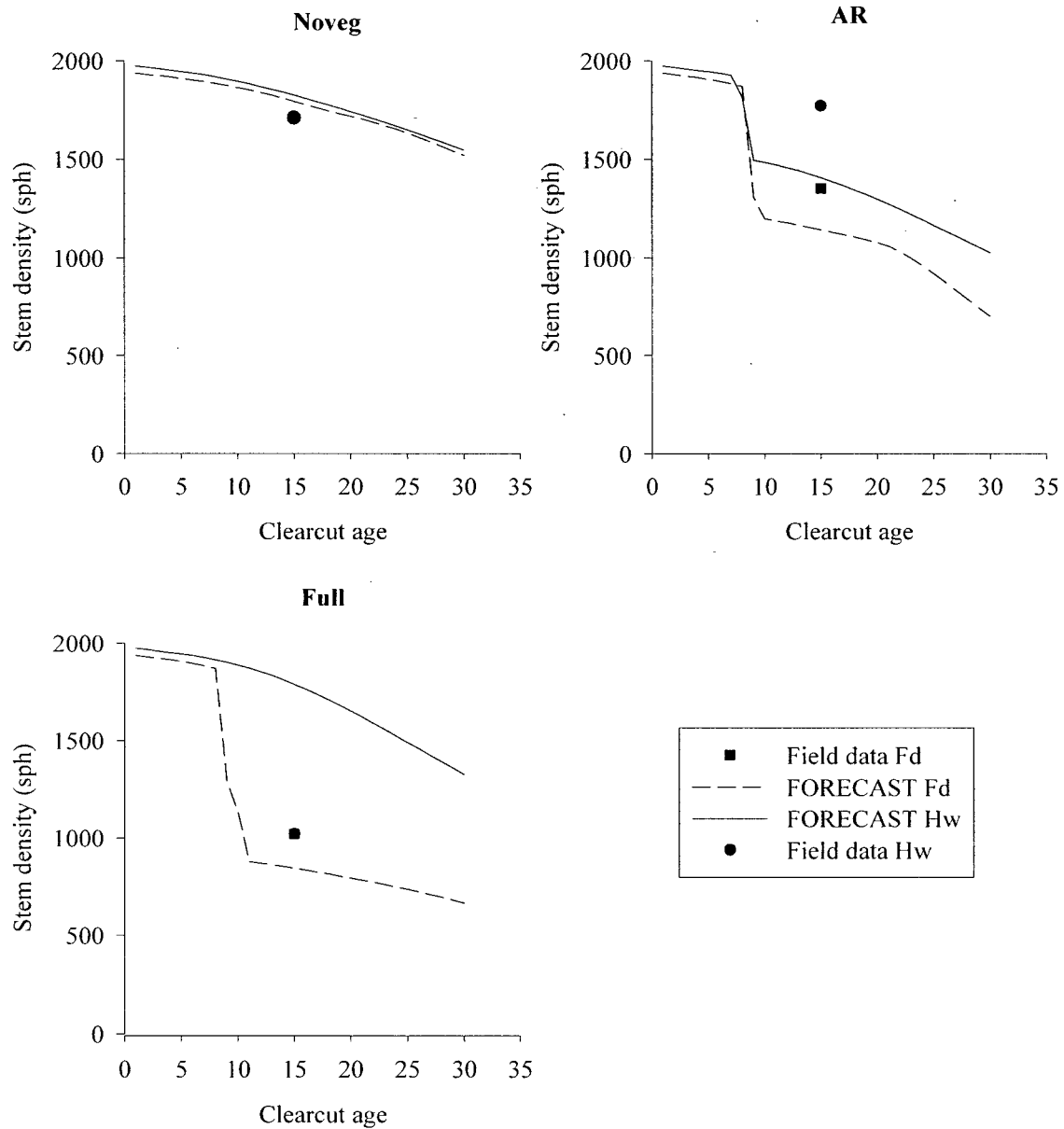


Fig 4.6 Comparisons between the **Douglas-fir and hemlock** simulated and measured **stem densities** (only for year 15) for the selected treatments in the VC plots.

4.3.3 Statistical evaluation of model performance

The results of the statistical test performed to compare the model prediction with the field records are presented in Table 4.6 for Douglas-fir and in Table 4.7 for hemlock.

Table 4.6 Statistics and tests that were used to compare the field results from VC experiment data with the FORECAST model outputs' for **Douglas-fir**. Where: e^* - Reynolds errors comparing the overall fit; R^2 - coefficient of determination; U - Theil's inequality coefficient; EF -modeling efficiency.

(Sample numbers are $n = 23$ for height, $n = 6$, for the other variables)

Statistic(Test)	Variables			
	Height (m)	Diameter (mm)	Density(sph)	Biomass(t/ha)
<i>Normality tests</i>				
Shapiro-Wilk	0.003	0.1067	0.4133	0.6502
Decision	Reject, non-normal	Accept, normal	Accept, normal	Accept, normal
Kolmogorov-Smirnov	<0.0100	>0.1500	>0.1500	>0.1500
Decision	Reject, non-normal	Accept, normal	Accept, normal	Accept, normal
Cramer-von Mises (p)	<0.0050	0.1939	>0.2500	>0.2500
Decision	Reject, non-normal	Accept, normal	Accept, normal	Accept, normal
Anderson-Darling (p)	<0.0050	0.1331	>0.2500	>0.2500
Decision	Reject, non-normal	Accept, normal	Accept, normal	Accept, normal
<i>Accuracy estimators</i>				
e^* at $\alpha = 0.05$	2.13	133.92	184.44	10.24
Accuracy	Acceptable	Acceptable	Acceptable	Acceptable
e^* at $\alpha = 0.20$	1.55	106.21	151.80	8.43
Accuracy	Acceptable	Acceptable	Acceptable	Acceptable
<i>Goodness of fit</i>				
R^2	0.87	0.02	0.97	0.96
Conclusion-prediction	Good	Poor	Good	Good
U	0.47	0.70	0.03	0.26
Conclusion-prediction	Good	Good	Good	Good
EF	0.74	-4.62	0.84	0.52
Conclusion-prediction	Good	Poor	Good	Good

Table 4.7 Statistics and tests that were used to compare the field results from VC experiment data with the FORECAST model outputs' for **western hemlock**. Where: e^* - Reynolds errors comparing the overall fit; R^2 – coefficient of determination; U – Theil's inequality coefficient; EF -modeling efficiency.

(Sample numbers $n = 23$ for height, $n = 6$ for the other variables)

Statistic(Test)	Variables			
	Height (m)	Diameter (mm)	Density(sph)	Biomass(t/ha)
<i>Normality tests</i>				
Shapiro-Wilk	0.0001	0.4087	0.55	0.58
Decision	Reject, non-normal	Accept, normal	Accept, normal	Accept, normal
Kolmogorov-Smirnov	0.01	>0.1500	>0.1500	>0.1500
Decision	Reject, non-normal	Accept, normal	Accept, normal	Accept, normal
Cramer-von Mises (p)	0.005	>0.2500	>0.2500	>0.2500
Decision	Reject, non-normal	Accept, normal	Accept, normal	Accept, normal
Anderson-Darling (p)	0.005	>0.2500	>0.2500	>0.2500
Decision	Reject, non-normal	Accept, normal	Accept, normal	Accept, normal
<i>Accuracy estimators</i>				
e^* at $\alpha=0.05$	2.87	50.27	556.96	3.68
Accuracy	Acceptable	Acceptable	Acceptable	Acceptable
e^* at $\alpha = 0.20$	2.09	39.87	458.38	3.03
Accuracy	Acceptable	Acceptable	Acceptable	Acceptable
<i>Goodness of fit</i>				
R^2	0.59	0.04	0.29	0.68
Conclusion-prediction	Average-Good	Poor	Poor	Good
U	0.51	0.91	0.21	0.25
Conclusion-prediction	Good	Good	Good	Good
EF	0.37	-3.36	-0.81	0.59
Conclusion-prediction	Good	Poor	Poor	Good

Normality tests of the errors

The normality tests were conducted to justify the use of parametric or non-parametric tests but they should be treated cautiously because of the reduced number of data points. However, the tests failed to reject the normality hypothesis in all cases but height. There are no non-parametric tests conducted here for the height data as it was considered that the tests performed are robust enough for the purpose of this thesis (Haefner 2005). As mentioned before, these

normality tests might provide a low accuracy measure of the goodness of fit for the specified variables (Yang et al. 2004).

Accuracy of model predictions

The Reynolds's errors criterion was used for the Blaney Lake modeling experiment and is used here as well. The results were in the range of standard deviation of data and higher than the expected errors especially for the smaller α (0.05) values, so these tests suggested that the accuracy of the predictions is acceptable, with the exception of average diameter for both species and stem density for hemlock. These results should be interpreted cautiously since the data set are represented by a reduced number of errors.

Goodness-of-fit

The results produced by the goodness of fit tests used here are relatively consistent for all four variables being considered. The tests results also reflect the graphical presentations. Both the modeling efficiency (*EF*) and the R square (R^2) criterion provided the same range of results for both Douglas-fir and hemlock with good predictions for height and biomass and poor fit for diameters and densities. The Theil's "*U*" coefficient considers all variables produced by the model to be comparable with those obtained from the field (Tables 4.6, 4.7). However, this criterion tends to have a larger fitting interval than the previous two indices. A value of $U=0$ represents a perfect model fit with the data, values of $0 < U < 1$ should be interpreted as an average prediction accuracy, whereas a value of $U > 1$ means that the model is not capable of producing a good prediction. The three customized levels of prediction ratings: "poor", "average" and "good" were based on the particularities of each test (e.g. a value of $EF = 0.79$ of the modeling efficiency coefficient is considered as representative for a good prediction level on a scale from 0 = "simple average" to 1 = "perfect prediction").

4.4 Discussion

4.4.1 Development of the VC treatment plots after 15 years

A more detailed analysis of the VC plot development and the ability of FORECAST to represent it were prevented by the damage to the installations by snow and the failure to

maintain the treatments after the 1997 partial re-measurements (Karakatsoulis 2002 Pers. Comm.). The 15-year growth trends for Douglas-fir and hemlock were generally consistent with those reported by Karakatsoulis (2004) after 10 years. However, it was apparent at the 15-year sampling that Douglas-fir was not coping as well as hemlock in the high competition plots. Specifically, relative to hemlock, the growth rate of Douglas-fir was starting to decline in the face of competition and higher mortality was observed on Full competition plots. This trend was also evident in the simulation runs where the model suggested that hemlock would have lower mortality rates and produce more biomass by year 30 (Fig. 4.5, 4.6). It is not clear why there were higher mortality rates for hemlock in the AR plots (Fig 4.6). It is expected that hemlock, a more shade tolerant species than Douglas-fir (Carter and Klinka 1992), will likely overtop alder in time and the stands will eventually become hemlock dominated mixtures. It is less clear how well the Douglas-fir will persist in the high competition stands.

The expected successional sequence for this area is that the disturbance that was applied – which would represent a landslide or a severe wind throw event followed by surface erosion – would be invasion by red alder and possibly black cottonwood with some shrub development – probably salmonberry. There would be some recruitment initially of Douglas-fir, hemlock and redcedar, depending on seed availability. The redcedar would also depend on deer populations and the severity of browsing – which might exclude the redcedar until it was protected by shrub growth. Thus, with little Douglas-fir seed and heavy browsing, the area might develop into a deciduous overstory with a hemlock understory and eventually become a hemlock stand. If there was abundant Douglas-fir recruitment, some of these might survive the competition and create a low density of DF in a deciduous stand. If deer browsing did not eliminate the redcedar, the future stand might become a redcedar stand with a few Douglas-fir and hemlock – similar to the stand upslope from the VC plots. Thus, the expected successional sequence would depend as much on seed availability during a short period of seedbed receptivity and deer browsing, as on the actual disturbance and the subsequent levels of competition.

4.4.2 Model evaluation

This second objective of this Chapter was to evaluate the capacity of FORECAST to represent a more diverse range of competitive environments at stand establishment than in the Blaney Chronosequence plots. The same calibration data set was used in both Blaney and VC

experiments. In this second experiment, however, the highly disturbed soil contributed to an improved seedbed for the emerging shrubs and natural regenerating tree species. The raking option in FORECAST (Kimmins et al. 1990; Kimmins et al. 1999) was successfully used here to simulate the removal of forest floor material and the associated loss of soil organic matter.

The performance of FORECAST was generally satisfactory: for most variables (with the exception of diameter) and treatments, the model forecasts were close to the field data or estimates thereof. The reduced period of time of the simulations might contribute to some extent to a less accurate prediction. As mentioned before, the diameters are not directly estimated by the model but calculated through equations using the biomass and height (Kimmins et al. 1999). Those equations are not properly calibrated for younger ages, therefore cannot be considered as accurate for stands younger than 10-15 years old (B. Seely, 2006 Pers. Comm.). This fact is more evident for Douglas-fir (Fig 4.1) than for the hemlock, where a better fit has been obtained for all three treatments (Fig 4.2).

Average top height was well represented for both species with better fit for the Douglas-fir data. Model simulations produced a good fit for the hemlock's height in Noveg treatments, and overestimated the height in the other two treatments (Fig 4.4). An explanation for the deviation is that the increased competition levels were not properly adjusted in the model, as alder growth might not be well represented in the first years.

The model produced well fitted simulations for stemwood biomass and density data for Douglas-fir (Fig 4.5, 4.6). Hemlock stemwood biomass was also well predicted while the hemlock densities were well predicted in the Noveg plots but underestimated for the AR and overestimated for the Full plots (Fig 4.6). Stemwood biomass is one of the major components of NPP (Net Primary Production) in FORECAST, so that the model is able to produce better predictions for this variable. Errors in representing density could also partially explain the errors in diameters. Also, errors in regression equations that convert the breast height diameters to collar diameters could have created errors in the "real" diameter data. Evaluation of model performance is always complicated when simulations are compared with regression-derived estimates of "reality" because these regression estimates may be in error (Blanco et al. 2007).

When comparing the model performance for the two species, the differences between their tolerances to shade were captured by the FORECAST model especially in the stemwood biomass simulations (Fig 4.5). The model shows an expected decline of Douglas-fir biomass

increment in the AR and Full sites. This can also be observed in the height simulations graphs (Fig 4.3). There is no remarkable difference between the AR and Full sites for any of the four Douglas-fir parameters. Hemlock, however, is projected to perform better than Douglas-fir under both the alder (AR) and mixed deciduous (Full) canopies, even though the simulated hemlock heights are slightly overestimated for these sites. The model appears to correctly represent the competition for light in the two treatments: AR - representing a closed alder canopy and Full – which was a mix of hardwood tree species with incomplete canopy closure plus a very dense shrub understory.

Generally, the values provided by the statistical tests confirmed what can be seen by inspecting the graphs. However, there are some contradictory results, so interpretations should be made with caution. The best model performance was for the height data in which real data were compared with simulated heights. The “real” biomass and diameter data were all derived indirectly from regression equations that have their own errors. The simulated stand density values provided a better fit for the Douglas-fir than for the hemlock.

The overall model performance can be characterized as acceptable for the level of accuracy necessary for young stand management. Important questions can be answered using the model outputs despite the fact that the data set is for a relatively short time period. The model can be successfully used to represent the different successional pathways that are possible with different timings and densities of recruitment of the different species (see Section 3.3.6)

Chapter 5-Synthesis

Both the forest and environmental communities support the use of ecosystem models in the design of systems and plans for the management of forest ecosystems. A key question about such models is how well are they able to address the complexity of real ecosystems, and how complex do they need to be to achieve adequate levels of predictive performance? This thesis has addressed the first part of this question in the context of simulating the stand establishment phase of stand development. The main objective was to evaluate the FORECAST model graphically and statistically against field data from two different experiments conducted in young conifer plantations. The first test focused on the first 20-25 years of stand development up to crown closure, a phase of stand dynamics that is not represented in most growth and yield or forest stand development models. FORECAST is capable of simulating the processes of stand initiation during this phase, but the question remains as to how useful it is to have models that accurately represent the early stages of stand development? Is the added model complexity justified by an improved accuracy of representation?

In Chapter 3, the main objective was to test FORECAST using field data obtained from the Blaney Lake Chronosequence study initiated in the early 1980's (Karakatsoulis and Kimmins 1993). The first part of the chapter documents the understory and overstory development over the post-clearcutting 23 years. Stand development patterns documented in the early measurements were significantly affected by the ingress of conifer and deciduous tree species. In particular, the total biomass and mean diameter of planted Douglas-fir were variably reduced in the presence of ingress with the degree of impact dependent on the timing and density of recruitment. The natural regeneration changed the stand composition, creating a mixed Douglas-fir - hemlock stand with smaller components of redcedar and red alder. While the hygric sites always had the highest growth rates, there was no consistent trend of increased growth of the planted Douglas-fir from xeric to hygric. This is interpreted as reflecting the assart period of increased nutrient availability and a lower level of moisture competition than later in the life of the stand. The variable ingress of natural regeneration further blurred expected patterns of growth of the planted trees across the moisture gradient. The anticipated differences in productivity among the three SMR classes are expected to develop and increase with time, but the anticipated growth of a monoculture Douglas-fir stand is not expected to be achieved due to the higher percentage of naturally regenerated hemlock on xeric and mesic sites and a higher

component of redcedar on the hygic sites. An important outcome of the study was the documentation of the “window of opportunity” for natural regeneration and the several cohorts that were established. This is interpreted to reflect differences in seed availability and perhaps microclimate for germinant establishment.

The importance of the natural regeneration was further explored in a virtual factorial experiment using the FORECAST model. Specifically, the potential competitive impact from hemlock ingress on the growth of a hypothetical Douglas-fir plantation was simulated for a range of densities of naturally regenerated hemlock establishing at different times since planting. The simulations were made using the same Blaney Lake data set and the results provided evidence that both the time and density of hemlock ingress are important factors for determining its long-term impact on the growth of the planted Douglas-fir.

The biggest challenge to such a modeling effort is to be able to accurately represent the growth of crop trees in the face of minor vegetation competition and tree natural regeneration. FORECAST was calibrated for the CWHdm subzone and the three SMR classes were simulated individually, including the minor vegetation development and the observed recruitment of tree natural regeneration. The model outputs were then compared with the field results using visual (graphical) and statistical techniques. The model results were generally in the range of the field-measured or estimated data values with best predictions for biomass and height and reasonably accurate estimations of diameter with the exception of the prediction of crop tree diameter when growing with extreme minor vegetation competition. The poor prediction of diameter in this case was the result of the fact the model does not work well for predicting diameters of small trees. The method of DBH calculation employed in the model (see Section 3.4.3) restricts its effectiveness to trees of a minimum size (usually 10 to 15 years old depending on species and growing conditions).

In Chapter 4 the ability of the model to project the impact of minor vegetation on tree growth was assessed for Douglas-fir and western hemlock using data from the long-term Vegetation Competition (VC) Plots. The modeling exercise for the VC experiment differed from the Blaney Lake by the fact that the organic soil layer was completely removed, which provided an improved seedbed for the shrubs and natural regeneration of tree species. Also, the simulations had to accommodate a more diverse range of competitive environments at stand establishment than in the Blaney Lake simulations. The general conclusion is that the model predicts most of the variables at a reasonable level of accuracy. Both the visual and statistical comparisons

provided evidence of a good fit between model and real data. The particularities of the selected three treatments were also captured by the model. As mentioned before, the diameter representation for young ages and small suppressed trees is problematical because of the limitations of the DBH equation employed in FORECAST.

Comparing the FORECAST model behavior between the two experiments, it can be concluded that the model is capable of simulating stand development both on sites with an undisturbed soil organic layer (Blaney) and on sites with a missing organic layer (VC). Overall, the model performed better for the Blaney Lake site. The strong effect of the naturally regenerated hemlock on the Blaney sites was well simulated by FORECAST; the model produced outputs close to reality. Although the complex effect of the competing vegetation is difficult to simulate, the model outputs demonstrated the model's capability to accurately represent overstory and understory competition even at such a small scale as the VC plots.

In terms of model usefulness in representing the early phase of stand development in much more detail than is achieved in most models, the arguments can be pro. and con. In intensively managed plantations competition from both minor vegetation and non-crop trees is controlled, so their representation in a stand model may be unimportant. In extensive forestry where weeds and stand density and composition are not managed, representation of crop-non crop plant species interactions may be important. However, the complexities of seedbeds, seed sources, rhizomatous/coppicing/sprouting species and the temporal and spatial diversity of these factors can be used to argue that the time and data costs involved in modeling this phase of stand development are not justified by the improvement in rotation-length accuracy. Forest ecosystems are complex and forecasts of the effects of early stand development pathways on rotation length growth and yield may be blurred by stochastic physical events and the dominant effect of soil and inherent site productivity. This, however, is a timber-centric perspective. Forests today must be managed for multiple values, and the biodiversity, wildlife, aesthetic and hydrological implications of early plantation establishment pathways can be very important. Models are needed that can examine the consequences of early stand establishment for these and other values, as well as timber values.

In a management system where the availability of both financial and human resources is not an issue and timber is the key value, simple tree population models may be quite adequate for the evaluation of the impact of alternative stand management scenarios. In contrast, in a more complex management system, where the natural and human resources are limited, the capability

to project both long term and short term effects of alternative stand establishment pathways is becoming critical (Seely et al. 2007). With a widespread lack of field experience over appropriate time scales for many of the contemporary silvicultural systems and with uncertainty related to anticipated climate change and natural disturbances, the need for complex modeling tools that are capable of representing key ecosystem processes at different levels of complexity is increasing. These complex models appear to be better equipped for today's management challenges than the models driven by empirical relationships (Korzukhin et al. 1996). This suggests that complex ecosystem models are becoming increasingly appropriate for decision support in forest management.

In terms of model applicability, FORECAST is certainly well equipped to be used as a forecasting tool in plantation management. This study presented several simulation exercises in which the FORECAST model successfully represented how planted conifers responded to different levels of competition and site productivity. Every year, a substantial amount of money is spent in BC and elsewhere to improve the methodologies of predicting conifer growth and yield associated with vegetation management. The shortcomings of competition indices suggests the need for simulation tools that can be used to relate the anticipated yield to specific levels of competition and to predict treatment cost/benefits (Walstad and Kuch 1987). The two major concepts in vegetation management, adapted from the agriculture, are the injury level ("the lowest density or size of a competing population that will cause economic damage" (Poston et al. 1983)) and the economic threshold ("the level of competing populations at which control measures should be initiated" (Stern et al. 1959)). Both concepts are based on the hypothesis that the degree of crop damage is directly related to the size or density of the competing population affecting it (Walstad and Kuch 1987). Thus, a tool that can predict both crop and competing species growth and development offers a great benefit to planning the management of competing vegetation. This study showed that the FORECAST model is capable of doing this at a level of accuracy necessary for vegetation management and can also extend our understanding of crop-non-crop vegetation interactions and consequences. By using FORECAST, managers should be able to evaluate various outcomes for multiple scenarios that can be simulated following the procedures described here for Blaney Lake Chronosequence and Vegetation Competition plots as well as in the simulated factorial experiment. FORECAST's capabilities enable users to compare multiple anticipated consequences of different scenarios,

and to identify the injury levels and the economic thresholds for a plantation influenced by non-crop vegetation.

The results presented here provide evidence of the usefulness of the ecosystem model FORECAST in projecting the development and growth of young conifer plantations in the CWHdm biogeoclimatical subzone. This study increases confidence in the FORECAST model for application in young stands. However, it must be emphasized again that the accuracy of model performances will reflect the availability of appropriate calibration data sets. An additional factor in model performance, one that is ignored in most other models, is the definition of the state of the ecosystem at the start of the simulation (the ECOSTATE file in the case of FORECAST). In my study the ECOSTATE file was prepared to reflect the known history of the study sites. The good performance of the model gives confidence in the ability of the model to do this. Experiments with changing the ECOSTATE file to represent a different history have produced very different results that do not accurately mimic the field data.

The performance of FORECAST has now been established in several studies. This provides confidence in the use of this model as the driver of landscape-level simulations. POSSIBLE FOREST FUTURES (PFF), a watershed-scale, multi-value, ecosystem management simulator already in an advanced stage of development. It extends FORECAST's capabilities at the level of a small watershed, and preliminary evaluations of PFF are to be conducted soon. Such a model at the appropriate spatial, temporal and complexity scales, could provide one of the best ways to forecast possible forest futures (Seely et al. 1999; Kimmins et al. 2001).

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APPENDIX 1

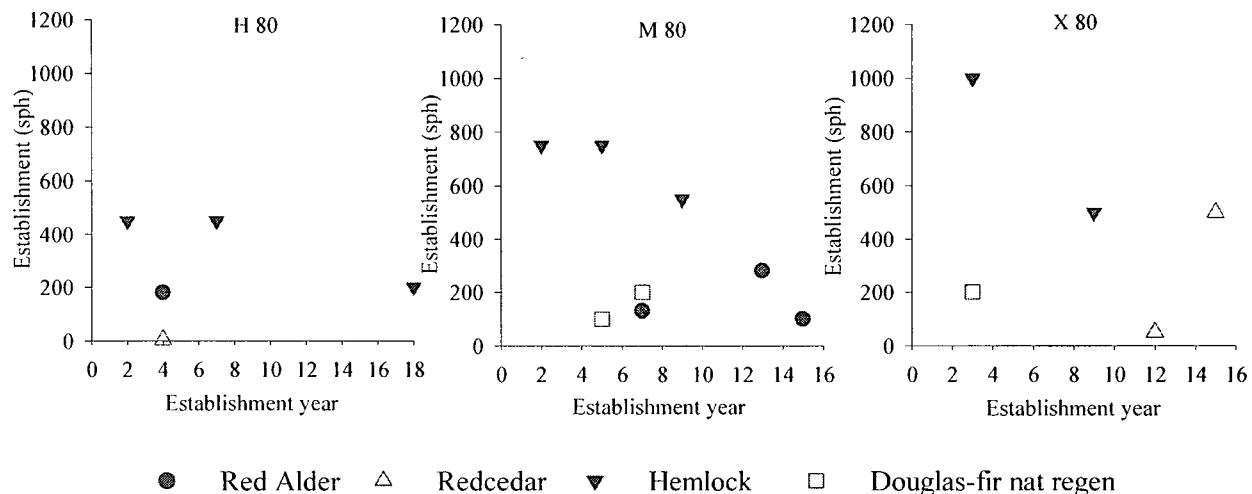


Fig A 1.1 Actual densities of the natural regenerated species represented relative to the year of establishment on each age-SMR combination on 1980 clearcut.

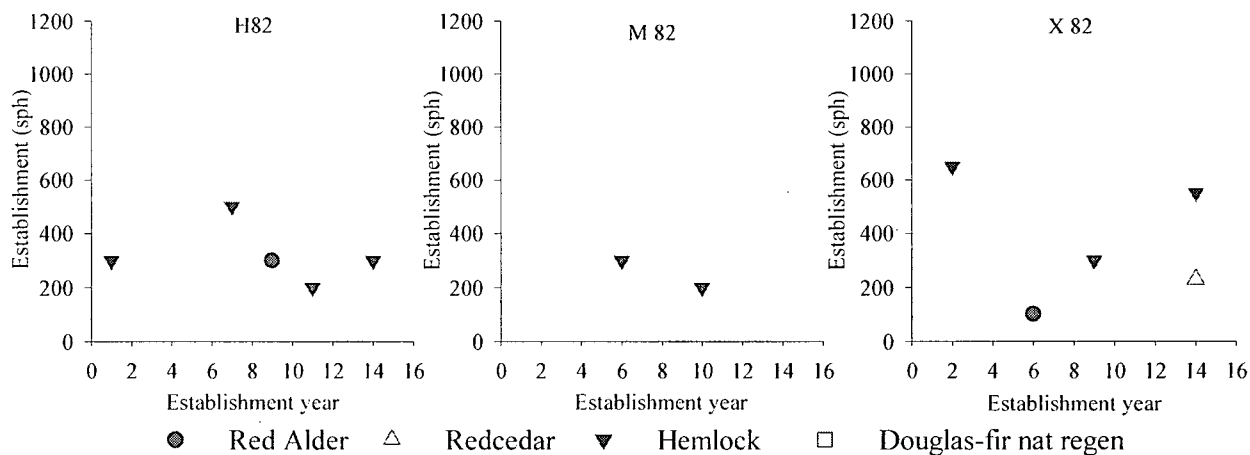
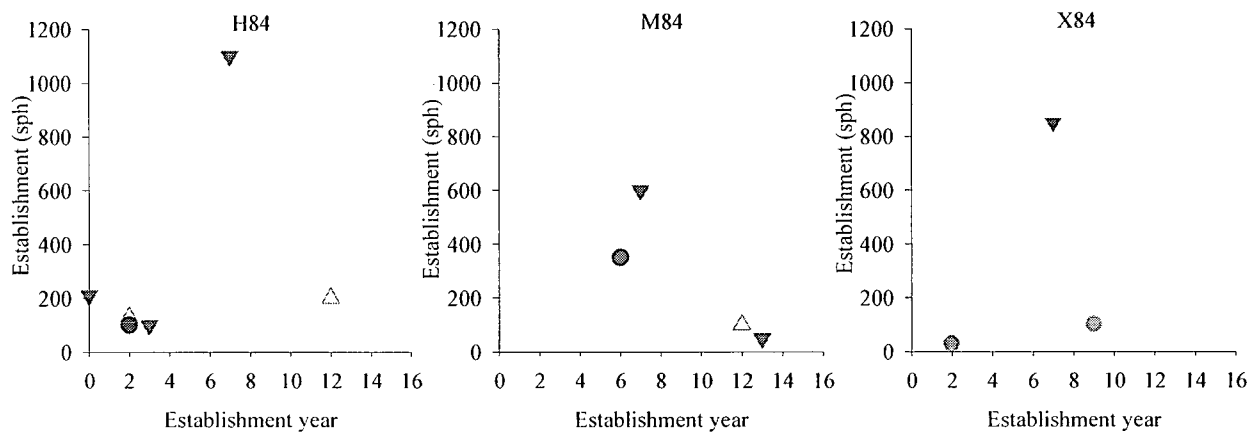
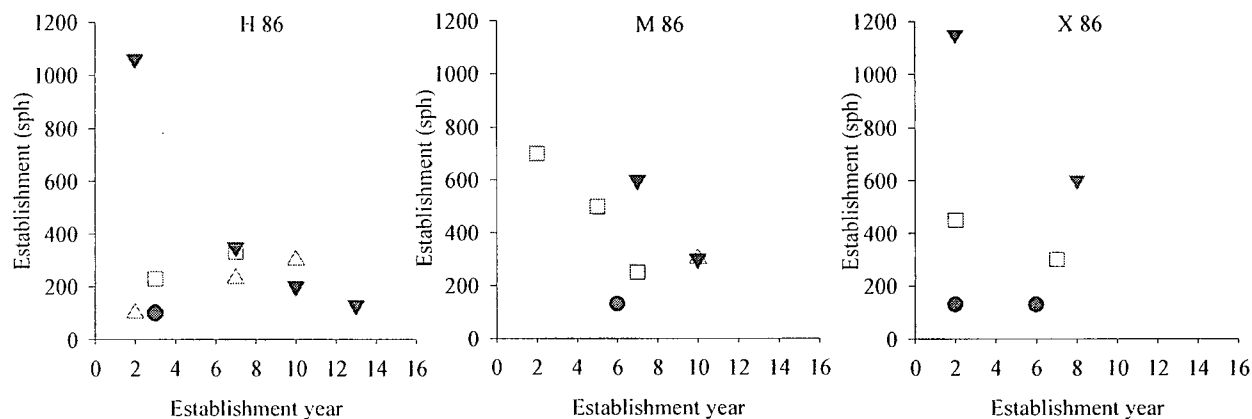


Fig A 1.2 Actual densities of the natural regenerated species represented relative to the year of establishment on each age-SMR combination on 1982 clearcut.



● Red Alder △ Redcedar ▼ Hemlock □ Douglas-fir nat regen
Fig A 1.3 Actual densities of the natural regenerated species represented relative to the year of emergence on each age-SMR combination on 1984 clearcut.



● Red Alder △ Redcedar ▼ Hemlock □ Douglas-fir nat regen
Fig A 1.4 Actual densities of the natural regenerated species represented relative to the year of establishment on each age-SMR combination on 1986 clearcut.

APPENDIX 2

Table A 2.1 Non-crop vegetation species measured on the Blaney study area by John Karakatsoulis (1993). The bolded species were also identified in the 2003 measurements and have the mentioned variables measured. All nomenclature follows Klinka et al. (1989).

Nr	Species	Common name
1	<i>Acer circinatum</i>	vine maple
2	<i>Acer macrophyllum</i>	bigleaf maple
3	<i>Alnus rubra</i>	red alder
4	<i>Anaphalis margaritacea</i>	pearly everlasting
5	<i>Athyrium filix-femina</i>	lady fern
6	<i>Betula papyrifera</i>	paper birch
7	<i>Blechnum spicant</i>	deer fern
8	<i>Carex sp.</i>	sedges
9	<i>Cornus canadensis</i>	bunchberry
10	<i>Dryopteris expansa</i>	spiny wood fern
11	<i>Epilobium angustifolium</i>	fireweed
12	<i>Gaultheria shallon</i>	salal
13	<i>Juncus sp.</i>	rush
14	<i>Polystichum munitum</i>	sword fern
15	<i>Populus trichocarpa</i>	cottonwood
16	<i>Prunus emarginata</i>	bitter cherry
17	<i>Pteridium aquilinum</i>	bracken fern
18	<i>Ribes sanguineum</i>	red-flowering currant
19	<i>Rubus leucodermis</i>	black raspberry
20	<i>Rubus parviflorus</i>	thimbleberry
21	<i>Rubus spectabilis</i>	salmonberry
22	<i>Rubus ursinus</i>	trailing blackberry
23	<i>Salix sp.</i>	willow
24	<i>Sambucus racemosa</i>	red elderberry
25	<i>Senecio vulgare</i>	common groundsel
26	<i>Solidago canadensis</i>	goldenrod
27	<i>Tiarella trifoliata</i>	three-leaved foamflower
28	<i>Vaccinium parvifolium</i>	red huckleberry