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An Overview of North American Forest Modeling Approaches and Technology and their Potential Application to Australian Native Forest Management

Project PG06-5046: Growth and Yield Modeling and Harvest Scheduling in Uneven-aged Mixed Species Forests

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An overview of North American forest modeling approaches and technology, and their potential application to Australian native forest management

Executive Summary

Forest Modeling Applications in North America and Its Strategic Implications for Australia's Forestry Sector

Since the mid-1990s a national program of Regional Forest Agreements has been implemented across Australia resulting in significant reductions in the area of native forest available for timber production. This has resulted in the need for both rationalization of the timber processing industry and enhanced forest management approaches to maintain a profitable and sustainable forest industry. Part of the management changes have included the development and implementation of advanced forest management planning systems, including tree level growth and yield simulation programs and integrated strategic and tactical planning models.

Much of the Australian resource is uneven-aged mixed species forest that is predominantly managed according to selection harvesting and shelterwood silvicultural systems. The complexity of natural forest management is compounded by environmental, social and economic expectations and restrictions. Computer modeling tools can be used to obtain the maximum sustainable yield, and satisfy multiple and often conflicting sustainable forest management objectives.

This report summarizes findings of a study into forest management modeling systems across North America. An overview and recommendations on natural forest management growth and yield modeling systems and approaches used for addressing the complexities of strategic wood supply forecasting and tactical harvest scheduling is presented.

The strategic importance of forest computer modeling technology on forestry businesses

When forestry planning computer models are appropriately deployed in organizations, they can bring significant tangible and intangible benefits. Tangible benefits include: cost savings, higher revenue through superior product quality and quantity, improved operational efficiency, increased forest productivity, market share and profitability. Intangible benefits include better and increased knowledge about the resource supply capacity and dynamics (volume and product mix over time and space) for both forest managers and stakeholders, better planning (less risk, more informed decisions), potentially better customer service, and improved competitive advantage (changing the company's cost position or transforming product differentiation).

North American Forest Management Issues

It is evident from research of scientific literature and interviews with industry, government and academic institutions that managers of forests on both public and private lands within North America are increasingly required to address more complex forest management planning issues. Likewise, the role of forest modeling technologies has also expanded beyond its traditional fiber supply forecasts to encompass a wide range of strategic issues.

Forest modeling used as the basis of forest management planning decisions has traditionally focused on wood production. On public lands, approaches have addressed often conflicting management objectives between financial goals (wood supply), the environment (wildlife habitat, water and sediment yields, biodiversity) and social needs (recreation, aesthetics). Trade-offs have been achieved by land use zoning and modified silviculture to satisfy stakeholder needs. Now new and more advanced quantitative approaches are being developed to model:

- Sustainability of forest systems from economic, environmental and social viewpoints
- Wildlife habitat (continuity and diversity of forest cover; deadwood retention)
- Uneven-aged mixed species natural forest management
- Natural disturbance events (catastrophic wind and fire events, disease outbreaks)

The application of forest modeling to these broad forestry concerns reflects both the increasing pressure on private and public forest owners to balance economic objectives with environmental and social needs, and also the realization that such technologies can offer new tools to support management decisions. This is quite evident in the way that forestry modeling systems and approaches are utilized throughout North America.

Lessons from North America

An examination of the North American marketplace for forest modeling systems reveals important differences in comparison to Australia, but also offers some potential ways in which Australia might take greater advantage of modeling systems already in use in North America.

(a) Employing Advanced Forest Modeling Systems Developed in North America

It is clear from the availability of high-end models developed in North America that there is no need for development of new products in Australia. Purchasing US and Canadian software and adapting them to local needs is more appropriate than developing local products. Technology developed and available in North America is generally more advanced and extensive than in Australia. The high level of investment by industry, government and universities into forestry modeling research and development reflects the magnitude and economic importance of the forestry sector in the US and Canada.

Historically Australian government agencies developed in-house forest models. Currently every state has developed its own native forest growth and yield modeling system. Since the 1990's Australian agencies have adopted a range of international forest modeling technology, especially for plantation management, as it is a more cost effective option. Australia has benefited from the purchase and adaptation of international software.

The Australian forestry sector should continue its strategy of purchasing these off-the-shelf products and working with developers to integrate specific Australian planning characteristics. Forestry companies can leverage off international software developments which is more cost effective. The software developers are able to provide "off the shelf" products for competitive pricing because of their market share, and also benefit from modeling systems that integrate the collective experience and knowledge of many different agencies involved in the development and use of the software products. Private companies in North America and New Zealand have continued to provide generic and customized products and demonstrated excellent service to forestry management clients in Australia.

Examples of North American software products that could be applied and adapted to Australian needs include:

- USDA Forest Service Forest and Vegetation Simulator - a forest growth and yield simulation model that would provide consistent and advanced modeling framework for native hardwood forest management in Australia.

- Oregon State University and Oregon Department of Forestry's Harvest and Habitat forest estate model - a spatial forest scheduling approach that redefines harvest units to facilitate scheduling spatially heterogeneous native forests, and enables the optimization of multiple objectives while simultaneously satisfying spatial and temporal constraints.

- Transport and roading network optimization technology integrated with forest management harvest schedules

Opportunity also exists for Australian forestry researchers and practitioners (biometricians, growth and yield modelers, and resource analysts) to work collaboratively with North America agencies. For example, developing more accurate and flexible prediction tools for modeling growth and yield in uneven-aged forest structures would be beneficial, particularly for modeling individual tree selection harvesting of perpetually irregular uneven-aged forest structures, or modeling the mosaic of spatial variation in stand structures and associated different silvicultural treatments done simultaneously within uneven-aged stands.

Developing techniques to generate yield tables that enable unrestricted combinations of temporal changes to the type, timing and intensity of silviculture within uneven-aged management units to provide greater flexibility in strategic-tactical level forest estate models, would provide enormous benefits for natural forest yield regulation.

(b) Pro-active Modeling to Meet Sustainability Requirements

Forests are no longer being managed solely for timber, and likewise, forest modeling is no longer solely for predicting wood supply. Modern forest modeling can be used to help meet multiple and often competing objectives. Given the current state of expectations on private and public forestland managers in both Australia and North America, it is prudent to apply modeling programs which can help to support management decisions.

Public and private forest lands in the United States and Canada are being increasingly scrutinized for sustainable forest management that emphasizes economic, environmental and social values. This comes after decades where North American forest managers practiced sustained yield management that prioritized economic values (timber production). Today, forest management objectives and constraints to management naturally vary widely between forest ownership classes; the type, scale and distribution of the resource; local regulatory requirements; and market and economic conditions. Ownership objectives may range from predominantly intensive wood fiber production, accommodating timber commodity and habitat management, to that of emulating natural ecological dynamics of vegetative succession and disturbance events.

Public lands are typically required to address multiple demands in its forest management objectives. This is addressed through land-use zoning of different emphases, spatial arrangements of harvesting, and the appropriate silviculture treatments (types, treatments and timing). For example, over the last decade, national forests in the Pacific Northwest have halted most commercial logging, with private forestlands now providing the bulk of timber harvests. National forests now emphasize non-timber forest services and products. Thus there is a significant difference between how private and public forestlands are managed in the U.S. However, it is probably fair to say that environmental scrutiny of forest management has extended from public forests to private forestlands, so that even commercial enterprises must be prepared to be proactive. Private lands have more rights and are able to make non-consultative land use decisions within guidelines and regulatory measures specified by relevant government agencies, and may make proactive decisions to accommodate trends in social and environmental expectations.

There are several dominant modeling approaches that are well developed to facilitate sustainable forest management that are addressed in this report, including:

- Use of approximation algorithms (heuristics) to enhance multiple objective forest management decision-making
- Wildlife habitat modeling
- Emulation of disturbance events in planning harvest schedules

Multiple objective modeling techniques have been implemented in Australia by explicitly zoning forest areas available for production, habitat and watershed protection and other values. Predetermining the land-use intention as fixed zones rather than addressing dynamic changes in the landscape over time can be far from optimal. Similarly, maximizing the total area without addressing the spatial patterns can be far

less optimal than aggregating contiguous areas covering a smaller total area. Technology exists to better characterize the heterogeneity of natural forests and allocate this to maximize the multiple goals while simultaneously meeting the many spatial and temporal constraints. Consideration of integrated Spatial-Temporal heuristic models with an Area Restriction Model formulation combined with goal programming objective functions, such as those developed by Oregon State University (Harvest and Habitat Model) or by Spatial Planning Systems in Ontario (Patchworks) may offer solutions to improving natural forest management planning.

In Australia, ecosystem preservation and sensitive watersheds have typically been integrated into landscape modeling, but less emphasis has been given to actively modeling the management of wildlife habitat in commercial forest management[1]. North American agencies have developed sophisticated approaches to modeling in both terrestrial and aquatic wildlife habitats as part of the forest management planning process. It is recommended that Australian modelers and researchers evaluate developments and procedures being used throughout North America. This report, which provides an overview of the current state of modeling in North America, can be used as a starting point.

In Ontario, Canada, the natural forest disturbance events are being emulated as part of the forest management plans. This has been a move away from small dispersed harvesting units so that a range of forest seral stages (forest successional stages) are created more along the lines of historical natural disturbance (fire events in boreal forests). This approach to sustainable forest management is unique and may offer a basis to managing natural Australian forestry.

(c) Adaptation of North American modeling to Australia requires modification, especially for Uneven-aged Native Forests

Although Australian eucalypts are quite unique evergreen hardwoods growing in a largely arid climate, there are fundamental similarities in the ecology and silvicultural systems with most pure and mixed species uneven-aged forests elsewhere in the world. Accordingly, it is potentially possible to utilize North American growth and yield modeling systems for these uneven aged forests, with certain caveats.

North American growth and yield simulators address clearcut, seed tree and group selection harvesting systems that are readily applicable to Australian even-aged, two-aged and mesic uneven-aged forests. However, the single tree selection harvesting systems are not readily applicable, as these are based on achieving a theoretical target balanced retained stand structure (negative exponential diameter frequency distribution) and desirable species mix, to provide a sustainable flow of wood products of preferred species over time.

Australian native hardwood forests are commonly uneven-aged and managed with selective harvesting silvicultural systems, but achieving a desirable retained stand structure is rarely sought or achievable. This is attributable to the initial irregular stand structures resulting from historical disturbance events, and native forest silvicultural practices are severely restricted in Australia due to economic, environmental and political (social) restrictions. Pressures have led to removal of the best merchantable and commercial trees in current harvests rather than managing for ideal long-term quality forests.

Application of these North American models to uneven-aged natural forest management is further hindered by the current lack of funds available in Australia (a) to capture the variability in the spatial distribution of stands and (b) to provide detailed inventory as inputs to pre-harvest planning and post harvest monitoring of stand structure and growth. Classification of the forest areas into strata and capturing details on the structure and composition of stands is necessary for modeling future growth, impacts of silviculture, and yield forecasts.

[1] Australia had developed a network of wildlife corridors, conservation reserves, and typically habitat areas of threatened species, riparian buffers and certain ecosystems are treated as harvest exclusion zones. Modified (less intensive) harvesting techniques are required in specific natural forest zones. Regulatory silvicultural restriction indirectly encourage recovery or maintenance of wildlife populations through constraints on forest structure changes (e.g. retention of habitat trees), opening sizes and harvesting patterns within natural forest zoned for wood production.

The technicalities of integrating growth, mortality, and recruitment functions and specifics of the harvesting systems into the models can be addressed. But to effectively adapt and implement the growth and yield model to natural forest management, particularly with the USDA Forest Services' FVS model, three factors will need to be addressed in Australia:

- more data will be required to classify and inventory natural forest stands
- single tree selection harvesting practices will need to be more consistent and priority given to the target retained stand structure to achieve stand level sustainable wood supply
- alternative harvesting models will need to be developed to model irregular forest structures, to reflect factors driving and impeding single tree selection harvesting of uneven-aged forest

(d) Realizing more accurate wood supply forecasts and harvest schedules

Optimization forest harvest scheduling models have become the dominant computer technology used for strategic level forest planning, as they have enabled forest managers to:

- generate repeatable and timely forest planning solutions (harvest schedules) that maximize or minimize goals (financial, volume, non-economic values);
- evaluate impacts of complex policy and planning issues on wood supply and cash flow; and
- build in a multitude of temporal wood supply, operational, financial and area constraints

However, the strategic model scenarios have often been developed to provide optimistic solutions that represent the upper level of forest productive capacity. Increasingly it is recognized that spatial constraints that apply at an operational level need to be considered to ensure that strategic level wood supply forecasts equate to what can actually be harvested on the ground. Spatially explicit forest planning systems such the Remsoft Forest Planning System (Spatial Woodstock and Stanley), Harvest and Habitat Model (Oregon State University), and Patchworks (Spatial Planning Systems in Ontario) all address spatial considerations. Remsoft addresses the problem as a two-stage hierarchical problem using linear programming for the strategic model and heuristics for the tactical model, while Oregon State University and Spatial Planning Systems have developed fully integrated models based on heuristic technology. Both approaches provide the ability to create harvest units (blocking) and address the main suite of spatial and temporal planning restrictions that forest managers are confronted with today.

Adverse risk and random catastrophic events should also be integrated into forest plans to reflect the uncertainty and natural disturbance events that are ever present in forest management. Risk factors include (a) physical risks affecting the volume and quality of timber, such as fire, storms, disease and insects; (b) financial risks affecting the price of inputs (labor, chemicals) and outputs (log products, land transactions);economic risks of tax, interest and exchange rate changes; (c) operational risks such as weather, which affects access and harvestability; and (d) regulatory risks affect land use (permissible harvesting, use of chemicals, road construction, wildlife habitat and other environmental considerations) and sale of products (certification).

In Australia much of the natural forest is state owned and managed without explicitly addressing the above-mentioned risks. Instead, losses are considered to be acceptable and manageable. Historically the magnitude of the wood supply capacity relative to supply commitments has been large so the relevant agencies had a sufficient buffer to account for losses over time and in different locations. However, following the implementation of Regional Forest Agreements (regulatory risk) around the country, the area of forest managed for timber production has declined markedly, reducing the ability to manage losses from physical risks.

North American organizations are continuing to develop sophisticated tools to help predict the risk of potential loss of forest area, and the level and type of damage to the forest condition. The USDA Forest Service has been developing modules that link to the growth and yield models for modeling fire and pest outbreaks. Integrating similar functionality in Australia would have obvious benefits, and it is recommended that forest fire and health researchers in Australia evaluate these with a view to potentially working in a collaborative manner with modeling programmers.

1. Introduction

Background: Challenges to Modeling Natural Forests

In contrast to plantation forests, natural forests are difficult to model because they inherently have more variability. Natural forests are subject to a myriad of variables and exhibit complexity that does not exist in plantation forests. They have inherent variability in tree species diversity, forest structures, successional changes, natural disturbance events, and dynamic interactions between stand elements. Natural forests often have a long and varied history of different forest management and silvicultural interventions. This is particularly true for uneven-aged mixed species forests managed with selection harvest silviculture. Additionally, management of natural forests is often subject to additional restrictions or public expectations which curbs the ability to silviculturally manage these resources in the most effective way to maintain healthy, vigorous and productive forests. For example, management of natural forest in both North America and Australia has changed from a purely long term sustainable yield of wood products to sustainable forest management, which entails managing for a whole range of objectives.

Since the mid 1990s a national program of Regional Forest Agreements has been implemented across Australia resulting in significant reductions in the area of native forest available for timber production. This has resulted in the need for both rationalization of the timber processing industry and enhanced forest management approaches to maintain a profitable and sustainable forest industry. Part of the management changes has included the development and implementation of advanced forest management planning systems, including tree level growth and yield simulation programs and integrated strategic and tactical planning models.

The Australian native forest resource predominantly comprises uneven-aged mixed species forest dominated by the genus Eucalyptus that are evergreen hardwoods. The forests are characterized by high levels of variability in the vertical and spatial structures, and typically comprise a complex mosaic of forest types (each of which has varying mixes of commercial and non-commercial species and variations in species shade tolerance). A wide range of silvicultural treatments are applied to accommodate the variability in the resource, though selection harvesting silvicultural systems are predominantly used across most states. Clearcutting and seed tree retention methods are used for the conversion of older uneven-aged forest into even-aged regrowth (and some plantation) in Tasmania, Victoria's East Gippsland and south-east New South Wales.

In Australia current harvesting operations are driven by wood production targets, and yet appropriate silvicultural practices are often restricted by economics and regulations. There is mounting political pressure in Australia to ban the residual clearcutting operations in natural forest and to convert stands to uneven-aged natural forest. Despite the extensive use of selective harvesting systems, natural forest silvicultural research is limited. Also, implementation of effective uneven-aged forest silviculture has become increasingly difficult as management is subject to increasingly more demanding and stringent political, environmental, and economic restrictions. Even in the absence of these restrictions, disturbances such as catastrophic wildfire events make effective natural forest management difficult. These naturally variable systems pose great challenges for forest planning.

Computer modeling tools can be used to help to maximise wood supply volumes, log product grade and species composition. Conflicting environmental, social, and political demands on forests also dictates the need for sophisticated computer technology. But modeling natural forests is recognized as being an extremely complex science. Modeling temporal and spatial variability is compounded by the often limited historic data on forest composition and stand dynamics, and the long time period required to ascertain the impacts following shifts in applied silviculture or following major natural disturbance events. Modeling natural forests is also hampered by the limited availability of funds for natural forest management inventory and aerial forest stratification and classification of these resources. ***Consequently, the complexity of the resource makes modeling growth and yield predictions and harvest regulation difficult, and limited modeling has been done relative to the more productive and profitable even-aged forest plantations.***

The Strategic Importance of Forest Computer Modeling Technology in Forestry Businesses

When forestry planning computer models are appropriately deployed in organizations, they can bring significant tangible and intangible benefits.

(a) Tangible benefits.

Investment in modeling improves the financial performance of organizations through cost savings, higher revenue through superior product quality and quantity, improved operation efficiency, increased forest productivity, market share and profitability.

(b) Intangible benefits enabled by the modeling technology.

Intangible benefits provided by the computer models on business processes and relationships include better and increased knowledge about the resource supply capacity and dynamics (volume and product mix over time and space) for both forest managers and stakeholders, and therefore better planning (less risk, more informed decisions), potentially better customer service, and improved competitive advantage (changing the company's cost position or transforming product differentiation).

The rapid pace of advancement and adoption of forest models, particularly spatial forest modeling technology, has enhanced and extended forest planning, management, and policy formulation/evaluation capabilities.

The emergence of this forest planning technology has eight main strategic implications for forest management.

- increases the accessibility, level, breadth and speed of critical information that is able to be generated about the resource
- improves forest planning that transforms business processes
- increases operational efficiencies
- increases the degree of internal communication and knowledge sharing with stakeholders (active stakeholder management)
- enhances forest productivity through more appropriate silviculture
- enhances effectiveness of forest management
- enhances value chain - profitability
- impacts the organization's competitive advantage.

Forestry models are abstractions of real world forest systems constructed for a range of forest research and management objectives. The primary focus of most forestry models is to provide quantitative information to facilitate forest management planning and policy decision making.

Specific objectives of forestry models include:

- Forest inventory updating
- Evaluation of silvicultural alternatives
- Forecasts of growth and yield forecast over time
- Harvest scheduling
- Modeling landscape level forest cover, habitat and land-use change over time and space

Models are aimed at providing accurate, consistent (unbiased) and repeatable information that is appropriate to the objectives (end use) of the information. The acceptable and achievable resolution, precision and scale of inputs and outputs required depends on the end-use of the information, together with objectives and constraints on capital and time required for data collection, formulating algorithms and generating and analyzing results.

Modeling the stand dynamics and silviculture of uneven-aged mixed species forests is complex, and creating harvesting schedules that address the forest management goals and constraints generates another layer of complexity to forest management planning. Some of the key complexities of uneven-aged mixed species forests that computer models are developed to emulate include:

- continuous temporal change due to growth, mortality and recruitment in forest stands
- natural vegetation succession is actively occurring so the species composition and structure is changing
- natural disturbance events (e.g. wildfires) vary from minor to catastrophic and vary in extent, intensity, frequency and spatial patterns
- forests are being managed with selective harvesting of commercial species and merchantable trees leaving an imbalance of non-commercial species and unmerchantable trees and an irregular forest structure
- effective silviculture is restricted by economic and regulatory factors (social, environmental) so reducing the productive capacity of the forest
- complex dynamics of uneven-aged forest are compounded by the species composition depending on the species mix, their relative abundance and their respective shade tolerances. (Note: silvicultural treatments are and can be formulated to control /influence this)
- spatial variation. Within short distances the forest structure (and species composition) can change due to site variation, random occurrence of seeds, natural patterns of site disturbance, and historic silvicultural intervention. This necessitates patch-specific silviculture to suit the ecology and to maximize the growth and yield potential of each site.
- spatial constraints on the size and adjacency of harvesting operations within defined periods to disperse harvesting units, and constraints on maintaining suitable aggregate blocks of undisturbed forest or mixes of forest stages for wildlife habitat
- temporal wood flow and financial constraints restricting harvest scheduling options
- multiple demands on sustainable uses of forest (economic, environmental, social)

North American forest managers are facing similar political and economic pressures to improve productivity while maintaining forest aesthetics and health. On private lands the demands are chiefly economic, but there is growing pressure for even private landowners to prove to the public that they are managing forests for non-timber objectives. Not surprisingly, there is a large market in North America for modeling programs which are used by public agencies, private landowners, and academia to meet these multiple land objectives.

The approaches of these programs offer a variety of potential applications in Australia, in spite of the fact that forest types vary considerably both within North America and in contrast to Australia. Even-aged forest silviculture is the more dominant management type used throughout North American forests, particularly the temperate Fir–Pine-Spruce-Hemlock forests of the Pacific North West, Southern pines in South East USA and the Canadian Boreal forest. But uneven-aged silviculture is practiced throughout much of the deciduous hardwood forests of the eastern USA and Canada, and the extensively managed multi-aged rangeland forest of Ponderosa pine in the western USA. Uneven-aged forest management also is better perceived by the public, and many public lands are now managed in this fashion due to political pressure stemming from environmental groups concerned about the ecological sustainability and other non-production forest uses.

The USDA Forest Service research stations and US universities are leaders in uneven-aged forest management research. Examples of current research in the US and Canada include, uneven-aged mixed species deciduous hardwood silviculture on the US southern Appalachian east coast (USDA Forest Service Bent Creek Experimental station in Asheville North Carolina, Universities of Tennessee Forest Resources Research in Oak Ridge and Virginia Polytechnic Institute and State University, and Yale University Eastern Hardwood Forest Research Initiative (southern bottomland hardwood and eastern upland hardwoods), uneven-aged management in pure longleaf pine in south-east US by University of Florida, northern hardwoods silvicultural research of Bartlett experimental stations in New Hampshire White Mountains and by Minstère des Ressources naturelles et de la Faune in Québec Canada.

Project Objective

Evaluate and synthesize information on current systems and approaches used for modeling stand dynamics and silvicultural systems in uneven-aged mixed species forests in North America, and their potential applicability to Australian natural forests.

Objectives

The objectives of the proposed research project at the World Forest Institute are to:

- evaluate and compile information on current systems and approaches used for modeling stand dynamics and silvicultural systems in uneven-aged mixed species forests, and the integration of this into strategic and tactical forest management modeling.

- identify ways to enhance current wood supply forecasting approaches in Australia to address spatial planning constraints and multiple-use objectives of forested land management.

The research will include the specific topics below and will apply to both even-aged and uneven-aged mixed/pure species forest management:

- characteristics of the growth and yield models and how these are utilised in modeling forests with different resource types, for different silvicultural regimes, for different scales (strategic and tactical level), and for different levels of heterogeneity/operation unit size/resolution (e.g. for different spatial patterns of forest types/structure within a harvesting unit)

- computer model technology used for timber supply forecasting and harvest scheduling for different forest resources and at different scales

- how wood and non-wood production related objectives and constraints (including spatial constraints) are modeled. In particular how spatial modeling (adjacency and fragmentation) is conducted to address competing and sometimes conflicting land uses e.g. how to address various fauna habitat requirements in addition to standard wood production and financial demand or production capacity constraints

Outputs and Outcomes

The output from the research is to provide an overview and recommendations on alternative forest management planning systems and approaches used to address the complexities of strategic wood supply forecasting and operation scheduling in uneven-aged mixed species native forests. The techniques will be implemented to:

- improve the quality of information available for strategic forest resource planning, operation scheduling and for the timber processing industry.

- achieve more effective, more profitable and lower risk forest management

- enhance the optimization of the multiple and increasingly stringent, conflicting and competing demands being imposed on the Australian native forest resource

Caveats
The author recognizes that specific features of the Australian forestry sector vary markedly from the North American forestry sector in terms of:

- native forest characteristics (species, stand structure, productivity, age / maturity distribution; ecology – natural succession pathways and disturbance events)
- geographic distribution of forests, proximity relative to population centres, markets and ports
- growing conditions - climatic and edaphic (site)
- forest management issues (socio-political, economic, ecological / environmental, regulatory)
- costs and revenue structures for forest operations, infrastructure and management;
- timber product market and trade conditions
- supply capacity relative to forecast demand for forest and wood products
- relative and absolute contribution to land use and economy
- forest ownership patterns

In addition, Australian forestry organizations have traditionally used a range of international approaches—beyond just North American models—for forest management planning. However, the breadth and depth of research in North America, and the functional applicability of some of these models to Australia still make the North American experience a worthwhile arena to explore.

The author also recognizes that in 2005, Mike McLarin produced a report "Forest Estate Modeling Of Multiple Use Forest Management" in North America as part of a Gottstein Trust funded study tour. The McLarin report reflects the result of interviews conducted with various agencies, corporations and software developers to ascertain their rationale for using certain modeling approaches and products. This report addresses growth and yield modeling, and looks at the range of software developed and why various models or approaches are being used. These two reports are complementary.

This report is aimed at two very different audiences and is structured in two parts. The main body of the report is designed to inform executive, managerial and non-technical forestry professionals, while the appendices are written for technical forestry professionals. The main report outlines salient features of North American forest planning models, trends in model development, and outlines some opportunities for the Australian forestry sector. The appendices provide a detailed overview of the complexities of uneven-aged forests, growth and yield model and the range of forest estate model used for wood supply analyses, operation scheduling and land-use planning.

2. Growth and Yield Modeling

This chapter presents an overview of different growth and yield simulation models available in North America. Characteristics of a potentially suitable growth and yield simulation model and its extensions for visualization and modeling disturbance events are described.

An examination of North American uneven-aged forest growth and yield modeling systems was undertaken with the objective of ascertaining whether there is potential to utilize these models for natural forest management in Australia.

The question of how to evaluate the applicability of a specific model for natural forest management planning in Australia should involve[2]:

- identifying the user needs in Australia in terms of essential and preferred information for forest planning
- examining and comparing model capabilities in North America and identifying features that are not being utilized in Australia
- establishing whether the stand and site data parameters are consistent and available in Australia
- determining whether the existing model algorithm forms and silvicultural/harvesting models represent or can be adapted to represent the ecology and silviculture of Australian natural forests.
- establishing whether the benefits outweigh the costs of data collection, calibration, mode adaptation and implementation of a new modeling system.

2.1. Growth and yield prediction models (simulators)

Growth and yield simulators can be classified in terms of several basic categories:

- Whole Stand Models
- Size Class Models
- Individual Tree Models - distance dependent
- Individual Tree Models - distance independent

An overview of growth and yield simulation model types and reasons for differences are outlined in Appendix 3.

Comprehensive books on growth and yield modeling include Vanclay (1994), Davis et al (2001), von Gadow and Hui (1999), and Hasenauer (2006).

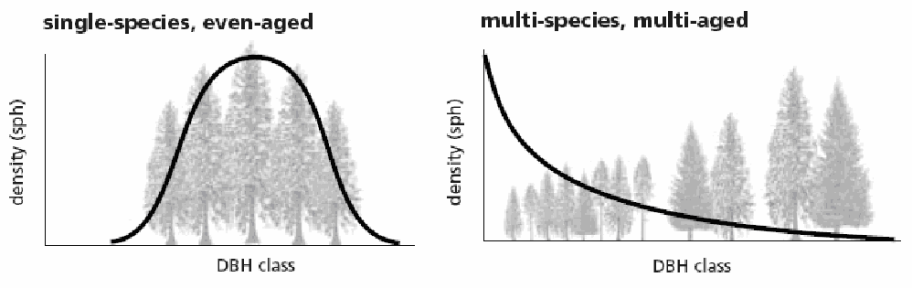
Individual tree models are considered to be more suitable and relevant to uneven-aged native forest being managed with selection harvesting systems. The heterogeneity of uneven-aged forests with irregular stand structures (negative exponential or multi-nodal distribution, Figure 1) and partial cuts in uneven-aged forests are not able to be suitably represented by whole stand models.

[2] Given the author's personal experience in growth and yield model development and application in NSW Australia, but an absence of knowledge about details in other states, a comprehensive evaluation of Australian modeling systems was not undertaken. Rather, characteristics of some of the more comprehensive and potentially suitable growth and yield simulators in North America have been described, and judgments made on the potential applicability of model features to Australia are documented

The findings of the author are supported by Groot et al (2004):

"Multi-cohort forest management planning requires forecasts of the development of stands with complex structure in response to silvicultural treatment and to natural disturbance, but current stand dynamics models in the region are applicable mainly to even-aged mono-specific stands. Possible modelling approaches for complex stands include i) the adaptation of current whole-stand growth and yield models, ii) distance-independent, empirically-derived individual-tree models, such as the USDA Forest Service Forest Vegetation Simulator, and iii) distance-dependent, empirically-derived or process-oriented individual-tree models. We conclude that individual-tree models are needed because observational data for fitting whole-stand models are not available for the full array of silvicultural treatments and natural disturbances encompassed by multi-cohort forest management. Predictive accuracy is a concern with individual-tree models, and the incorporation of coarse-scale constraints into these models is a promising means to control error"

Figure 1: Even and Uneven-Aged Stand Structures



Source: BC Ministry of Forests (2007a)

The following Table 1 lists some of the most common published computer based growth and yield simulators that have been developed in North America. The list is divided by region and major species.

Table 1: North American Growth and Yield Simulators

Growth & Yield Simulators

Model	Description	Model Class	Region of Application	Major Species	Stand Species Composition	Stand Structure & Management	Developer	Web link	Reference
ACORM	**A**merican **C**yanamid **O**ptimal **R**eforestation **M**anager. A growth and yield model for planted loblolly and slash pine in the Piedmont and Coastal plain regions. The software package is designed to provide financial analyses of various site preparation treatments and to evaluate the impact of herbicide applications on loblolly pine plantations.	Stand Level	Southern USA	Loblolly and Slash Pine	Pure species	Even aged	Originally released in 1997 by American Cyanamid.	http://sofew.cfr.msstate.edu/papers/0112carley.pdf	Carley and Grado (1999)
ACORn	ACORn (**A C**omprehensive **O**zark **R**egeneratio**n** simulator) that predicts the number and species of trees that will regenerate following harvest in upland oak stands in the Ozark Highlands of Missouri and adjacent states.	Young stand model	Central States	Upland Oaks	Pure species	Even aged	USDA Forest Service	http://ncrs.fs.fed.us/4154/products/acorn.html http://nrs.fs.fed.us/tools/software/	Dey, Ter-Mikaelian, Johnson and Shifley (1996)
AMORPHYS	AMORPHYS: **A** forest model based on tree **MOR**phology and **PHY**Siology. Forest model designed to estimate the growth and development of trees in an even-aged stand with intensive silviculture and varying climatic and atmospheric conditions. Applicable to loblolly pine plantations in Virginia and North Carolina, natural spruce and fir forests in Maine.	Gap simulator (Successional)	Southern USA; Northeast	Loblolly Pine; Fir	Pure and mixed species	Even aged	U.S. Department of Agriculture Forest Service, Northeastern Research Station	http://eco.wiz.uni-kassel.de/model_db/mdb/amorphys.html	Valentine et al (2000)
ASPEN	A stand level growth and yield simulation model for Circumboreal **Aspen** plantations (Populus tremuloides and P. tremula)	Stand Level	Northeast/Mid Atlantic	Aspen	Pure species	Even aged	University of Minnesota & U.S. Department of Agriculture	http://www.d.umn.edu/~ghost/FMSASPEN.HTM http://nrs.fs.fed.us/tools/software/	Host and Perala (2007) Perala, Leary and Cieszewski (1995)
CACTOS	**CA**lifornia **C**onifer **T**imber **O**utput **S**imulator. Individual tree growth and yield simulator for California mixed conifer types.	Individual Tree Distance Independent	West Coast States	Mixed conifer	Pure and mixed species	Uneven aged	Model developed through public and private industry cooperative (Northern California Forest Yield Cooperative) and are supported by the University of California, Berkeley.	http://www.cnr.berkeley.edu/~wensel/cactos/cactoss.htm	Wensel and Biging (1987)
CalPro	A Spreadsheet **Prog**ram for the Management of **Cal**ifornia Mixed-Conifer Stands. Economic analysis functionality.	Stand Level	California	Mixed Conifer	Mixed species	Uneven aged	University of Wisconsin & USDA Forest Service	http://www.forest.wisc.edu//facstaff/buongiorno/book/CalPro/CalPro.htm http://www.fs.fed.us/pnw/pubs/pnw_gtr619.pdf	Liang, Buongiorno and Monserud. (2004).
CLIMACS	CLIMACS (**C**omputer **L**inked **I**ntegrative **M**odel for **A**ssessing **C**ommunity **S**tructure) is a simulation model of forest succession for western Oregon and Washington. Douglas fir, western hemlock, mountain hemlock, western red cedar, noble fir, Pacific silver fir. Based on FORET (Shugart and West 1977), a succession model for eastern Tennessee, which in turn was modified from JABOWA (Botkin et al 1972), a simulator for forests of the northeastern United States. Simulates successional patterns over long time horizons. Does not simulate growth and yield output such as volume by size class or species, nor the effects of any management activity other than clearcut harvest of trees.	Gap simulator (Successional)	Pacific North West	Douglas fir, western hemlock, mountain hemlock, western red cedar, noble fir, Pacific silver fir.	Pure and mixed species	Even aged	U.S. Department of Agriculture Forest Service, Pacific Northwest Forest and Range Experiment Station Forest Science Department, Oregon State University	www.fs.fed.us/psw/publications/documents/psw_gtr174/psw_gtr174.pdf	Dale and Hemstrom (1984)
Conifers	**C**alifornia and **O**rego**n** **I**nteractive **F**orest **E**cosystem **R**esponse **S**imulator. Young stand model. Individual-**plant** growth and yield simulator for young mixed-conifer stands in southern Oregon and northern California . Conifers provides forecasts for young plantations of single species or mixed-species growing with or without competition from shrubs.	Individual Tree Distance Independent & young stand model	West Coast States	Mixed conifer	Pure and mixed species	Even aged	USDA Forest Service Pacific Southwest Research Station and the California Forest Research Association	http://www.fs.fed.us/psw/programs/ecology_of_western_forests/projects/conifers/	Ritchie (2005)
COPPICE	Simulates growth parameters of northern red oak stump sprouts in southwestern Wisconsin.	Individual Tree Distance Independent	Lake States (WI)	Red oak	Pure Species	Even aged	USDA Forest Service, North Central Forest Experiment Station		Johnson and Rogers (1984)
Cryptos	**C**ooperative **R**edwood **Y**ield **P**roject's **T**imber **O**utput **S**imulator. Individual tree growth and yield simulator for young-growth redwood and Douglas-fir forest stands found in the north coastal region of California.	Individual Tree Distance Independent	West Coast States	Mixed conifer; Redwood and Douglas fir	Mixed species	Uneven aged	Model developed through public and private industry cooperative and are supported by the University of California, Berkeley.	http://www.cnr.berkeley.edu/~wensel/cryptos/crypt.htm	Wensel, Krumland and Meerschaert (1987)
CS-TWIGS	**T**he **W**oodsman's **I**deal **G**rowth Projection **S**ystem. Individual tree regional growth and yield model (DOS program) for forests in the North Central region. Central States (Indiana, Illinois, and Missouri) variant. Includes management and economic analysis components. Adapted to USDA Forest Vegetation Simulator as Central States variant.	Individual Tree Distance Independent	Central States particularly IL, IN, MO	Hardwoods	Pure and mixed species	Even- and uneven aged	USDA Forest Service North Central Forest Experiment Station.	http://nrs.fs.fed.us/tools/software/ http://www.fs.fed.us/fmsc/fvs/variants/cs.php	Miner, Walters and Belli (1988)
DFETAL	Whole stand model that predicts the growth of homogeneous young Douglas-fir plantations less than 20 years old (models average tree in stand) on Coast range of Oregon and Washington. Diagnostic tool for predicting the effects of interspecific competition (hardwoods and shrubs) and vegetation management on growth and yield of the stands.	Stand Level	Pacific North West	Douglas fir	Pure species	Even aged	Oregon State University. No longer supported or distributed.	www.fs.fed.us/psw/publications/documents/psw_gtr174/psw_gtr174.pdf	Opalach et al (1990)
DFIT	DFIT (**D**ouglas-**f**ir **I**nterim **T**ables) is a whole-stand simulator for Douglas-fir in the Pacific Northwest. Coast range of Oregon and Washington. Replaced by DFSIM.	Stand Level	Pacific North West	Douglas fir	Pure species	Even aged	U.S. Department of Agriculture Forest Service. Pacific Northwest Research Station	www.fs.fed.us/psw/publications/documents/psw_gtr174/psw_gtr174.pdf	Bruce, DeMars and Reukema (1977)
DFSIM	DFSIM (**D**ouglas-fir **Sim**ulator) is a managed stand growth and yield simulator for coastal Douglas-fir. A modified version DFSIM WITH ECONOMICS includes an economics option.	Stand Level	West Coast States	Douglas fir	Pure species	Even aged	USDA Forest Service. Pacific Northwest Forest and Range Experiment Station.	http://www.fs.fed.us/pnw/software/DFSIM14/DFSIM.htm	Curtis, Clendenen and DeMars (1981) Fight, Chittester and Clendenen (1984)
EAC	Growth and yield stand level model for the **e**lm-**a**sh-**c**ottonwood uneven-aged forest types in Indiana USA	Stand Level	Central States (IN)	bottomland hardwood (elm-ash-cottonwood)	Pure and mixed species	Uneven aged	U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station.	http://www.treesearch.fs.fed.us/pubs/10739	Shifley, Moser and Brown (1982)
ECONHDWD	A growth and yield model for the **econ**omic assessment of reducing **h**ar**dwood** competition in unthinned loblolly pine plantations.	Stand Level	Southern USA	Loblolly Pine	Pure species	Even aged	Virginia Polytechnic Institute and State University	http://www.fw.vt.edu/g&y_coop/econhdwd.htm	Sprinz, Burkhart, and Amateis (2000)

Growth & Yield Simulators

Model	Description	Model Class	Region of Application	Major Species	Stand Species Composition	Stand Structure & Management	Developer	Web link	Reference
ERGYS	**E**astern **R**egion **G**rowth and **Y**ield **S**imulators (ERGYS) includes GROAK, SILVAH, OAKSIM and TWIGS. Includes economic analysis	Consolidated Model	Central States, Lake States, and Northeast	Hardwoods	Pure and mixed species	Even- and uneven aged	U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station.		Gullet (1986)
FASTLOB	Stand-level growth and yield model for managed (fertilized and selectively thinned) loblolly pine plantations.	Stand Level	Southern USA	Loblolly Pine	Pure species	Even aged	Virginia Polytechnic Institute and State University	http://www.fw.vt.edu/g&y_coop/fastlob.htm	Amateis, Burkhart, Allen and Montes (2001)
FIBER	**F**orest **I**ncrement **B**ased on **E**cological **T**ypes. An individual-tree, distance-independent stand matrix growth and yield model for simulating the management and growth of forest stands in the Northeast USA. Includes the management of even-aged and multi-aged spruce-fir, mixedwood, and northern hardwood stands. FIBER uses a two-state matrix approach to model the dynamics of transition probabilities of growth between diameter classes. A variant is included within NED-SIPS.	Individual Tree Distance Independent	Northeast/Mid Atlantic	Spruce-fir, mixed wood, and northern hardwood stand	Pure and mixed species	Even- and uneven aged	USDA Forest Service Northern Research Station	http://www.treesearch.fs.fed.us/pubs/4321 http://www.treesearch.fs.fed.us/pubs/21776 http://www.fs.fed.us/ne/durham/4104/products/fiber.html	Solomon, Herman and Leak (1995)
FOREGEN	FOREGEN is a stochastic model that simulates **fo**rest **regen**eration in openings in northern hardwood stands that range in size from single-tree openings to clearcuts. The model incorporates the effects of seed development, dispersal, germination, seedbed conditions, advanced regeneration, and weather. The output is species composition of the established regeneration at 3 years after harvest. Provides input to growth simulators.	Young stand model	Northeast USA	Northern Hardwoods	Pure and mixed species	Even aged	U.S. Department of Agriculture Forest Service, Northeastern Research Station	http://www.fs.fed.us/ne/durham/4104/products/regen.html	Solomon and Leak (2002)
FPS	**F**orest **P**rojection and Planning **S**ystem (FPS). Growth and yield model for single and mixed species; even- and uneven-aged stands. Multi-region multi-species growth model. Includes USA and Canadian growth models. 16 regional libraries (Pacific Northwest, Inland Northwest, Western Montana, Northern Interior California, Coastal British Columbia, Interior British Columbia, Alberta & Saskatchewan, Coastal California, Western Oregon, Western Washington, Eastern Washington, Northern Idaho, Eastern Oregon, Northern California, Southeast Alaska, Hawaiian Islands). Each with 8-14 species site, taper, growth, mortality parameters. FPS software includes functions for forest inventory, growth projection, silvicultural planning and long-term harvest scheduling.	Individual Tree Distance-Dependent	USA, Canada	Hardwood and Softwood	Pure and mixed species	Even- and uneven aged	J. Arney, Oregon, USA	http://www.forestbiometrics.com/Software.htm	Milner (1996)
FVS	**F**orest **V**egetation **S**imulator (FVS). Includes uneven- and even-aged forest management for pure and mixed conifer, hardwood and mixed species stands. The simulator is linked to visualization and post-processing software. Most widely applicable model in USA. 20 variants covering all forest regions of the USA. Also applied in BC and Ontario Canada. Formerly called PROGNOSIS. Incorporates earlier models such as STEMS, TWIGS and GENGEM.	Individual Tree Distance Independent	USA	Hardwood and Softwood	Pure and mixed species	Even- and uneven aged	Developed and supported by the USDA Forest Service in cooperation with many universities, public & private contributors.	www.fs.fed.us/fmsc/fvs	Dixon (2007); Stage (1973)
FVS Ontario	Adaptation of the Lakes States variant of USDA Forest Service FVS to the boreal and mixed-wood regions of Ontario. Individual tree, non-spatial growth and yield computer model. Includes growth and management of the most common hardwoods and softwoods of the Great Lakes St. Lawrence region of central Ontario and the forested boreal region of northeast Ontario.	Individual Tree Distance Independent	Ontario	Hardwoods and softwoods	Pure and mixed species	Even- and uneven aged	Joint undertaking between the Canadian Ecology Centre, the Canadian Forest Service-Larentian Forestry Centre, the Ontario Ministry of Natural Resources, Tembec Inc, and ESSA.	http://www.fvsontario.ca/home_index.htm http://www.essa.com/downloads/prognosis/variants.htm	Woods and Parton (Undated)
GaPPS	**G**eorgi**a** **P**ine **P**lantation **S**imulator (GaPPS). Growth and yield of planted loblolly and slash pine in the Piedmont and Coastal Plain regions. System includes a thinning and fertilization algorithm. Includes 4 growth simulators.	Stand Level	Southern USA (Piedmont Upper and Lower Coastal Plain)	Loblolly and Slash Pine	Pure species	Even aged	The University of Georgia Forest Biometrics Consulting	http://www.bugwood.org/acrobat/98018.pdf	Moorhead and Dangerfield (1998) Burgan, Bailey and Brooks (1989)
GENGYM	**Gen**eralized **G**rowth and **Y**ield **M**odel (GENGYM) is a diameter class (deterministic regression) growth and yield model for mixed conifer and ponderosa pine stands in the Southwest United States. This is now represented as an individual tree level model in FVS (Central Rockies variant)	Other	South West USA	Mixed conifer and ponderosa pine	Pure and mixed species	Even- and uneven aged	USDA Forest Service, Rocky Mountain Forest and Range Experiment Station	http://www.fs.fed.us/fmsc/fvs/variants/cr.php	Edminster et al (1991)
G-HAT	**G**rowth of **H**ardwoods **A**fter **T**hinning (G-HAT). A distance independent individual tree growth and yield model for Southern Appalachian mixed hardwood stands following thinning.	Individual Tree Distance Independent	Southern Appalachians	Appalachian mixed hardwood stands; GA,NC,TN,VA	Mixed species	Even aged	Virginia Polytechnic Institute and State University	http://www.fw.vt.edu/g&y_coop/models.htm	Harrison, Burkhart, Burk, and Beck (1986)
GNY	Nova Scotia's **G**rowth **a**nd **Y**ield stand level model for natural unmanaged and managed hardwood and softwood forests.	Stand Level	Nova Scotia	Hardwood and softwood	Pure species	Even aged	Nova Scotia Department of Natural Resources	http://www.gov.ns.ca/natr/forestry/gny2004/growthandyield.htm	Nova Scotia Department of Natural Resources (2006)
GROAK	Whole stand level model for growth and yield of even-aged upland oak stands .	Stand Level	Northeast/Mid Atlantic (IA,IL,IN,KY,MO,OH)	Upland Oaks	Pure species	Even aged	USDA Forest Service	http://ncrs.fs.fed.us/pubs/ch/ch_5_10.pdf http://ncrs.fs.fed.us/pubs/ch/ch_7_05.pdf	Perkey (1986)
GROWPINE	**GRO**w **W**hite **PINE** (GROWPINE) Whole stand level growth and yield model. Unthinned old field white pine plantations of southern and eastern Ohio.	Stand Level	Midwest	White pine (Ohio Plantations)	Pure Species	Even aged	USDA Forest Service	http://ncrs.fs.fed.us/pubs/ch/ch_5_10.pdf http://ncrs.fs.fed.us/pubs/ch/ch_7_05.pdf	Perkey and Wilkins (1989).
G-SPACE	Individual tree / distance dependent model for even-aged pure white fir in northern Sierra Nevada. Possibly ponderosa pine in future.	Individual Tree Distance-Dependent	California	White fir and ponderosa pine	Pure species	Even aged	Department of Environmental Science, University of California, Berkeley	http://www.fs.fed.us/psw/publications/documents/psw_gtr174/psw_gtr174.pdf	Cavallaro, 1988
LPSIM	**L**odgepole **P**ine **Sim**ulator (LPSIM) is a syand level growth and yield simulator for natural even-aged lodgepole pine stands in central Oregon. Growth is allocated by means of a proportional volume growth disaggregation function. No longer any technical support.	Stand Level Disaggregative	Pacific North West	Lodgepole pine	Pure species	Even aged	U.S. Department of Agriculture Forest Service. Pacific Northwest Research Station	www.fs.fed.us/psw/publications/documents/psw_gtr174/psw_gtr174.pdf	Dahms (1983)

Growth & Yield Simulators

Model	Description	Model Class	Region of Application	Major Species	Stand Species Composition	Stand Structure & Management	Developer	Web link	Reference
LS-TWIGS	**T**he **W**oodsman's **I**deal **G**rowth **P**rojection **S**ystem. Individual tree regional growth and yield model (DOS program) for forests in the North Central region. Lake States (Michigan, Minnesota, and Wisconsin) variant. Includes management and economic analysis components. Adapted to USDA Forest Vegetation Simulator as Lake States variant.	Individual Tree Distance Independent	Lake States	Hardwoods	Pure and mixed species	Even- and uneven aged	USDA Forest Service North Central Forest Experiment Station.	http://nrs.fs.fed.us/tools/software/ http://www.fs.fed.us/fmsc/fvs/variants/ls.php	Miner, Walters and Belli (1988)
MGM	The **Mi**xedwood **G**rowth **M**odel (MGM) is a deterministic, distance-independent, individual tree-based stand growth model for Canadian boreal forests. Pure or mixed stands of white spruce, trembling aspen, lodgepole pine and black spruce may be simulated. Regional variants for British Columbia, Alberta, Saskatchewan, and Manitoba. Tree list or stand description.	Individual Tree Distance Independent	Canada	Sw, At, Pl, (Sb).	Pure and mixed species	Even- and uneven aged	University of Alberta Department of Renewable Resources; Government of Alberta; Western Boreal Growth and Yield Association; and Alberta Mixedwood Management Association (MWMA)	http://www.for.gov.bc.ca/hre/gymodels/MGM/index.htm http://www.rr.ualberta.ca/research/mgm/mgm.htm	Huang and Titus (1995)
MSU: Cloblolly Cslash NLongleaf	**M**ississippi **S**tate **U**niversity growth and yield systems include the Cutover Slash Pine Plantation Growth and Yield Model (CSlash), Natural Even-Aged Longleaf Pine Growth and Yield Model (NLongleaf) and Cutover Loblolly Pine Plantation Growth and Yield Model (CLoblolly). Formerly the Cutover Loblolly Plantation Model (MSUGY) is a growth and yield computer program used to illustrate the impacts of thinning on wood production and LEV.	Stand Level Disaggregative	Southern USA	Southern Pines (Slash, Longleaf and Loblolly)	Pure species	Even aged	Mississippi State University Growth and Yield Cooperative	http://fwrc.msstate.edu/software.asp	Matney and Farrar (1992)
NATLOB	Diameter distribution growth and yield model for unthinned **nat**ural stands of **lob**lolly pine. Piedmont and Coastal Plain regions of Virginia and North Carolina.	Stand Level Disaggregative	Southern USA	Loblolly Pine	Pure species	Uneven aged	Virginia Polytechnic Institute and State University	http://www.fw.vt.edu/g&y_coop/natlob.htm	Burk and Burkhart (2001)
NCSU	**N**orth **C**arolina **S**tate **U**niversity managed Loblolly pine plantation growth and yield simulator.	Stand Level	Southern USA	Loblolly pine	Pure species	Even aged	School of Forest Resources, North Carolina State University		Hafley and Buford (1985)
NED-SIPS	NED/SIPS (Stand Inventory Processor and Simulator) is a stand based program for managing forest inventory data and simulating stand growth with FIBER, OAKSIM, SILVAH and NE-TWIGS growth and yield models. Includes an economic analysis routine.	Stand level	Northeast/Mid Atlantic	Hardwoods	Pure and mixed species	Even- and uneven aged	USDA Forest Service Northeastern Forest Experiment Station	http://www.fs.fed.us/ne/burlington/ned/sipshome.htm	Simpson, Kollasch, Twery and Schuler (1996)
NE-TWIGS	**T**he **W**oodsman's **I**deal **G**rowth **P**rojection **S**ystem. Distance-independent individual-tree growth and yield model for hardwoods in the Northeastern United States. Adapted to USDA Forest Vegetation Simulator as Northeast variant. A variant is included within NED-SIPS. Economic analysis functionality.	Individual Tree Distance Independent	Northeast/Mid Atlantic (CT,DE ,KY,MA,MD,ME,NH,NJ, NY,OH,PA,RI,VT,WV)	Hardwoods	Pure and mixed species	Even- and uneven aged	USDA Forest Service Northeastern Forest Experiment Station	http://www.fs.fed.us/fmsc/fvs/variants/ne.php	Hilt and Teck (1989).
NorthPro	A spreadsheet **pro**gram for the management of uneven-aged **North**ern hardwood stands. Economic analysis functionality.	Stand Level	Northeast/Mid Atlantic (Wisconsin and Michigan)	Northern Hardwoods (maple-beech-birch)	Mixed species	Uneven aged	University of Wisconsin & USDA Forest Service	http://www.forest.wisc.edu//facstaff/buongiorno/book/NorthPro/Northpro.htm	Liang et al (2004).
OAKSIM	An individual-tree growth and yield **sim**ulator for managed, even-aged, upland **oak** stands of southern Ohio and eastern Kentucky. A variant is included within NED-SIPS	Individual Tree Distance Independent	Northeast/Mid Atlantic (KY,OH)	Upland oaks	Pure species	Even aged	USDA Forest Service Northeastern Forest Experiment Station	http://www.fs.fed.us/ne/newtown_square/publications/research_papers/pdfs/scanned/OCR/ne_rp562.pdf	Hilt (1985)
ORGANON	**OR**egon **G**rowth **AN**alysis and project**ION**. Individual tree growth and yield model for Pacific North West conifer and hardwood types. Three versions: mixed species, even- and uneven-aged stands of Southwest Oregon with tree ages up to 350 years (SWO version), (2) young-growth (up to 120 years old) Douglas-fir and/or western hemlock even- and uneven-aged stands of Northwest Oregon (NWO version), and (3) young growth even-aged stands of Douglas-fir and/or western hemlock in western Oregon, Washington and British Columbia (SMC version).	Individual Tree Distance Independent	West Coast States	Douglas-fir, Western Hemlock and Hardwood	Pure and mixed species	Even- and uneven aged	Developed at Oregon State University. Supported by public & private industry cooperatives.	http://www.cof.orst.edu/cof/fr/research/organon/	Hann (2006)
PCWTHIN	Whole stand and diameter distribution models for thinned, old field planted loblolly pine in the Virginia Piedmont and Coastal Plain regions.	Stand Level	Southern USA	Loblolly Pine	Pure species	Even aged	Virginia Polytechnic Institute and State University	http://www.fw.vt.edu/g&y_coop/pcwthin.htm	Cao, Burkhart and Lemin (2001)
PPSIM	**P**onderosa **P**ine Managed-Yield **SIM**ulator (PPSIM) is a whole stand growth model that simulates yields of natural and managed ponderosa pine stands	Stand Level	Pacific North West	Ponderosa pine	Pure species	Even aged	U.S. Department of Agriculture Forest Service. Pacific Northwest Research Station.	www.fs.fed.us/psw/publications/documents/psw_gtr174/psw_gtr174.pdf	DeMars and Barrett (1987)
PPYMOD	**P**onderosa **P**ine **Y**ield **M**odel. This variable density yield tables, now a spreadsheet version, provide yields for unthinned ponderosa pine plantations in the southern Cascades and northern Sierra Nevada ranges of California	Stand Level	Pacific North West	Ponderosa pine	Pure species	Even aged	U.S. Department of Agriculture Forest Service. Pacific Southwest Research Station.	www.fs.fed.us/psw/publications/documents/psw_gtr174/psw_gtr174.pdf http://www.fs.fed.us/psw/programs/ecology_of_western_forests/projects/growth_yield/simulation_ppymod.shtml	Oliver and Powers (1978)
Prognosis BC	PrognosisBC is an adaptation of the U.S. Forest Service Forest Vegetation Simulator (FVS) Northern Idaho (NI) variant, for southern and central British Columbia (BC or Southern Interior Variant). Individual tree growth and yield model for uneven- and even-aged forest management of pure and mixed conifer, hardwood and mixed species stands. Applicable to the Interior Douglas-Fir(IDF) and the Interior Cedar Hemlock (ICH) biogeoclimatic zones. Proposed to include the northern Sub-Boreal Spruce and Sub-Boreal Pine-Spruce (SBS/SBPS) biogeoclimatic zone. Enables partial cutting in complex stands; pest and habitat models available.	Individual Tree Distance Independent	British Columbia	Pw, Lw, Fd, Bg, Hw, Cw, Pl, Se, Py, Hm.	Pure and mixed species	Even- and uneven aged	BC Ministry of Forests Research Branch, University of British Columbia	http://www.for.gov.bc.ca/hre/gymodels/progbc/index.htm	Robinson (2000)
PSME	PSME is a stand level growth model that simulates the development of plantation Douglas fir stands with mixed evergreen species, up to age 10. Applicable to Coast range of southern Oregon.	Stand Level	Pacific North West	Douglas fir	Pure species	Even aged	Oregon State University.	www.fs.fed.us/psw/publications/documents/psw_gtr174/psw_gtr174.pdf	Harrington et al (1991)

Growth & Yield Simulators

Model	Description	Model Class	Region of Application	Major Species	Stand Species Composition	Stand Structure & Management	Developer	Web link	Reference
PTAEDA2	Southern region-wide individual tree growth and yield of planted loblolly pine on cutover, site-prepared areas. Program includes a thinning and fertilization algorithm This is a distance-dependent model that simulates the growth of loblolly pine plantations. PTAEDA2 has been linked to MAESTRO, a biological process model that refines timber production estimates from PTAEDA2 and provides process outcomes.	Individual Tree Distance-Dependent	Southern USA	Loblolly Pine	Pure species	Even aged	Virginia Polytechnic Institute and State University	http://www.fw.vt.edu/g&y_coop/models.htm	Burkhart et al. (2001)
PTAEDA3.1	Simulation of Individual Tree Growth, Stand Development and Economic Evaluation in Loblolly Pine Plantations.	Individual Tree Distance-Dependent	Southern USA	Loblolly Pine	Pure species	Even aged	Virginia Polytechnic Institute and State University	http://www.fw.vt.edu/g&y_coop/models.htm	Burkhart et al. (2004)
RP2005	Red Pine growth and yield projection (spreadsheet) model for even-aged stands in the Lake States. Includes economic analysis.	Stand level	Lake States	Red Pine	Pure species	Even aged	U.S. Department of Agriculture Forest Service. Northern Research Station.	http://ncrs.fs.fed.us/pubs/viewpub.asp?key=9031	Buckman et al (2006)
RPGrow$	Spreadsheet that projects stand-level growth and yield with financial analysis of red pine plantations in the Lake States.	Stand Level	Lake States	Red Pine	Pure species	Even aged	USDA Forest Service	http://www.ncrs.fs.fed.us/epubs/gtr156.html http://ncrs.fs.fed.us/pubs/qtr/other/qtr_nc156.html	Hyldahl and Grossman (1993)
RVMM	**R**egional **V**egetation **M**anagement **M**odel. Individual tree-level and stand-level predictions of growth and yield for young stands Douglas-fir and associated vegetation species in the Coast Range and Cascade Mountains of Oregon and Washington.	Individual Tree Distance Independent & Stand Level Disaggregative & Young Stand Model	West Coast States	Douglas fir	Pure species	Even aged	USDA Forest Service and Oregon State University	http://www.cof.orst.edu/cof/fr/research/organon/rvmm/rvmm_idx.htm	Shula, Knowe and Radosevich (1998)
S1988f	Growth and yield of mid-rotation fertilization of planted slash pine.	Individual Tree Distance Independent	Southern USA	Slash Pine	Pure species	Even aged	Developed at The University of Georgia in cooperation with The University of Florida.	http://www.forestry.caf.wvu.edu/jBrooks/	Burgan, Brooks and Bailey (1988)
SE-TWIGS	**T**he **W**oodsman's **I**deal **G**rowth **P**rojection **S**ystem. Individual tree regional growth and yield system for southern conifers and hardwoods.	Individual Tree Distance Independent	Southern USA	Southern Pines & hardwoods	Pure and mixed species	Even- and uneven aged	USDA Forest Service. Currently being incorporated in the USDA Forest Vegetation Simulator.		Meldahl and Bolton (1989, 1990, 1990b)
SILVA	Silva is a gap simulation model using climatic and adaphic factors. Developed to examine SO2 effects Sierra Nevada forest composition and included a stochastic fire frequency model. Based on JABOWA model (Botkin et al 1972). Growth is deterministic. Mortality and recruitment are stochastic. No silvicultural systems or yield outputs for forest management decision support.	Gap simulator (Successional)	California	Ponderosa pine and mixed conifer	Pure and mixed species	N/A	Lawrence Livermore National Lab. University of California	www.fs.fed.us/psw/publications/documents/psw_gtr174/psw_gtr174.pdf http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=6529437	Kercher and Axelrod (1984)
SILVAH	**SILV**iculture of **A**llegheny **H**ardwoods (SILVAH) is a stand level growth and yield simulator for Allegheny and Northern hardwood stands of the Allegheny Plateau and Allegheny Mountain region. Version 5.5 includes analysis and prescriptions for oak ecosystems. A SILVAH variant is included within NED-SIPS.	Stand table projection	Northeast/Mid Atlantic (PA, NY)	Allegheny hardwoods (cherry, maple, oak)	Pure and mixed species	Even- and uneven aged	USDA Forest Service Northeastern Forest Experiment Station	http://www.fs.fed.us/ne/warren/silvah.htm	Marquis and Ernst (1992)
SLPSS	**S**hort**L**eaf **P**ine **S**tand **S**imulator (SLPSS). Individual tree growth model for natural shortleaf pine in western Arkansas and eastern Oklahoma	Individual Tree Distance Independent	Southern USA	Shortleaf Pine	Pure species	Uneven aged	Developed from a cooperative study by Oklahoma State University, US Forest Service Southern station, and the Quachita and Ozark National Forests.	http://ncrs.fs.fed.us/pubs/qtr/other/qtr_nc212/qtr_nc212bs.pdf	Huebschmann, Lynch, and Murphy (1998)
SORTIE	SORTIE-ND (SORTIE neighborhood dynamics) is a spatially explicit individual tree, stochastic, growth model that simulates forest stand dynamics in natural and managed ecosystem. It is a system designed to designed to understand investigate the interactions between trees and the environment. Originally developed for Northwest Connecticut hardwood forests but applied in Canada and internationally.	Gap simulator (Successional)	NorthEast USA; Canada	Hardwood	Pure and mixed species	Even- and uneven aged	Institute of Ecosystem Studies, NY	http://www.sortie-nd.org/ http://www.sciencemag.org/feature/data/deutschman/forest_model.htm http://www.wiz.uni-kassel.de/model_db/mdb/sortie.html	Pacala et al (1993)
SOS	**S**imulation **O**f **S**tands (SOS) is a whole-stand growth and yield model developed for even-aged Douglas-fir stands in the inland Northwest USA (northern Idaho, Montana, central Idaho, northeast Oregon, central and northeast Washington).	Stand Level	Inland Northwest USA	Douglas fir	Pure species	Even aged	Department of Forest Resources University of Idaho and Potlatch Corporation	www.fs.fed.us/psw/publications/documents/psw_gtr174/psw_gtr174.pdf	Zhang, Moore and Newberry (1993)
SouthPro	Microsoft spreadsheet **pro**gram that simulates the management, growth, and yield of uneven-aged loblolly pine stands in the **South**ern United States. Economic analysis functionality.	Stand Level	Southern USA	Loblolly Pine (softwoods plus soft and hard hardwoods)	Pure and mixed species	Uneven aged	University of Wisconsin & USDA Forest Service	http://www.forest.wisc.edu//facstaff/buongiorno/book/SouthPro/SouthPro.htm http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr112.pdf	Schulte, Buongiorno, Lin and Skog. (1998)
SPS	**S**tand **P**rojection **S**ystem (SPS). Growth and yield model for single and mixed species; even- and uneven-aged stands. Includes USA and Canadian growth models. (Pacific northwest, inland northwest, western Montana, southwest Oregon/northern California, western British Columbia, interior British Columbia, Alberta, Saskatchewan, Manitoba). Input at variable resolution (stand level averages, stand table or tree list) and generates tree list.	Individual Tree Distance Independent	USA, Canada	Hardwood and Softwood	Pure and mixed species	Even- and uneven aged; Natural and managed stands.	Mason Bruce and Girard Ltd, Portland Oregon	http://www.drsystemsinc.com/Downloads/SPS%20v%204_1%20Overview.pdf http://www.masonbruce.com/	Arney (1985)
STIM, WINSTIM	**S**tand and **T**ree Integrated **M**odel (STIM) is an empirical growth and yield model that integrates a stand-level sub-model with an individual-tree, distance-independent sub-model. Simulates growth for natural and thinned even-aged stands of coastal western hemlock (coastal British Columbia, Washington and Oregon) and trembling aspen (across Canada). Unique dual model architecture Tree list or stand description.	Individual Tree Distance Independent & Stand Level Disaggregative	Pacific North West	Coastal Western Hemlock and Aspen (Hwc, At)	Pure species	Even aged	Canadian Forest Service, Victoria	http://www.for.gov.bc.ca/hre/gymodels/STIM/index.htm	Bonnor, De Jong, Boudewyn and Flewelling (1995)

Growth & Yield Simulators

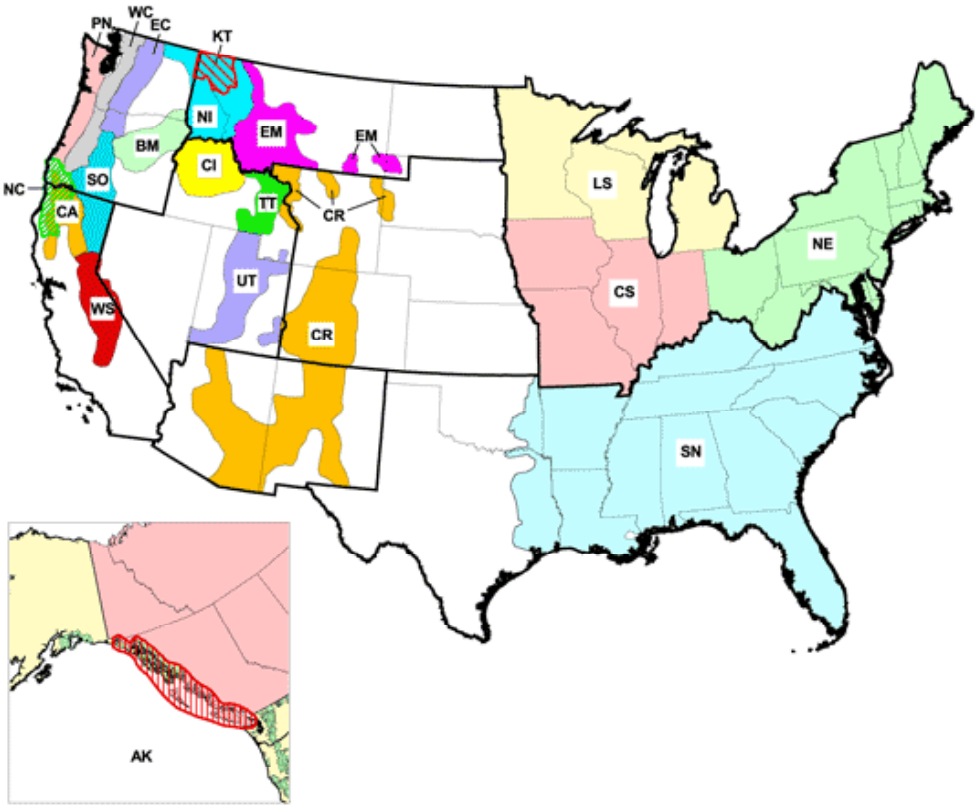
Model	Description	Model Class	Region of Application	Major Species	Stand Species Composition	Stand Structure & Management	Developer	Web link	Reference
SYLVER	A **S**ilviculture practices model that evaluates the impact of **Y**ield, **L**umber **V**alue and **E**conomic **R**eturn. Consists of models that grow stands (TASS), buck logs, saw lumber, grade boards and perform financial analyses. It integrates the yield data from TASS and other sub-systems, and predicts wood quality, product recovery and financial return for various management regimes It is developed in full for coastal Douglas-fir and partially for western hemlock, Sitka spruce, western red cedar, interior Douglas-fir, lodgepole pine and white spruce. Does not predict yield of complex stands (mixed-species and/or uneven-aged stands). Economic analysis based on lumber value.	Individual Tree Distance-Dependent	British Columbia	Interior coastal Douglas-fir, Western Cedar, Sitka Spruce, Lodgepole Pine, White Spruce. Fdc, Fdi, Hwc, Hwi, Ss, Bg, Cw, Pl, Sw	Pure species	Even aged; Natural and managed stands	BC Ministry of Forests Research Branch	http://www.for.gov.bc.ca/hre/gymodels/SYLVER/index.htm	Mitchell and Polsson (1993)
Systum-1	Individual-tree/distance-independent growth and yield simulator developed for use in young plantations (mixed conifer stands) in northern California and southern Oregon. The simulator predicts growth of young plantations up to an age where other simulators can be used. Tree lists created for CACTOS and ORGANON. Prototype model - predecessor to Conifers model.	Individual Tree Distance Independent & young stand model	West Coast States	Mixed conifer	Mixed species	Even aged	USDA Forest Service Pacific Southwest Research Station	http://www.fs.fed.us/psw/programs/ecology_of_western_forests/projects/systum1/	Ritchie and Powers (1993)
TADAM	TADAM (**T**ASS **A**pproximation by a **D**ynamical **A**ggregated **M**odel) is a stand-level growth model fitted to output from TASS for planted stands of Coastal Douglas-fir. Includes growth models for British Columbia Coastal Douglas-fir (TADAM-df), Interior lodgepole pine(TADAM-p), and Interior white spruce (TADAM-s) plantations.	Stand Level	British Columbia	Douglas-fir,lodgepole pine, white spruce	Pure species	Even aged	University of Northern British Columbia	http://forestgrowth.unbc.ca/tadam/	García (2005)
TASS	**T**ree **A**nd **S**tand **S**imulator (TASS). Individual-tree distance-dependent growth and yield simulator for even-aged stands of pure coniferous species of commercial importance in coastal and interior forests of British Columbia. It generates the yield table database for TIPSY and is also the growth and yield model within SYLVER.	Individual Tree Distance-Dependent	British Columbia	Interior coastal Douglas-fir, Western Cedar, Sitka Spruce, Lodgepole Pine, White Spruce. Fdc, Fdi, Hwc, Hwi, Ss, Bg, Cw, Pl, Sw	Pure species	Even aged	BC Ministry of Forests Research Branch	http://www.for.gov.bc.ca/hre/gymodels/TASS/index.htm	Di Lucca (1999)
TAUYIELD	Growth and yield system for thinned and unthinned loblolly pine plantations on cutover, site-prepared lands. Predicts and project whole stand and stand distribution characteristics, and contains financial analysis functionality. Piedmont and Coastal Plain sites across the natural growing range of loblolly pine.	Stand Level	Southern USA	Loblolly Pine	Pure species	Even aged	Virginia Polytechnic Institute and State University	http://www.fw.vt.edu/g&y_coop/tauyield.htm	Amateis, Radtke and Burkhart. (Undated)
TIPSY	**T**able **I**nterpolation **P**rogram for **S**tand **Y**ields (TIPSY) is a growth and yield program that accesses to the managed (natural or planted) forest stand yield tables generated by TASS and SYLVER, interpolates yield tables from the database, customizes and displays information summaries and graphics for a specific site, species and management regime. Does not predict the yield of complex stands (mixed-species and/or uneven-aged stands). Economic analysis function.	Individual Tree Distance Independent	British Columbia	All commercial species. Fdc, Fdi, Hwc, Hwi, Ss, Bg, Cw, Pl, Sw	Pure species	Even aged	BC Ministry of Forests Research Branch	http://www.for.gov.bc.ca/hre/gymodels/TIPSY/index.htm	Di Lucca (1999)
TMS	**T**imberland **M**anagement **S**imulator (TMS). Stand level growth and yield model (web based decision tool) for Loblolly pine plantations on cutover land. Includes thinning options.	Stand Level	Southern USA	Loblolly pine	Pure species	Even aged	Texas Forest Service	http://tfsfrd.tamu.edu/tdss/models/tis.asp	Lenhart (1996) Harrison and Borders (1996)
TREELAB	Stand level growth and yield simulation model for plantation coastal Douglas-fir for young stands (up to age 50). Geographic scope the Douglas-fir belt from central Oregon to southern British Columbia, west of the cascade crest.	Stand Level	Pacific North West	Douglas Fir	Pure species	Even-aged	Stand Management Cooperative, University of Washington	http://www.cfr.washington.edu/research.smc/treelab/Website/TreeLab_home.htm	Pittman and Turnblom (2003)
TRULOB	Individual tree-level growth and yield model for managed loblolly pine plantations (cutover and site-prepared stands)	Individual Tree Distance Independent	Southern USA	Loblolly Pine	Pure species	Even aged	Virginia Polytechnic Institute and State University	http://www.fw.vt.edu/g&y_coop/trulob.htm	Amateis, Burkhart and Zhang (Undated)
VDYP	**V**ariable **D**ensity **Y**ield **P**rediction model. VDYP7 is an empirical growth and yield prediction system for unmanaged natural stands of pure or mixed composition. Predicts average yields and provide forest inventory (CFI) updates over large management areas (Timber Supply Areas, Tree Farm Licenses).	Stand Level	British Columbia	All 32 BC commercial species	Pure and mixed species	Even aged	BC Ministry of Forests Research Branch	http://www.for.gov.bc.ca/hts/vdyp/	BC Ministry of Forests and Range (2007)
WestPro	A spreadsheet **pro**gram for Simulating Uneven-aged Douglas-fir Stand Growth and Yield in the Pacific North**west**. Economic analysis functionality.	Stand Level	Pacific North West	Douglas fir (softwoods plus hardwoods)	Pure and mixed species	Uneven aged	University of Wisconsin & USDA Forest Service	http://www.forest.wisc.edu//facstaff/buongiorno/book/WestPro/WestPro.htm http://www.fs.fed.us/pnw/fia/ear/jfried/programs/westpro/ http://www.fs.fed.us/pnw/pubs/gtr574.pdf	Ralston et. al. (2003)
WestProPlus	A stochastic spreadsheet program for the management of all-Aged Douglas-fir / western hemlock forests in the Pacific Northwest. Economic analysis functionality.	Stand Level	West Coast States	Douglas fir and western Hemlock	Pure and mixed species	Uneven aged	University of Wisconsin & USDA Forest Service	http://www.forest.wisc.edu//facstaff/buongiorno/book/WestProPlus/ http://www.fs.fed.us/pnw/pubs/pnw_gtr674.pdf	Liang, Buongiorno and Monserud. (2006).
WINYIELD	Timber Yield Forecasting and Planning Tool. Forest growth, yield, and financial analysis tool for southern forests. Includes 14 growth simulators.	Stand Level	Southern USA (South-wide, Piedmont, Coastal Plain, Gulf Coast)	Southern Pines	Pure species	Even aged	The Tennessee Valley Authority.	http://www.bugwood.org/acrobat/98018.pdf	Moorhead and Dangerfield (1998) Hepp (1994)
XENO	A distance dependent stand growth model for single or mixed species under both natural and managed stands. Model simulates development of coastal Douglas-fir and western hemlock. Economic analysis capability.	Individual Tree Distance-Dependent	British Columbia	Douglas fir and western Hemlock	Pure and mixed species	Even aged	MacMillan Bloedel Ltd, Nanaimo Canada	http://www.for.gov.bc.ca/hfp/silviculture/OAF1/GYModelstrategy.pdf http://www.for.gov.bc.ca/hfp/publications/00083/sdm-72.htm	Northway (1989)
YIELD	Includes GROAK, a yellow poplar model and models for southern pine	Consolidated Model	Southern States	Hardwoods and Southern Pine	Pure species	Even aged	Tennessee Valley Authority		Hepp (1982)
YIELD-MS	Includes G-HAT, OAKSIM, SILVAH and TWIGS. Includes economic analysis	Consolidated Model	Central States; Appalachian Region.	Hardwoods	Pure and mixed species	Even aged	Tennessee Valley Authority		Hepp (1987)
YPOP	Stand-level growth and yield model for thinned stands of **Y**ellow-**Pop**lar	Stand Level	Southern Appalachians	Yellow-poplar	Pure Species	Even aged	Virginia Polytechnic Institute and State University	http://www.fw.vt.edu/g&y_coop/models.htm	Knoebel, Burkhart and Beck (1986)
ZELIG	Individual tree gap growth simulation model for northern boreal forests of Canada.	Gap simulator (Successional)	Northern Canada	Boreal	Pure and mixed species	Uneven aged	University of Virginia	http://www.daac.ornl.gov/BOREAS/bhs/Models/Zelig.html http://eco.wiz.uni-kassel.de/model_db/mdb/ftpmodels/zelig/	Urban (1990) Liu and Ashton (1995)

2.2. The FVS Model

Of the growth and yield simulators listed above, the Forest Vegetation Simulator (FVS) is the most suitable for modeling uneven-aged native forests in Australia. FVS is an individual-tree, distance-independent growth and yield model developed by the USDA Forest Service. FVS (Prognosis pre 1980's) was originally developed by Dr. Albert R. Stage in the late 1970s (Stage, 1973) and now FVS is continuously developed and maintained by the Forest Management Service Center (FMSC) in Fort Collins, Colorado.

The model has been calibrated for 20 geographic areas across the United States,referred to as model variants (Figure 2). Two variants have also been developed in Canada: PrognosisBC for Southern British Columbia and a variant for the boreal and mixed-wood regions of Ontario (Figure 3).

Figure 2: Geographic Coverage of Forest Vegetation Simulator in USA.



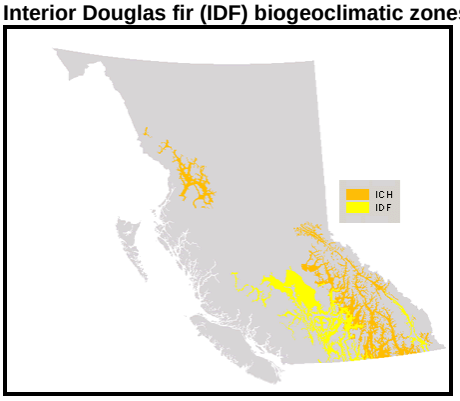
Variant	Code	COV	ESTB	FFE	PPE	DFB	DFTM	DM	MPB	WRD	WSBW
Southeast Alaska and Coastal British Columbia	AK		x					x			
Blue Mountains	BM	x		x	x	x	x	x	x	x	x
Inland California and Southern Cascades (ICASCA)	CA			x							
Central Idaho	CI	x	x	x	x	x		x	x	x	x
Central Rockies	CR			x		x		x	x	x	x
Central States	CS										
East Cascades	EC	x		x		x	x	x	x	x	x
Eastern Montana	EM	x	x	x			x	x	x	x	x
Klamath Mountains	NC	x		x				x			
Kootenai, Kaniksu, and Tally Lake (KooKanTL)	KT	x	x	x	x			x	x	x	x
Lake States	LS			x							
Northeast	NE			x							
Northern Idaho (Inland Empire)	NI	x	x	x	x	x	x	x	x	x	x
Pacific Northwest Coast	PN			x			x	x			x
Southern	SN			x							
South Central Oregon and Northeast California (SORNEC)	SO	x		x	x		x	x	x	x	x
Tetons	TT	x		x		x	x	x	x	x	x
Utah	UT			x		x	x	x	x	x	
Westside Cascades	WC			x				x		x	
Western Sierra Nevada	WS	x		x				x			

Code	FVS Extension
COV	COVER/SHRUBS
ESTB	Regeneration/Establishment
FFE	Fire and Fuels Extension to FVS
PPE	Parallel Processing Extension
DFB	Douglas-fir Beetle
DFTM	Douglas-fir Tussock Moth
DM	Dwarf Mistletoe
MPB	Mountain Pine Beetle
WRD	Western Root Disease
WSBW	Western Spruce Budworm

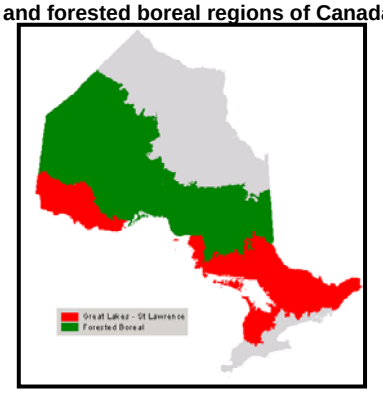
Source: www.fs.fed.us/fmsc/fvs/index.shtml

Figure 3: Geographic coverage of Forest Vegetation Simulator in Canada.

Prognosis^{BC} Interior Cedar Hemlock (ICH) and Interior Douglas fir (IDF) biogeoclimatic zones



FCV^{Ontario} Great Lakes –St Lawrence and forested boreal regions of Canada



Source: www.essa.com/downloads/prognosis/variants/htm

FVS can simulate the growth and yield for a wide range of silvicultural treatments for most major forest tree species, forest types, and stand conditions. The model is designed to simulate even and uneven-aged, pure and mixed-species stand management. The FVS growth and yield model has been extended by a range of modules that simulate the effects of fire, pests, and disease. FVS is also compatible with the Stand Vegetation Simulator (SVS) module that provides 3-dimensional vertical and aerial views of forest stand structures by age or over time.

Silvicultural Systems

FVS has the capacity to model forest development with most silvicultural systems in both even-aged and uneven-aged, single or mixed-species stands:

- Individual tree selection
- Group selection
- Shelterwood
- Seed-Tree
- Clearcut

Figure 4: Examples of Silvicultural Prescriptions Created for FVS

Individual Tree Selection:

```
**************************************************************************
* P_PPpp_IT.kcp --- Rx for PP overstory w/ PP understory: Individual Tree Select
*   - Basal Area Target = 50 Square Feet                                 *
*   - Q-slope to regulate tree frequency per diamter class  = 1.4        *
*   - Diameter of Beginning Class = 2"                                   *
*   - Diameter of Ending Class = 18"                                     *
*   - Diameter Class Increment = 2"                                      *
*   - Number of Legacy Trees = 2                                         *
*   - Average Legacy Tree Diameter = 20"                                 *
*   - Cutting Cycle Length = 20-years                                    *
**************************************************************************
```

Group Selection – Ponderosa Pine:

```
**************************************************************************
* P_PPpp_GS.kcp --- Rx for PP overstory w/ PP understory: Group Selection  *
*   Opening Size: 0.5 acre                                               *
*     - Tallest Tree Height of 110 feet                                  *
*     - Height Multiple of 1.5 times                                     *
*     - Calculation:  ((((110*1.5)/2)**2)*3.141593)/43,560               *
*                     {area of a circle}/{area of an acre}               *
*   Proportional Area: 1/6 or 16.7%                                      *
*     - Harvest Tree Age of 120 years                                    *
*     - Cutting Cycle Length of 20 years                                 *
*     - Calculation: 120/20                                              *
*                    {cutting cycle length}/{harv tree age}              *
*   Small Tree Height Growth Multiplier: Additive Scaled Factor          *
*     - ATOPHT: After-thin average of top 40 tree heights                *
*     - Radius: Opening Size basis                                       *
*     - Calculation:  (Radius*2)/ATOPHT=1; Factor=1.0                    *
*                     (Radius*2)/ATOPHT=2; Factor=1.5                    *
*                     (Radius*2)/ATOPHT=3; Factor=2.0                    *
*   Small Tree Mortality Multiplier: Reduction Scaled Factor             *
*     - ATOPHT: After-thin average of top 40 tree heights                *
*     - Radius: Opening Size based                                       *
*     - Calculation:  (Radius*2)/ATOPHT=1; Factor=1.0                    *
*                     (Radius*2)/ATOPHT=2; Factor=0.9                    *
*                     (Radius*2)/ATOPHT=3; Factor=0.1                    *
*   Group Age 120+/0: Group Select Cut; 9"=< dbh < 99"                   *
*     - Nat. Regen. of 302 TPA of PP 5 yrs after thinning w/ ave. age of 2 yrs *
*   Group Age 30: Precommerial Thin from below to 302 TPA, 0"=< dbh <5"   *
*   Group Age 60: POL Thin from below to 60 BA, 5"=< dbh < 9"            *
*   Group Age 90: Commercial Thin PP to 60 BA, 9"=< dbh < 99"            *
**************************************************************************
```

Shelterwood:

```
**************************************************************************
* P_PPpp_SW.kcp --- Rx for PP overstory w/ PP understory: Shelterwood     *
*   Age 120+/0: Seed Cut to 40 BA                                        *
*     - Nat. Regen. of 150 TPA of PP 5 yrs after thinning w/ ave. age of 2 yrs *
*     - Nat. Regen. of 300 TPA of PP 10 yrs after thinning w/ ave. age of 2 yrs*
*     - Nat. Regen. of 100 TPA of PP pulse w/ 75% surv. following thins  *
*   Age 20: Overstory Removal                                            *
*     - Leave 6 of the largest trees for snags                           *
*   Age 30:  Precommerial Thin from below to 302 TPA, 0"=< dbh <5"       *
*   Age 60:  POL Thin from below to 60 BA, 5"=< dbh <9"                  *
*   Age 90:  Commercial Thin PP to 60 BA, 9"=< dbh                       *
**************************************************************************
```

Seed-Tree:

```
**************************************************************************
* P_PPpp_ST.kcp --- Rx for PP overstory w/ PP understory: Seed-Tree      *
*   Age 120+/0: Seed-Tree Cut to 10 TPA                                  *
*     - Nat. Regen. of 150 TPA of PP 5 yrs after thinning w/ ave. age of 2 yrs *
*     - Nat. Regen. of 300 TPA of PP 10 yrs after thinning w/ ave. age of 2 yrs*
*     - Nat. Regen. of 100 TPA of PP pulse w/ 75% surv. following thins  *
*   Age 30:  Precommerial Thin from below to 302 TPA, 0"=< dbh <5"       *
*   Age 60:  POL Thin from below to 60 BA, 5"=< dbh <9"                  *
*   Age 90:  Commercial Thin PP to 80 BA, 9"=< dbh                       *
**************************************************************************
```

Clearcut:

```
**************************************************************************
* P_PPpp_CC.kcp --- Rx for PP overstory w/ PP understory: Clearcut       *
*   Age 120+/0: Clearcut Cut                                             *
*     - Nat. Regen. of 150 TPA of PP 5 yrs after thinning w/ ave. age of 2 yrs *
*     - Nat. Regen. of 300 TPA of PP 10 yrs after thinning w/ ave. age of 2 yrs*
*     - Nat. Regen. of 100 TPA of PP pulse w/ 75% surv. following thins  *
*   Age 30:  Precommerial Thin from below to 302 TPA, 0"=< dbh <5"       *
*   Age 60:  POL Thin from below to 60 BA, 5"=< dbh                      *
*   Age 90:  Commercial Thin PP to 60 BA, 9"=< dbh                       *
**************************************************************************
```

Source: Vandendriesche (2004)

Outputs

FVS reports variables in two types of tables and files:

(a) biological based variables that affect forest growth and reflect stand conditions of the stockable area
- Stand Composition Table
- Tree and Stand Attributes Table
- Structural Statistics Table
- Reports from the fire, cover, and regeneration establishment extensions

(b) commodity based variables that reflect stand conditions on the total stand area
- Summary Statistics Table,
- Treelist Output file,
- FVSSTAND file
- Stand Visualization file.

FVS generates both stock tables and yield tables with a wide range of user definable attributes. For example:
- Trees per acre and species
- Average diameter
- Average height
- Basal area per acre
- Cubic volume per acre
- Board volume per acre
- Overstorey cover type
- Understorey component
- Habitat structural stage
- Snag counts
- Wildfire hazard
- Insect infestation hazard

Outputs are both tabulated and provided graphically. Stand structures can also be represented visually using the extension SVS.

Figures 5 to 10 illustrate examples of the FVS report outputs.

Figure 5: Example of FVS Stand Composition Report

FOREST VEGETATION SIMULATOR VERSION 6.21 -- INLAND EMPIRE PROGNOSIS RV:10.02.02 10-03-2002 13:47:45

STAND ID: S248112 MGMT ID: NONE SHELTERWOOD PRESCRIPTION FOR THE USER'S MANUAL

STAND COMPOSITION (BASED ON STOCKABLE AREA)

YEAR	STAND ATTRIBUTES	PERCENTILE POINTS IN THE DISTRIBUTION OF STAND ATTRIBUTES BY DBH (DBH IN INCHES) 10	30	50	70	90	100	TOTAL/ACRE OF STAND ATTRIBUTES	DISTRIBUTION OF STAND ATTRIBUTES BY SPECIES AND 3 USER-DEFINED SUBCLASSES
1990	TREES	0.1	0.1	3.2	6.1	8.5	12.7	590. TREES	27.% DF2, 15.% GF2, 15.% GF1, 10.% C2
	VOLUME:								
	TOTAL	5.8	8.0	8.5	9.6	11.5	12.7	1843. CUFT	20.% LP1, 18.% GF1, 18.% L1, 17.% DF1
	MERCH	8.0	8.4	9.5	10.4	11.5	12.7	1214. CUFT	26.% LP1, 23.% L1, 22.% DF1, 8.% GF1
	MERCH	8.0	8.4	9.5	10.4	11.5	12.7	6386. BDFT	26.% L1, 25.% LP1, 21.% DF1, 9.% L2
	REMOVAL	0.1	0.1	0.1	1.2	3.2	10.4	326. TREES	48.% DF2, 28.% GF2, 18.% C2, 4.% L2
	VOLUME:								
	TOTAL	8.0	8.0	9.6	9.6	10.4	10.4	330. CUFT	35.% LP2, 33.% L2, 27.% DF2, 5.% C2
	MERCH	8.0	8.0	9.6	9.6	10.4	10.4	260. CUFT	36.% LP2, 35.% L2, 29.% DF2, 0.% ---
	MERCH	8.0	8.0	9.6	9.6	10.4	10.4	1309. BDFT	44.% L2, 30.% LP2, 26.% DF2, 0.% ---
	RESIDUAL	4.0	5.3	6.2	7.9	9.5	12.7	264. TREES	33.% GF1, 19.% C1, 19.% DF1, 13.% L1
	ACCRETION	5.3	6.2	7.9	9.4	10.9	12.7	92. CUFT/YR	27.% GF1, 22.% DF1, 16.% L1, 12.% LP1
	MORTALITY	6.1	7.9	8.4	9.5	11.5	12.7	15. CUFT/YR	36.% LP1, 32.% L1, 19.% GF1, 10.% DF1

Source: Dixon, 2006

Figure 6: Example of FVS Stand Attributes Report

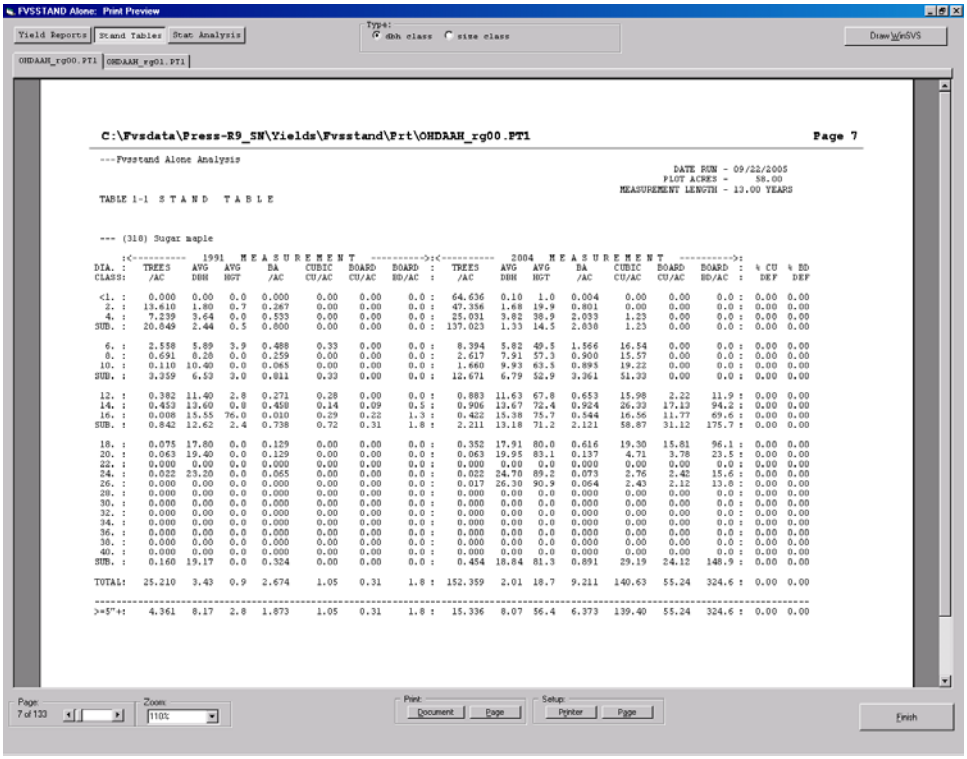
FOREST VEGETATION SIMULATOR VERSION 6.21 -- INLAND EMPIRE PROGNOSIS RV:10.02.02 10-03-2002 13:47:46

STAND ID: S248112 MGMT ID: NONE SHELTERWOOD PRESCRIPTION FOR THE USER'S MANUAL

	ATTRIBUTES OF SELECTED SAMPLE TREES								ADDITIONAL STAND ATTRIBUTES (BASED ON STOCKABLE AREA)					
YEAR	INITIAL TREES/A %TILE	SPECIES	DBH (INCHES)	HEIGHT (FEET)	LIVE CROWN RATIO	PAST DBH GROWTH (INCHES)	BASAL AREA %TILE	TREES PER ACRE	STAND AGE	QUADRATIC MEAN DBH (INCHES)	TREES PER ACRE	BASAL AREA (SQFT/A)	TOP HEIGHT 40/A (FT)	CROWN COMP LARGEST FACTOR
1990						(10 YRS)								
	10	GF2	0.10	3.00	65	0.00	0.0	90.00						
	30	DF2	0.10	2.00	55	0.00	0.0	90.00						
	50	C2	3.20	17.00	45	0.60	3.0	30.00						
	70	GF1	6.10	38.00	75	1.20	24.8	19.71						
	90	LP1	8.50	59.34	25	1.03	62.4	10.15						
	100	DF1	12.70	67.00	35	1.60	100.0	4.55						
									60	5.1	590.	85.	63.4	104.8
									RESIDUAL:	7.0	264.	71.	64.3	88.0

Source: Dixon, 2006

Figure 7: Example of FVS Stand Table Report



Source: Vandendriesche, 2005.

Figure 8: Example of FVS Stand Summary Statistics Report

FOREST VEGETATION SIMULATOR VERSION 6.21 -- INLAND EMPIRE PROGNOSIS RV:10.02.02 10-03-2002 13:47:46

STAND ID: S248112 MGMT ID: NONE SHELTERWOOD PRESCRIPTION FOR THE USER'S MANUAL

SUMMARY STATISTICS (PER ACRE OR STAND BASED ON TOTAL STAND AREA)

	START OF SIMULATION PERIOD								REMOVALS						AFTER TREATMENT						GROWTH THIS PERIOD					
YEAR	AGE	NO OF TREES	BA	SDI	CCF	TOP HT	QMD	TOTAL CU FT	MERCH CU FT	MERCH BD FT	NO OF TREES	TOTAL CU FT	MERCH CU FT	MERCH BD FT	BA	SDI	CCF	TOP HT	RES QMD	PERIOD YEARS	ACCRE PER	MORT YEAR	MAI MERCH CU FT	FOR TYP	SS ZT
1990	60	536	77	164	95	63	5.1	1675	1104	5805	296	300	236	1190	64	132	80	64	7.0	10	84	13	18.4	201	23
2000	70	1188	87	190	104	71	3.7	2079	1570	7870	0	0	0	0	87	190	104	71	3.7	10	108	8	25.8	201	13
2010	80	1686	115	244	133	78	3.5	3085	2561	13048	0	0	0	0	115	244	133	78	3.5	10	126	12	35.0	201	13
2020	90	1094	144	267	160	83	4.9	4232	3661	18365	951	1312	1153	5996	106	180	122	80	11.7	10	116	18	43.3	201	13
2030	100	1511	128	240	140	86	3.9	3894	3406	17248	0	0	0	0	128	240	140	86	3.9	10	138	11	48.0	267	13
2040	110	1739	154	278	165	93	4.0	5160	4563	24179	0	0	0	0	154	278	165	93	4.0	10	151	18	54.1	267	13
2050	120	1085	179	290	186	100	5.5	6489	5852	31929	1053	5041	4514	24478	38	55	33	73	14.9	10	33	7	60.3	267	12
2060	130	1239	44	90	37	68	2.5	1705	1577	9121	22	1705	1577	9121	0	30	1	8	0.3	10	19	0	57.5	201	14
2070	140	1791	16	78	28	35	1.3	195	11	70	0	0	0	0	16	78	28	35	1.3	10	153	0	53.5	201	34
2080	150	1889	90	226	119	59	3.0	1725	823	4261	0	0	0	0	90	226	119	59	3.0	10	251	7	55.4	201	23
2090	160	1419	182	371	216	74	4.8	4165	3126	15565	0	0	0	0	182	371	216	74	4.8	0	0	0	66.9	201	12

Source: Dixon, 2006

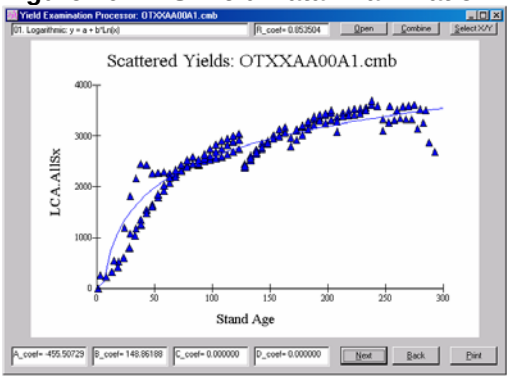
Figure 9: FVS Yield Table (segment)

Yield table OHDB1HA1.yld : Oak-Hickory, Deep Soils – Bottomland, Sawtimber Size Class, High Site Productivity, Shelterwood Silvicultural Treatment, Timing Option 1.

Strata	Proj_Year	St_Age/05	Stand_Age	SiteIndex	StDnIndex	CulmMAI-T	CulmMAI-S	Qd_Mn_Dia	For_Type_	Plt_Acres	Trt_Acres
OHDB1HD1e	2109	21	103.00	77.00	296.00	24.84	17.24	5.03	503.00	15.00	15.00
OHDB1HD1r	2009	1	5.00	77.00	138.00	362.78	272.66	5.90	503.00	15.00	0.00
OHDB1HD1r	2014	2	10.00	77.00	170.00	329.88	262.53	4.11	503.00	15.00	15.00
OHDB1HD1r	2019	3	15.00	77.00	96.00	127.58	97.19	2.84	503.00	15.00	0.00
OHDB1HD1r	2024	4	20.00	77.00	145.00	96.07	72.90	3.68	503.00	15.00	0.00
OHDB1HD1r	2029	5	25.00	77.00	182.00	78.87	58.32	4.31	503.00	15.00	0.00
OHDB1HD1r	2034	6	30.00	77.00	212.00	73.75	48.62	4.96	503.00	15.00	0.00
OHDB1HD1r	2039	7	35.00	77.00	239.00	77.10	41.87	5.62	503.00	15.00	0.00
OHDB1HD1r	2044	8	40.00	77.00	258.00	82.77	36.85	6.29	503.00	15.00	0.00
OHDB1HD1r	2049	9	45.00	77.00	267.00	86.41	33.56	6.98	503.00	15.00	0.00
OHDB1HD1r	2054	10	50.00	77.00	264.00	86.46	31.47	7.71	503.00	15.00	0.00
OHDB1HD1r	2059	11	55.00	77.00	330.00	85.55	31.96	8.45	503.00	15.00	0.00
OHDB1HD1r	2064	12	60.00	77.00	290.00	76.44	33.82	8.61	503.00	15.00	0.00
OHDB1HD1r	2069	13	65.00	77.00	289.00	71.49	36.39	5.91	503.00	15.00	0.00
OHDB1HD1r	2074	14	70.00	77.00	304.00	67.20	38.39	5.82	503.00	15.00	0.00
OHDB1HD1r	2079	15	75.00	77.00	295.00	61.21	38.71	5.96	503.00	15.00	0.00
OHDB1HD1r	2084	16	80.00	77.00	293.00	56.36	38.20	5.35	503.00	15.00	0.00
OHDB1HD1r	2089	17	85.00	77.00	302.00	52.44	37.25	5.30	503.00	15.00	0.00
OHDB1HD1r	2094	18	90.00	77.00	283.00	46.02	33.43	5.22	503.00	15.00	0.00
OHDB1HD1r	2099	19	95.00	77.00	295.00	43.63	32.72	4.94	503.00	15.00	0.00
OHDB1HD1r	2104	20	100.00	77.00	303.00	40.93	31.23	5.00	503.00	15.00	0.00
OHDB1HD1r	2109	21	105.00	77.00	300.00	42.47	32.05	5.17	503.00	15.00	15.00

Source: Vandendriesche, 2005.

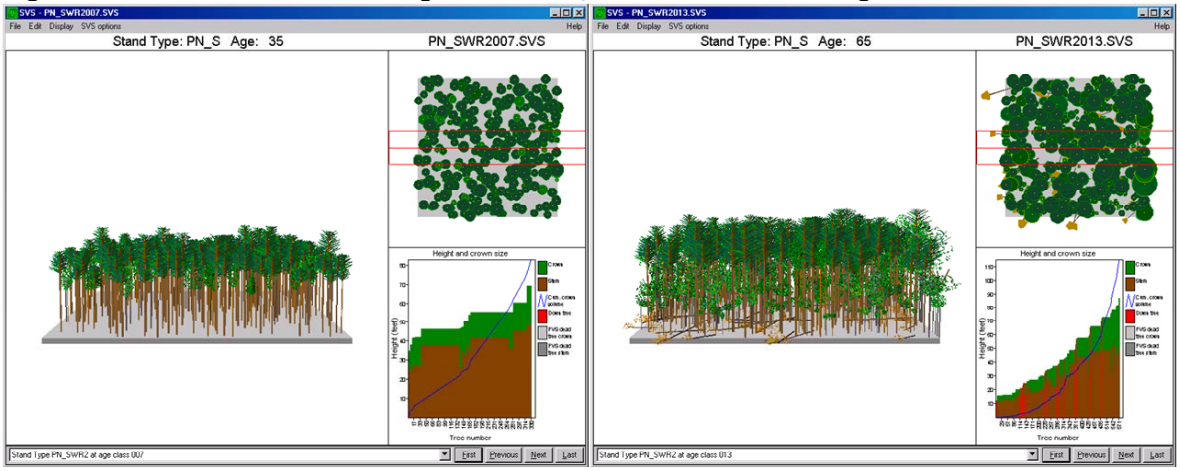
Figure 10: FVS Yield Data Examination Processor



Source: Vandendriesche, 2005.

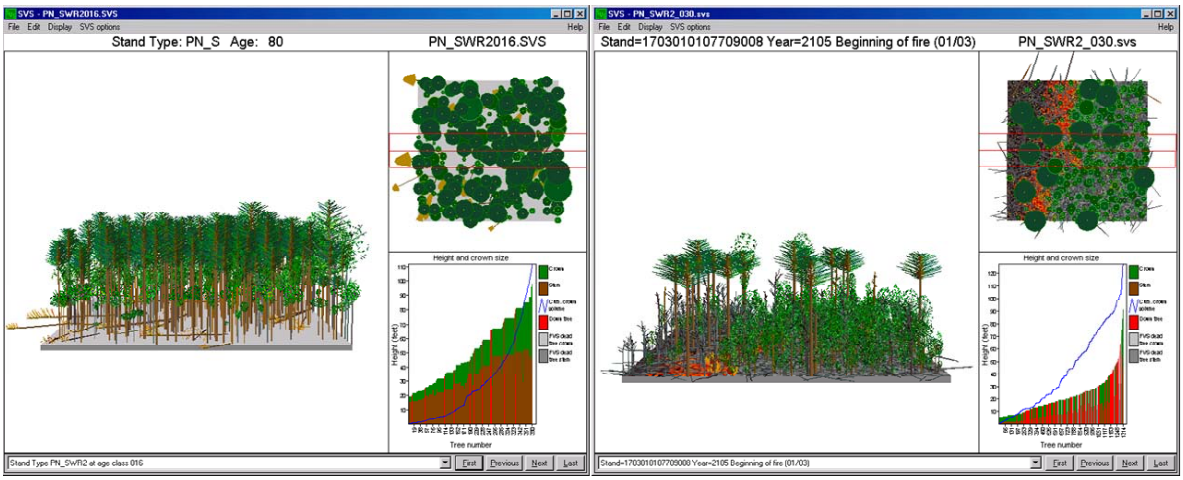
Figures 11 to 14 provide an example of stand development modeled with FVS and the visualization capability of SVS. In the following figures FVS has been used to model the growth and mortality of shortleaf pine and the recruitment of oak hickory stand under a shelterwood system. The change in forest species composition is modified by a fire event.

Figure 11: Shortleaf Pine Existing Stand Data, Year 35 and 65 old Age Classes



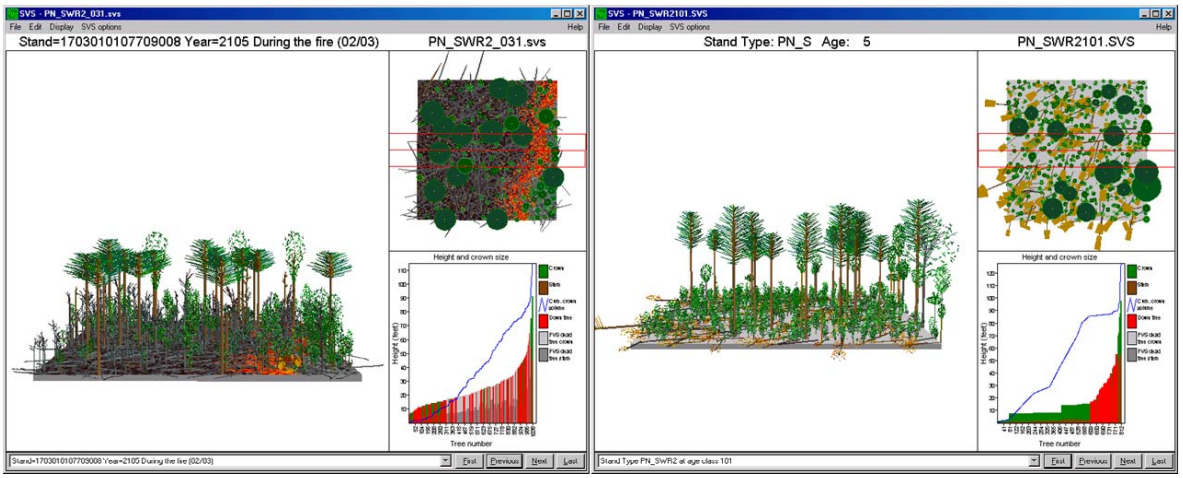
Source: Vandendriesche, 2005.

Figure 12: Shortleaf Pine Existing Stand Data, Year 80 old Age Class, Shelterwood with Reserves, follow-up Prescribed Burn



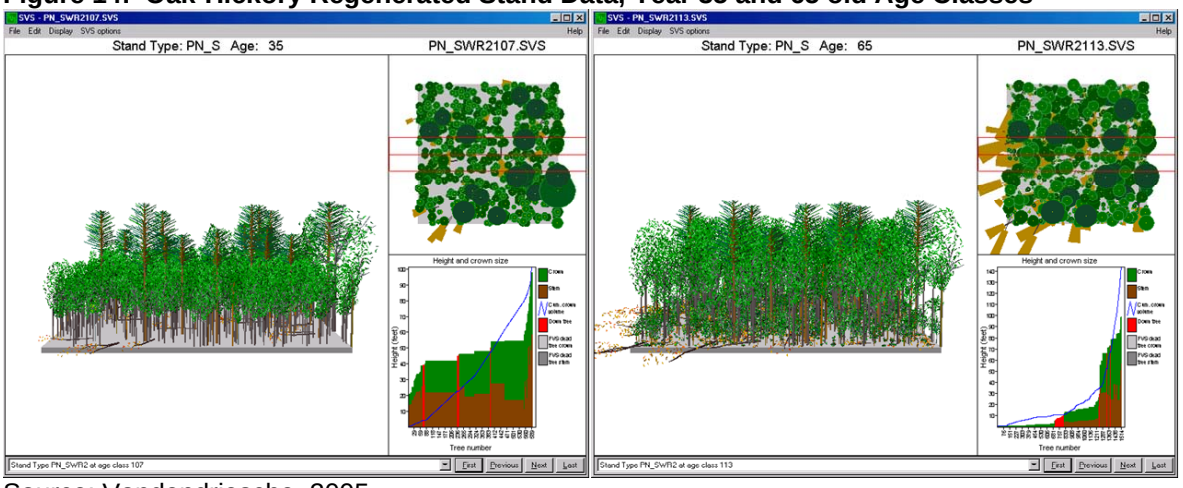
Source: Vandendriesche, 2005.

Figure 13: Shortleaf Pine Existing Stand Data, Year 80 old Age Class and Oak-Hickory Regenerated Stand Data, Year 5 old Age Classes



Source: Vandendriesche, 2005.

Figure 14: Oak-Hickory Regenerated Stand Data, Year 35 and 65 old Age Classes



Source: Vandendriesche, 2005.

2.3. Adaptation and Implementation of North America Growth and Yield Simulators for modeling Australian natural forests

While the North American growth and yield simulator FVS (and Prognosis BC) offers tremendous functionality that could be of benefit to growth and yield modeling in Australia, there are some adaptation issues that would need to be addressed and limitations exist in terms of silvicultural systems. Some of the reporting functionality and extensions to the model for modeling stand structures and modeling disturbance events are some of the particularly valuable add-ons. The visualization of stand structures would assist with understanding forest stand dynamics and the impact of silviculture, and assist in educating stakeholders with changes that occur and the impact of silvicultural restrictions on stand structure, composition, vigor and health.

Simulation Model Type

As an individual-tree, distance-independent growth and yield model, FVS can be applied, with adaptations, to NSW. Currently in NSW Forests, native forest simulators are using tree list based individual tree models because stand level models are not suitable for modeling the irregular stand structures and selective harvesting systems of State Forests. Distance dependent models are also not advocated because of the cost of data collection, plus the complexity of modeling recruitment, mortality and harvesting of trees of different qualities.

Suitability of growth, mortality and recruitment modules.

Although Australian eucalypts are unique evergreen hardwoods and the production forests largely occur in temperate and sub-tropical climatic zones that are characterized by quite arid seasonal conditions, there are fundamental similarities in the ecology and silvicultural systems with most pure and mixed species uneven-aged forests elsewhere in the world. Data inputs on stand and tree level parameters for the growth and yield simulators are also largely universal.

(a) Fitting of models to Australian forest types and species

Australian biometric equations may be readily transferable to models developed in North America. Model forms present in FVS might be fitted to Australian growth data. Supplementary data may be required for some models such as crown dimensions.

(b) Metrication
Imperial to metric conversion is required in US models. Prognosis BC uses metric outputs.

Suitability of silvicultural systems, particularly the harvesting models

(a) Modification of harvesting models to represent different silvicultural practices

FVS can effectively model both even and uneven-aged silvicultural systems. The individual tree selection method does vary from Australian practices that would necessitate harvest model adaptations.

The harvesting models for individual tree selection of uneven-aged forests in FVS and Prognosis BC are based on a desirable target diameter distribution. In uneven-aged silviculture the basis of managing the forest is to control the stand structure (diameter regulation). This contrasts with even-aged forests that are managed on an area basis according to a silvicultural regime for a given rotation length.

Guiding diameter frequency distribution curve shapes based on *de Liocourt's q* factor (q is the ratio of trees in adjacent diameter classes), are the dominant approach in the United States for uneven-aged silviculture. A target reverse J diameter distribution (negative exponential curve) is used to guide the level of removal so that each stand provides a sustainable yield of products. The diameter distribution changes as the uneven-aged stand matures over time due to tree growth, recruitment, and mortality. Periodic harvesting is undertaken when there is sufficient volume of appropriate diameter classes for viable harvest operations, and to achieve a target desired post-harvest diameter frequency distribution.

Other techniques are used to regulate uneven-aged stands without employing diameter frequency distributions to control the timing and level of harvest and retention, particularly in irregular uneven-aged stands. With these approaches the age and diameter classes are permitted to fluctuate. Examples include:

- financial maturity – extract optimum value from growing stock. If the diameter distribution is unbalanced, then balance can only be achieved by cutting some trees before or after they are financially mature.

- diameter limit partial cutting (and "high grading") – cutting all trees above a minimum limit that can be utilized without financial loss (zero margin selection cutting). Cutting to strict minimum diameter limits is purely for maximum financial return and not cutting for sustainability or regard for future value increase. Unless the stand is being liquidated, this is often only an approximate guide to determining tree removal. Trees above a certain limit will be retained if they are increasing in value, or are to provide regeneration seed and habitat. Similarly trees below the diameter limit may be removed if it is of poor quality, species, vigor, or to release trees in dense patches.

Smith et al (1997) stress that there are many valid reasons for maintaining uneven-aged stands other than sustained yield or financial maturity (viz. aesthetics, wildlife habitat, seedling ecology, protection of the stand and soil), and these objectives can be achieved without a balanced diameter frequency distribution. Smith et al (op. cit) state that "*warping the patterns of harvest removals to fit some preordained diameter distribution commonly interferes with fulfilling many other logical purposes.*"

In North America many uneven-aged natural stands are managed according to selective harvesting systems[3] . Where forests are managed with selection harvesting silvicultural systems to maintain or achieve an uneven aged forest structure, the silvicultural specifications are based on achieving a theoretical target stand structure (negative exponential diameter frequency distribution) and desirable species mix, to provide a sustainable flow of wood products of preferred species over time.

Harvesting to achieve target residual stands according to a target structure and species composition is rarely achievable in Australian forests. This is attributable to the initial highly irregular stand structures, but also because uneven-aged harvesting is being driven by wood production targets and appropriate silvicultural practices are restricted by economics and regulations. Current simulation models in NSW have broad target structures in terms of diameter and tree quality classes, but strict diameter frequency distribution are not adhered to. The NSW growth and yield simulators harvest when sufficient volume is available for a viable operation, while retaining a suitable growing stock defined in very broad terms.

It is suggested that harvest models that cater for regular and irregular diameter distributions be looked at for single tree selection. Also worth considering are silvicultural regulations and the question of whether there are ideal retained structures that should be aimed for or can ever really be achieved in the current political and economic climate.

(b) Australian silvicultural considerations that are difficult to build into harvest and growth models.

The silviculture is natural eucalypt forest is severely restricted and difficult to model for reasons including:

[3] Some even-aged stands are being converted to uneven-aged stands on public lands, and various private industrial forests are converting uneven aged stands to even-aged stands.

- impacts of inappropriate silvicultural systems for shade intolerant Eucalypt forest

Australian forest management regulations outlined in the Regional Forest Agreements specify the type and intensity of silvicultural systems applied in Eucalyptus forest types. Many of these silvicultural regulations have been the product of environmental pressure and politics and were not silviculturally driven. The conversion of uneven aged forest to even-aged regrowth (or plantation) through clearcutting or seed tree silvicultural systems is only permitted in some areas of SE NSW, Victoria and Tasmania. Most of the uneven-aged forests are in fact managed with single tree selection and low intensity group selection harvesting methods that are unsuitable for effective regeneration and vigorous growth of the preferred and mostly intolerant species. Many of the forests would be better suited to more intensive harvesting practices such as clearcut and seed tree silvicultural systems to emulate the ecosystems where natural fire, wind or snow disturbance is prevalent. It is difficult to emulate the regeneration, growth and stand dynamics resulting from inadequate opening sizes and site disturbance. Insufficient data and experience are available to predict future composition, structure and condition of these stands.

- impacts of selective harvesting restrictions on forest condition

Intensive selective harvesting practices and restrictions on silvicultural improvement of stands have left many mature multi-aged forests stagnant and economically unviable. The Regional Forest Agreements have set many wood supply targets from reduced production forest areas that cannot be met from sustainable yield management of the native forests. To meet contractual commitments from selectively harvested stands, forest managers need to harvest all trees bearing the minimum sawlog dimensions. This practice will result in abnormally lengthened cutting cycles, and quite irregular structures potentially favoring noncommercial species before these stands will provide future yields.

Where regulations prohibit the removal of low quality trees such that only desirable species and trees with high quality sawlogs are removed, the condition of these forests will deteriorate unless silvicultural culling (non-commercial thinning, poisoning, ring-barking) is undertaken. Individual trees are routinely retained for wildlife habitat trees within forest zones designated for commercial harvest. Within commercial forest, harvesting of non habitat trees without sawlogs is not permitted in many of Australia's native forests. Timber Stand Improvement (TSI) involving the culling on un-merchantable and non-commercial species is prohibited or uneconomic in many situations due the absence of market for low quality and small wood (pulp) products or high cost of extraction of these to processing or export facilities.

In the absence of disturbance events such as wild fire, these silvicultural restrictions collectively reduce stand regeneration, tree growth, favor more shade tolerant (and sometimes less commercial) tree species, and reduce the economics of harvesting operations. The stands require intervention such as TSI, thinning or reset silviculture (harvesting), to remove the large unmerchantable and noncommercial species to promote regeneration and to stimulate growth on commercial merchantable trees.

Data Reporting Functionality

In addition to its elegant design and the extensive and flexible functionality included in the FVS growth and silvcultural/harvest models, the types of outputs (stand and stock tables) and model extensions such as SVS and disturbance models provide features that would be advantageous for forest modelers and planners in Australia.

Other values of using FVS model

- Regularly updated open source code
- Model functionality
- Synergies of development features being based on a wide range of users
- Opportunity for collaborative research and development of more universally applicable systems

It is worth noting that the BC Ministry of Forests selected FVS as basis of PrognosisBC to model the development of complex stands in BC for three main reasons:

"First, its growth equations are a function of tree size, vigour and dominance, and not age.

Second, site productivity is described by site characteristics rather than tree characteristics: the model is based on BEC[4] rather than Site Index.

Finally, it has a track record of over 3 decades of reliable use and its open source code is supported through regular bug fixes and enhancements provided by a broad user community."
(BC Ministry of Forests, 2007b)

A comprehensive account of the process involved in adapting and implementing FVS is outlined by the Ontario Ministry of Natural Resources (OMNR, 2007).

[4] Biogeoclimatic Ecosystem Classification (BEC) system designed specifically for British Columbia's ecosystems. BEC site factor information is correlated with measures of site productivity, or site index (SI), to enhance forest stand growth predictions.

3. Forest Estate Modeling in North America

A review of North American forest estate models reveals a broad array of approaches from both private sector technology/consulting firms as well as public agencies and universities. Indeed the decentralized and competitive nature of the American forest and business sectors means that there is a plethora of products and independent research on modeling being undertaken by these organizations. Each model offers strengths in certain areas and each have limitations.

The major harvest scheduling and wood supply forecasting tools used in North America are outlined on Table 2. Traditional strategic models are based on linear programming techniques, but integrated strategic-tactical and stand alone tactical software products are based on heuristic techniques to enable spatial forest planning.

Table 2: Forest Estate Models - Strategic and Tactical Scheduling Models

Forest Estate Models

Model	Description	Planning Level	Modeling Solution Approach / Model Formulation	Spatial Functionality	Developer / Supplier	Web Link	Reference
ATLAS (FPS)	ATLAS (**A** **T**actical **L**andscape **A**nalysis **S**oftware) is a spatially explicit timber harvest block scheduling simulation model. ATLAS simulates how different policies related to harvest flows, opening size (adjacency), riparian buffers, seral stage distributions and patch size distributions will affect harvest and retention levels across the landscape. Includes economic and road network analysis functions. The latest rewrite of ATLAS is called FPS (**F**orest **P**lanning **S**tudio).	Strategic & Tactical	Simulation	Spatial adjacency constraints (maximum opening size, and green-up delays). Pre-block whole estate prior to harvest scheduling simulation.	Dr John Nelson University of British Columbia, Vancouver	http://www.forestry.ubc.ca/atlas-simfor/atlas/about.html	Nelson (2003) Sutherland, Wells and Nelson (1996)
CASH 6	**C**ritical **A**nalysis of **S**chedules for **H**arvesting version 6 (CASH 6) Spatial timber supply simulation model. Operates in two modes: aspatial mode for long term strategic analyses (does not track the spatial relationship between cutblocks) or spatial for 20 year tactical harvest scheduling plans.	Strategic & Tactical	Simulation	Spatial constraints at tactical level.	Timberline Natural Resource Group, Victoria	http://www.timberline.ca/analysis.html	
COMPLAN	Spatial forest estate harvest scheduling simulation model. Timber supply and forest harvest operation scheduling. Harvest at individual cutblock or stand level. Includes economic functionality.	Strategic & Tactical	Simulation	Spatial constraints (adjacency green-up and nontimber cover constraints).	Simons-Reid Collins, Vancouver developed. Acquired by Olympic Resources Management, then JS Throwers and now Timberline Natural Resource Group.	http://www.timberline.ca/newsletter/january2003/index.html#Complan http://www.srd.gov.ab.ca/forests/pdf/canfor/DFMP_Appendix_3_RTSA_Main_Text.pdf	
FSOS	**F**orest **S**imulation **O**ptimization **S**ystem Model (FSOS) is a spatially and temporally explicit forest estate model developed for sustainable forest management. Enables simultaneous strategic, tactical and potentially operational planning. Concepts include: (a) two common landscape indicators to quantify non-timber resource objective (patch size and age class distributions); (b) dynamic cut block and patch building; (c) the integration of short- and long-term planning; and (d) target-oriented, adaptive forest ecosystem planning. FSOS uses a simulated annealing algorithm and a resource weighting approach to schedule harvest units to achieve a desired forest ecosystem state.	Strategic and Tactical simultaneously.	Target-orientated optimization and regulation-based Simulation. Simulated annealing Heuristic Search Algorithms is used.	Spatial constraint modeling capability. Area restriction model that conducts blocking and scheduling simultaneously. Manage for specific patch size distributions within each seral class for long-term biodiversity objectives.	Dr. Guoliang Liu and Dr. John Nelson, University of British Columbia Hugh Hamilton Limited	http://www.fsos.ca/fsos.htm	Liu, Nelson and Wardman (2000)
FSSIM	**F**orest **S**ervice **Sim**ulator. Forest estate simulation model. No economic analysis capability.	Strategic	Simulation	Approximates spatial harvest restrictions (area exclusions).	British Columbia Ministry of Forests and Range	www.for.gov.bc.ca/ftp/HTS/external/!publish/FSSIM/fssim_tech.doc http://www.cortex.ca/wor-tim-dfam.html	B.C. Ministry of Forests (1997) Cortex consultants (2004)
HABPLAN	Habplan is a program for spatial forest harvest scheduling and habitat management. Habplan uses a simulation approach, based on the Metropolis Algorithm, to generate feasible (near optimal) harvest schedules. Habplan Version 3 has a limited Linear Programming (LP) capability.	Strategic	Model Type I formulation optimization. Heuristics: Stochastic simulation (Metropolis algorithm) for spatial models. Exact: Also has linear programming capability to calculate non-spatial optimal solution.	Model spatial constraints	National Council for Air and Stream Improvement (NCASI)	http://ncasi.uml.edu/projects/habplan/	NCASI (2006) Van Deusen (2001)
HARVEST & HABITAT	The Harvest and Habitat Model is a spatial harvest scheduling model. Strategic and tactical level considerations are integrated in the same model and rather than in a multi-stage hierarchical manner. Option for a multi-criteria objective function structure to satisfy multiple forest management goals. Includes roading network functions.	Strategic and Tactical (Integrated)	Optimization Model Type II Formulation. Heuristics: Simulated Annealing Algorithm	Simultaneous blocking and scheduling (Area Restriction Model). Includes adjacency constraints to enforce clearcut sizes and greening up periods, and models the distribution of floating patches of complex forest across the landscape.	Prof. John Sessions. Oregon Department of Forestry and Oregon State University Department of Forest Engineering	http://www.odf.state.or.us/DIVISIONS/Management/Asset_Management/HH/8_Overview%20of%20HnH%20Model.pdf http://www.oregon.gov/ODF/STATE_FORESTS/docs/ESF/Elliott_FMP/FMP_H_clean.pdf	Session et al (2006) Boston and Bettinger (2006)
HARVEST	Timber Harvest Allocation Model. Model is not designed to find an optimal harvest scheduling solution, rather it is designed to assess consequences of timber management strategies on landscape patterns such as successional stage distribution, forest type composition, spatial distribution of forest interior and edge habitats, and the spatial patch structure. Converts output from the harvest-scheduling program SPECTRUM into a HARVEST input file so SPECTRUM schedules to be simulated in a spatial context. Visually portrays the non-spatial outputs from SPECTRUM and enables evaluation of the spatial feasibility of a model solution when harvest activities are subject to adjacency constraints not addressed in SPECTRUM (harvest opening size, green-up interval). HARVEST stochastically allocates stands for harvest to meet temporal flow and spatial constraints	Strategic	Stochastic simulation model. A random number sequence is used to simulate harvesting activity.	Spatial constraints include: Average harvest area size with standard deviation. Dispersion method for harvest locations (dispersed; clumped; group selection that randomly chooses stands and then harvests small openings (groups or patches); or oldest first) Harvest adjacency restrictions (green-up delays) and riparian buffers.	Eric Gustafson USDA Forest Service North Central Research Station	http://ncrs.fs.fed.us/4153/Harvest/harvhome.htm http://www.ncrs.fs.fed.us/4153/harvest/harvhome.asp http://www.ncrs.fs.fed.us/4153/Harvest/v60/v6_0.htm	Gustafson and Crow (1999) Leefers, Roberts and Gustafson (2005) Gustafson and Rasmussen (2005)
LANDIS-II	LANDIS is a spatially explicit landscape model designed to simulate forest landscape change over large spatial and temporal scales. LANDIS stochastically simulates forest landscape disturbance (fire, wind, harvesting, insects, climate change), forest succession, management, and seed dispersal across large (> 10,000 ha) landscapes.	Strategic	Stochastic simulation model. No optimization of management actions.	Spatial units used for modeling.	Dr. David Mladenoff and Dr. Hong He Forest Landscape Ecology Laboratory, University of Wisconsin-Madison. USDA Forest Service North Central Research Station	http://www.fs.fed.us/institute/news_info/evaluation_LDSM.pdf http://landis.forest.wisc.edu/ http://web.missouri.edu/~umcsnrlandis/index.php http://ncrs.fs.fed.us/4153/landis/	He et al (2005) Scheller et al (2007)
OPTIONS	Spatially explicit forest estate simulation model for timber supply and forest operation scheduling. OPTIONS may be run in an aspatial mode. Determine the impacts of various forest management activities at the forest and stand level. The model designed to address all environmental and other resource requirements first with timber harvesting as a residual. Grows and manages individual stands (polygons) each year according to their actual forest inventory data. Utilizes internal growth algorithms and treatment schedules to project stands into the future. Use yield table values where inventory data are unavailable.	Strategic	Simulation. Deterministic.	Spatial relationships between all analysis units (polygons) across all (up to 50) GIS layers/coverages. No limits on the number of polygons. Pre-block whole estate prior to harvest scheduling simulation.	D.R. Systems Inc, Nanaimo,BC	http://www.drsystemsinc.com/prod_options.html	
PATCHWORKS	Forest management optimization model that integrates operational-scale decision-making within a strategic-analysis environment enabling spatially explicit harvest allocations can be developed over long-term planning horizons. Can generate and evaluate alternate harvest, roading and silvicultural plans. Enables the optimization of either a single objective function or multiple-objective goal programming objective functions. Provides a unique visual mechanism to analyze trade-off's between competing sustainability goals. Patchworks road planning and design capabilities implement a unique multiple-product to multiple-destination road layout procedure that includes road access and transportation costs within the strategic modeling framework, enabling analysis of the interrelationships between access, hauling and delivered wood costs or other indicators of sustainability.	Strategic and Tactical (Integrated)	Model Type II formulation optimization model. Simulated annealing heuristics for the solution algorithm	Area Restriction Model (ARM) design enables simultaneous blocking of adjacent forest patches and scheduling that solve spatial restrictions on opening size and adjacency delays. Mechanisms to control the spatial allocations of management treatments or the retention of forest structures, including: - Patch size distributions by area or frequency. Multiple patch categories can be modeled simultaneously - Variable adjacency delay timings based on user specified criteria - Multiple sub-regional targets can be used to implement zonal constraints - Road access models can implement rational economic criteria - Manual imposition of go/no-go zones that change over time	Tom Moore and Carey Lockwood, Spatial Planning Systems, Ontario	http://www.spatial.ca/ http://eco.wiz.uni-kassel.de/model_db/mdb/hsg.html	Lockwood and Moore (1993)
RELMdss	**R**egional **E**cosystems and **L**and **M**anagement **D**ecision **S**upport **S**ystem (RELMdss) is a forest estate model which proportions aspatial forest-wide, strategic planning solutions from SPECTRUM to spatial tactical sub-units of the forest and tests the feasibility of the forest-wide solution on a geographically specific basis. After RELM proportions the SPECTRUM strategic solution to sub-units, each sub-unit can then be analyzed for project level feasibility using SNAP software.	Tactical	Linear Programming based optimization	SPECTRUM forest planning scenarios are assigned each compartment based on the area in each compartment. Two methods are used: - minimum area option minimizes the area treated and meets the target if possible. Does not violate constraints on the maximum area of mature timber, maximum area that can be cut without violating a wildlife constraint and/or damaging a watershed. - equivalent risk option distributes the harvest activities across the planning area wherever flexibility allows, and only violates constraints to ensure the target is met.	Richard Church, Alan Murray, Michael Figueroa, Phil Aune. U.S. Forest Service Cooperative Research Project: University of California, National Center for Geographic Information Analysis (NCGIA), USDA Forest Service Pacific Southwest Forest Research Station, Washington Office Ecosystem Management Analysis Center.	http://www.fs.fed.us/institute/planning_center/plan_relm.html	USDA Forest Service (1998)

Forest Estate Models

Model	Description	Planning Level	Modeling Solution Approach / Model Formulation	Spatial Functionality	Developer / Supplier	Web Link	Reference
RVLM (SELES project)	**R**obson **V**alley **L**andscape **M**odel (RVLM) is a spatial model for forest dynamics developed to assess the vulnerability of timber supply to non-recoverable losses due to natural disturbance. Incorporates forest growth, succession, harvesting and natural disturbances. 4 submodels of succession and natural disturbance: Ecological Succession Model, Western Hemlock Looper Outbreak Model, Mountain Pine Beetle Model, Stand-Replacing Fire Model.	Strategic	Stochastic simulation	Spatially explicit model. Raster based. Includes block size, adjacency and road access constraints. Forest cover constraints can be specified based on age (e.g. minimum % over 250 years) or height (e.g. a maximum % under 5 meters).	BC Ministry of Forests	http://www.for.gov.bc.ca/hcp/enhanced/robson/efmpp/research/RV%20NATDisturbance%20Scenario.pdf	Sutherland, Eng and Fall (2001)
SELES	**S**patially **E**xplicit **L**andscape **E**vent **S**imulator (SELES). Research and decision-support model for exploring problems related to conservation and resource management. Processes modeled have included forest succession and encroachment, natural disturbances such as fires, insect outbreaks and flooding, and management activities such as timber harvesting and livestock grazing. SELES models consist of two components: (a) a set of spatial raster layers and global variables specify the landscape state and (b) a set of model descriptions that define the model behavior.		Simulation (stochastic and deterministic options). Incorporate aspects of cellular automata, percolation models, discrete-event simulation, and spatio-temporal Markov chains.	Spatially explicit model.	Dr Andrew Fall. Simon Fraser University, British Columbia	http://www.cs.sfu.ca/research/SEED/	Fall (2003)
SFMM	**S**trategic **F**orest **M**anagement **M**odel (SFMM) is a non-spatial strategic forest estate model. Enhancements of the model are ongoing, with the aim of including the ability to model habitat for a range of wildlife species, and to model tolerant hardwood forests managed under the selection silvicultural system.	Strategic	Optimization	Non-spatial.	Ontario Ministry of Natural Resources	http://www.aimms.com/aimms/references/case_studies/ontario_ministry_of_natural_resources_forestry.html http://www.forestresearch.ca/partnership_projects/fibre_production/130-010.htm	Kloss (2002)
SIMFOR	SIMFOR (**SIM**ulator of **FOR**ests) simulates the effects of harvest schedules (from ATLAS) on wildlife and calculates spatial landscape indices. The system evaluates forest vegetation/habitat structure and calculates summary indicators of landscape patterns and available wildlife habitat (seral stage, patch size and edge characteristics). SIMFOR can be used in conjunction with ATLAS to model a combination of timber supply, habitat supply, and biodiversity indices, or as a stand alone tool projecting natural forest development. Addresses landscapes between 5,000 and 150,000 ha in size.	Strategic and Tactical	Simulation	Spatially explicit model.	Dr. Fred Bunnell Centre for Applied Conservation Research within University of British Columbia, Vancouver	http://www.forestry.ubc.ca/atlas-simfor/simfor/about.html http://www.forestry.ubc.ca/simfor/	Wells and Moy (2002) Sutherland, Wells and Nelson (1996)
SPATIAL WOODSTOCK	Strategic forest estate model for timber management planning (harvest scheduling and economic wood supply analysis), wildlife habitat management, climatic change, simulation of forest ecosystems (vegetation succession in natural areas), stochastic wood supply from non-industrial private forest land, and analysis of random disturbance events such as fire. Integrates with Allocation Optimizer to create allocation strategies between forest and processing/export nodes. Include age dependent and time dependent yield tables. Financial modeling for cashflow analysis and valuations.	Strategic or Tactical	Generalized Type II Model formulation optimization using linear programming and goal programming. Includes Monte Carlo simulation option.	Spatial functions include: fragmentation analysis (building contiguous patches of a minimum size), maximum clearcut block size, and adjacency (green up delays) constraints, and predetermined harvest schedules can be enforced. Stratum or area based modeling option. Pre-blocking is done before scheduling (Unit Restriction Model). Financial / volume-based strategic plan from Woodstock, then use Stanley (Area restriction model) to spatially allocate the planned harvest and other treatments to blocks creating a spatial plan.	Remsoft Inc. New Brunswick, Canada	http://www.remsoft.com/products.php?id=1	Walters, Feunekes, Cogswell and Cox (1999)
SPECTRUM	Strategic forest estate model. Based on FORPLAN LP Harvets Scheduling Model. Applications include: forest plan amendment and revision; landscape/watershed scale analysis; analysis of management strategies; land and resource allocation; estimating sustainable goods and services; identifying pathways to desired future condition; management activity scheduling; environmental effects analysis; economic analysis; tradeoff analysis; sensitivity analysis; and policy analysis Analytical features include: - Flexible spatial and temporal scales (scale independent strata based and area based analysis units; up to 90 time periods of any length) - Mathematical programming options (linear programming, goal programming, mixed integer programming) - Objective function options (Maximize or minimize a single outcome or measure of performance, Minimize under-achievement of goals, Minimize over-achievement of goals, Minimize both of the above at once, MAX/MIN--maximize the minimum level of occurrence of a critical resource, MIN/MAX--minimize the highest level of occurrence of an undesirable outcome) - Natural disturbance and ecological simulation - Include age dependent, time dependent and sequence dependent yield tables.	Strategic	Generalized Model Type II optimization based on linear programming, goal programming and mixed integer programming options.	No spatial modeling functionality. SpectraVision is an ArcView extension designed to display model solutions generated by a Spectrum forest planning model. Spectrum to Harvest (Spec2Harv) is a program that automatically converts harvest schedules generated by the Spectrum model into script files that can be used by the HARVEST simulation model to simulate the implementation of the Spectrum schedules in a spatially explicit way.	Washington Office Ecosystem Management Analysis Center and USDA Forest Service Rocky Mountain Forest and Range Experiment Station, Fort Collins Colorado.	http://www.fs.fed.us/institute/PAG/SPECTRUM.shtml	USDA Forest Service (1999)
STANLEY	Stanley is spatial harvest block scheduling software that automates the process of developing a spatial harvest plan. Stanley spatially allocates strategic harvest (and treatment) schedules developed using Spatial Woodstock to harvest blocks. (First create a volume-based strategic plan the allocate the harvest to spatial blocks). Stanley is a modified area restriction model that groups polygons together in various arrangements to obtain harvest blocks for a tactical harvest schedules that optimally achieve the strategic forest planning objectives	Tactical	Optimization based on heuristic algorithms.	Simultaneous blocking and spatial allocation of harvest schedule (modified Area Restriction Model). Recognizes spatial (clearcut opening size restrictions, green-up adjacency delays, aggregate patches) and flow constraints.	Remsoft Inc. New Brunswick	http://www.remsoft.com/products.php?id=3	Remsoft Inc. (1996)
TELSA	**T**ool for **E**xploratory **L**andscape **S**cenario **A**nalyses (TELSA) is a spatially explicit, GIS-based landscape-level model for simulating terrestrial ecosystem (forest) dynamics. The model simulates vegetation succession, natural disturbances, and management. TELSA models alternative management strategies and assumptions about natural disturbances, and the impacts biodiversity and other resource indicators such as timber, landscape health, and habitat supply can be assessed from the indicators: - areas annually affected by natural disturbances and management activities, - vegetation composition (cover type distribution, seral stage distribution) - landscape structure (patch size distribution, amount of interior habitat, amount of edge) Forest modeling approach involves blocking the forest first, followed by stochastic simulation to examine a range of outcomes associated with natural disturbances.	Strategic	Monte Carlo Simulation	Spatial mapping of landscape or strata functionality. Generates area disturbed including the range of area disturbed or the frequency of disturbance for different polygons; seral stage distribution; count and area distribution of patch size classes and interior habitat; and the length of edge between different seral stages or age classes.	ESSA Technologies Ltd. BC Ministry of Forests USDA Forest Service	http://www.essa.com/downloads/telsa/index.htm	ESSA Technologies Ltd (2005)
TREEFARM	Timber supply simulation model. Similar to FSSIM mode.	Strategic	Simulation	Approximates spatial harvest restrictions.	Stirling Wood Group Inc, Victoria	http://www.for.gov.bc.ca/hts/tsr1/ration/tfl/t19/19f-0009.htm http://www.for.gov.bc.ca/hfp/publications/00083/sdm-72.htm	
WOODLOT	Woodlot for Windows is a simulation model that calculates the maximum non declining even flow harvest rates over multiple rotations on woodlot licenses in B.C. (AAC determination). The model is limited to calculating harvest level for areas under 1000ha and with less than 400 polygons. Utilizes yield curves generated by British Columbia growth and yield models VDYP and TIPSY.	Strategic	Simulation	Approximates spatial harvest restrictions.	B.C. Ministry of Forests, Resources & Tenures & Engineering Branch	http://www.enfor.com/software/woodlot/WLRM31.pdf http://www.for.gov.bc.ca/HTH/woodlots/aac-program.htm	Enfor Consultants Ltd. (2002)

3.1. Examples of Modeling Systems

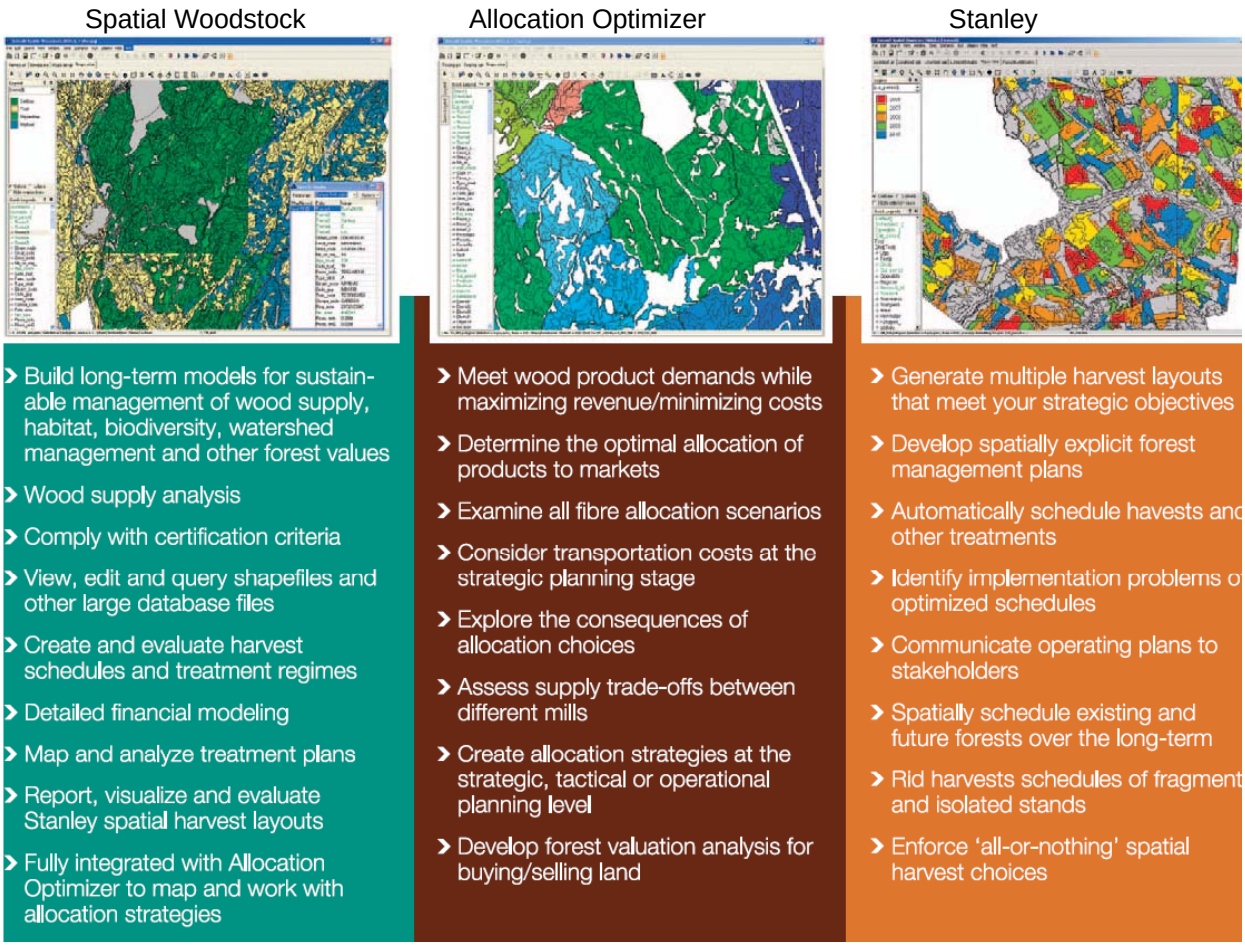
The following section discusses the characteristics of three of these forest estate models developed in North America that take two quite different approaches to providing management planning solutions. All offer scope for modeling uneven-aged forest management in Australia.

Remsoft Spatial Planning System

The Remsoft Spatial Planning System (RSPS) is now the most popular forest estate modeling system used globally today, including in Australia. The system is well suited to the management of even-aged forests and has been used extensively for selection harvested uneven-aged forest using time dependent yield tables.

The RSPS is a forest modeling system comprising three modules developed by Remsoft Inc based in New Brunswick Canada (www.remsoft.ca). The first two modules—Spatial Woodstock and Stanley—are spatial forest optimization models designed to generate strategic timber supply forecasts and provide activity schedules used in strategic and tactical forest management planning. The third module—Allocation Optimizer—is a log product allocation model that enables the user to the model the timber supply chain from forest to market.

Figure 15: Remsoft Spatial Planning System Modules



Source: Remsoft (2007) www.remsoft.com

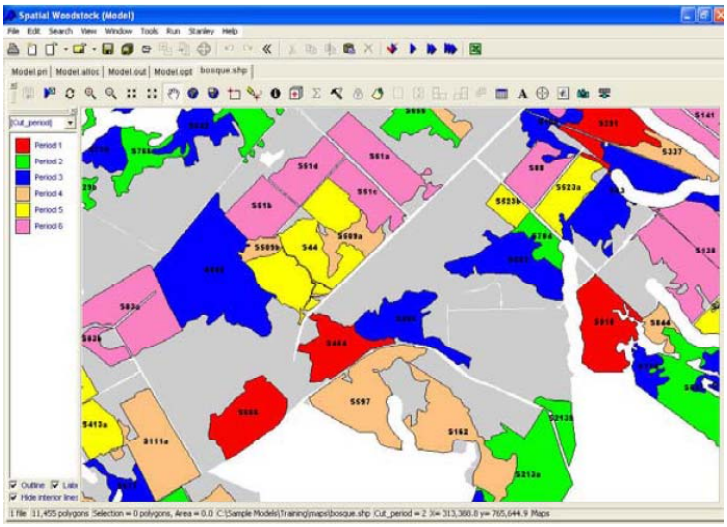
Spatial Woodstock and Stanley are two specific models that provide a systematic and effective hierarchical approach to modeling strategic and tactical forest plans. Spatial Woodstock reports, visualizes and evaluates Stanley spatial harvest layouts. Woodstock is also fully integrated with Allocation Optimizer to map and work with allocation strategies. Details on how these models are integrated are detailed by Feunekes and Cogswell (1997), Walters and Feunekes (1994) and Walters et al (1999).

Spatial Woodstock is a strategic forest management system (though it can be applied to generate tactical plans) that can be run as a linear programming (LP) or a Monte Carlo simulation model. The LP model has a generalized Model II formulation (Johnson and Scheurman, 1977) and enables goal programming objective functions to be formulated. The model is used for both strata and area based forest modeling. The model is designed to process both age dependent yield tables for even-aged forest but also time dependent yield tables used for uneven-aged forest modeling. The spatial modeling capabilities include the ability to model adjacency (restricting clearcut openings and minimum green-up period before harvesting adjacent forest) and fragmentation constraints (building contiguous patches of a minimum size), and predetermined harvest schedules can be enforced.

The applications of Spatial Woodstock include long term models for wood supply analysis, harvest scheduling and other silvicultural treatment plans, wildlife habitat management, and vegetation succession in natural areas. The stochastic modeling functionality enables impacts of variation in wood supply due to catastrophic events to be modeled. The goal programming option enables the simultaneous sustainable management of wood supply, habitat, biodiversity, watershed management and other forest values. The model includes functionality for financial modeling and forest valuations. (http://www.remsoft.com/case_studies.php)

The Stanley module is a tactical planning model that automates the process of developing a spatial harvest plan. It translates strategic forest management solutions from Spatial Woodstock into practical harvest schedules and other operation plans. Stanley is based on a modified Area Restriction Model (ARM) approach and uses blocking routines to map the strategic harvests predicted by the linear programming in the Woodstock model. In Woodstock, management units (e.g. stands) of a similar composition and structure are aggregated into single classes and silvicultural treatment areas are assigned to these classes. The LP model does not treat (e.g. harvest) discrete management units, but the aggregate classes and the LP model assume the classes are infinitely divisible. Stanley implements a forest management schedule by assigning silvicultural treatments to discrete management units, while simultaneously recognizing spatial (clearcut opening size restrictions, green-up adjacency delays, aggregate patches) and flow constraints. Walters et al (1999) point out that Stanley assigns the harvest prescriptions to individual stands by grouping them where possible, and it also rearranges the stands to satisfy the constraints. Prescriptions are assigned to the contiguous blocks to be harvested in the same period and these are identified as harvest units on the spatial harvest schedule.

Figure 16: Spatial Woodstock Image of Harvest Block defined in Stanley.



Source: Remsoft (2007) www.remsoft.com

Remsoft products have captured a large part of the global market share by marketing a system that:

(a) provides both the modeling functionality necessary for forest management planning, through
- strategic and tactical planning functions
- ability to address spatial and temporal constraints,
- representation of uneven and even-aged forest with time and age dependent yield tables
- financial and volume based modeling
- simulation and optimization functions
- stochastic modeling option
- reporting in tabular, graphics and maps
- model development flexibility – template can be structured in innumerable ways
- flexible and easy to use data entry and output formats

(b) has proven effectiveness (performance) and flexibility of modeling systems

(c) has excellent training, documentation, support service, user groups, web site with technical information, case studies and model upgrades, effective client management

(d) offers continuous interaction with clients to develop and customize new functionality

(e) offers competitive pricing with affordable software and training, whereas competitors either do not actively market products or products do not offer the same range of functionality

Patchworks
Patchworks was developed by Lockwood and Moore of Spatial Planning Systems based in Ontario Canada (www.spatial.ca) who were the first developers of an ARM model for blocking patches of forest and addressing spatial planning considerations (Lockwood and Moore ,1993).

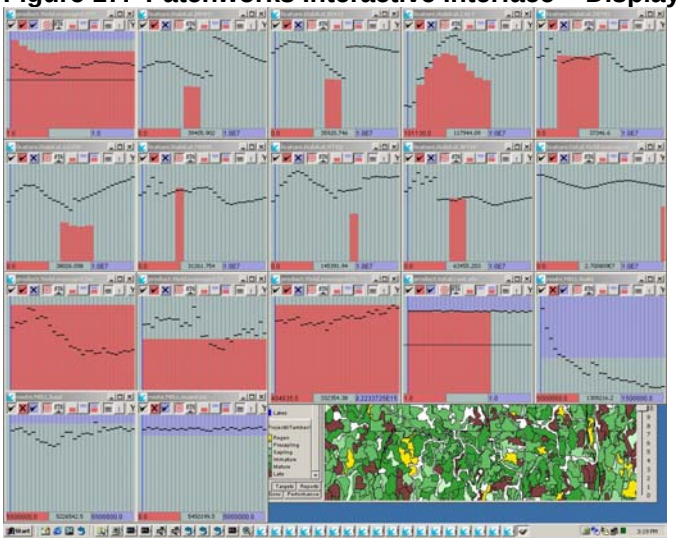
Patchworks is a spatially explicit sustainable forest management optimization model that integrates operational-scale considerations into the strategic planning framework. The model is designed to both generate strategic timber supply forecasts (150 – 200 years) and generate short to medium term spatial harvest schedules. The model has a uniquely flexible, interactive interface enabling the user to modify constraints and view solutions graphically and spatially while a run is being processed. Stand dynamics and silviculture can be represented at a stratum or management unit (stand) level. The model can account for wood volume, economic factors (harvest costs, multiple product values, silvicultural costs, road construction and hauling costs), forest succession seral stages, and wildlife habitat. Patchworks includes a road network building and log allocation (model products, multiple destinations) functionality. (http://www.forestresearch.ca/partnership_projects/spatial_analysis/120-201.htm)

Patchworks is based on a Model II formulation optimization model and uses simulated annealing heuristics for the solution algorithm. The model is designed as an ARM that enables blocking of adjacent forest patches and solving spatial restrictions on opening size and adjacency delays.

Patchworks enables the optimization of either a single objective function or multiple-objective goal programming objective functions. The model is structured with penalty functions, so the violation of some constraints (soft constraints) is permissible and the model minimizes violations by maximizing the objective function value. The model provides a visual mechanism to analyze trade-offs between competing sustainability goals (Refer Figure 1).

The fully integrated nature of the model offers powerful and efficient modeling capabilities, particularly with the use of heuristics and pure ARM approach. The model is being used extensively throughout Canada for modeling forest managed with clearcut silviculture regimes. Patchworks is being adapted for natural patch disturbance emulation in Ontario. The model design has the potential to be used for modeling the management of selection harvested uneven-aged forest provided suitably structured yield tables can be formulated.

Figure 17: Patchworks Interactive Interface - Displaying Multiple Goals (Target Charts)



The Harvest and Habitat Model

This system developed by the Oregon Department of Forestry and Oregon State University Department of Forest Engineering, to model sustainable forest management. The activity scheduling system is used in conjunction with other computer tools including data collection, growth and yield simulations, a decision support system, and post-processing visualization tools.

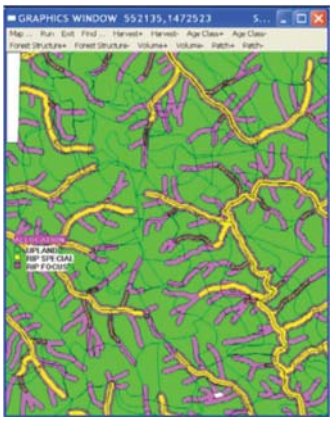
Sessions et al (2006) outline details on a spatial harvest scheduling model that simultaneously schedules timber harvest, forest structure, and transportation (road construction and log transport) at the landscape scale. Strategic and tactical level considerations are integrated in the same model and are not carried out in a multi-stage hierarchical manner. The Harvest and Habitat Model is a harvest scheduling model based on a Model II formulation and uses simulated annealing as the solution algorithm. The Harvest and Habitat model includes the option for a goal programming problem objective function structure to satisfy multiple forest management goals. The spatial modeling functionality is based on an ARM design and includes adjacency constraints to enforce clearcut sizes and greening up periods, and can model the distribution of floating patches of complex forest across the landscape.

The smallest land unit, a parcel, is defined by Sessions et al (2006) as being homogeneous in terms of stand (forest type, structure), slope and aspect, riparian classification, harvest unit, watershed, specific wildlife habitats, and a special classification for the current or desired future condition. The parcel sizes used in a comprehensive wood supply review of Tillamook State Forest in Oregon USA (Sessions et al, 2006) ranged in size from 0.01 ha to approximately 50 ha, with the majority greater than 2 ha in size. The Harvest and Habitat model creates logical harvest units averaging about 20 ha by coordinating the harvesting treatments among parcels subject to the goals and constraints of the model. The harvest unit is the spatial unit that incorporates physical and economic considerations involved in implementing a silvicultural prescription.

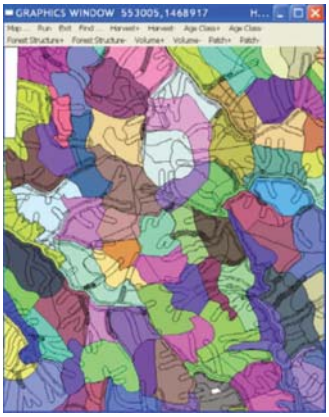
Sessions et al (2006) use a land parcel as opposed to the stand or a larger and higher level management unit, as the parcel land unit provides enormous flexibility for modeling forest management and enables the potential to attain a higher objective function value. Although the stand represents a contiguous area which is homogeneous in terms of its current state and is often considered a logical modeling decision unit it was considered unsuitable for several reasons: (a) existing stands may be too large to satisfy current forest practice rules; (b) stand boundaries may not coincide with management opportunities and costs related to slope and aspect; (c) stands may comprise subdivisions (e.g. wildlife habitat, riparian zone) that must be managed with a different set of management activities that recognize wildlife or other management objectives.

The Harvest and Habitat model coordinates activities within harvest units. "Parcels within the same harvest unit do not need to receive the same treatment, but treatments must occur at the same time. For example, when an upland parcel within a harvest unit is treated, a riparian parcel within the same harvest unit can be treated. However, if the upland parcel is not receiving a harvest, then the riparian parcel cannot be treated. Similarly, it is not required that all upland parcels within a harvest unit receive the same treatment, but the treatments must occur at the same time. For example, parcels on an east aspect within a harvest unit must be treated at the same time as those on a west aspect (i.e., thinned to different densities)." Sessions et al (2006).

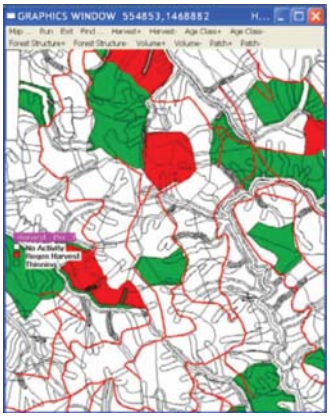
Figure 18: Harvest Units – Parcels, Blocking and Adjacency Restrictions



Upland & Riparian Zones Parcels



Harvest Units (20 ha av)



5 year partial cut (green) regeneration harvests (red) and road system

Source: Sessions et al (2006)

Sessions et al (2006) have structured the model with a goal programming problem objective function structure to handle multiple goals, since they are useful in multi-criteria problems where a feasible solution does not exist without violating one or more constraints. The relative values (weights and structure of the penalty functions) of the goals are adjusted to examine different scenarios, such as trade offs between timber harvested and lapsed time required to achieve complex forest structure (target distribution of patches of complex forest of differing size floating across the landscape). Multiple model runs need to be made to identify dominant solutions for a given set of penalty weights since the simulated annealing heuristic is stochastic.

The Harvest and Habitat model integrates a wide range of functionality required for modeling forests on public lands in particular where multiple and often competing demands are present. The use of goal programming with penalty weights to address multiple objectives, the ability to pre-block land parcels into harvest units, the adjacency/green-up, dynamic aggregation of complex layered forest patches for biodiversity/wildlife habitat conservation, and the incorporation of road networks spatially so that development and costs are correctly accounted for, are all appealing features of the model

A major strength in all three spatial models is the ARM approach so that (a) more efficient groupings of parcels or stands (element of Harvest Unit) are derived, but perhaps more importantly (b) the timing of silvicultural activities are coordinated within harvest units that comprise parcels with different treatment schedules. This feature represents a significant benefit for modeling mosaics of "stands of trees" within uneven-aged forest harvest units.

3.2. Case Studies in Uneven-Aged Forest Management

In North America, forest resource management planning considers a range of financial and regulatory restrictions in determining fiber supply and harvest schedules. Forest managers on public lands also address multiple management goals to meet stakeholder expectations of sustainable forest management.

Substantial research has been undertaken by government and private agencies to ascertain ways to model solutions to many of these management planning issues, and much can be found in the literature. Advances in computer technology hardware and spatial software are now enabling the research to be translated into sophisticated planning tools. The application of this technology is very recent and in some cases is restricted by financial or data availability. Consequently few published examples of applications exist. Some of the core functions that are being integrated in forest estate modeling and examples of their application follow.

- *Spatial adjacency constraints to restrict clearcut harvesting of adjacent harvest units.* Guidelines and regulations imposed on areas of clear-cut size, the minimum buffer width between harvest openings, and the minimum time interval between cuts of adjacent areas (green-up intervals) to maintain forest cover or connectivity. The planning regulations vary between public or private tenure, and by state in the USA or province in Canada. Adjacency methods focus on keeping harvest activity separated by time and space, and increase forest fragmentation since the harvest openings are dispersed over the landscape.

- *Spatial planning methods are adopted to preserve connectivity and minimize fragmentation of old growth (late successional reserve) forest to maintain forest biodiversity and wildlife habitat (particularly that requiring interior forest conditions and limited forest edge).* Connectivity methods focuses on trying to aggregate stands with similar conditions to create a contiguous area of old growth forest to minimize fragmentation.

- *Wildlife Habitat Modeling*
  Canadian government and USDA Forest Service national forests are managed under forest plans that contain guidelines on managing for timber, wildlife, water and other non-forest, social and environmental requirements.

- *Integrating uncertainty into wood supply forecasts through use of stochastic modeling*

  Uncertainty and multiple risks characterize forest management over long term planning horizons due to the large variety of natural, economic, and operational hazards affecting forest ecosystems. Applications of risk analysis are surprisingly rare, despite the large assortment of sophisticated forest planning tools that are available today.

The following examples illustrate the application of various modeling features to North American uneven-aged forest management.

(a) Modeling Connectivity and Shifting Mosaics of Closed Canopy Forests

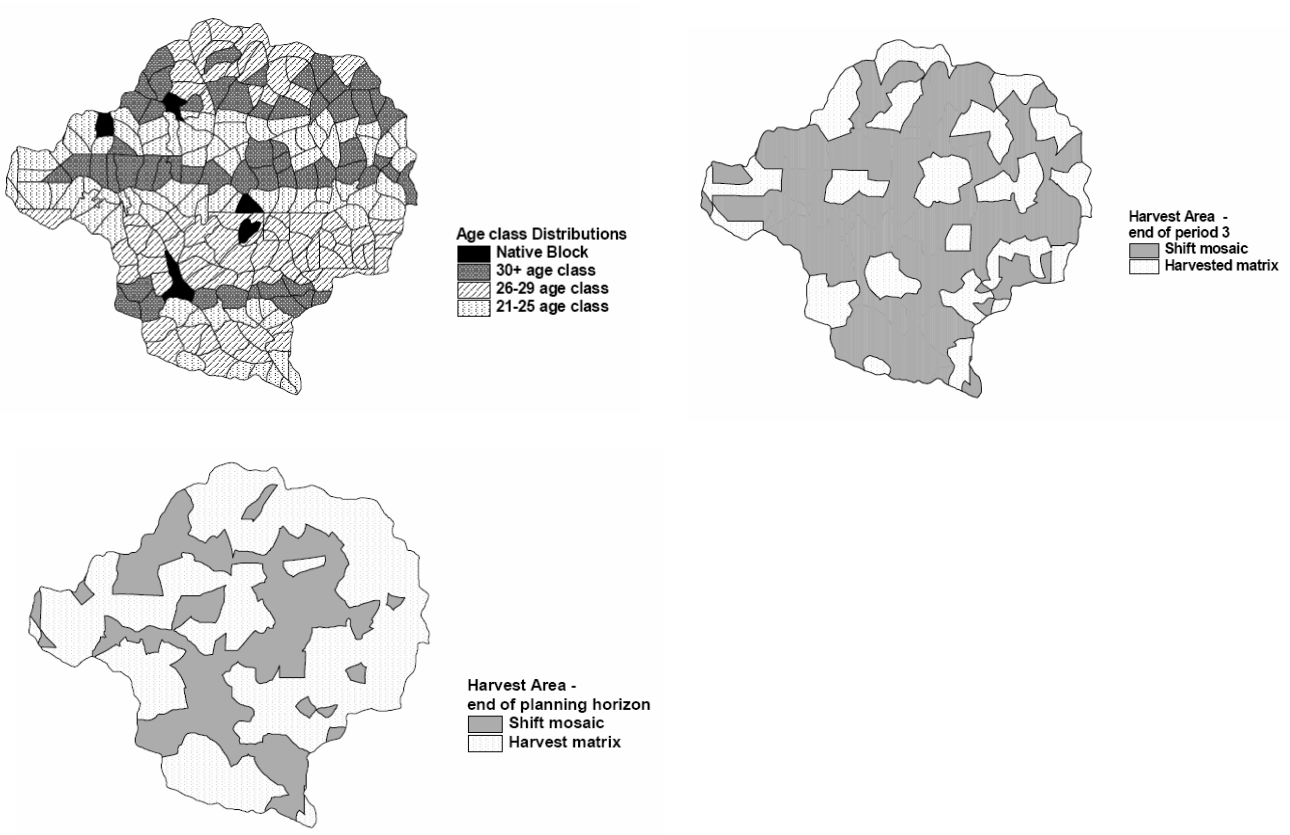
The Harvest & Habitat combinatorial harvest scheduling model was used to successfully model sustainable forest management options at Tillamook State Forest, Oregon, USA (Sessions et al 2006). In this model, contiguous areas were created, including the ability to model shifting mosaics of closed canopy stand connectivity to maintain and improve biodiversity.

The shifting mosaics method is detailed by Boston and Bettinger (2006) where the authors used the approach to improve biodiversity conservation within plantation forests by integrating the connectivity of

remnant native forest patches. The approach is synonymous with connecting specific seral stages of stand types (e.g. old growth) within managed uneven-aged forest.

The model formulation detailed by Boston & Bettinger (2006) was structured to enable both economic and biodiversity goals to be set simultaneously, while meeting constraints on the forest products supply schedule. The biodiversity goals set were (a) to create a shifting mosaic of closed-canopy stands that connect the remnant native forest patches, (b) to maximize the amount of interior forest habitat created each period, and (c) to restrict the maximum clear fell area that could be created for any period. In addition to achieving forest management goals, Boston and Bettinger (2006) note that this modeling approach is useful in quantifying the costs and benefits of various levels of biodiversity protection.

Figure 19: Shifting Closed Canopy Mosaic



Source: Boston & Bettinger (2006)

(b) Examples of Natural Disturbance Pattern Emulation

The Ontario Ministry of Natural Resources has produced guidelines (OMNR, 2001) for management of forestland in the Province, to emulate natural disturbance patterns. OMNR is providing direction for forest managers to create a managed landscape that more closely resembles those created by fire, with the aim of conserving biological diversity. The guidelines will eventually create a landscape that is more natural to those created by many previous species-specific wildlife habitat plans. The guidelines are defined in terms of the location and size of disturbances, the residual stand structure, species composition of the forest and its age class distribution. Table 3 and Table 4 outline components of the approach.

Table 3: Forest Management Natural Disturbance Pattern Considerations

The Coarse Filter	The Fine Filter
Forest composition • maintenance of habitat	**Vulnerable, Threatened & Endangered species** • patch size for caribou • site-specific habitat protection (e.g.. bald eagle, red-shouldered hawk, ginseng and other plants) • peregrine falcon nest site management plan • landscape-level habitat supply (e.g., red-shouldered hawk)
Age Class Structure • movement toward natural • maintenance of older ages	
Forest Patches • shape • range of sizes • amount and size of mature habitat patches • placement (natural landscape texture) • fire salvage • prescribed burns	**Featured Species** • landscape-level habitat supply (e.g., marten, moose, pileated woodpecker) • deer yard management plans • site-specific habitat protection (e.g., moose aquatic feeding areas, mineral licks, osprey nests, heronries, goshawk nests, fish spawning areas)
Residual patches • peninsular • insular • riparian buffers	
Residual trees • live cavity trees • snags • downed coarse and fine woody debris	

Source: OMNR, 2001

Table 4: Planned Clearcuts in Ontario – size frequency, temporal and spatial separation requirements

Clearcut Parameter[1]	Parameter Requirement/Description[1]
Size Frequency	80% < 260 ha (Boreal Forest) 90% < 260 ha (Great Lakes-St. Lawrence Forest)
Timeframe for Creation	≤ 5 years (i.e. detailed planning term; does not apply to shelterwood)
Separation Distances (edge to edge) Between and Amongst Different Sized Clearcuts *NB. Separation distances are averages amongst similar sized clearcuts. Spacing of proposed cuts will be considered and assessed during the spatial allocation of the allowable harvest area during planning.*	If 3 m* regeneration in adjacent clearcut is not reached and the clearcut is less than 20 years old, 10 - 260 ha clearcuts should be separated an average 200 m (minimum 100 m); for every 100 ha increase in the size of clearcuts separate by an additional 50 m from clearcuts of similar size. Separate dissimilar sized clearcuts by the distance indicated by the smaller clearcut.
Time Before Harvest of Adjacent Areas Can Occur	20 years or 3 m* regeneration in earlier cut, whichever occurs first
Characteristics of Forest Separating Two Clearcuts or Shelterwood cuts	Within the separation break, at least 200 m will include forest ≥ 3 m* in height and .3 stocking. For larger separation distances between clearcuts (i.e. 600 m or more) at least 70% of the intervening terrestrial landbase is required to be in forest ≥ 6 m* in height and .3 stocking. * Assumes regeneration standard is met and free to grow

[1] These parameters and requirements apply equally to two clearcuts as well as a clearcut and a natural disturbance.

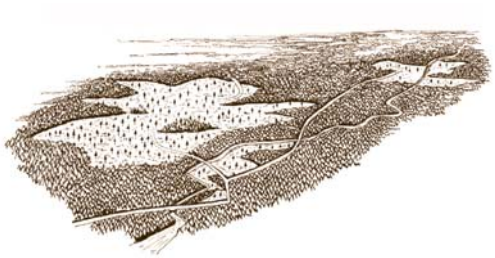
Source: OMNR, 2001

Part of the objective is to modify harvest patterns (clearcut boundaries, size, frequency, and distribution, as shown in Figure 20 and Figure 21.

Figure 20: Change in harvest boundaries and stand structure



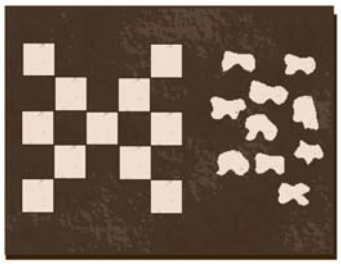
Clearcut



Clearcut emulating natural disturbance pattern

Source: OMNR, 2001

Figure 21: Change at the landscape level patterns – size and distribution of clearcuts



Old style with evenly sized and distributed cuts



Variable sizes with variable spacing

Source: OMNR, 2001 ; Kimmins (2004)

Patchworks (Moore, pers comm.) is being adapted and utilized to implement the natural disturbance emulation approach. Patchworks will be used to generate long term fiber supply forecasts and harvest schedules based on a range of objectives and constraints—the challenge will be integrating all the objectives.

Remsoft (2007a) is also adapting the RSPS to enable the patch analysis that will provide the functionality to model the varying sizes, shapes and locations of harvest openings to emulate natural disturbance.

(c) Integration of Wildlife Habitat Goals in Forest Management

Managing for the retention and enhancement of wildlife habitat in production forests is an increasing requirement across North America. Timber production often conflicts with certain wildlife species, while others require open areas or young forest or early seral stages. The Washington State Department of Natural Resources (Jaross, 2007) is currently implementing habitat modeling into its strategic and operational planning process. It is utilizing the Remsoft Planning System to integrate habitat modeling for the marbled murrulet seabird species and the Northern Spotted Owl.

A comprehensive forest modeling study by Bettinger et al (2001) demonstrated an effective approach to integrating wildlife species habitat goals and land management. Bettinger et al (op.cit.) report three types of wildlife goals that can be used.

- Non-spatial goals – total habitat area
- Spatial goals – minimum patch size such as interior forest
- Spatial goals - adjacency of different habitat types (e.g. two different seral stages such open meadows next to single storey canopy with snags)

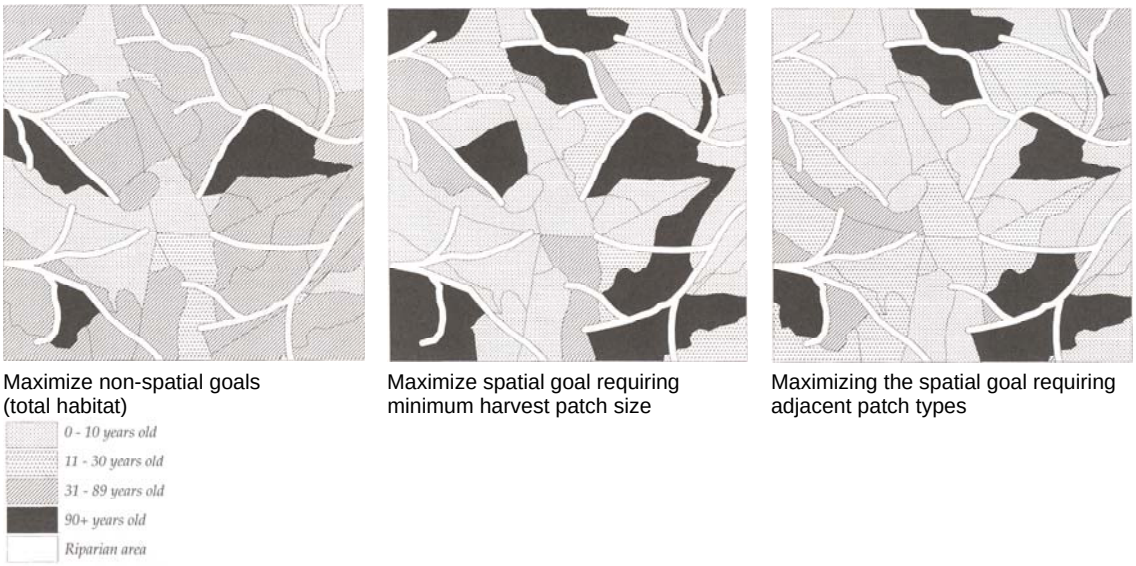
(Bettinger and Sessions, 2003) emphasize that different patterns and connectivity of forest cover are also required to achieve effective wildlife habitat and may include:

- requiring forest patches be distributed across the landscape and connected by corridors
- that forest patches contain certain seral stages (or stand types), possibly in certain complex arrangements
- maintaining large contiguous area of forest (200 – 500 acres) of late seral stage forest to enhance interior forest habitat
- monitoring rate of movement of contiguous interior forest habitat across the landscape.

The wildlife habitat can either be a static design reserve (e.g. old growth forest), and/or dynamic contiguous patches of production forest that is mature or of a certain seral stage.

Bettinger et al. (op. cit.) present details on formulating the goals and constraints, and demonstrate the successful implementation of these with spatial heuristic forest planning tools.

Figure 22: Landscape Condition Under Alternative Habitat Management Plan Goals

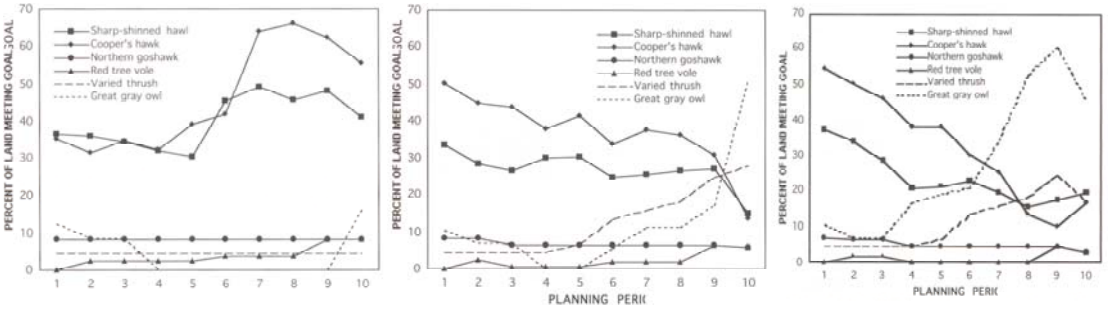


Maximize non-spatial goals (total habitat)

Maximize spatial goal requiring minimum harvest patch size

Maximizing the spatial goal requiring adjacent patch types

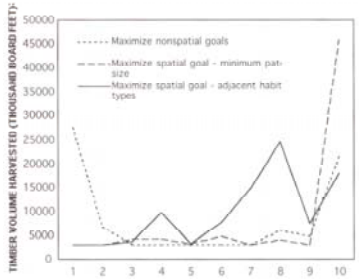
Figure 23: Percentage Achievement of Goal and impacts on other species and timber produced



Maximize non-spatial wildlife species habitat goals

Maximize spatial goal requiring minimum harvest patch size for varied thrush habitat

Maximizing the spatial goal requiring adjacent patch types for gray owl habitat



Source: Bettinger et al (2001)

(d) Modeling Risks - Incorporating Physical and Financial Risk in Harvest Scheduling

Harvest scheduling by North American industrial forest owners such as corporations, timberland investment management organizations (TIMO's) and real estate investment trusts (REIT's) is routinely conducted on a financial basis (maximizing the forest estate net present value subject to various cashflow, wood supply and operational constraints) and incorporate a suite of risk factors. In contrast many public agencies (US Federal and state government agencies, and the Canadian Provincial government) and small woodland owners commonly manage forests with the aim of maximizing the non-declining or sustainable wood supply and/or non-economic objectives.

Risk factors that are being integrated into forest harvest scheduling and general forest management include physical, financial, operational and regulatory factors:

- physical risks affect the volume and quality of timber, such as fire, storms, disease and insects
- financial risks affect the price of inputs (labor, chemicals) and outputs (log products, land transactions). These include economic risks of tax, interest and exchange rate changes.
- operational risks affect operations such as weather, which affects access and harvestability
- regulatory risks affect land use (permissible harvesting, use of chemicals, road construction, wildlife habitat and other environmental considerations) and sale of products (certification)

Risk management approaches depend on the type, frequency and severity of the potential loss, and the planning horizon, planning level and application. The nature of the adjustment will depend on whether the harvest schedule is being used to generate a wood supply forecast and cashflow for purposes of asset valuation, or to ensure sufficient wood fiber is available for supplying exiting contractual commitments.

In Australia much of the natural forest is state owned and managed without explicitly addressing the above-mentioned risks. Instead, losses are considered to be acceptable and manageable. Historically the magnitude of the wood supply capacity relative to supply commitments has been large so the relevant agencies had a sufficient buffer to account for losses over time and in different locations. However, following the implementation of Regional Forest Agreements (regulatory risk) around the country, the area of forest managed for timber production has declined markedly, reducing the ability to manage losses to physical risks.

In contrast, American timberland owners—especially those in the private sector, where most of the commercial timber is harvested—incorporate risk into their modeling programs to anticipate potential losses. Generally physical risk is addressed by making adjustments to growth rates and expected volume and quality of product yields. The yield per unit area is normally adjusted downwards. Alternatively, where risk adjustments are not explicitly deducted, a buffer wood supply may be modeled to ensure there is not a shortfall between actual supply capacity and contractual commitments. Conversely wood supply commitments in Australia could be negotiated so that a large proportion of the wood supply capacity is under long term contract, but medium and short term sales are progressively conducted to absorb any "surplus" uncommitted fiber. So the modeled wood supply level can be set at a percentage higher than the commitment level.

Financial risks are addressed by using pessimistic costs, conservative price expectations, and/or higher discount rates in the harvest scheduling model. The financial estimates vary depending on the planning horizon and planning level. If the harvest scheduling is for strategic planning, average forecasted price trends based on short to medium term historic prices maybe used. Current year seasonally adjusted prices or spot prices may be used for medium term tactical and operational harvest schedules. In commercially driven native forest operations in Australia, (e.g. S.E. Australia) risk factors that should be considered include harvesting and haulage costs, presence of market, and product prices, especially for those products destined for export.

Forest management outputs and outcomes are often very different from those planned as a result of random (stochastic) events such as catastrophic fires, hurricanes, ice and snow storms, drought and insect outbreaks, that cannot be predicted with certainty. The unpredictable nature of events in terms of location, frequency, patterns and severity of damage or loss have traditionally been either ignored or coarse adjustments have been made to growth rates and expected product yields.

Ways of modeling stochastic events include (Davis et al ,2001):

- Adjust yield tables of outcomes to reflect expected or average values based on historic variation. No distinction is made for higher risk age classes, variation in timing, location and size of the disturbance events.

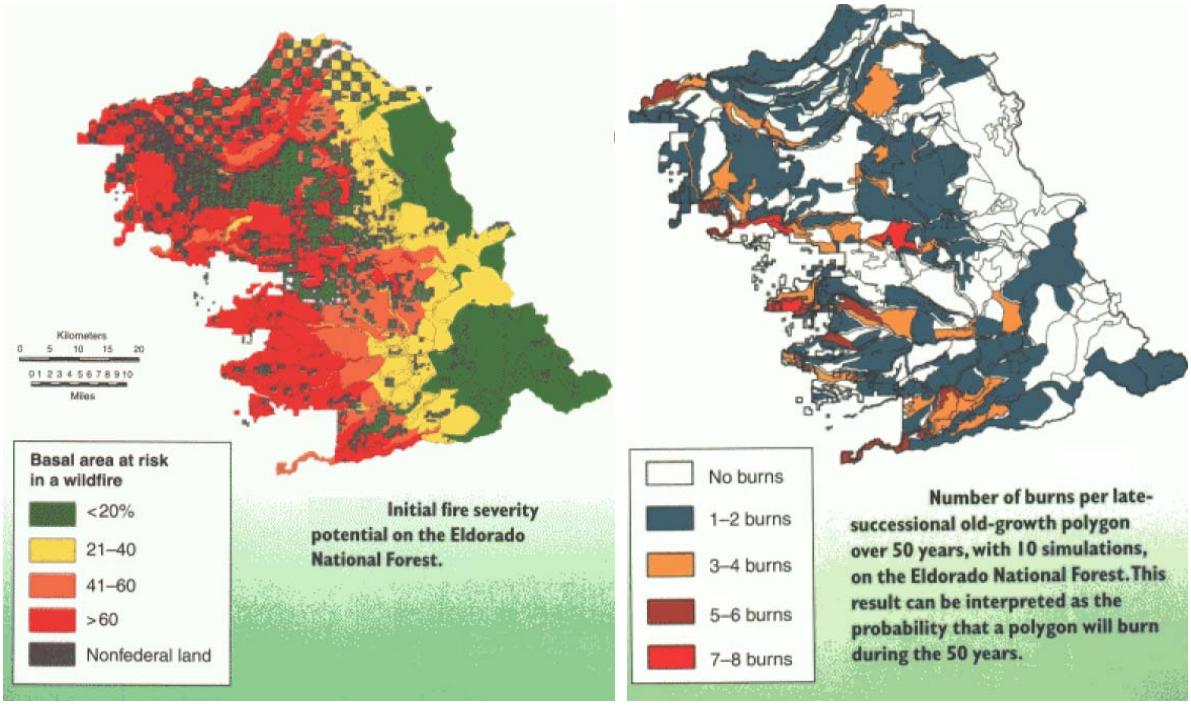
- Sequential programming where the probability of a stand being lost or damaged is applied every year to all stands at random. If selected the relevant yields, costs and revenues are adjusted for those stands selected.

- Spatially defined disturbance events (intensity, size, shape, location and event probability distribution) are correlated to the forest and site conditions based on historic data, then extrapolated spatially to stands in each future planning period.

North American organizations are continuing to develop sophisticated tools to help predict the risk of potential loss of forest area, and the level and type of damage to the forest condition. The USDA Forest Service has been developing modules that link to the growth and yield models for modeling fire and pest outbreaks. Integrating similar functionality in Australia would have obvious benefits, and it is recommended that forest fire and health researchers in Australia evaluate these with a view to potentially working in a collaborative manner with modeling programmers.

Catastrophic losses in forests due to fire, wind, disease and pests are being modeled in forest planning. At the landscape level simulation tools have been used to model fire events. Johnson et al (1998) integrated wildfire into strategic planning in the USA Sierra Nevada ranges. Refer Figure 24 for example of simulation results.

Figure 24: Simulated Risk Severity Classification and Probability of Fire



Source: Johnson et al 1998.

The probability and spatial distributions of stochastic disturbance events such as fire can be integrated into the Remsoft forest estate simulation model to revise wood supply forecasts. Models with well developed natural disturbance functionality include LANDIS-II (He et al, 2005), SELES (Fall, 2003), and TELSA (ESSA Technologies Ltd, 2005)

Future Developments in Forest Estate Modeling

Trends in literature suggest that future forest estate models will continue to integrate increasingly more functions to optimize complex and spatially irregular forest resources; continue to address multi-objective sustainable forest management; have enhanced performance of integrated spatial strategic and tactical planning models; advance modeling of forest disturbance events and other risks, provide more complex transport infrastructure handling; and integrate more flexible and advanced visualization features.

4. Summary

Modeling natural forests is recognized as being an extremely complex science, particularly uneven-aged mixed species forest managed with selection harvest silviculture. This is due to the inherent natural variability in species mixes, forest structures, ecological successional change, irregular but continuous natural disturbance events and variable management histories, dynamic interactions between stand elements, and the changes created by different types of silvicultural intervention.

Even-aged forest silviculture is the more dominant management throughout North American forests, particularly the temperate Fir–Pine-Spruce-Hemlock forests of the Pacific North West, Southern pines in South East USA and the Canadian Boreal forest. But uneven-aged silviculture is practiced throughout much of the deciduous hardwood forests of the eastern USA and Canada, and the extensively managed multi-aged rangeland forest of Ponderosa pine. Significant effort is being made in North America to understand and improve natural forest management through research into stand dynamics and silviculture of uneven-aged pure and mixed hardwood, and mixed hardwood/conifer forests.

In contrast, uneven-aged silviculture is more common in the natural forest management throughout Australia, and there is mounting political pressure to ban the remaining clearcut and coupe logging and convert to uneven-aged natural forest management. Despite the extensive use of selective harvesting systems natural forest silvicultural research is limited. Also implementation of effective uneven-aged forest silviculture has become increasingly difficult as management is subject to increasingly more demanding and stringent political, environmental, and economic restrictions. Even in the absence of these restrictions the periodic catastrophic wildfire events make effective natural forest management difficult and modeling these natural systems poses a challenge for forest planners.

This report explores aspects of technology and approaches used in North American uneven-aged forest management to enable stand level growth and yield modeling, and examines the forest estate models developed for wood supply analyses, harvest scheduling, and sustainable forest landscape management.

In North America advanced quantitative approaches are being developed to model:

- Sustainability of forest systems from economic, environmental and social viewpoints
- Wildlife habitat (continuity and diversity of forest cover; deadwood retention)
- Uneven-aged mixed species natural forest management
- Natural disturbance events (catastrophic wind and fire events, disease outbreaks)

An examination of the North American marketplace for forest modeling systems reveals important differences in comparison to Australia, but also offers some potential ways in which Australia might take greater advantage of modeling systems already in use in North America.

1. It is clear from the availability of high-end models developed in North America that there is no need for development of new products in Australia. Purchasing US and Canadian software and adapting them to local needs is more appropriate than developing local products. Technology developed and available in North America is generally more advanced and extensive than in Australia. The high level of investment by industry, government and universities into forestry modeling research and development reflects the magnitude and economic importance of the forestry sector in the US and Canada.

The Australian forestry sector should continue its strategy of purchasing these off-the-shelf products and working with developers to integrate specific Australian planning characteristics. It would be more cost effective for Australian forestry companies to leverage off international software developments. The software developers are able to provide “off the shelf” products for competitive pricing because of their market share, and also benefit from modeling systems that integrate the collective experience and

knowledge of many different agencies involved in the development and use of the software products. Private companies in North America and New Zealand have continued to provide generic and customized products and demonstrated excellent service to forestry management clients in Australia.

Additional advances could be achieved in natural forest management through:

(a) Introduction and adaptation of various North American software such as:

- USDA Forest Service's Forest and Vegetation Simulator - a forest growth and yield simulation model that can provide a consistent and advanced modeling framework for native hardwood forest management in Australia.

- Oregon State University and Oregon Department of Forestry's Harvest and Habitat forest estate model - a spatial forest scheduling approach that redefines harvest units to facilitate scheduling spatially heterogeneous native forests, and enables the optimization of multiple objectives while simultaneously satisfying spatial and temporal constraints.

- Adoption of transport and roading network optimization technology integrated with forest management harvest schedules

(b) Collaborative Research

Opportunity exists for Australian forestry researchers and practitioners (biometricians, growth and yield modelers, and resource analysts) to work collaboratively with North American agencies. For example, developing more accurate and flexible prediction tools for modeling growth and yield in uneven-aged forest structures would be beneficial, particularly:

- Modeling individual tree selection harvesting of perpetually irregular uneven-aged forest structures

- Modeling the mosaic of spatial variation in stand structures and associated different silvicultural treatments done simultaneously within uneven-aged stands

Developing techniques to generate yield tables that enable unrestricted combinations of temporal changes to the type, timing and intensity of silviculture within uneven-aged management units to provide greater flexibility in strategic-tactical level forest estate models, would provide enormous benefits for forest yield regulation.

2. Pro-active Modeling to Meet Sustainability Requirements

Forests are no longer being managed solely for timber, and likewise, forest modeling is no longer solely for predicting wood supply. Modern forest modeling can be used to help meet multiple and often competing objectives. Given the current state of expectations on private and public forestland managers in both Australia and North America, it is prudent to apply modeling programs which can help to support management decisions.

Public and private forestlands in the United States and Canada are being increasingly scrutinized for sustainable forest management that emphasizes economic, environmental and social values. This comes after decades where North American forest managers practiced sustained yield management that prioritized economic values (timber production). Today, forest management objectives and constraints to management naturally vary widely between forest ownership classes; the type, scale and distribution of the resource; local regulatory requirements; financial cost and revenue structures, economic conditions; and the relevant timber supply and market conditions (size of market, species and quality of products, wood basket, current and forecast wood supply including local region, inter-regional and international competition). The level of competing and some times conflicting demands on production forest depends on the rights, stewardship responsibilities and ownership objectives. These may range from predominantly intensive wood fiber production, accommodating timber commodity and habitat

restoration/production, to that of emulating natural ecological dynamics of vegetative succession and disturbance events.

Public lands are typically required to address multiple demands in its forest management objectives. This is addressed through land-use zoning of different emphases, spatial arrangements of harvesting, and the appropriate silviculture treatments (types, treatments and timing). For example, over the last decade, national forests in the Pacific Northwest have halted most commercial logging, with private forestlands now providing the bulk of timber harvests. National forests now emphasize non-timber forest services and products. Thus there is a significant difference between how private and public forestlands are managed in the U.S. However, it is probably fair to say that environmental scrutiny of forest management has extended from public forests to private forestlands, so that even commercial enterprises must be prepared to be proactive. Private lands have more rights and are able to make non-consultative land use decisions within guidelines and regulatory measures specified by relevant government agencies, and may make proactive decisions to accommodate trends in social and environmental expectations.

There are several dominant modeling approaches that are well developed to facilitate sustainable forest management that are addressed in this report.

- Use of approximation algorithms (heuristics) to enhance multiple objective forest management decision-making
- Wildlife habitat modeling
- Emulation of disturbance events in planning harvest schedules

Multiple objective modeling techniques have been implemented in Australia by explicitly zoning forest areas available for production, habitat and watershed protection and other values. Predetermining the land-use intention as fixed zones rather than addressing dynamic changes in the landscape over time can be far from optimal. Similarly, maximizing the total area without addressing the spatial patterns can be far less optimal than aggregating contiguous areas covering a smaller total area. Technology exists to better characterize the heterogeneity of natural forests and allocate this to maximize the multiple goals while simultaneously meeting the many spatial and temporal constraints. Consideration of integrated Spatial-Temporal heuristic models with an Area Restriction Model formulation combined with goal programming objective functions, such as those developed by Oregon State University (Harvest and Habitat Model) or by Spatial Planning Systems in Ontario (Patchworks) may offer solutions to improving natural forest management planning.

In Australia ecosystem preservation and sensitive watersheds have typically been integrated into landscape modeling, but less emphasis has been given to actively modeling the management of wildlife habitat modeling in commercial forest management. North American agencies have developed sophisticated approaches to modeling in both terrestrial and aquatic wildlife habitats as part of the forest management planning process. It is recommended that Australian modelers and researchers evaluate developments and procedures being used throughout North America.

In Ontario, Canada, the natural forest disturbance events are being emulated as part of the forest management plans. This has resulted in a move away from small dispersed harvesting units so that a range of forest seral stages (forest successional stages) are created more along the lines of historical natural disturbance (fire events in boreal forests). This approach to sustainable forest management is unique and may offer a basis to managing natural Australian forestry.

3. Adaptation of North American modeling to Australia requires modification, especially for Uneven-aged Native Forests

Although Australian Eucalypts are quite unique evergreen hardwoods growing in a largely arid climate, there are fundamental similarities in the ecology and silvicultural systems with most pure and mixed species uneven-aged forests elsewhere in the world. Accordingly, it is potentially possible to utilize North American growth and yield modeling systems for these uneven aged forests.

In North America many uneven-aged natural stands are managed according to selective harvesting systems. Where forests are managed with selection harvesting to maintain or achieve an uneven aged forest structure, the silvicultural specifications are based on achieving a theoretical target stand structure (negative exponential diameter frequency distribution) and desirable species mix, to provide a sustainable flow of wood products of desirable species over time.

Australian native hardwood forests are commonly uneven-aged and managed with selective harvesting silvicultural systems, but achieving a desirable retained stand structure is rarely sought or achievable. This is attributable to the initial irregular stand structures resulting from historical disturbance events, and native forest silvicultural practices are severely restricted in Australia due to economic, environmental and political (social) restrictions. Pressures have led to removal of the best merchantable and commercial trees in current harvest rather than managing for ideal long-term quality forests.

North American growth and yield models address clearcut, seed tree and group selection harvesting systems that are readily applicable to Australian even-aged, two-aged and mesic uneven-aged forests. However, the single tree selection harvesting systems are not readily applicable, as these are based on achieving this theoretical balanced retained stand structure and species composition.

Application of the models to uneven-aged natural forest management is further hindered by insufficient funds available to capture (a) the variability in the spatial distribution of stands (mixed species uneven-aged are highly irregular spatially except where recent large scale disturbance events, due to site variations and irregular temporal and spatial disturbance history) and (b) to provide detailed inventory as inputs to pre-harvest planning and post harvest monitoring of stand structure and growth. Classification of the forest areas into strata and capturing details on the structure and composition of stands is necessary for modeling future growth, impacts of silviculture, and yield forecasts.

The technicalities of integrating growth, mortality, and recruitment functions and specifics of the harvesting systems into the models can be addressed. But to effectively adapt and implement the growth and yield model to natural forest management, particularly with the USDA Forest Services' FVS model, three factors will need to be addressed in Australia:

- more data will be required to classify and inventory natural forest stands
- single tree selection harvesting practices will need to be more consistent and priority given to the target retained stand structure to achieve stand level sustainable wood supply
- alternative harvesting models will need to be developed to model irregular forest structures, to reflect factors driving and impeding single tree selection harvesting of uneven-aged forest

As for adapting North American growth and yield models to Australian forests, certain Australian silvicultural considerations need to be incorporated:

(a) impacts of inappropriate silvicultural systems for shade intolerant Eucalypt forest

Australian forest management regulations outlined in the Regional Forest Agreements specify the type and intensity of silvicultural systems applied in Eucalyptus forest types. Many of these silvicultural regulations have been the product of environmental pressure and politics and were not silviculturally driven. In some areas of SE NSW, Victoria and Tasmania, the conversion of uneven aged forest to even-aged regrowth (or plantation) through clearcutting or seed tree silvicultural systems is permitted. However, most of the uneven-aged forests are managed with single tree selection and low intensity group selection harvesting methods that are unsuitable for effective regeneration and vigorous growth of the preferred and mostly intolerant species. Many of the systems would be better suited to more intensive selective harvesting practices such as clearcut and seed tree silvicultural systems to emulate the ecosystems where natural fire, wind or snow disturbance is prevalent. It is difficult to emulate the impacts of the changing stand dynamics from insufficient site disturbance and openings for regeneration and growth. Insufficient data and experience are available to predict future composition, structure and condition of these stands.

(b) impacts of selective harvesting and silvicultural restrictions on forest economics

Intensive selective harvesting practices and restrictions on silvicultural improvement of stands has left many mature multi-aged forests stagnant and economically unviable.

The Regional Forest Agreements have set many wood supply targets from reduced production forest areas that cannot be met from sustainable yield management of the native forests. To meet contractual commitments from selectively harvested stands, forest managers need to harvest all trees bearing the minimum sawlog dimensions. This practice will result in abnormally lengthened cutting cycles, and quite irregular structures potentially favoring noncommercial species before these stands will provide future yields.

Where regulations prohibit the removal of low quality trees such that only desirable species and trees with high quality sawlogs are removed, the condition of these forests will deteriorate unless silvicultural culling (non-commercial thinning, poisoning, ring-barking) is undertaken. Individual trees are routinely retained for wildlife habitat trees within forest zones designated for commercial harvest. Within commercial forest, harvesting of non habitat trees without sawlogs is not permitted in many of Australia's native forests. Timber Stand Improvement (TSI) involving the culling on un-merchantable and non-commercial species is prohibited or uneconomic in many situations due the absence of market for low quality and small wood (pulp) products or high cost of extraction of these to processing or export facilities.

In the absence of disturbance events such as wild fire, these silvicultural restrictions collectively reduce stand regeneration, tree growth, favor more shade tolerant (and sometimes less commercial) tree species, and reduce the economics of harvesting operations. The stands require intervention such as Timber Stand Improvement (TSI), thinning or reset silviculture (harvesting), to remove the large unmerchantable and noncommercial species to promote regeneration and to stimulate growth on commercial merchantable trees.

4. Realizing more accurate wood supply forecasts and harvest schedules

Optimization forest harvest scheduling models have become the dominant computer technology used for strategic level forest planning, as they have enabled forest managers to:

- generate repeatable and timely forest planning solutions (harvest schedules) that maximise or minimize goals (financial, volume, non-economic values);
- evaluate impacts of complex policy and planning issues on wood supply and cashflow; and
- build in a multitude of temporal wood supply, operational, financial and area constraints

However, the strategic model scenarios have often been developed to provide optimistic solutions that represent the upper level of forest productive capacity. Increasingly it is recognized that spatial constraints that apply at an operational level are required to ensure strategic level wood supply forecasts equate to what can be harvested on the ground. Also the impacts of adverse risk and random catastrophic events are integrated into forest plans to reflect the uncertainty and natural disturbance events that are ever present in forest management.

(a) Use of spatial planning methods to link strategic and tactical planning

Spatially explicit forest planning systems such the Remsoft Forest Planning System (Spatial Woodstock and Stanley), Harvest and Habitat Model (Oregon State University), and Patchworks (Spatial Planning Systems in Ontario) all address spatial considerations. Remsoft addresses the problem as a two-stage hierarchical problem using linear programming for the strategic model and heuristics for the tactical model, while Oregon State University and Spatial Planning Systems have developed fully integrated models based on heuristic technology. Both approaches provide the ability to create harvest units (blocking) and address the main suite of spatial and temporal planning restrictions that forest managers are confronted with today.

(b) Incorporating Physical and Financial Risk in Harvest Scheduling

Risk factors that are being integrated into forest harvest scheduling and general forest management include physical, financial, operational and regulatory factors:

- physical risks affect the volume and quality of timber, such as fire, storms, disease and insects
- financial risks affect the price of inputs (labor, chemicals) and outputs (log products, land transactions). These include economic risks of tax, interest and exchange rate changes.
- operational risks affect operations such as weather, which affects access and harvestability
- regulatory risks affect land use (permissible harvesting, use of chemicals, road construction, wildlife habitat and other environmental considerations) and sale of products (certification)

North American organizations are continuing to develop sophisticated tools to help predict the risk of potential loss of forest area, and the level and type of damage to the forest condition. The USDA Forest Service has been developing modules that link to the growth and yield models for modeling fire and pest outbreaks. Integrating similar functionality in Australia would have obvious benefits, and it is recommended that forest fire and health researchers in Australia evaluate these with a view to potentially working in a collaborative manner with modeling programmers.

Future Directions

Some future areas of forest modeling research that would be beneficial for uneven-aged forest management planning include finding:

- Better ways to model the growth and yield for harvest units that comprise multiple stands that vary in species composition, vertical structure and spatial patterns, and to link this to forest estate models

- Better ways to model uncertainty of forest risks and limitations of growth and yield models, in timber supply forecasting and harvest scheduling

Resource planning is subject to continuous change—from environmental factors, political and regulatory change, changes in societal expectations and needs, economic cycles, and technological developments—that requires adaptive management. Part of this includes the adoption of new technology advances.

It is hoped this report provides some options and some direction in technological developments in the immediate future for resource managers and planners.

Views on appropriate technology and direction for development beyond the immediate future might be gleaned from a quote on the future management of forests Davis et al (2001):

"We expect the future will find society in both the United States and the world to zone its forest land so as to have areas allocated to intensive wood and fiber production, areas for joint commodity and habitat production, and areas primarily for the protection and restoration of ecosystem processes. Forest management at its highest level will involve coordinating the contribution of mixed ownerships in all three zones to sustain regional, national, and global ecosystems. Clearly, this will also require resolution of legal and political issues over private rights and public responsibilities and over competitive versus cooperative models of social and economic organization."

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Appendix A Nomenclature / Glossary Definitions

age class distribution A histogram of the area occupied by distinct age classes of forest.

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

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

cohort. Aggregation of trees that starts as the result of a single disturbance. If age of trees within a cohort is very narrow then it is a single age class that is even-aged. (Smith et al 1997)

combinatorial optimization
Combinatorial optimization problems are concerned with the efficient allocation of limited resources to meet desired objectives when the values of some or all of the variables are restricted. Constraints restrict the possible alternatives that are considered feasible. In combinatorial problems there are many possible feasible alternatives to consider and one overall goal determines which of these alternatives is best.

In a combinatorial optimization model the activities and resources are indivisible, so only a finite number of alternative feasible solutions exist. Combinatorial optimization is the process of finding one or more best (optimal) solutions in a well defined discrete problem space. The models are computer programs with a function to be optimized and constraints restricting the possible solutions whose functional forms are normally linear but may be non-linear functions.

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

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

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

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

generalized Model II Model II is a form of linear programming harvest scheduling models where decision variables represent a stand only over the course of a single rotation. In traditional Model II, once the stand is harvested, the area in the original decision variable is transferred to a new decision variable at age 0. Generalized Model II not only allows the transfer of area when a stand is harvested, but also allows transfers due to mortality or silvicultural treatment and allows transfers to ages other than 0. (Remsoft, 2004)

goal programming A LP minimization problem where the objective function sums deviations from stated output goals; if all goals can be met exactly, then the objective function value is zero. Goals may be weighted equally or they may have different weights; goals with higher weights are favored over those with lower weightings. (Remsoft, 2004)

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

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

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

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

Lagrangian relaxation A modeling technique where hard constraints are transferred into the objective and penalties are imposed on the objective function if they are not satisfied (violated).

Linear programming An optimization technique that will choose the best alternative from a set of possible or feasible alternatives. It is a method of allocating scarce or limited resources among competing activities in an optimal manner. LP models are composed of a linear objective function subject to linear constraints. (Remsoft, 2004)

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

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

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

Monte Carlo simulation A modeling technique that allows some activities to occur based on a probabilistic basis. Although the activity may occur with probability (P) in any given run, there is no guarantee that it will occur. Therefore, each simulation run can yield different results; in a regular inventory projection model where activities occur with certainty, the answer is always the same no matter how many times you run the model. (Remsoft, 2004)

Optimal A mathematical programming concept for a class of solutions to a problem definition in which the objective function value is at a global maximum or minimum. (Remsoft, 2004)

Optimal Solution An optimal solution is a feasible combination of decision variables that yields the highest objective function value for a maximization problem and the lowest objective function value for a minimization problem. Although no other solution exists for a given problem that will yield a higher objective function value, other solutions may exist that yield the same objective function value. These are termed alternative optimal solutions. (Remsoft, 2004)

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

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

sensitivity analysis A method used to determine the relationships between measures and assumptions used in an analysis, and to determine the effects of changing the value of measures and assumptions on

the results of an analysis; is usually conducted by recalculating an analysis a number of times each with a change in one measure or assumption at a time.

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

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

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

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

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

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

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

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

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

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

Type I Model Formulation

Type I models retain the identification of individual analysis units (AU) throughout the planning horizon. The AU's may include geographical division of a stratum or harvesting units such as compartments or stands. The model evaluates the alternatives for managing an analysis unit over multiple rotations. A predetermined schedule of operations over multiple rotations is applied in the first period to the analysis unit and this is retained for the whole planning horizon. The yields based on a predetermined schedule of operations over multiple rotations is represented with time dependent yield tables. Each analysis unit is assigned one yield table for the complete planning horizon.

The yield table is constructed from the expected flow of yields from the predetermined sequence of management actions. A key feature of the Type I Model is that the yield table is based on a proposed management schedule for the whole planning horizon over multiple rotations. The management schedule comprises the current intended silvicultural regimes (type, intensity and timing of operations, and rotation lengths) and future regeneration species and silvicultural regime. The management schedule underpinning each yield table represents one of many possible options for both the existing and all future stands.

The management schedule assigned in the first modeling period applies for the entire planning horizon to an analysis unit to form a management unit whose integrity is retained throughout the planning horizon. The other key feature of Model I formulation is that the analysis unit remains identifiable throughout the planning horizon. Only one decision variable (management regime) is applied to an analysis unit. The

decision variable represents one of many possible management schedules for both the existing and all future stands.

Type II Model Formulation

In Type II models the analysis unit is an age class within a development type or crop type (that are in turn various amalgamations of geographical / administrative areas and forest types). Analysis units are assigned a yield table from a range of management alternatives for a single rotation only. The sequence of current and future options over the planning horizon are not pre-determined. At the end of the rotation analysis units lose their identity upon being clearfelled and become a new age class. If different age classes within an analysis unit are cut in the same period these will be merged into the new age class. The new age class may be regenerated as alternative species and managed with a different silvicultural regime. At critical ages for silvicultural treatments the whole or part of the analysis unit may be transferred to another management option e.g. from unthinned to thinned stand.

In Type I models the analysis units are treated as an area whose management is traced throughout the planning horizon. In a Type II Model the situation is more complex since an analysis unit can be an individual stand or an entire stratum. When an analysis unit is large (e.g. stratum age class covering a number of stands in geographical areas) and is partially cut within a period, it is difficult or impossible to identify which geographic unit is being cut as the integrity of the area unit is not maintained. The management can be traced if smaller and unique areas are defined.

Since a Type II harvest regulation model is able to choose from a suite of yield tables and select different clearfell ages for each rotation, and the integrity of analysis units does not need to be preserved, so virtually unlimited combination of management schedules can be derived over the planning horizon. This provides a large amount of modeling flexibility which is beneficial in regulating wood supply from an irregularly structured forests estate.

The Type II models are particularly suited to even-aged forests where age-dependent yield tables are used. Uneven-aged forests are typically modelled with time-dependent yield tables.

Age–dependent yield tables are normally used for Type II models in conjunction with a range of constraints outlining clearfell age ranges, possible transfer options between silvicultural regimes, replanting/regeneration options (species, silvicultural regimes) and in what proportions of each option.

Appendix B Natural Forest Management: Structures, Stand Dynamics and Silviculture.

Modeling natural forests is recognized as being an extremely complex science, particularly uneven-aged mixed species forest managed with selection harvest silviculture. This is due to the inherent natural variability in species mixes, forest structures, ecological successional change, irregular but continuous disturbance natural events and variable management histories, dynamic interactions between stand elements, and the changes created by different types of silvicultural intervention.

Modeling the temporal and spatial variability is compounded by the often limited historic data on forest composition and stand dynamics, and the long time period required to ascertain the impacts following shifts in silviculture applied or following major natural disturbance events. This situation is also hampered by the limited availability of funds for natural forest management inventory and aerial forest stratification and classification of the resource.

Even-aged forest silviculture is the more dominant management throughout North American forests, particularly the temperate Fir–Pine-Spruce-Hemlock forests of the Pacific North West, Southern pines in South East USA and the Canadian Boreal forest. But uneven-aged silviculture is practiced throughout much of the deciduous hardwood forests of the eastern USA and Canada, and the extensively managed multi-aged rangeland forest of Ponderosa pine. Significant research effort is being made in North America to understand and improve natural forest management through research into stand dynamics and silviculture of uneven-aged pure and mixed hardwood, and mixed hardwood/conifer forests.

In contrast, uneven-aged silviculture is more common in the natural forest management throughout Australia, and there is mounting political pressure to ban clearcut and coupe logging and convert to uneven-aged natural forest management. Despite the extensive use of selective harvesting systems natural forest silvicultural research is limited. Also implementation of effective uneven-aged forest silviculture has become increasingly difficult as management is subject to increasingly more demanding and stringent political, environmental, and economic restrictions. Even in the absence of these restrictions the periodic catastrophic wildfire events make effective natural forest management difficult and modeling these natural systems poses a challenge for modeling and forest planning.

Management and research into uneven-aged forests in North America continues as this is often the most suitable form of management for various forest ecosystems, but there is increased engagement in this form of management in some areas (particularly on public lands) due to political pressure stemming form environmental groups concerned about the ecological sustainability and other non-production forest uses. The following section examine some of the reasons for and against uneven-aged forest management.

This chapter provides a systematic classification of the various natural forest systems, stand dynamics and disturbance events, and an overview of the silvicultural systems that are used. This lays a foundation of understanding stand level growth and yield modeling options available, and on forest estate models developed for wood supply analyses, harvest schedules, and sustainable forest landscape management.

B.1 Reasons For and Against Uneven-aged Forest Management

Reasons for supporting practice of uneven-aged management:

- Aesthetics – especially public lands and small forest owners unwilling to wait for regeneration cover following harvest of mature forest.
- Continuous flow of wood products at stand level. This is applicable to small forest holdings where an even flow of income is preferred.
- Continuous flow of wood product mix (different diameters) for markets that cannot be achieved from small holdings of insufficient even-aged stands.
- Continuous canopy cover is necessary for soil and water protection in unstable sites.
- Maintenance of vertical and spatial structural diversity for wildlife habitat.
- The ecology of the stands are best managed by using selective harvesting silviculture – such as regeneration of shade-tolerant species.

Disadvantages in uneven aged forest management:

- Intensive management required. This results in regular entry into stands requiring more road investment, increased harvest damage to residual stand.
- Higher harvesting costs as lower volume removed per unit area; extraction productivity is lower.
- Revenue is lower since the average piece-size is often smaller - to maintain ideal stand structure and to obtain sufficient volume for viable harvesting, a range of diameter trees are harvested.

B.2 Forest structures, composition and patterns

Many natural forest are not uneven-aged and mixed stands, and what appears uneven-aged are in fact even-aged. In North America some species occur in truly pure (monospecific) uneven-aged stands such as Ponderosa pine on dry sites that can be managed to maintain the uneven-aged canopy cover. Many natural stands of mixed hardwoods or mixed hardwood/conifer stands with variable sized trees are in fact not uneven-aged, but actually uneven-sized even-aged stands of regrowth following a major disturbance event or release cutting. Large areas of the US east coast forests fall into this classification as they were historically high-graded or cut-over for pasture but are now reverting back to forest cover. This has resulted in a layered structure of shade intolerant species in the upper strata (initial fast growing species) and increasingly shade tolerant slow growing trees in successively lower strata. Depending on the species mix and site conditions, such stands show changing composition over time as the initial dominant emergents are overtopped or replaced by the more shade tolerant species. Active silviculture is required in these stands to maintain a healthy vigorous forest otherwise will need to be replaced with a clearcut, seedtree or shelterwood harvest.

This section provides a structured account of the many and varied natural forest structures that are evident in the North American and Australian landscapes.

B.2.1 Stand Structures in Natural Forests

Natural stands are traditionally classified in terms of age class structures and species mix. Often stands are classified as pure or mixed species, as being even-aged, two-aged or uneven aged stands, and as balanced or irregular. Figure 25 illustrates some of the different stand structures recognized by Smith et al (1997)

- Even aged (single cohort)
    - Pure
    - Stratified mixture
    - Mixed single canopy

- Uneven-aged (multiple cohort)
    - Balanced stand (pure or mixed)
    - Irregular stand (pure of mixed)

- Double cohort (two age classes)
    - Pure
    - Mixed

Even-aged stands

Even-aged stands generally comprise one age class or at least the same cohort. (Smith et al,1997). Even-aged stands often occur naturally after a major disturbance (such as wildfire) destroys the forest and stand regeneration is initiated and maintain their even-aged structure until the next major disturbance occurs. The BC Ministry of Forests (1995) defines even-aged stands as having:

- a narrow range of tree ages (the regeneration period between the oldest and youngest trees is not greater than 20% of the length of a standard managed rotation)
- regeneration established relatively synchronously within a short period following a major disturbance,
- one or two distinct and well-represented age classes, and
- typically an even canopy (although even-aged species mixtures can form two- or multi-layered stands).

Smith et al (1997) identify 3 subcategories of even-aged stands:

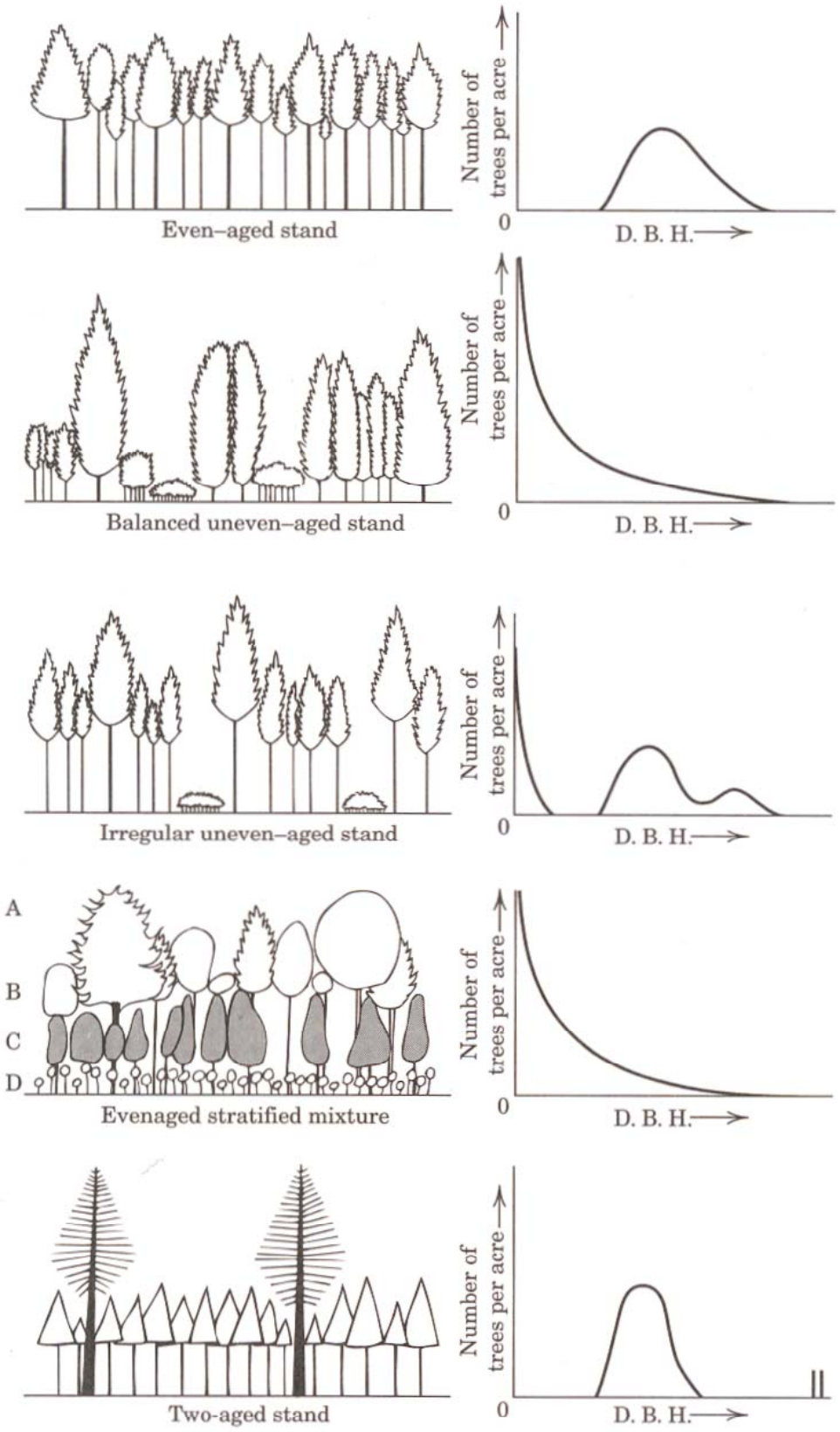
(a) Pure even-aged single canopied species

The diameter distribution of pure (single species) even-aged stands generally have a near normal distribution (unimodal). These even-aged stands generally have a well-developed canopy with a regular top at a uniform height. These stands are very common naturally as they usually result after severe natural disturbances such as wildfire or windstorms. Managed stands are typically in this class and are managed using clearcutting silvicultural systems. Plantations are planted or aerially seeded, while natural stands propagate naturally.

(b) Mixed Single Canopy

Two or more species of the same age in a stand are intermingled (not small patches or clumps) and have uniform rates of height growth and form a single canopy stand. This stand structure is uncommon as one species typically suppresses the other species as the stands mature. On certain sites the difference in growth may be accentuated. Loblolly and shortleaf pine mixtures exhibit these characteristics. In certain mixes it may be necessary to constantly thin the stands to remove inter-species competition and maintain a single canopy.

Figure 25: Stand Structures – Vertical cross section and diameter distribution



Source: Smith et al, 1997

(c) Single Cohort Stratified Mixture

Mixed species even-aged stands can have quite different structures depending on the species mix. Mixes of conifer and hardwood species, or trees of different shade tolerances are often characterised by a layered forest structure (not to be confused with uneven-aged). The level of difference varies by species mix, as it depends on the growth rates and maximum tree size (diameter and height) and competitive ability of each species for a given site, the stand conditions, and the relative shade tolerance of the trees. In this situation the stands may be characterized by multimodal (2 or more) or balanced reverse j-shaped diameter and height distributions. Different diameter classes represent different species with different heights rather than different age classes

In simple stratified mixtures each species occupies a different stratum as they have different height and tolerance levels. There may be more than one species in a stratum. The species are normally arranged with intolerant species in the upper strata, and successively lower layers occupied by more shade tolerant species. This vertical pattern of species changes for some mixes later in stand development, with intolerants being superceded by slower growing tolerants.

Uneven-aged stands

Uneven-aged stands, or multi-cohort stands, comprise at least three well-represented and well-defined age classes of trees (differing in height, age, and diameter) that are closely intermingled on the same area Smith et al (1997). These three classes can be broadly defined as: regeneration (or regeneration and sapling), pole, and mature (or small and large sawtimber). Uneven-aged stands develop as either the result of tree mortality and the formation of gaps in the canopy, or harvesting of the stand at short regular intervals. These stands have an uneven and highly broken or irregular canopy (often with many gaps) as a result of periodic disturbance events. (BC Ministry of Forests, 2007)

Johnson et al (2005) point out that uneven-aged stands are usually comprised of small even-aged groups of trees that blend into one another. A distinguishing characteristic is the stand structure, with vertical crown stratification and range of tree diameters within a relatively small area. The BC Ministry of Forests (2007) defines an uneven-aged stand as a mosaic of small even-aged clumps and scattered individual trees. Stand age classes develop with a high degree of randomness in space and time, and are the result of perpetual cycles of random disturbances such as low-intensity fires, windthrow, and insect or disease attacks. The disturbance events cause scattered mortality followed by new regeneration and growth of advanced regeneration, resulting in temporal waves of different age-classes dispersed throughout the stand.

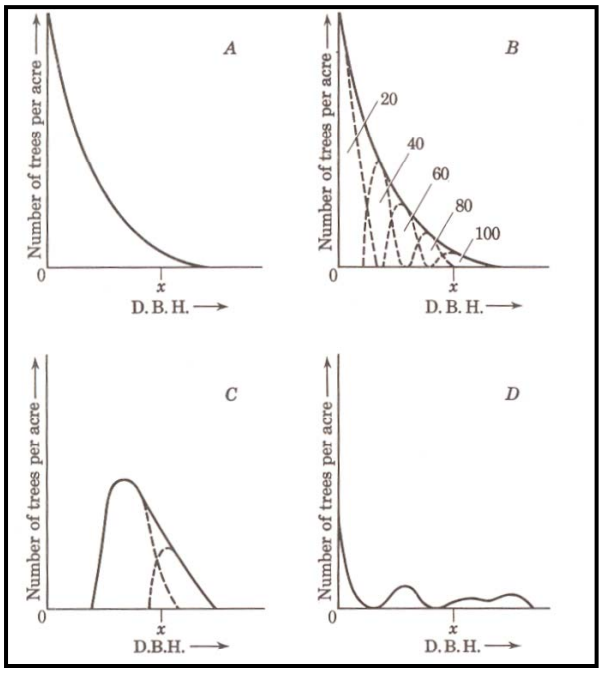
Theoretical uneven-aged stands have a diameter distribution with reverse J shaped distribution that is related to tree age, rather than differential growth rates of various species that occurs in mixed species single cohort stands. The diameter distribution in a multi-cohort stand is a composite of individual cohort distributions, as illustrated in Figure 26. In true uneven-aged stands, vigor is maintained in all age classes. Most stems occur in the smallest age/size class, as regeneration quickly fills the frequent canopy gaps that occur in the uneven-aged stand. This density of trees declines as age/size classes increase through normal species competition, such that the largest age/size classes can be quite scattered (although distribution may be highly regular). Since regeneration is initiated in small gaps, more shade-tolerant tree species are generally favored. (BC Ministry of Forests, 2007)

Smith et al (1997) distinguish between balanced and irregular uneven-aged stands:

(a) A balanced stand comprises three or more equally spaced cohorts or age classes each of which occupies approximately equal area. The diameter distribution is characterized by a smooth reverse J shaped curve described above.

(b) An irregular uneven-aged stand has irregularly spaced cohorts or age classes, so it has an irregular diameter distribution. This is typical in many unmanaged stands and partially cut stands.

Figure 26: Diameter Distributions of Uneven-aged Stands



A. All-aged stand of 1 acre containing sufficient trees in each diameter class to produce an unvarying number of trees of optimum size (of diameter *x* or larger) at rotation age.

B. A balanced uneven-aged stand of the same diameter distribution may be composed of five age classes, each occupying an equal area, with a 100 year rotation.

C. A stand of two closely spaced age classes and no advance reproduction. Selection cuttings in this stand will produce abnormally high yields of timber until all existing trees reach optimum size. Thereafter they will yield nothing until all new growth reaches merchantable size. It is difficult to create a balanced distribution in such stands in one rotation period, especially if the smaller trees do not respond to release after selection cuttings.

D. An example of irregular uneven-aged distributions that may be found in virgin stands. This one contains four well distributed age classes, one of which is well beyond optimum age for economic rotation. Such a stand could be gradually converted to the balanced form provided that the intermediate age classes did not deteriorate after partial cutting.

Source: Smith et al, 1997

The complexity of the stands is compounded by species composition. Most multi-cohort stands are usually mixtures of species. Pure uneven-aged stands usually only occur where there are soil moisture deficiencies or occasional light fires. These are often small pure groups of even-aged stands, but where cohorts interface the older cohorts impede the growth of younger cohorts. e.g. Ponderosa pine forms natural multi-cohort stands

Mixed multi-cohort stands are usually complex with species randomly intermingled with other species and comprising random small patches of different age cohorts and stratified mixtures. These stands are characterized by trees of a given species (or tolerance class) and different ages occurring in different layers and diameter classes. This “chaotic” structure results from patchy disturbance events. Irregular age classes are more common and are the result of random events of nature and “high grading” silviculture. The balanced stand with a reverse J shaped diameter distribution curve is mostly created by silvicultural management. “*The best silvicultural solution for managing such stands lies in diagnosing the processes taking place in each separate part and treating it accordingly*” Smith et al (1997)

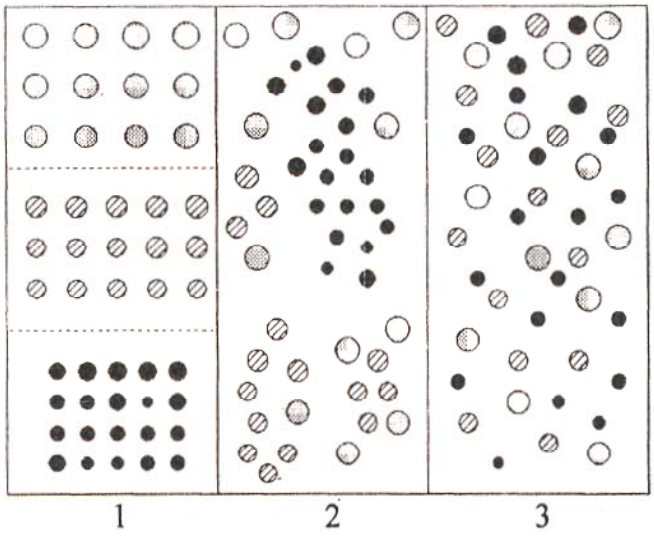
Double-Cohort Stands

Two-age class stands occur in two-layered natural or managed stands. These stands may be mixed or pure species composition. These are an intermediate classification of forest that may be temporary or continuous. Typically a new cohort starts beneath the canopy of an older cohort that is partially or entirely eliminated. These can be the result of fire in an even-aged stand, periods of drought, grazing pressure, or lack of flooding that restricts regeneration for extended periods of time in an otherwise uneven-aged stand, or active management (shelterwood or seed tree silvicultural systems).

B.2.2 Spatial patterns of Natural Forests

Forests with the same frequency (height and diameter) distributions can be have quite different spatial structures. Figure 27 illustrates hypothetical arrangements of the same number of 3 different species, ranging from groups of pure species in the same forest area, to species intermixed and clustered in a seemingly random pattern. The spatial structure of trees in mixed forests is important because the spatial pattern affects the stand dynamics - the growth, mortality and recruitment of individual trees or certain species varies depending on their shade tolerance, relative competitiveness and relative proportions. The scale of analysis areas (forest, stand, plot) and the required resolution of modeling affects the importance of the spatial structure.

Figure 27: Different spatial arrangements in mixed species forest



Source: von Gadow and Hui (1999)

B.3 Stand Dynamics and Disturbance Events

This section of the report addresses aspects of stand dynamics and pathways of ecological succession in uneven-aged stands created by silvicultural intervention and disturbance events.

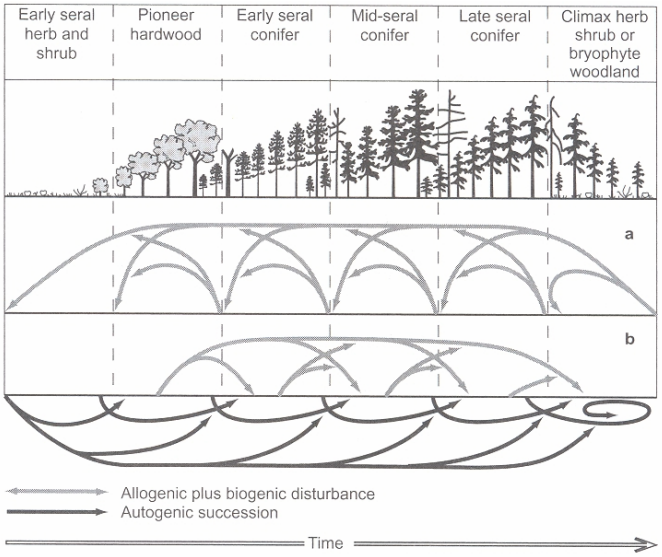
The dynamics of natural forest stands are complex with interactions between the growth, mortality, and recruitment of trees and other vegetation. The interactions depend on the mix of species, the relative composition of each species, the shade tolerance of each species, the site conditions and how each species responds to that site, the structure and density of the stand. These dynamics are compounded by result of natural ecological succession; the severity, scale, frequency and type of natural forest disturbance events (fire wind, snow, insect invasion); and the type, intensity, and frequency (length of cutting cycle) of silvicultural interventions.

Comprehensive accounts of North American ecology, stand dynamics, silviculture and disturbance regimes in uneven-aged forests are described in:

- Forest Stand Dynamics by Oliver and Larson(1996)
- Forest Dynamics and Disturbance Regimes – studies from temperate evergreen-deciduous forests by Frelich (2003)
- North American Terrestrial Vegetation by Barbour and Billings (2000)
- The North American Forest – Geography, Ecology, and Silviculture by Walker (1999)
- The Ecology and Silviculture of Mixed Species Forests by Kelty et al (1992)
- Ecology and management of Central Hardwood Forests by Hicks (1998)
- The Ecology and Silviculture of Oaks by Johnson et al (2005)

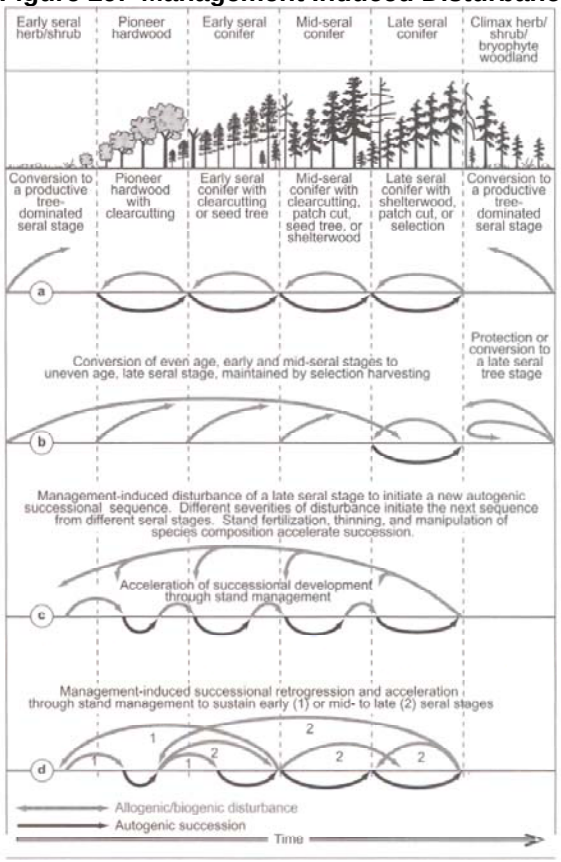
Forest ecosystems are naturally subject to continuous change through natural vegetation change from competition (autogenic disturbance) and disturbance events (allogenic disturbance). The expected pattern of forest ecosystem development deviates with disturbance events. There are a wide range of possible successional consequences (regressive and progressive) from natural disturbance and management intervention (biogenic disturbance), that vary in the type and severity of disturbances and in different seral stages. (Kimmins, 2004). Figure 28 to Figure 30 illustrate the impacts of natural succession, disturbance events and silvicultural intervention of changes to natural forests

Figure 28: Natural Succession interacting with Natural Disturbance Events



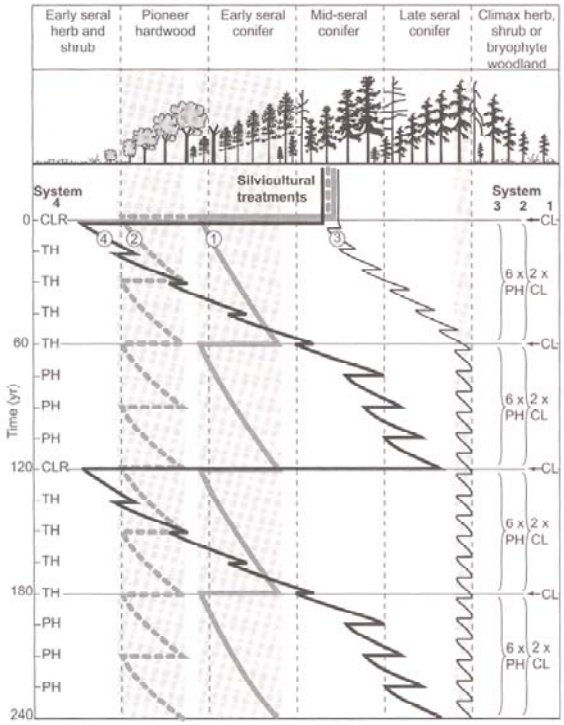
Source: Kimmins (2004).

Figure 29: Management Induced Disturbance to Achieve Different Seral Stages.



Source: Kimmins (2004).

Figure 30: Strategies for Managing Ecosystem Disturbance to Achieve Silvicultural Objectives

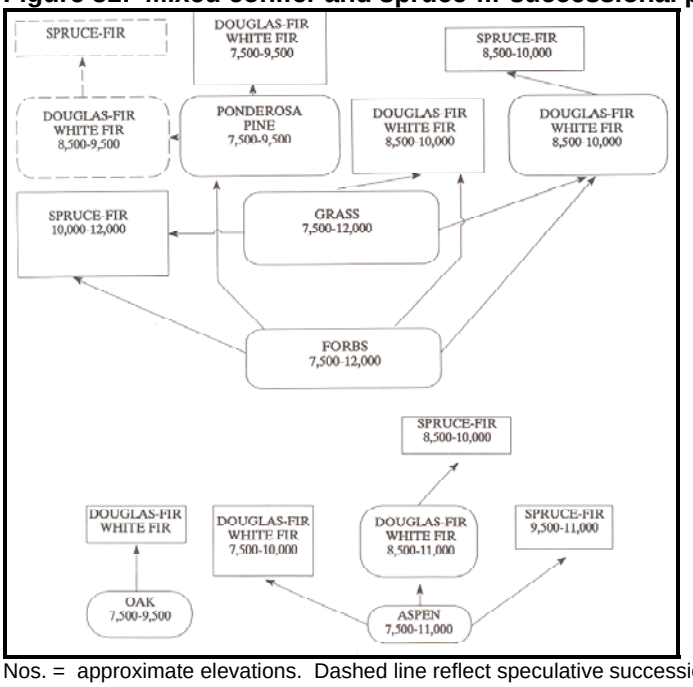


Source: Kimmins (2004)

Pathways of forest structure and composition altered by silviculture

The following Figure 31 and Figure 32 illustrate examples of natural succession in conifer and hardwood forest.

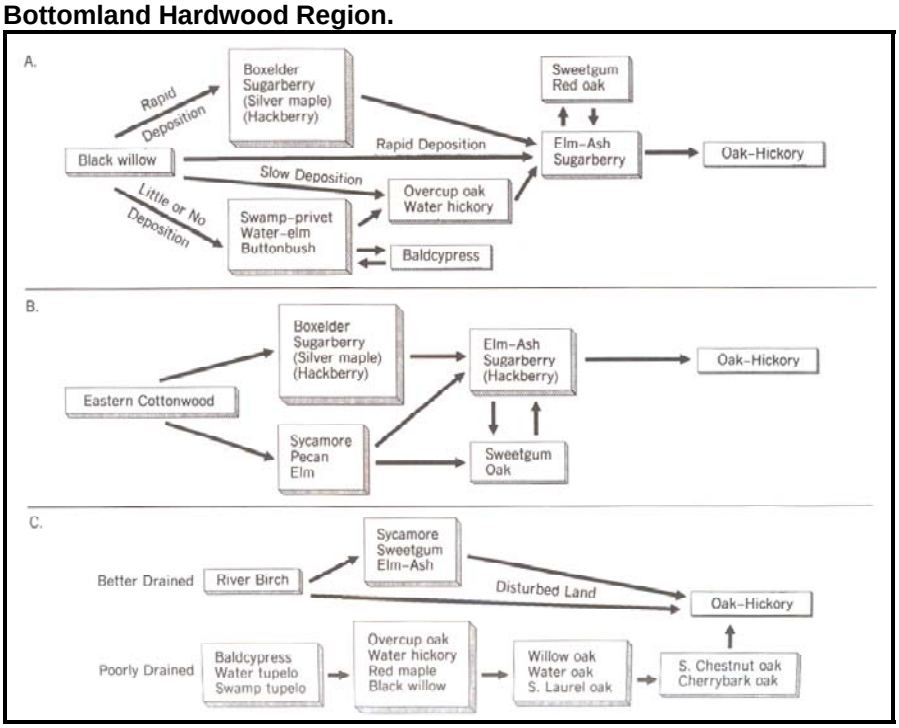
Figure 31: Mixed conifer and spruce-fir successional pathways in Southwest Canada



Nos. = approximate elevations. Dashed line reflect speculative successions.

Source: Barrett 1995

Figure 32: Patterns of natural succession in major and minor stream bottoms of the Southern Bottomland Hardwood Region.

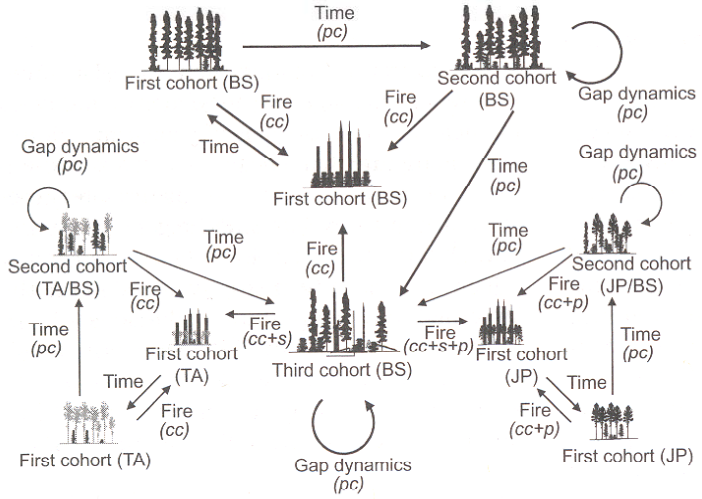


A. Succession beginning on poorly drained sites at low elevations in major bottoms.
B. Succession beginning on better-drained higher-elevation sites in major bottoms.
C. Succession in minor bottoms.

Source: Barrett 1995

Figure 33 and Figure 34 illustrate examples of the ability to manipulate stand condition and composition from succession in conifer and hardwood forest.

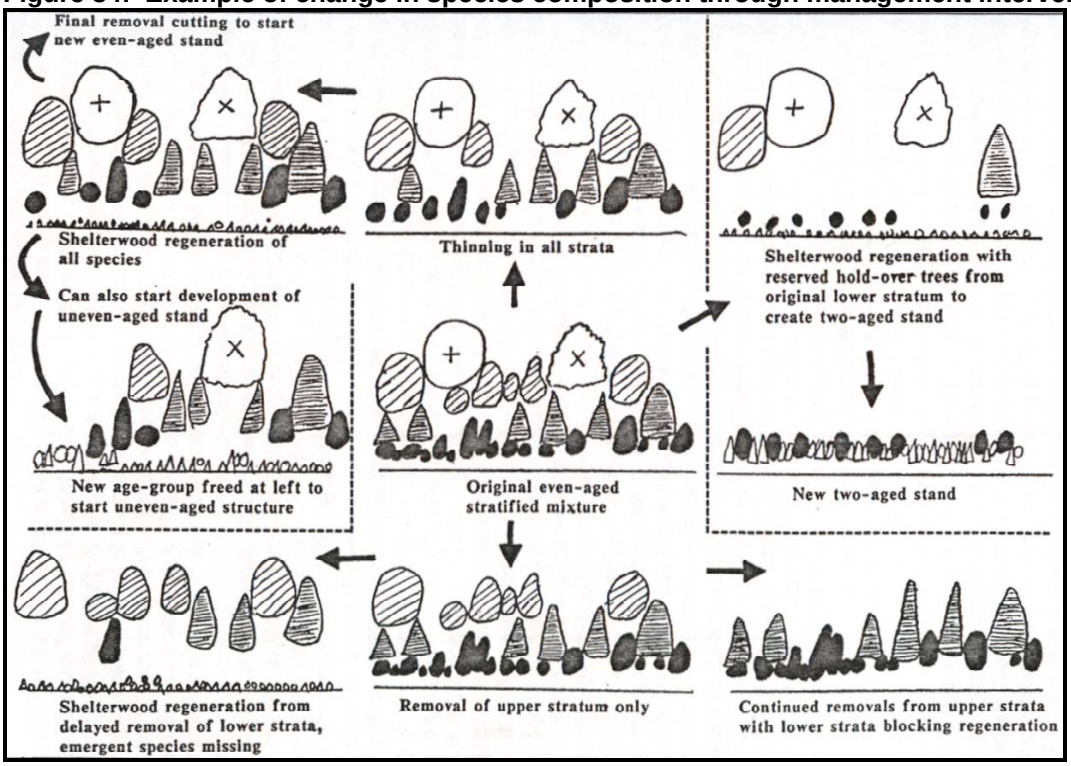
Figure 33: Example of change in forest composition from combination of natural disturbance and management intervention.



Conceptual model of natural forest dynamics proposed for Quebec's Matagami ecoregion and the corresponding management strategy. BS = Black Spruce, JP = Jack Pine, TA = Trembling Aspen, cc = clearcutting, p = planting, pc = partial cutting, s = selective cutting.

Source: Gauthier et al (2004).

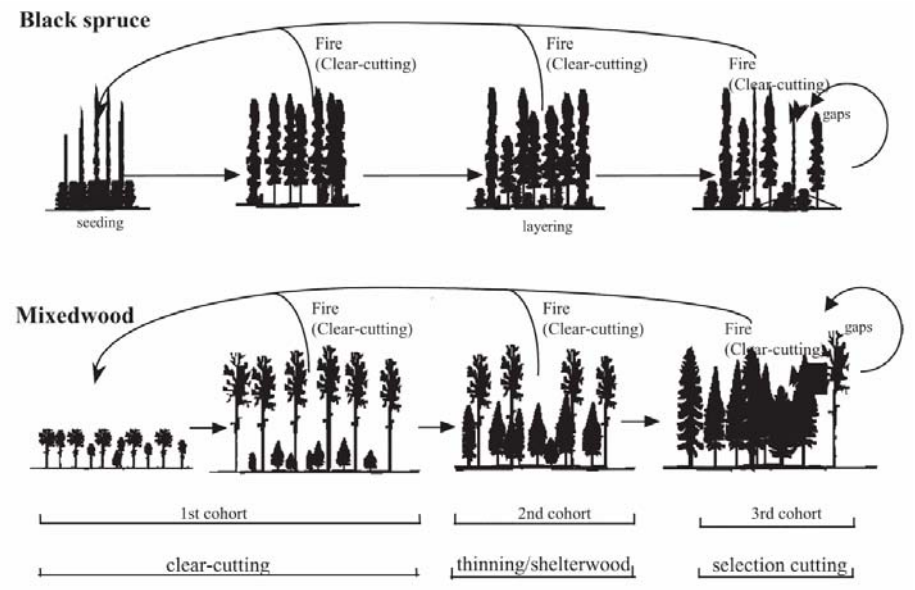
Figure 34: Example of change in species composition through management intervention



Pathways for the silvicultural treatment of stratified mixtures; original even-aged stand containing 5 species in center.

Source: Kelty et al ,1992.

Figure 35: Stand dynamics (progression of cohorts under long fire periods) of managed multicohort boreal forests in eastern Canada.



Source: Groot et al 2004.

How are these stand dynamics, silviculture and disturbance events integrated into modeling.

Stand growth and yield models focus on the stand dynamics and silviculture of a specific seral stage. The growth and yield model may emulate successional changes over a rotation length or within the planning horizon modeled. Ecological changes (between seral stages) can potentially be modeled at a forest estate level but are limited by the nature of growth and yield models

Major shifts in forest structure and species composition (or seral stages) resulting from silviculture are usually addressed through forest estate modeling by regenerating stands into different forest types or seral stages.

The various pathways (changes in stand structure, composition and condition) for a given forest resulting from different silvicultural treatments are able to be represented by yield tables associated with different silvicultural treatments. A stand is able to be simply transferred to another forest class when the silvcultural treatments occur.

Disturbance events are typically captured through stochastic modeling, but can be modeled deterministically.

B.4 Silvicultural Systems for Natural Forest Management

The primary systems used for uneven-aged forest management include:

(a) single tree selection
(b) group selection

A selection or uneven-aged silvicultural system is used to develop or maintains a mixture of three or more distinct, well-represented age classes. The management goal is to create and maintain the stand and age structure over time, though selection systems may convert even-aged stands to uneven-aged stands. (BC Ministry of Forests, 1995)

The primary systems for even-aged silviculture include:

(a) clearcut
(b) seed tree regeneration
(c) shelterwood system

These silvicultural systems generally produce and maintain even-aged stands with similar age and size, but the stand structure may be modified by variable species composition, retention of reserves, and variable cutting patterns.

Uneven-aged management is generally considered to be more difficult than even-aged management since all age classes are mixed together and therefore can be difficult to isolate and quantify. Uneven-aged management has been limited in Canada and the USA, although interest is increasing.

Comprehensive accounts of North American forest silviculture are described in:

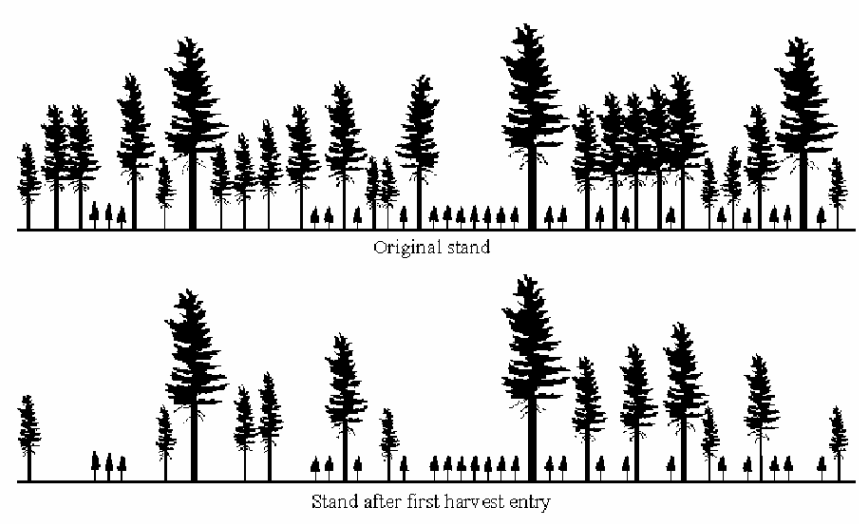
- The Practice of Silviculture: Applied forest ecology by Smith et al (1997)
- Regional Silviculture of the United States by Barrett (1995)

B.4.1 Single tree selection

Single-tree selection involves periodically harvesting individual mature commercial tree species from a stand, so that the desired stand age and size structure, species composition and stocking are maintained. Scattered individuals are removed to minimize site disturbance while maintaining a balanced distribution of size classes within a small area, maintaining near full site occupancy, and reserving sufficient trees with good growth potential, able to achieve regeneration after each harvest. To maintain an uneven-aged structure periodic recruitment of regeneration trees to replace trees that die or are harvested is necessary. The recruitment must be sufficient to maintain the desired stand density, yield and tree quality. The maximum size of the canopy gap created is limited to the size of the largest trees harvested, though larger gaps are sometimes created when senescing trees are salvaged, where natural gaps occur. Johnson et al (2005) note that in practice some openings are unavoidably created as a result of irregular mortality, associated salvage cutting and irregularities in the forest canopy.

Single tree selection is suitable for forests of very tolerant species which would otherwise be overtaken by intolerant species under a more intensive silvicultural regime. Single-tree selection is usually applied in mixed age or mixed species stands where the stand structure and species composition permit successful regeneration in small canopy openings created by removing single trees. Single-tree selection may be applied where commercial merchantable mature trees are scattered amongst a well stocked even-aged regrowth stand or in mature stands of low timber value.

Figure 36: Individual Tree Selection Silviculture

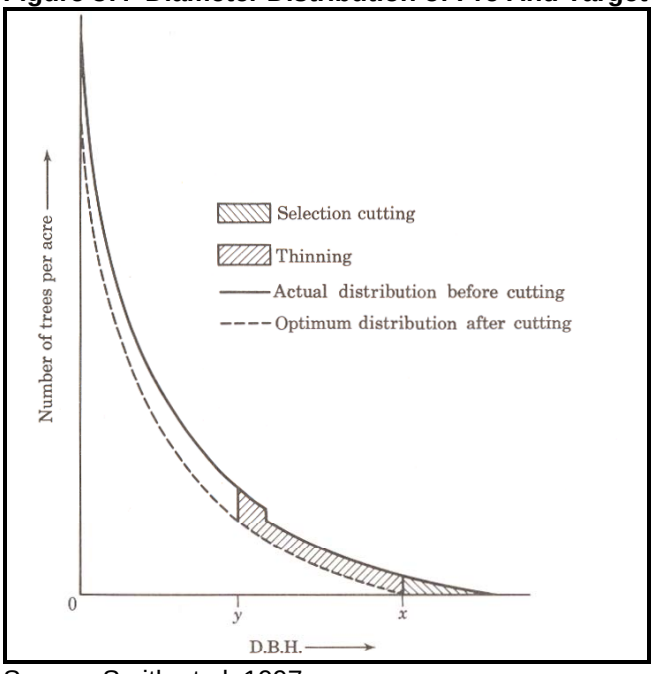


Source: BC Ministry of Forests,1995.

Single-tree selection is usually described by diameter distribution in contrast to even-aged stands that are defined by age class. Balanced diameter distributions form the basis of traditional approaches to uneven aged silviculture, though actual distributions are commonly irregular.

Even-aged forests are managed on an area basis according to a silvicultural regime for a given rotation length. In uneven-aged silviculture the basis of managing the forest is to control the stand structure (diameter regulation). The diameter distribution changes as the uneven-aged stand matures over time due to tree growth, recruitment, and mortality. A target reverse J diameter distribution (negative exponential curve) is used to guide the level of removal so that each stand provides a sustainable yield of products. Periodic harvesting is undertaken when there is sufficient volume of appropriate diameter classes for viable harvest operations, and to achieve a target desired post harvest diameter frequency distribution. Refer Figure 37.

Figure 37: Diameter Distribution of Pre And Target Post Thinning In Uneven-Aged Stand

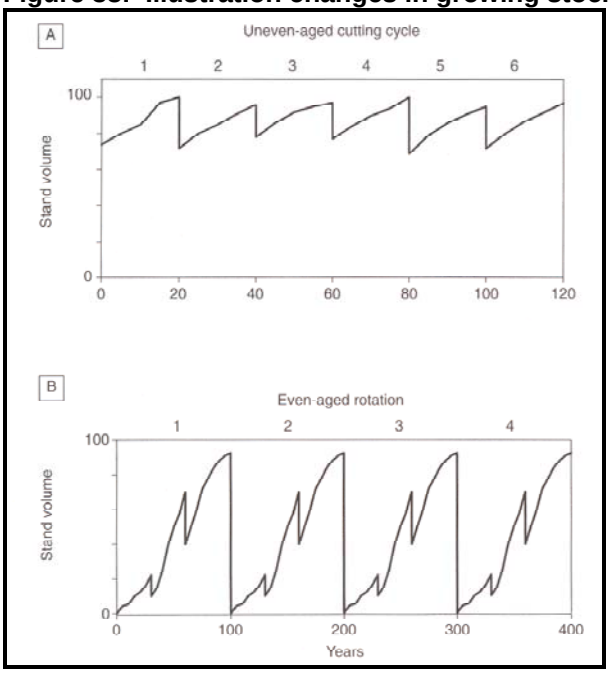


Diameter distribution of a balanced uneven-aged stand under intensive management, indicating the number of trees of different diameter classes theoretically removed in a single cutting. All tree larger than diameter x, which has been set as the index of rotation age, are removed. The trees of smaller diameter may also be reduced in number by thinning, provided that they are larger than the tree of lowest diameter (y) which can be profitably utilized. Under extensive practice there would have been no cutting of trees less than diameter x and most of those represented above as being cut in thinnings would have been lost through natural suppression.

Source: Smith et al, 1997

The length of cutting cycles (amount of time between successive harvests in a stand) divided by the rotation length (time for tree to reach economic or ecological maturity) is the proportion of the stand cut each removal operation to maintain an even wood supply. e.g. 15 year cutting cycle over 90 year rotation involves selectively cutting trees equating to 1/6 stand in each removal operation. Refer Figure 38.

Figure 38: Illustration changes in growing stock with even- and uneven-aged silviculture



Change in the relative stand volume for forest under uneven-aged and even-aged silviculture.
A. Volume change over six cutting cycles in an uneven-aged stand
B. Volume change over four 100-year rotations in an even-aged stand. In this example, two intermediate cuttings are made within each rotation.

Source: Johnson et al, 2005

Guiding diameter frequency distribution curve shapes based on *de Liocourt's q* factor (q is the ratio of trees in adjacent diameter classes), are the dominant approach in the United States for uneven aged silviculture. Other techniques are also used to determine a target stand density and structure over the range of diameters.

This form of yield regulation is complex. Ducey (2006) points out that as it is necessary to:

- define a "normative" condition for stands
- regulate the amount and timing of harvest
- provide a stand structure that allows adequate desired regeneration
- provide a stand structure that allows vigorous growth of residual stems

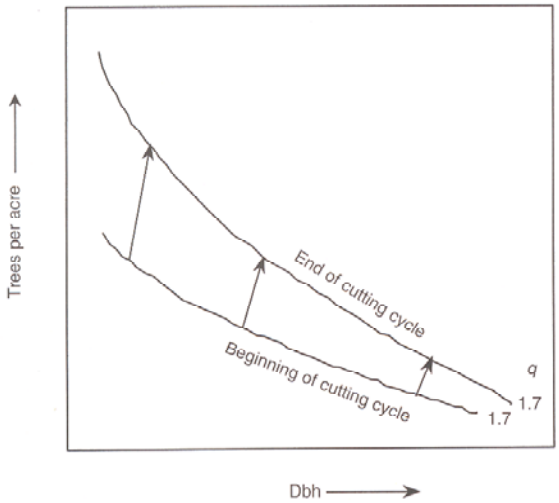
Diameter regulation is derived from the mathematical equation **BDq**
Where

B = The total retained basal area (ft2/acre) after harvest required for regeneration and growth (often specified for 6"and larger classes). B depends on cutting cycle. This variable is important as it directly impacts success and type of regeneration, and on the growth rate of residual trees. Long-term research is required to determine the necessary regeneration composition and residual growth.

D = The maximum diameter tree to leave (determined by economics but is important for structure of the stand). This variable is typically based on economic factors, but structural considerations are necessary to address retention of trees in the stand structure for regeneration and wildlife habitat reasons.

q = *de Liocourt's q* factor that sets the curve shape. The q factor represents the future goal of the stand. Decisions on the steepness of the diameter frequency distribution depends on stand ecology (mortality, recruitment, growth balance), how much growing stock should be allocated to harvest or future products. (Ducey, 2006)

Figure 39: Guiding curves for Uneven-aged forest Individual Tree Selection Silviculture



The theory and application of guiding curves assume that the shape of the selected diameter distribution, and thus q, remains relatively constant during the cutting cycle.

Source: Johnson et al 2005

Smith et al (1997) stress that there are many valid reasons for maintaining uneven-aged stands other than sustained yield or financial maturity (viz. aesthetics, wildlife habitat, seedling ecology, protection of the stand and soil), and these objectives can be achieved without a balanced diameter frequency distribution. Smith et al (op. cit) state that "*warping the patterns of harvest removals to fit some preordained diameter distribution commonly interferes with fulfilling many other logical purposes.*"

Other techniques are being used to regulate uneven-aged stands without employing diameter frequency distributions to control the timing and level of harvest and retention, particularly in irregular uneven-aged stands. With these approaches the age and diameter classes are permitted to fluctuate. Examples include:

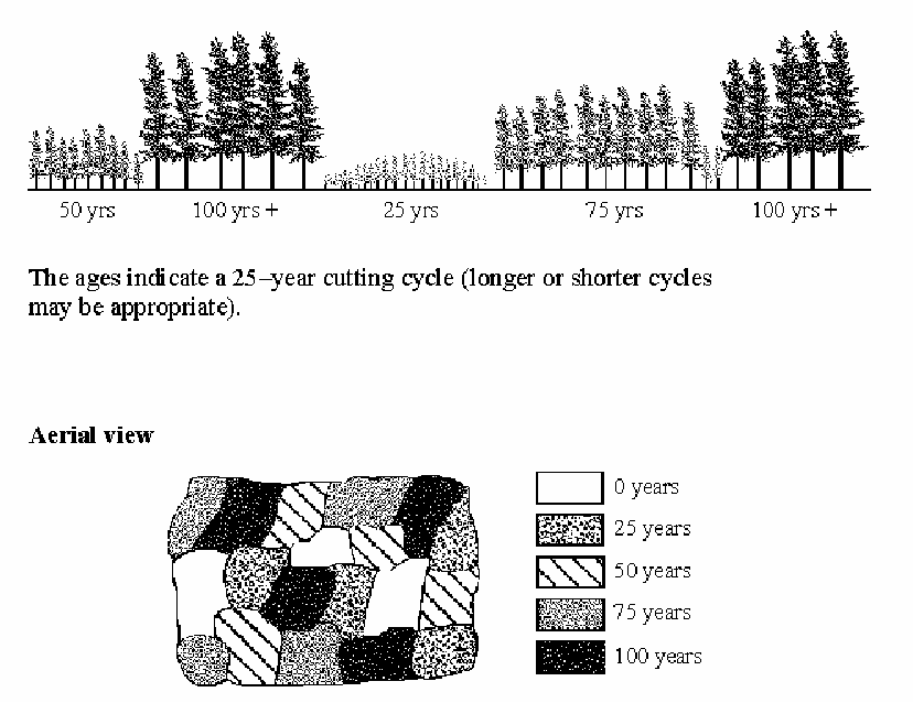
- financial maturity – extract optimum value from growing stock. If the diameter distribution is unbalanced, then balance can only be achieved by cutting some trees before or after they are financially mature.

- diameter limit partial cutting (sometimes "high grading") – cutting all trees above a minimum limit that can be utilized without financial loss (zero margin selection cutting). Cutting to strict minimum diameter limits is purely for maximum financial return and not cutting for sustainability or regard for future value increase. Unless the stand is being liquidated, this is often only an approximate guide to determining tree removal. Trees above a certain limit will be retained if they are increasing in value, or are to provide regeneration seed and habitat. Similarly trees below the diameter limit may be removed if poor quality, species, vigor, or to release trees in dense patches.

B.4.2 Group selection

The group selection system involves harvesting small groups of commercially mature trees creating a canopy opening for regeneration while retaining adjacent groups of previously selectively logged growing stock. Refer Figure 40. The managed stand structure comprises numerous small uniform even-aged stands of trees. Typical planned openings in the canopy range from 0.2 acre to 0.5 acre, but are often calculated as 2 – 3 times the current tree height to ensure sufficient light penetrates the gap to get adequate regeneration.

Figure 40: Group Selection Silviculture

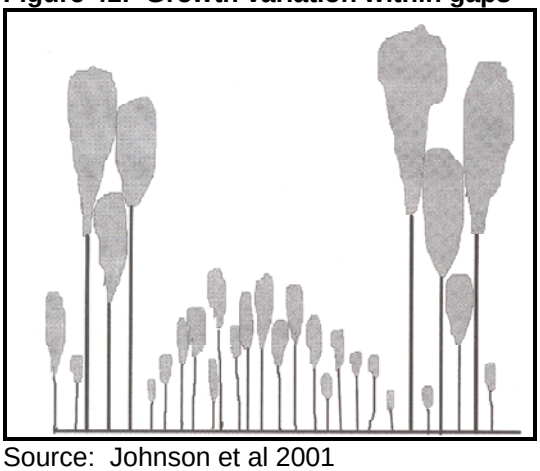


Source: BC Ministry of Forests,1995.

The group selection method is aimed at perpetuating the harvest and providing light for the regeneration of intolerant and mid-tolerance species that are difficult to regenerate with single tree selection systems, while maintaining a relatively continuous and homogeneous canopy cover. This system is designed as a compromise between the need to conserve immature growing stock, regeneration requirements of intolerant species and the need to address ecological and timber values. The silvicultural system maintains an irregular forest, but can also be applied to more uniform stands to convert them to multi-aged forest to enhance ecological diversity.

Group selection silviculture comprises a number of cutting cycles (amount of time between successive harvesting of groups of trees in a stand) undertaken each rotation (time for tree to reach economic or ecological maturity) e.g. 15 year cutting cycle over 90 year rotation involves selectively cutting trees equating to 1/6 stand in each removal operation. So a forest area will be progressively harvested leaving gaps that in time regenerate forming small groups of even–aged forest. Each group (gap regeneration) is typically treated as an even-aged stand and thin / clearcut provided the groups are large enough and identifiable in the forest matrix. Otherwise the groups may be treated as uneven aged forest and harvest to a specified stand structure – so migrate to single tree selection

Figure 41: Growth variation within gaps

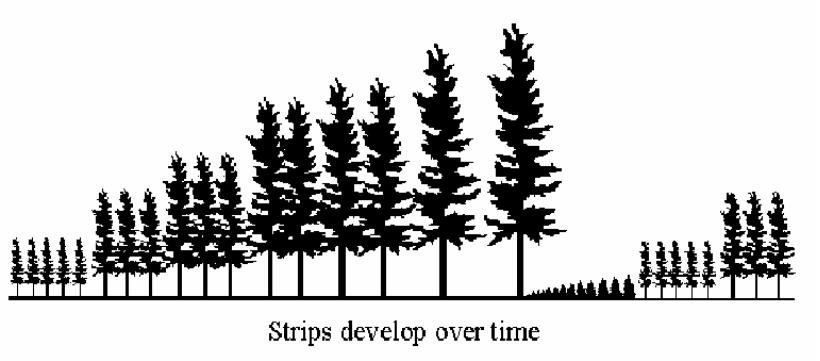


Group openings can provide adequate light for development of shade intolerant species that often fail to regenerate under single tree selection. Reproduction grows most rapidly near the centre of the opening because of shading and root competition from the adjacent stand.

Source: Johnson et al 2001

A variation to group selection is the strip selection method illustrated in Figure 42. The mature stand is progressively cut generally in linear strips that are orientated to minimize damaging effects of wind on the residual stand or to provide shading of cut strips by the uncut areas.

Figure 42: Strip selection method

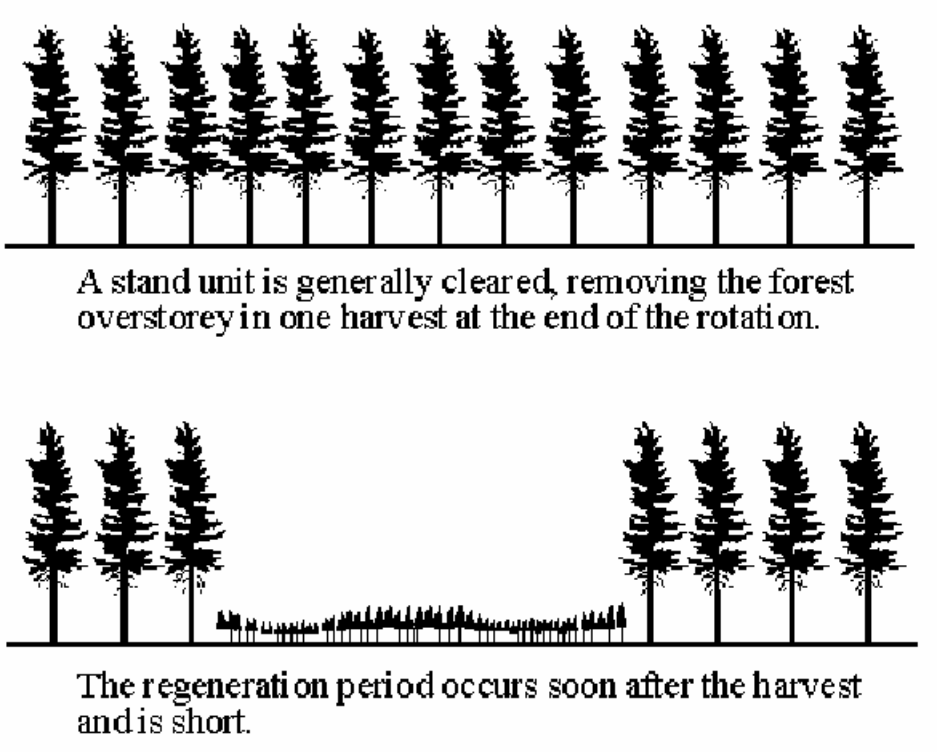


Source: BC Ministry of Forests,1995.

B.4.3 Clearcut

A clearcut silvicultural system removes an entire stand of trees from a large (greater than one hectare and greater than two mature tree heights) and contiguous area in a single harvesting operation at the end of the stand rotation. In natural forests a new even-aged crop is regenerated within a short period after harvest by natural regeneration, retention of natural advance regeneration or direct seeding.

Figure 43: Clearcut Silviculture



Source: BC Ministry of Forests,1995.

B.4.4 Seed Tree Regeneration

A seed tree silvicultural system is where a low density of high quality seed trees are retained after the initial harvest removes all other trees, to provide a seed source for natural regeneration of a replacement even-aged stand. The seed trees may be removed once natural regeneration is successful. The seed (establishment) cut is sometimes preceded by a preparatory cut to promote crown development and seed production. There are two variations of the seed tree system:

(a) Uniform seed tree system where individual trees excluded from harvesting are uniformly distributed throughout the stand

Figure 44: Uniform Seed Tree System



Source: BC Ministry of Forests,1995.

(b) Grouped seed tree system where uniformly distributed clusters of trees are excluded from harvesting.

Figure 45: Grouped Seed Tree System



Source: BC Ministry of Forests,1995.

B.4.5 Shelterwood System

A shelterwood harvest method involves gradual removal of an entire stand using a series of partial cuttings – often two or three harvesting operations resembling heavy thinnings. This system maintains a single stage even-aged forest for most of the rotation, but shelterwood systems differ from clearcuts in that the new stand regeneration is initiated before the existing overstorey is completely harvested. When the final harvest sequence in the overstorey occurs, the understorey stand becomes the overstorey maintaining its age since regeneration

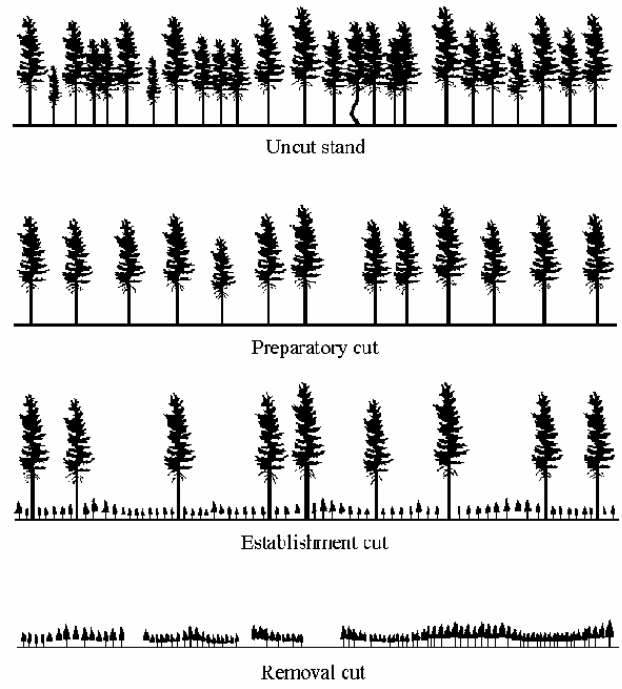
In two step shelterwood the initial harvest (establishment cut) of a mature stand opens the canopy and creates suitable seedbed conditions and the retained trees provide a source of seed and protection for new regeneration. The final cut (removal cut) removes the competitive effect of retained trees and promotes the growth and development of the regeneration. In three step shelterwood systems the establishment cut is preceded by a preparatory cut to encourage crown expansion of residual trees and increase seed production (flowering or seed-bearing cone development, and windfirmness. Under these shelterwood systems natural regeneration becomes established as a result of one of the removals under the protection of the residual stand. In both shelterwood systems, the best trees are retained for the final removal cut to obtain maximum value from the additional growth and to produce the best seed.

BC Ministry of Forests (2007) details variations in the shelterwood systems including:

(a) Spatial arrangement of retained trees is critical

- **Uniform shelterwood system** – shelterwood treatment applied uniformly over the whole stand.

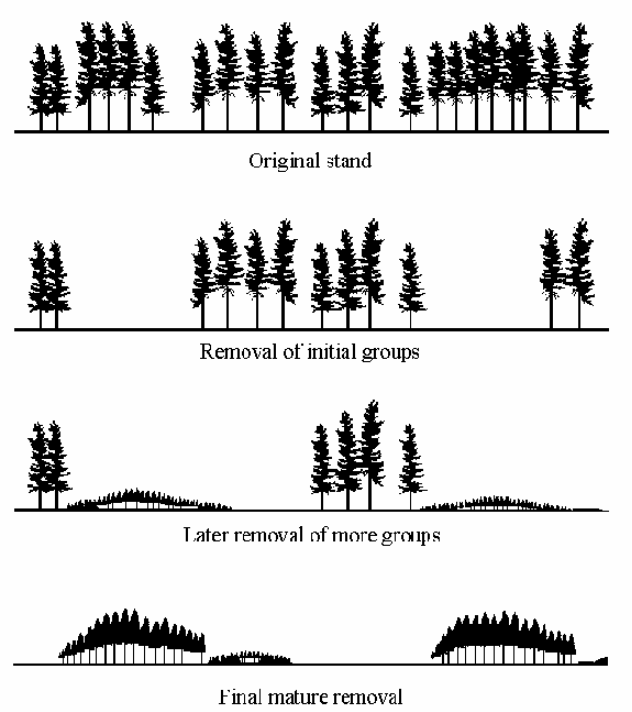
Figure 46: Uniform shelterwood system



Source: BC Ministry of Forests,1995.

- **Group shelterwood method** - small gaps of 1 - 2 tree lengths in diameter are created in the stand. The adjacent trees can shelter the new regeneration growing in the gaps. Further cuts expand existing openings or create new openings.

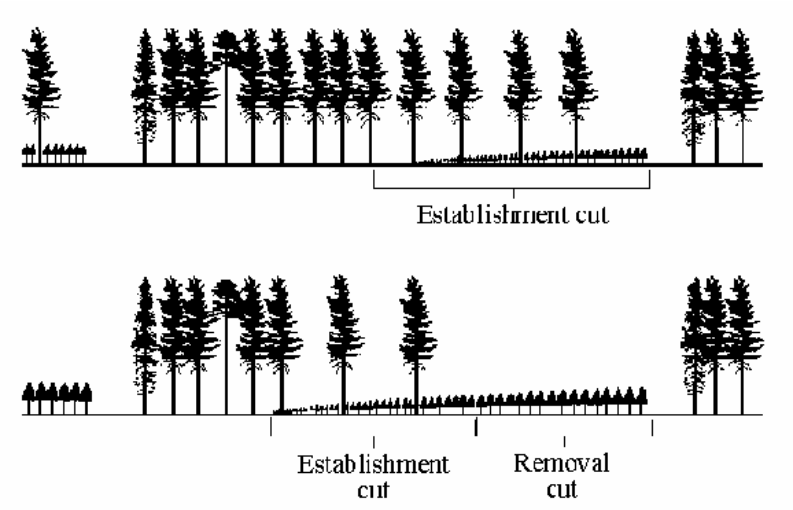
Figure 47: Uniform shelterwood system



Source: BC Ministry of Forests,1995.

- **Strip shelterwood method** - harvesting made in uniformly narrow strips that advance progressively through a portion of the block over the regeneration period to provide some protection against windthrow. Each adjacent strip receives the next stage of shelterwood treatment.

Figure 48: Strip Shelterwood Method

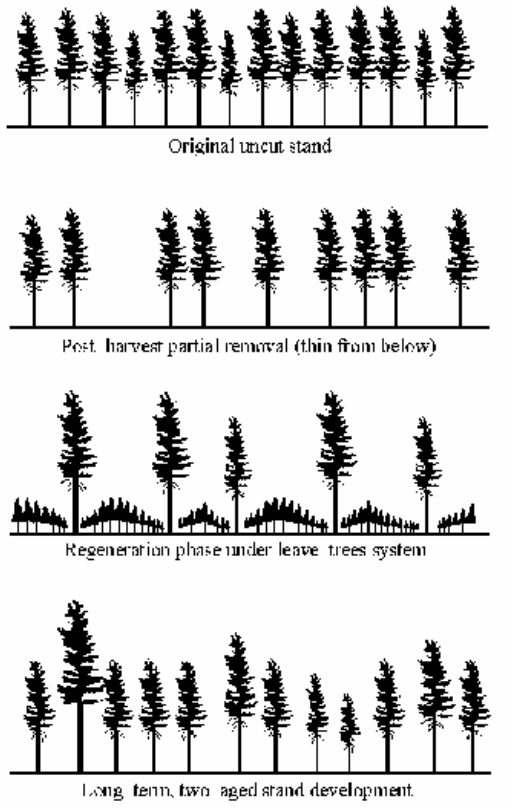


Source: BC Ministry of Forests,1995.

(b) Timing of overstorey removal is determinant

- **Irregular shelterwood** - shelterwood system with irregular extended regeneration period. The reserved trees are retained for indefinite periods beyond the regeneration phase (e.g. from 20 per cent of the rotation to several rotations). Residual trees accumulate volume increment and initiate new age classes of regeneration, but promotes structural diversity and may achieve non-timber stand objectives such as aesthetics, wildlife, biodiversity, or hydrological green-up. "Irregular" refers to the subsequent variation in tree heights in the new stand.

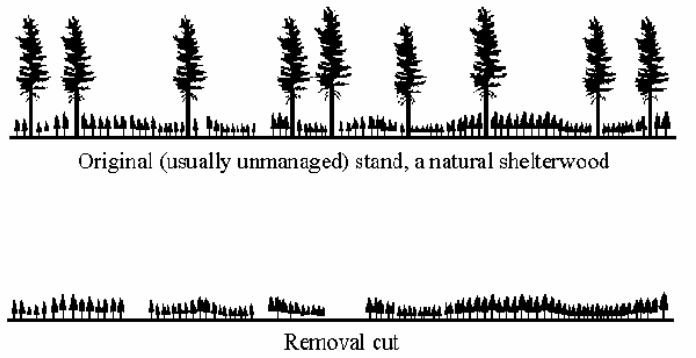
Figure 49: Irregular Shelterwood Method



Source: BC Ministry of Forests,1995.

- **Natural shelterwood** or “Overstorey removal" - the regeneration is established naturally under the shelter of an overstorey before it is removed.

Figure 50: Natural Shelterwood Method

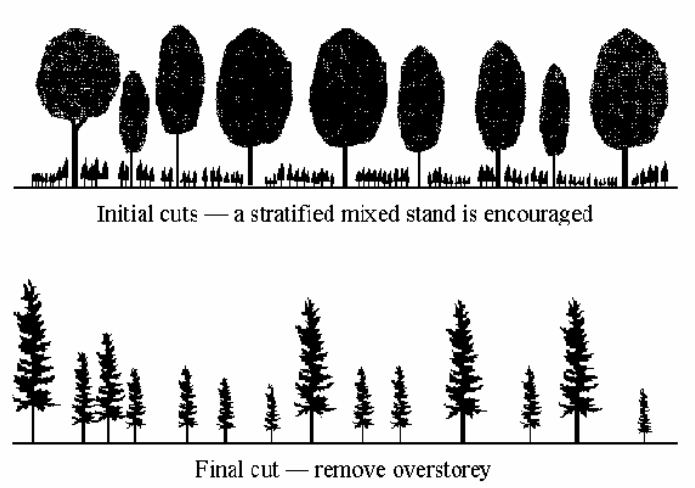


Source: BC Ministry of Forests,1995.

(c) Management of different species in different canopy layers

- **Nurse-tree shelterwood** - a system that encourages development of two stories in a stand, each containing a different species or mix of species. Intolerant species form the overstorey while the understorey comprises tolerant species.

Figure 51: Nurse-Tree Shelterwood Method



Source: BC Ministry of Forests,1995.

- **Shelterwood with reserves**

Johnson et al (2005) also discuss shelterwood with reserves which is a modified shelterwood system that can be applied where there is only an initial harvest and shelterwood trees are retained to provide fauna habitat and uneven aged forest with greater structural diversity than the initial forest.

B.5 Silviculture Implementation Issues

Management of natural forest lands are often subject to additional restrictions or public expectations which curbs the ability to silviculturally manage these resources in the most effective way to maintain healthy, vigorous and productive forests. The need for sustainable forest management as opposed to purely long term sustainable yield of wood products has created changes within North America and Australia forest management.

Uneven-aged silviculture is used extensively in North American public forests, particularly in mixed hardwood conifer and mixed hardwood forest of the east coast, and in extensively managed rangeland forest of ponderosa pine. Many of the North-American uneven-aged stands are managed according to selective harvesting systems, and some even-aged stands stands on public lands are being converted to uneven-aged (Note that various private industrial forests are converting uneven aged stands to more financially viable even-aged stands). Where forest is managed with selective silvicultural systems (single tree selection or group selection harvesting) to maintain or achieve an uneven aged forest structure the silvicultural specifications are ostensibly based on achieving a theoretical target stand structure (negative exponential diameter distribution) and desirable species mix, to provide a sustainable flow of wood products of desirable species over time. (Different objectives naturally apply to uneven-aged stands that are managed with uniform or irregular shelterwood silvicultural systems). Intensive silviculture such as thinning to a minimum target stocking or using herbicides / noncommercial thinning is necessary to promote preferred tree species in mixed stands and for general stand improvement in irregular and high graded forest.

It is difficult to manage Australia's uneven-aged natural forests for long term health, compared to how North American uneven-aged forests are managed, where silviculture is conducted to achieve a target for forest structure. The silvicultural practices in uneven-aged native forests are always a trade-off between (i) current harvesting for commercial products in sufficient volume and in diameter classes to satisfy market commitments and enable a viable and profitable harvest operation; and (ii) the need to retain a stand with a structure and species composition that promotes a healthy and vigorous sustainable supply of desirable wood products. In Australia current harvesting operations are driven by wood production targets, and appropriate silvicultural practices are often restricted by economics and regulations.

Restrictions on Australian silviculture that would need to be incorporated into any adaptation of North American growth and yield models, include:

(a) impacts of inappropriate silvicultural systems for shade intolerant Eucalypt forest

Australian forest management regulations such as outlined in the Regional Forest Agreements established since the early 1990's specify the type and intensity of silvicultural systems applied in *Eucalyptus* forest types. Many of these silvicultural regulations have been the product of environmental pressure and politics not silviculturally driven decisions. In some areas of SE NSW, Victoria and Tasmania the conversion of uneven aged forest to even-aged regrowth (or plantation) through clearcutting or seed tree silvicultural systems is permitted. However, most of the uneven-aged forests are managed with single tree selection and low intensity group selection harvesting methods that are unsuitable for effective regeneration and vigorous growth of the preferred and mostly intolerant species. Many of the systems would be better suited to more intensive selective harvesting practices such as clearcut and seed tree silvicultural systems to emulate the ecosystems where natural fire, wind or snow disturbance is prevalent. It is difficult to emulate the impacts of the changing stand dynamics from insufficient site disturbance and openings for regeneration and growth. Insufficient data and experience are available to predict future composition, structure and condition of these stands.

(b) impacts of harvesting to minimum diameter limits and selective removal of high quality sawlog trees

Many of Australia's selectively managed natural forest stands are irregular in structure, species composition, condition (quality and vigor) as a result of historical management and natural disturbance events. However, this situation is exacerbated as a result of more recent of intensive selective harvesting practices and restrictions on silvicultural improvement of stands.

The Regional Forest Agreements have set many wood supply targets from reduced production forest areas that cannot be met from sustainable yield management of the native forests. To meet contractual commitments from selectively harvested stands, forest managers need to harvest all trees bearing the minimum sawlog dimensions. This practice will result in abnormally lengthened cutting cycles, and quite irregular structures potentially favoring noncommercial species before these stand will provide future yields.

Where regulations prohibit the removal of low quality trees or it is uneconomic to do so, such that only desirable species and trees with high quality sawlogs are removed, the condition of these forests will deteriorate where unless silvicultural culling (non-commercial thinning, poisoning, ring-barking) is undertaken.

Individual trees are routinely retained for wildlife habitat trees within forest zones designated for commercial harvest[5]. Within commercial forest, harvesting of non habitat trees without sawlogs is not permitted in many of Australia's native forests. Timber Stand Improvement (TSI) involving the culling un-merchantable and non-commercial species is prohibited or uneconomic in many situations due the absence of markets for low quality and small wood (pulp) products or high cost of extraction of these to processing or export facilities.

In the absence of disturbance events such as wild fire, these silvicultural restrictions collectively reduce stand regeneration, tree growth, favor more shade tolerant (and sometimes less commercial) tree species,

[5] This is in addition to habitat exclusion areas and protected, inaccessible or uneconomic forest areas.

and reduce the economics of harvesting operations. There are many examples of mature multi-aged forest that have become stagnant and are not viable to harvest. The stands require intervention such as TSI, thinning or reset silviculture (harvesting), to remove the large unmerchantable and noncommercial species to promote regeneration and to stimulate growth on commercial merchantable trees.

There are limited data available to model the future growth and yield of these forests

Appendix C Growth and Yield Predictors (simulation models)

Growth and yield models are designed to emulate essential elements of forest dynamics and silvicultural intervention, to provide information on the forest stand and products it yields over time. Typically growth and yield models are simulation models, meaning the initial stand condition is grown through time according to a series of algorithms representing the stand dynamics. The components applicable to the stand or trees represented include

- Growth (basal area, diameter, height and volume)
- Mortality
- Recruitment (uneven aged)

Silvicultural management of the stand (thinning, pruning, harvesting) is represented by reducing the basic stand parameters by the type and number of trees removed (or pruned) and generating yield (stock) tables. Harvesting (thinning and other partial cuts) may be achieved using mathematical functions or rule based simulation. The residual stand continues to be grown for each successive year according to the model algorithms.

C.1 Classifications

Growth and yield models can be categorized in terms of empirical, process based, ecosystem succession (or gap) and hybrid models. All the models generate results at a stand level in quantity measures per unit area (hectare or acre). The inputs and outputs vary by model type and objectives of the model.

This report is concerned mainly with empirical models used for predicting growing stock (stand and stock tables) and yields for use in forest management. These predictive models often sacrifice details of growth processes to achieve greater efficiency and provide more accurate information for forest management.

Process models (also known as mechanistic or physiological models) model the processes of growth and model photosynthesis, respiration and the allocation of photosynthates to roots, stems and leaves based on inputs such as sunlight, temperature and soil nutrient levels. (e.g. 3PG - Landsberg 1986, Mäkelä 1992; Landsberg and Waring, 1997; Fournier et al, 2000). These models help to provide a better understanding of growth and stand dynamics, but have not yet successfully been used for predicting timber yields for forest management. Vanclay (1994)

Ecosystem succession models (e.g. Shugart 1984, Botkin1993) model species succession, but are generally unable to provide reliable information on timber yields. Examples include the FORCYTE model (Kimmins 1988), SILVA and ZELIG. Vanclay (1994).

C.2 Empirical Growth and Yield Model Types

Empirical growth and yield simulators can be classified in terms of several basic categories or architecture based on the level of detail modeled. It should be noted that models may not fit precisely in any of these classes. A more comprehensive classification is provided by Davis et al (2001) and an original and commonly cited classification is outlined by Munro (1974).

- Whole Stand Models (aggregated values only, diameter free)
- Whole stand models (disaggregative)
- Diameter (Size) Class Models
- Individual Tree Models - distance dependent
- Individual Tree Models - distance independent

- Hybrid

(a) Whole stand models

Whole stand models rely on overall stand values as the basic modeling unit. Input stand parameters include age, site productivity (site index), basal area, stand density (stocking for plantations and basal area for natural forests), stand volume and parameters representing the diameter distribution. The whole stand model simulators are computer programs that include equations that determine and control age-related development of stand variables (height and maximum height, average height, predicted diameter). The algorithms forecast stand growth over time, prior and following silvicultural treatments until time of final harvest.

Comparatively little information is required to simulate the growth of a stand, but provide general information about the future stand, such as forecasts of basic parameters that define a stand such as volume, basal area and stocking (number of trees) over stand age or over time. No details of the individual trees in the stand are determined. Stem size distributions may be inferred from existing or predicted distributions. Despite this limitation, many whole stand models have been developed, but not normally for uneven-aged mixed forests. The model generate age-dependent yield tables applicable to monospecific even-aged stands, with maximum ages up to 150 years depending on species. Many stand models are designed to model even-aged forests managed with clearcut silvicultural systems. The silvicultural system regimes emulated may include multiple partial cuts (non commercial and commercial thinning), possibly pruning and fertilizer application.

Uniform (balanced structure and single or consistent species mix) uneven-aged (two-aged and multi-aged) forests managed according to partial cut silvicultural systems including shelterwood, group selection and single tree selective harvesting are also sometimes modeled. Forest stands with an irregular structure and species composition are better represented with individual tree level models.

Two variations exist:

(i) Aggregated values only
The volume growth or yield per unit area is predicted for the whole stand e.g. DFSIM model.

(ii) Size class information
In addition to volume growth or yield per unit area, the number of trees by diameter (DBH) classes is obtained by using a diameter distribution (probability density functions) approach. (The stocking of each diameter class is a function of stand variables cf diameter class models are empirically determined).

(b) Diameter class models.

The diameter class model approach is a compromise between whole stand models and single-tree models and provides some information regarding the structure of the stand. The growth of each diameter class in a stand is simulated separately. The growth and volume of an average tree in each diameter class is calculated and multiplying by the number of trees in each class. The diameter class parameters are aggregated to provide stand level parameters.

The most widely used technique is the method of stand table projection which essentially produces a histogram of stem diameters. The other method is the diameter class growth model (Davis et al. ,2001)

(c) Individual tree models

Single-tree models provide the most detailed (higher resolution) approach. This modeling approach uses individual trees as the modeling unit. The minimum input required is a list specifying the size of every tree in the stand. Some models also require the spatial position of the tree, or tree height and crown class. Stand growth and yield forecasts are is achieved by modeling at the tree level and aggregating results to

the stand level to obtain stand characteristics such as mean height, mean diameter, and diameter frequency distributions.

Tree growth is predicted as a function of its attributes, site quality and competition from neighbors. The individual stand components are modeled independently (diameter increment, mortality, recruitment/ regeneration, height increment). Predicted tree heights may be based on the predicted tree diameter using H/D functions. The diameter and height are used for a tree of a given species and stand density to provide individual tree volumes. Some models calibrate total basal area growth (sum of all individual tree basal areas) to that of a stand level basal area growth. The models may be linked to harvesting and conversion simulators, and more complex model may include modeling of branches and internal stem characteristics (e.g. Mitchell 1988, Vanclay 1989).

Two variations of tree level models exist depending on whether tree locations are used:

(i) distance independent

The spatial distribution of trees in the initial stand is not modeled, so individual tree growth (or size class / cohort) is predicted based on its attributes, site productivity and stand level variables (age, basal area or stocking, overtopping basal area).

Tree level model enable both even- and uneven-aged stands to be modeled using the full range of silvicultural systems (clearcut, shelterwood, group selection and single tree selective harvesting.

Examples include the USDA Forest Service Forest Vegetation Simulator (FVS) (Teck et al 1996) and the Organon model (Hann, 2006). FVS can provide forecast for stands with complex structure, though highly irregular stands are not simulated well , except in the short term (10 years).

Hökkä and Groot (1999) who developed an empirical single tree distance independent model for peatland black spruce, concluded that for highly clumped spatial distributions, spatial models may be necessary to characterize competition more exactly. (Groot et al 2004).

(ii) distance dependent

These models use data on individual tree positions and/ore distances between the trees to control individual tree growth. Each tree is assigned coordinates in the initial stand condition. This enables the effects of competition on tree growth, tree quality / form, mortality and recruitment to be better modeled. This also enables harvesting operations (harvesting rules or functions) to incorporate the spatial distribution of retained and removed trees in addition to the residual condition stand, target yields (species, tree quality, product volumes).

The location (plus the frequency, species and tree quality) of tree mortality and tree regeneration / recruitment is generated by stochastic mechanisms based on stand condition (structure, species composition, age, spatial distribution of trees), site quality, tree attributes and competition by the immediate neighboring trees and other ground cover.

Peng (2000) outlines how spatial information is used to calculate a competition index for each tree. Groot et al (2004) details how CORONA (Groot, 2004) is being adapted to provide a better measure of competition based on light interception rather than statistically based competition indices in individual-tree growth models. Groot et al (2004) also outlines that SORTIE (Pacala et al, 1993, 1996), a partly process based model, is being explored as an option for modeling Canadian forests (Coates et al. 2003).

Examples include TASS and FPS models.

(d) Hybrid

It is possible to combine elements of stand-level, diameter class and tree level models together. For example certain parameters such as mortality may be calculated using a self thinning function that is a stand level model. Mortality of individual tree in an individual tree model tree list is determined applying total mortality is applied using a stochastic tree level survivor function. (Pretzch et al 2006).

Examples include STIM, LPSIM, and RVMM

C.3 Reasons for differences in approaches

The level of detail modeled (resolution - modeling at the tree level or modeling at the aggregate stand level), type of outputs (dimensionality), projection length, and level of precision required depends on objectives of modeling and constraints on cost, data availability and algorithms, and characteristics of the forest stands and the silvicultural systems modeled. There is often a balance between the quality and quantity of data collected.

(a) Objectives for modeling.

Individual-tree models offer flexibility in describing forest structure and simulating silvicultural operations (e.g. thinnings), though they may not estimate overall stand parameters (volume and basal area) as accurately as whole stand models. Often short term model projections based on detailed information are best and long term projections based on simple whole stand models perform best. (Burkhart, 2003 – In Modeling forest systems).

(b) Stand type and silvicultural system

Homogenous even-aged mono-specific stands (plantations) managed with clearcut silviculture: Stand level models with diameter distribution functions provide satisfactory forecast of growth and yield (volumes of product grades and diameters), provided site quality and silvicultural are comparatively uniform.

Simulating and forecasting growth and yield of even-aged, single species, regularly spaced forest requires a different approach compared with complex forests that are uneven-aged, mixed species, patchy forests.

(c) Limited data available from growth plots to provide modeling flexibility

Individual tree data not recorded to enable tree level model.

Algorithms suitable for tree level growth models not developed as not tree level data recorded or interaction between components of stand not modeled e.g. interactions between tree growth, mortality and recruitment. This is compounded by different rates of growth among species, different maximum tree sizes and varying shade tolerances, impacts of selectively harvesting certain species.

Individual trees coordinates (spatial location) are not recorded in long term growth plots so restricting distance dependent tree level modeling.

C.4 Proposed Standardized Growth and Yield Description & Evaluation

Pretzsch et al (2006) provide a recommended 10 point standardized description and evaluation of growth models and growth simulators.

Criterion	Model Properties
1. Model Approach	• Spatial resolution (competition, regeneration, treatment) • Age dependency • Principle of growth model (e.g. potential/reduction, direct estimation, growth equations using site factors or site indices, site-specific growth potential) • Deterministic and stochastic model components • Flow Chart
2. Range of Application	• Silvicultural scenario studies • Updating forest stands • Updating of larger assessment units • Instruction, professional training, research
3. Parameterization and calibration specifications	• Specifications with regards to region • Site specifications • Types of mixtures and stand structure • Integrated treatment variants • Integrated tree species • Tree dimensions covered
4. Input	• Area shape and size • Minimum input data requirements • Additional input data to be possibly processed • Automatic generation of missing information • Database interface • Maximum number of trees per calculated area
5. Program Control	• Use (interactive, batch-mode) • Possibilities of program control (visual, algorithmic) • Interactive changing of equations • Interactive changing of coefficients • Saving of interim results with continuation
6. Output	• Tree lists • Stand characteristics • Yield characteristics at forest enterprise level • Structural characteristics at stand and forest enterprise level • Economic measures • Biomass components • Visualization methods (spatial representation, diagrams) • Interfaces with other programs
7. Sub-models of the growth simulator	• Database • Increment model (model principles) • Representation of liberation felling effects • Crown model (dynamic, static) • Mortality model • Ingrowth model • Stochastic components of sub-models • Derivation of coefficients
8. Additional algorithms	• Statistical timber grading • Thinning algorithms • Determination of ingrowth co-ordinates • Biomass equations • Inventory equations • Prediction loops for forestry enterprises • Abort criteria and data complementation • Three-dimensional stand visualization • Consideration of edge effects • Quantification of spatial structure • Continuous updating
9. Model validation	• Precision • Bias • Accuracy • Sensitivity analysis
10. Software and hardware	• Operating system • Hardware requirements • Current version giving year and date • Programming language • Program approach (structured, object-oriented)

C.5 Stand Growth and Yield Flow Patterns

There are 3 classical types of yield tables used to represent potential yields of timber from forest areas:

(a) Age dependent yield tables. These contain yields that are a function of stand age. Traditional yield tables include extracted and/or retained volumes of products by age. However, yield tables are more flexible and used as a repository for more than just physical fibre yields. The yield table contains values for each stand age, which may include harvested product volume (yield), growing stock (inventory) product volume, or other stand parameters (SPH, BA, height, DBH), financial data (costs, revenues), carbon level, or environmental measures such as habitat condition, fauna population characteristics, and seral stage.

The stand growth and yield of clearcut silviculture are shown in Figure 52 and Table 5.

Figure 52: Age-dependent Yields Even-aged Forest Growth and Yield
(single rotation,2 commercial thins and clearfell)

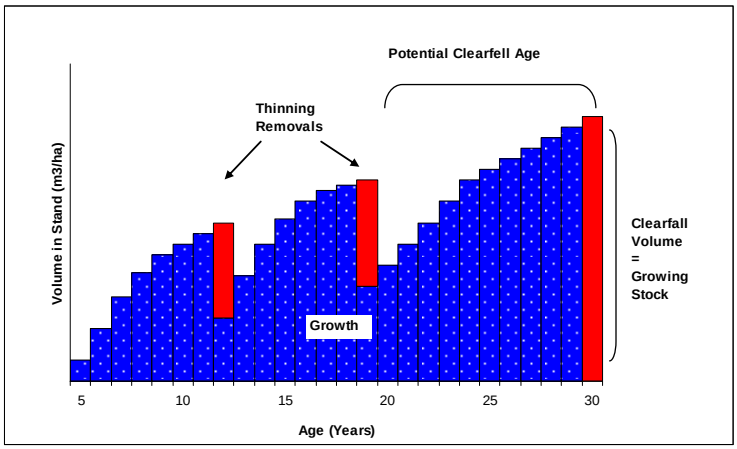


Table 5: Age-dependent Yield Table. Even-aged single rotation
(2 commercial thins and clearfell. Pure (monospecific) stand.)

Year	Sawlog Volume (m3/ha)	Pulplog Volume (m3/ha)	Thin Sawlog Volume (m3/ha)	Thin Pulplog Volume (m3/ha)	Total Merchantable Volume (m3/ha)
5	0	40	0	0	40
6	0	100	0	0	100
7	0	160	0	0	160
8	0	206	0	0	206
9	0	240	0	0	240
10	0	260	0	0	260
11	0	280	0	0	280
12	0	180	0	120	300
13	0	200	0	0	200
14	0	260	0	0	260
15	0	306	0	0	306
16	34	306	0	0	340
17	54	306	0	0	360
18	74	296	0	0	370
19	45	135	80	120	380
20	66	154	0	0	220
21	91	169	0	0	260
22	120	180	0	0	300
23	153	187	0	0	340
24	190	190	0	0	380
25	220	180	0	0	400
26	252	168	0	0	420
27	286	154	0	0	440
28	322	138	0	0	460
29	360	120	0	0	480
30	400	100	0	0	500

(b) Time dependent yield tables. These contain yields that are a function of time. The yield dependency is based on time rather than age as it reflects unique harvest removal patterns associated with an area / site over time and does not reflect stand age nor time since last harvest event for the whole area Examples include uneven-aged forest, or non-wood measures such as roading infrastructure. Time dependent yield tables includes those referred to as uneven-aged yield tables.

Time dependent yield tables vary in structure depending on the silvicultural system. Typically time dependent yield tables will show the yield for successive cutting cycles for the whole planning horizon. This yield table reflects regular timing and intensity of cuts in balanced forest. In more irregular forest structures the cutting cycle length and volume and product/species mix will vary.

The stand growth and yield of uneven-aged silviculture are shown in Figure 53 and Figure 54.

Figure 53:Time-dependent yields. Net Change in Growth and Yield of Uneven-aged Forest (Selection harvesting)

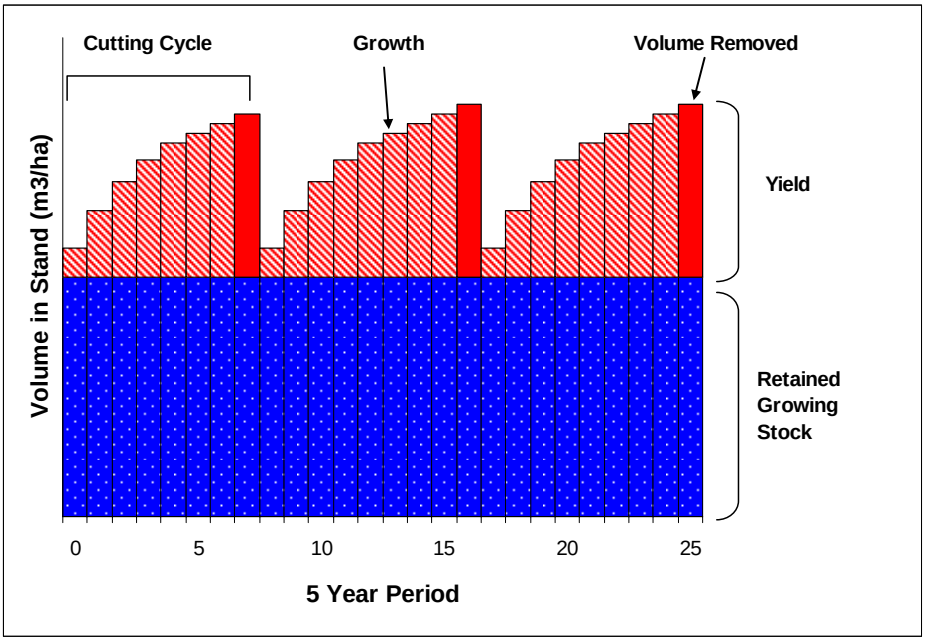


Figure 54: Relationship between Growth and Yield in Multi-cohort Uneven-aged Forests

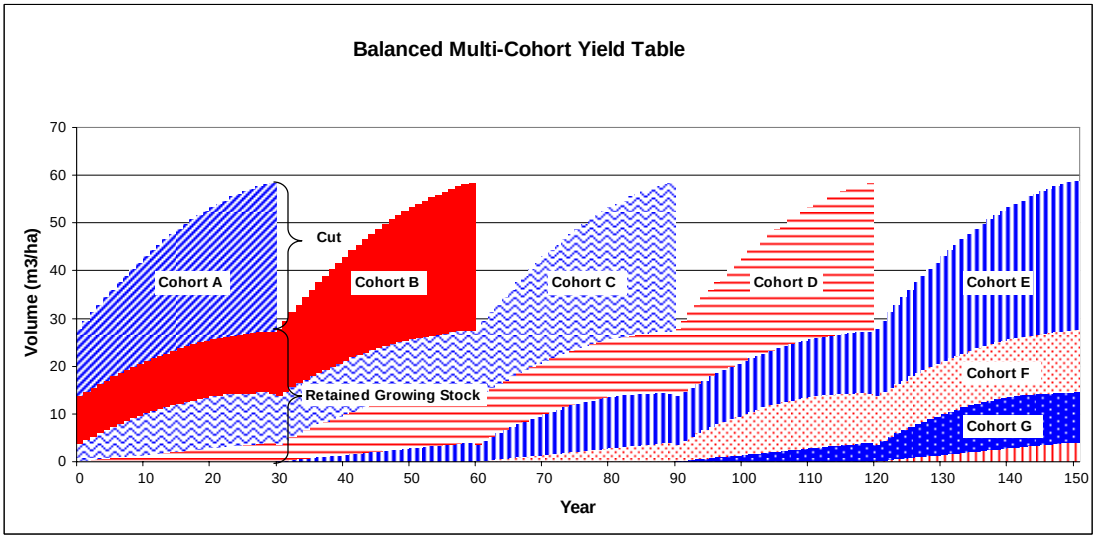
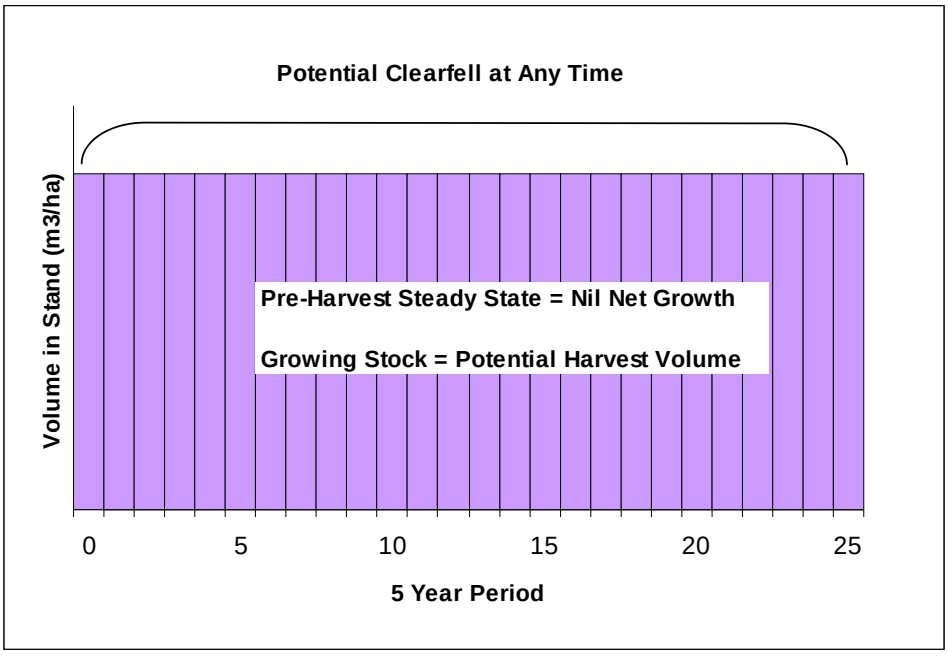


Table 6: Time-dependent Yield Table - Selection harvesting of uneven-age stand.
Pure species stand (commercial species)

Time (5 Year Period)	Merchantable Growing Stock Volume (m/ha)	Yield High Quality Sawlog (m3/ha)	Yield Low Quality Sawlog (m3/ha)	Yield Pulplog (m3/ha)	Total Merchantable Yield (m3/ha)
0	56	0	0	0	0
1	64	0	0	0	0
2	70	0	0	0	0
3	75	0	0	0	0
4	78	0	0	0	0
5	80	0	0	0	0
6	82	0	0	0	0
7	50	20	12	8	40
8	56	0	0	0	0
9	64	0	0	0	0
10	70	0	0	0	0
11	75	0	0	0	0
12	78	0	0	0	0
13	80	0	0	0	0
14	82	0	0	0	0
15	84	0	0	0	0
16	50	20	12	8	40
17	56	0	0	0	0
18	64	0	0	0	0
19	70	0	0	0	0
20	75	0	0	0	0
21	78	0	0	0	0
22	80	0	0	0	0
23	82	0	0	0	0
24	84	0	0	0	0
25	50	20	12	8	40

Figure 55: Time Dependent Yields for Uneven-aged Forest – clearfell



Areas assigned with a time dependent yield table representing a steady state forest which will be clearfelled would logically be regenerated as an age dependent yield tables.

Shelterwood System Yield Tables are in a unique group. These can be treated **as** age dependent yield tables if regular shelterwood but time dependent if irregular shelterwood.

Shelterwood yield tables may be treated as time dependent yield where the forest vertical structure (relative age and size of cohorts) do not exhibit the classical two stage shelterwood system of overstorey removal once sufficient regeneration has occurred. The level and timing of treatments has deviated from an ideal two stage structure which maximises the site growth and yield. Achieving an ideal structure has been influenced by forest management including and variable levels of thinning or overstorey removal depending on market product demands, funding available for silvicultural treatments and the need to attenuate wood supplies from an imbalanced forest structure to provide long term sustainable yields.

The shelterwood silvicultural system generates a volume and yield profile similar to an even-aged plantation since for most of the stand life it is even-aged and only when thinning occurs later in the rotation does regeneration occur creating an understorey cohort. In well managed shelterwood system the overstorey volume will be removed before the understorey contributes merchantable volume, so the yield table will not show volumes of both cohorts simultaneously. (Refer Figure 56). Following the overstorey removal the younger regeneration cohort becomes the overstorey cohort. The change in stocking resulting from silvicultural treatments and regeneration events is illustrated in Figure 57.

The stand growth and yield of even-aged shelterwood silviculture are shown in Figure 56 and Figure 57.

Figure 56: Shelterwood Silvicultural System Volume Profile Over Time

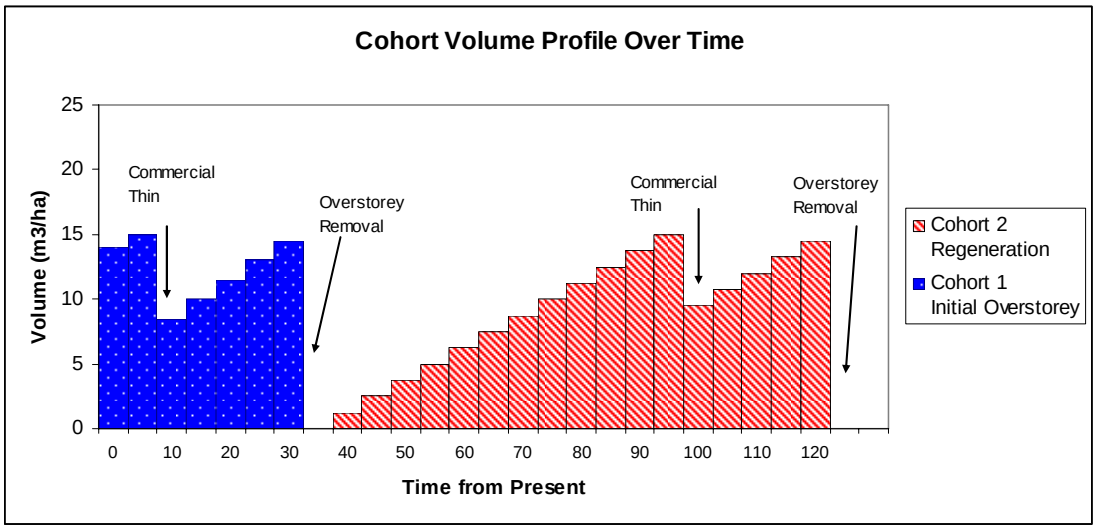
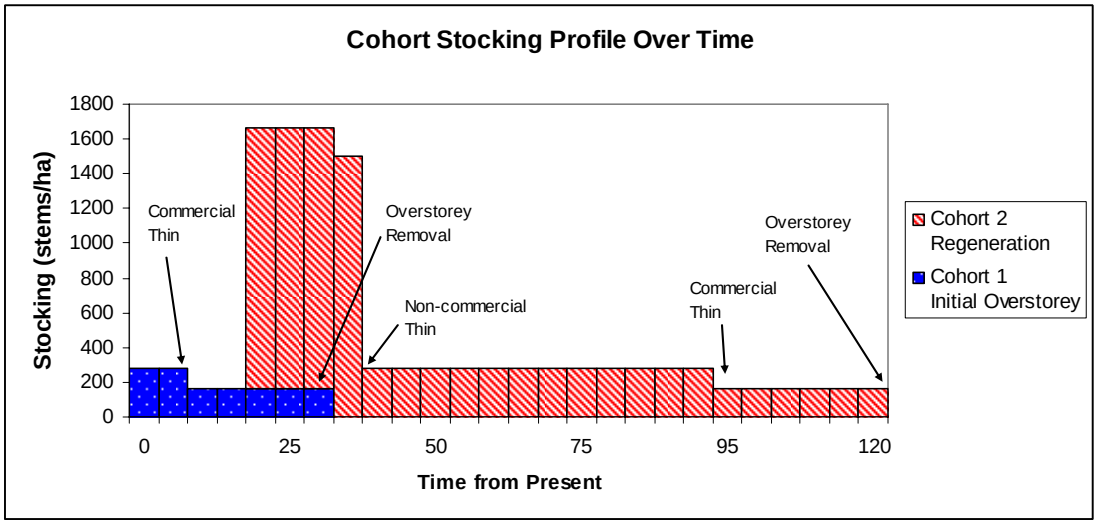
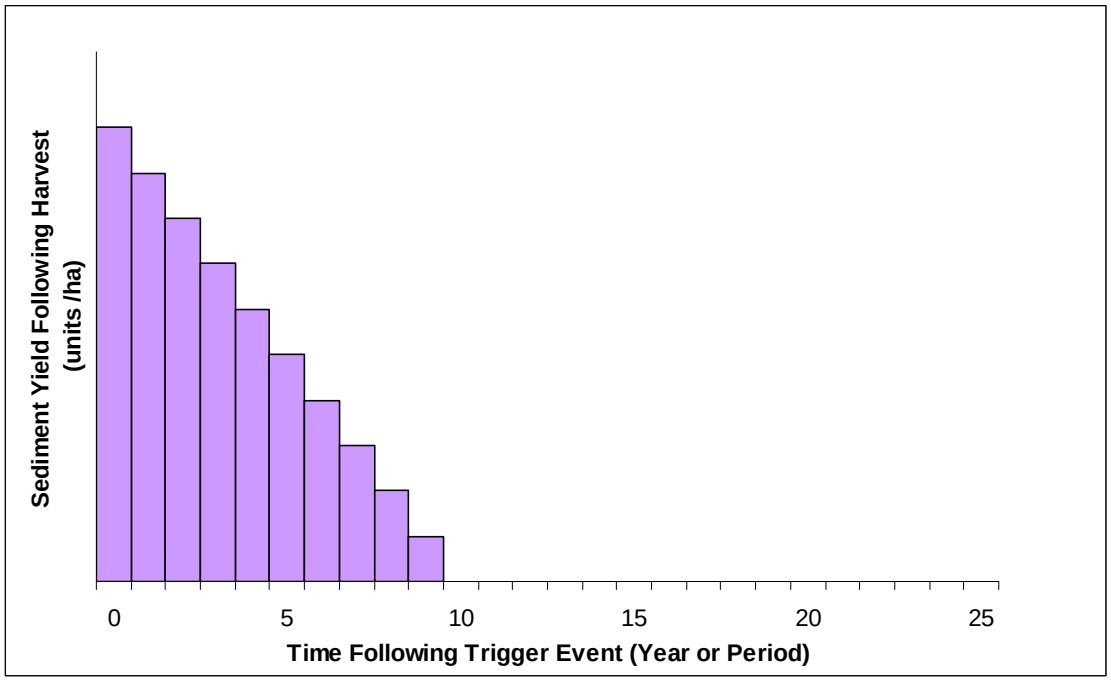


Figure 57: Shelterwood Silvicultural System Stocking Profile Over Time



(c) Sequence dependent yield tables. These contain yields by time period for situations where a silvicultural activity (such as site preparation, planting, thinning, harvesting) or event (e.g. fires) in a given period triggers a sequence or flow of yields (commodity outputs or environmental outcomes) for a period of time. e.g. Harvesting creates sediment loading in waterways to temporarily increase – initially high, declining as the site is stabilized with vegetative cover. This yield table option is only present in some harvest scheduling models but can be represented as additional products in an age dependent yield tables.

Figure 58: Sequence Dependent Yields – Operation triggered "yields"



Appendix D Forest Estate Modeling Technology and Approaches

Forest estate computer models have been developed to provide quantitative solutions for complex forest management planning issues, and to evaluate consequences of management activities (and exogenous variables) on the stock and flow of harvestable timber and the achievement of other non-timber objectives. Key functions traditionally include timber supply forecasting and forest operation planning such as harvest scheduling. Modeling approaches are developed to achieve forest management goals within the context of often conflicting economic, social/political, environmental and regulatory factors. The models also vary depending on the planning level (strategic, tactical, operational), length of planning horizon, and whether both aspatial and spatial factors are being addressed.

Forest estate models have become the foundation of a wide range of applications such as strategic land-use allocation decisions, sustainable forest management zoning, forest valuations (discounted cashflow associated with wood supply scenarios), wildlife habitat modeling, natural disturbance event emulation, and forest risk modeling. Further examples of the forest management planning decision aided by forest estate models are outlined in Table 7.

Table 7: Examples of forest management decisions

Type of Decision	Example
Extent and distribution of reserves	Wilderness
Management emphases for area where active management will occur	high-intensity timber production, scenic areas; big game emphasis;
Types of activities allowed	Timber harvest, prescribed fire
Aggregate harvest level over time	Even-flow, non-declining yield
Silvicultural system	Even-aged, uneven-aged
Age structure of forest	Area by 10 year age classes
Size and shape of treatment units	Small units versus large units
Spatial pattern of treatment units	Concentrated or dispersed cutting blocks
Protection strategy	Wildfire suppression policy
Vertical and horizontal diversity / stand density	Approach to partial cutting and prescribed burning
Regeneration harvest timing	Rotation age (even-aged), cutting cycle (uneven-aged)
Regeneration method	Clearcutting, clearcutting with leave trees, shelterwood, selection. Prescribed fire, natural disturbance

Source: Davis et al, 2001

This chapter provides background on modeling approaches, solution methods, harvest scheduling software, the question of management objectives, future modeling directions within North America and cites several case studies that utilize different technology and approaches to forest estate modeling.

The classification of models are defined in terms several different attributes:

- Planning level (strategic, tactical, operational)
- Mathematical technique (simulation, optimization – exact or heuristic techniques)
- Optimization models are classified in terms of Model I or II formulation
- Heuristic handling of harvest units often defined in terms of an Area Restriction Model (ARM) or Unit Restriction Model (URM) approach
- Models can be stratum based (usually strategic level) or area based (tactical level)

D.1 Planning Level: Resolution and Scale

Forest planning involves temporal, spatial and planning level issues. Forest planning is complicated by a complex and dynamic resource, and conflicting constraints imposed on forest management.

Hierarchical planning

Forest planning is a hierarchical process that typically comprises three scales of planning:

- Strategic
- Tactical
- Operational

Some of the distinguishing characteristics addressed at different planning levels are outlined in Table 8.

Table 8: Features of Forest Modeling Planning Levels

Feature	Planning Level		
	Strategic	Tactical	Operational
Purpose	Availability / Resource Acquisition	Allocation / Resource Use	Execution
Answers Question	How much of what and when	Where (Approx)	Which blocks and precisely when
Planning Horizon	Long Term	Medium Term	Short Term
Management Planning Level	Top	Middle	Bottom
Information	External / Internal	External / Internal	Internal
Level of Detail	Highly Aggregated	Moderately Aggregated	Very Detailed
Uncertainty Level	High	Moderate	Low
Risk	High	Moderate	Low
Scope	Broad	Medium	Narrow
Spatial Detail (Resolution)	Low	Medium	High
Output	Wood Supply Forecast / Management Strategy	Operations Schedule (Indicative)	Operation Plan

Source: Remsoft (2004) and Gunn, E.A. (2005).

Strategic Level Modeling – Wood Supply Forecasting

Strategic forest plans are overarching plans that address landscape level goals and constraints over a long planning horizon. Lower levels of planning—tactical and operational–within the strategic goals and constraints, address shorter term, more spatial and more logistical issues. In general a strategic plan may identify total land dedicated to different uses and specific quantities of different timber types to be harvested. This level of planning is not concerned with the exact geographic location where these activities will occur. The strategic forecasts provide an indicative assessment of how much wood and what type of wood can be produced from a forest estate.

Tactical Level Modeling – Harvest Scheduling

Tactical level planning focuses on where and when silvicultural treatments, harvesting operations, and reserved areas are to be prescribed or scheduled. Tactical level modeling provides a schedule of precisely where forecast wood will come from. Features addressed in tactical level harvest scheduling include:

- sub-optimal harvest timing within management units featuring multiple strata of different floristic composition, structures and growth potential
- more restricted constraints on harvest timing and location
- water catchment or wood supply regulation
- species and product mix regulation
- harvesting discrete blocks not unregulated across landscape
- regulating harvesting of adjacent blocks
- controlling dispersal and/or aggregation of harvesting activities
- stochastic modeling of fire events to provide a buffer in wood supply forecast
- risk management scenarios – addressing the adverse impacts of broad strata classifications, variation in inventory data and overestimates of growth and yield

Operational Level Modeling

Operational modeling addresses the execution of tactical plans including finer details and logistics of scheduling operations on a weekly and monthly basis. Often reference is made to operational level harvest scheduling, that should be defined as tactical.

D.2 Mathematical Modeling Solution Methods

Forest estate models are based on a range of mathematical programming techniques (linear, integer, mixed integer, quadratic, and dynamic programming, heuristics) to ascertain allowable cuts and solve operation scheduling problems over multiple rotations. Two broad categories of forest estate models exist: simulation and optimization. Each has its own advantages and disadvantages, but in general optimization techniques have been more widely and successfully used in forest management planning than simulation techniques for forest estate level modeling.

Simulation models

Simulation-based forest estate models are computer programs that simulate the outputs of flows and stocks of timber and non-timber resources, resulting from user defined management options. Simulation models incorporate mathematical relationships representing predetermined outputs and outcomes for each management activity on different forest resources. The model is not based on optimizing a user defined objective function, rather the simulator shows the consequences of decisions on silvicultural treatments on the product flows (volumes, cashflow) and retained growing stock. Deriving a wood supply forecast or harvest schedule is a trial and error process and dependent on the skill of the model user.

Mathematical programming models (optimization models)

Optimization methods have been developed for forest planning where the area comprises multiple stands each having several alternative treatment schedule options. The objective of the forest modeling is to identify a treatment schedule for each forest stand (harvest unit, stratum, or compartment) that is optimal at the forest level, not the stand level. The models identify appropriate silvicultural systems, rotation ages/cutting cycle lengths, harvest intensities and operation location over the planning horizon.

Optimization-based forest estate models are computer programs that search for an optimal solution for a forest management planning scenario. Optimization models are designed to maximize or minimize an objective function while simultaneously satisfying constraints. They are used to determine which timber units to harvest each period to meet projected demands and satisfy silvicultural, economic, environmental, social, sustainability, and other planning constraints. Examples of objective functions include maximizing

the volume of timber harvested each year to maximize the net present value of forest management, or minimize costs. Examples of constraints include temporal flow constraints (minimum or maximum levels, limits of variability in flows), restrictions on silvicultural options, and maximum contiguous harvest areas.

Optimization techniques have been more widely and successfully used in forest management planning than simulation techniques for forest estate level modeling.

There are two categories of optimization models: (a) exact techniques that find a truly global optimal solution if a feasible solution exists and (b) heuristic techniques that find a "best solution" or a range of near-optimal solutions to a planning problem.

Linear programming techniques—a form of exact techniques—have traditionally been used for forest estate modeling, particularly strategic level modeling. However, forest management planning problems are often multi-objective, multi-stakeholder, non-linear, non-additive and spatial, and are computationally too difficult or not possible to solve with these traditional optimization techniques. Consequently, heuristic techniques have been developed and adopted.

Sessions at al (2001) outlines that although there have been advances in solving large mixed integer linear programming programs that can provide optimal solutions, the decrease in solution time still has not been dramatic enough to abandon heuristic approaches, which tend to offer faster solutions. Thus, where time is an issue, heuristic approaches may be a more viable option. An explanation of these techniques follows.

D.2.1 Exact Techniques

Exact techniques are designed to find the mathematically optimal solution if a feasible solution exists. Examples of their use are shown in Table 9.

Linear programming (LP)
LP is a mathematical programming technique that will isolate the best alternative from a set of feasible options. LP models are composed of a linear objective function subject to linear constraints. LP will optimize the allocation of limited resources among competing activities. LP handles decision variables that can be fractional.

Integer programming (IP)
IP is a mathematical programming technique that works on the same principles as LP but the formulation only has integer decision variables.

Mixed integer linear programming (MILP)
MILP is a mathematical programming formulation that includes both fractional and integer variables.

Goal programming (GP)
GP is a LP minimization problem where the objective function sums deviations from stated output goals; if all goals can be met exactly, then the objective function value is zero. Goals may be weighted equally or they may have different weights; goals with higher weights are favored over those with lower weightings (Remsoft, 2004).

Non-linear methods are mathematical programming techniques used where the relationship between variables in the objective function and constraints are not linear.

- Dynamic programming
- Quadratic programming
- Geometric programming

Table 9: Exact Technique Applications in Forest Planning

Type of Exact Technique and Use	*Citation in literature*
Linear Programming	*George Dantzig, 1998*
Harvest scheduling	*Remsoft, 1994,2007*
	USDA FS
Integer Programming	*Crowe et al. ,2003;*
	Martins et al. ,1999, 2000
Mixed Integer Linear programming	*McDill et al 2002*
Dynamic programming	
optimizing individual stand growth	*Pelkki, 1999*
optimizing decisions between neighboring stands	*Swallow et al ,1997*
development for spatially constrained management plans	*Borges et al ,1999*
	Hoganson and Borges, 1998

D.2.2 Heuristic Techniques

A heuristic is a search algorithm that does not necessarily find the global optimum but can produce relatively good solutions within reasonable time. The performance of different heuristics may vary depending on the complexity of the planning problem. (Pukkala & Kurttila. 2005.)

Linear Programming and Mixed Integer Linear Programs have been used for forest planning since the 60's to support decision making on forest harvesting and management. Since the 1990's the use of heuristic optimization algorithms in forest planning instead of the more traditional LP methods has developed as a result of multiple decision-makers, multiple -objectives, spatial and non-linear forest management objectives and constraints, and the combinatorial nature of forest management planning problems. (Pukkala & Kurttila. 2005.) To address the complex nature of these forest management problems, sophisticated models are being developed using solution algorithms such as local search heuristics, random search approaches, strengthening of mixed integer model formulations and Lagrangian relaxation. (Weintraub et al. 2000).

The derivation of an optimal solution for combinatorial optimization problems such as harvest scheduling is difficult. The difficulty arises from the fact that unlike linear programming, whose feasible region is a convex set, in combinatorial problems, a lattice of feasible points—or in the mixed-integer case, a set of disjoint halflines (or line segments)—must be searched to find an optimal solution. In linear programming any local solution is a global optimum due to the convexity of the LP problem, but combinatorial optimization problems have many local optima and finding a global optimum to the problem means having to establish that a particular solution dominates all feasible points by arguments other than the calculus-based derivative approaches of convex programming. (Hoffman and Padberg. Undated).

There are a range of different approaches for solving combinatorial optimization problems, and some model developers have combined solution techniques into "hybrid" solution procedures.

Heuristic techniques are solution techniques that are based on logical rules to find an optimal solution, and provide results with less computational effort than exact methods but an optimal solution cannot be guaranteed. Heuristic techniques quickly eliminate infeasible or poor solutions, but many combinatorial optimization problems are large, complex and irregular and consequently may have multiple local optima. To search for a global optima, the local neighborhood search algorithms are combined with strategies to move to other parts of the solution space and find other optima. Convergence on the global optimal cannot be guaranteed but if the strategies are repeated a sufficient number of iterations, a near optimal solution should be achieved.

In forestry, applications of heuristic techniques began in the early 1990s and have been growing rapidly in strategic and tactical forest planning, particularly the latter. Development of heuristics has intensified along several broad lines (Sessions et al, 2003):

1. Stochastic Monte Carlo neighborhood search heuristics

    - Monte Carlo
    - Hero
    - Simulated Annealing
    - Threshold Acceptance
    - Great Deluge
    - Raindrop

2. Non-stochastic search techniques,
    - TABU search (Hill Climbing)

3. Evolutionary algorithms
    - Genetic algorithms

Li et al (2006) stated that metaheuristics[6] consistently provides better solutions than standard heuristics alone. This is attributable to combination of approaches have different behavior in regions of the solution space at different times.

Monte Carlo (also called Random ascent)
A process where the harvest scheduling solution is randomly developed. The initial solution involves assigning a random management prescription (harvest or no harvest; intensity, type and timing of harvest) to management units over the planning horizon. The process is repeated for a user-defined number of iterations. Each iteration represents a new solution. The assigned values must be eligible options and not violate constraints. For each iteration the objective function is calculated and if it is higher than the preceding iteration this is saved as the best solution. The best solution is reported once the maximum number of trials has finished. (Davis et al 2001; Pukkala, 2006)

Hero
A heuristic technique where the initial solution is the best of a number of prior random solutions. The treatment of stands are sequentially evaluated to see whether another treatment would improve the objective function. Improved solutions replace previous solutions. (Pukkala, 2006)

Simulated Annealing
A modeling technique where the feasible region of the planning problem is searched using a random search technique with the objective of converging on an optimal solution, known as a steady (or frozen) state. An initial solution (feasible or infeasible) is developed by randomly assigning management prescriptions (harvest or no harvest; intensity, type and timing of harvest) to management units over the planning horizon. The heuristic technique converges on the "best" solution by randomly selecting a single management unit in the latest "best" solution and assigning a new random harvest prescription to make a new "temporary" solution. The temporary solution becomes the "best" solution if the objective function increases. However, the change to the solution may be made even if it is worse than the current best solution. An "acceptance" value is determined based on an "annealing" function that accounts for the difference between the temporary and preceding "best" solution and the number of iterations completed relative to the maximum number specified for the simulation. If a randomly drawn number is within the "acceptance" value range the temporary solution is used to update the "best" solution. The acceptance value tightens depending on the length of search by a change of a parameter in the annealing function. This tightening reduces the likelihood of change to the current solution. At the end of the iterative procedure the solution with the best objective function value is reported as the solution.

[6] A metaheuristic is a heuristic method for solving a very general class of computational problems by combining "black-box' heuristic procedures to obtain a near optimal solution more efficiently.

"[Simulated annealing is a] technique to find a good solution to an optimization problem by trying random variations of the current solution. A worse variation is accepted as the new solution with a probability that decreases as the computation proceeds. The slower the cooling schedule, or rate of decrease, the more likely the algorithm is to find an optimal or near-optimal solution." (Davis et al 2001)

Threshold Accepting
This is a modeling technique similar to simulating annealing, but it has a much simpler acceptance decision logical. The decision to accept a candidate solution occurs if the move produces an objective function at least as good at the current solution less a threshold value. The threshold is gradually reduced, so reducing the probability of accepting an inferior move decreases after a specified number of moves, and the modeling process ends once no further solution is achieved or the threshold is very small. The technique accepts inferior solutions to avoid premature convergence to a local optimum. (Pukkala, 2006)

Great Deluge
This technique similar to simulated annealing and threshold acceptance. An initial user defined objective function ("water level") is set and all candidate moves are accepted if they are above the level. When the move improves the objective function this increases the acceptance level by a user defined amount (rain event occurs and raises water level). The acceptance level gradually converges on the best objective function and stops when they meet. Random moves may be used to improve the solution. (Pukkala, 2006).

Raindrop

A modeling technique that commences with the development of a randomly defined feasible solution to the modeling problem. As the forest plan is developing, a management unit and harvest period not currently in the solution is selected at random. Then deterministic changes to other affected management units are imposed. The selected move is then forced into the solution regardless of any potential constraint violations, and list of those management units affected is compiled. From this list, the management unit physically nearest the centroid of the original selected management unit is identified, and the next best alternative harvest period for this unit, (one that does not result in a constraint violation with the originally selected unit), is selected and forced into the solution. Any adjacency constraint violations that occur necessitates an adjustment of the affected management unit's harvest timing such that the next best harvest timing is selected regardless of the resulting additional infeasibilities. All management units that are affected by this change to the solution are then added to the list of affected units. This process is repeated creating a "radiating, spatially sprawling adjustment process" that is continued until all infeasibilities have been corrected. This becomes the end of one search process iteration. The process is continued for a user-defined number of iterations and the current solution to the problem reverts back to the previously saved best solution. (Bettinger and Zhu 2006).

Tabu Search
A modeling technique where an initial random solution (feasible or infeasible) is developed then a "neighborhood" of potential changes to the current solution is derived. The objective function value is calculated then the best move is temporarily selected. A move is "tabu" (forbidden) if it has been selected within a certain number of iterations in the last change (tabu tenure). If the best move is not "tabu" the best solution will be replaced by the temporary solution. If the best move is "tabu" then the solution is evaluated in terms of aspiration criteria. If over-riding the tabu move restriction results in a solution better than the "best" solution, the temporary solution becomes the best current solution. If the tabu move is not favorable then the move is rejected and another candidate from the neighborhood is selected. The process continues until the maximum number of iterations are reached and the best solution is reported, or if a certain number of iterations pass without a solution improvement.

Tabu search logic is characterised by a search algorithm that constrains repetition of certain moves and permits making non-improving moves in the solution space, to rapidly direct searches throughout the feasible region of the solution space. A search algorithm rapidly converges on optimal solutions if the best solution is progressively selected. The tabu search algorithm, in contrast, is able to avoid being stopped at local maxima in the planning problem solution space and locate global maxima. This is achieved by being able to make "non-improving" moves to the solution and by imposing "tabu" options that avoids the algorithm following a sequence of moves that may cycle back to a solution found. (Davis et al 2001, Pukkala, 2006)

Genetic Algorithms
A modeling technique where the feasible region of the planning problem is searched using two local optima solutions. Two initial random solutions (feasible or infeasible) are developed. The list of "good" solutions (parents) are kept in memory. Two solutions (grouping of management units with unique combination of harvest prescriptions over time) are selected and the solutions are split at a randomly defined cross over point (certain period, geographical split) and recombined so that each new solution has different segments of each parent solution. The objective function value is calculated for each new solution (offspring). The model repeats this process for a defined number of iterations and the best solution is selected and reported. Multiple variations exist for how parents are selected, and how cross-overs and mutations occur. Genetic algorithms have also been combined with other heuristic techniques (metaheuristics). (Davis et al 2001)

Table 10: A brief categorization of search processes used in forest planning

Search technique	Type of change to a developing forest plan	Number of units whose status is changed
Traditional exact methods (LP, IP)	Deterministic	Many
Dynamic programming	Deterministic	Many
Monte Carlo simulation	Random	Many
Simulated annealing	Random	One
Threshold accepting	Random	One
Tabu search	Deterministic	One
Genetic algorithms	Random	Many
Sequential search [a)]	Deterministic	One
Sequential quenching and tempering [b)]	Both	Many

[a)] Pukkala and Kangas (1993)
[b)] Falcão and Borges (2002)

Source: Bettinger and Zhu 2006

Application of Heuristics

The application of heuristic techniques has been explored for different aspects of harvest scheduling and landscape modeling. Refer Table 6. Weintraub et al (2000) present a summary of developments in forest management models andcombinatorial algorithms. Bettinger and Zhu (2006) report that spatial forest planning has spanned the fields of:

- forest transportation (e.g.Weintraub et al, 1995)
- wildlife management (e.g. Bettinger et al , 1997)
- aquatic system management (e.g. Bettinger et al. 1998)
- biological diversity (e.g. Kangas and Pukkala, 1996)
- clearcut size distributions (e.g. Murray et al. 2004)

A number of studies have been conducted comparing the relative merits of the different approaches including Davis et al. (2001); Pukkala (2006), and Bettinger et al (2002).

Table 11: Heuristic Applications in Forest Planning

Type of Heuristic and Use	*Citation in literature*
Monte Carlo	
Addressing adjacency constraints	*O'Hara et al (1989)* *Clements et al (1990)* *Daust and Nelson (1993)* *Jamnick and Walters (1993)*
Scheduling harvest unit / transportation system activities	*Nelson and Brodie (1990)*
Linking strategic and tactical forest planning efforts	*Nelson et al (1991)*
Developing wildlife conservation plans	*Haight and Travis (1997)*
Simulated Annealing	*Kirkpatrick et al. (1983),*
Addressing adjacency constraints	*Lockwood and Moore (1993)* *Murray and Church (1995)*
Scheduling harvest unit / transportation system activities	*Murray and Church (1995)* *Sessions et al. (2000)* *Chung and Sessions (2000)* *Dahlin and Sallnas (1993)* *Van Deusen (1999)*
Thresh hold acceptance	*Dueck and Scheuer (1990)* *Bettinger et al. (2003)*
The Great Deluge	*Dueck (1993)*
Tabu Search	*Glover (1989)*
Addressing adjacency constraints	*Murray and Church (1995)* *Bettinger et al (1999a)* *Richards and Gunn (2000)*
Scheduling harvest unit / transportation system activities	*Murray and Church (1995)* *Bettinger et al. (2002)* *Boston and Bettinger (1999)*
Incorporating wildlife and aquatic resource goals	*Bettinger et al (1997)* *Bettinger et al (1998)* *Bettinger et al (1999b)* *Kliskey et al (1999)*
Genetic Algorithms	
Developing strategic plans	*Holland (1975)* *Pesonen et al (1995)* *Mullen and Butler (2000).*
Tactical harvest schedule	*Dewey et al, (2006)*
Sequential Search	*Pukkala and Kangas (1993)*
Sequential quenching and tempering	*Falcao and Borges (2002)*
Hybrid Heuristics	*Boston and Bettinger (2002)* *Borges et al. (1999)*
Other	
Addressing adjacency constraints	*Yoshimoto and Brodie (1994)* *Yoshimoto et al (1994)*
Scheduling harvest unit / transportation system activities	*Sessions and Sessions (1997)* *Van Deusen (1999)* *Weintraub et al (1994)* *Weintraub et al (1995)*

Source: Adapted from Davis et al 2001. Annotated.

D.2.3 Modeling Approaches

D.2.3.1 Modeling formulations

Forest estate models are based on a range of mathematical programming techniques (linear, integer, mixed integer, quadratic, and dynamic programming, heuristics) to ascertain allowable cuts and solve operation scheduling problems over multiple rotations.

Forest estate models are typically based on one of two conventional model formulations – Type I Model or Type II Model. This model formulation has a significant impact on the logic of how harvesting units are treated and which yield tables are used. The broad distinction is that Type I models retain the identity of a forest area and allocates a single time dependent yield tables in the first period that applies for the whole planning horizon. This yield table represents yields from a pre-determined sequence of harvesting events. In Type II models the harvest units identity does not have to be retained over time. Rotation length age-dependent yield tables are typically used. Yield tables are only assigned for a single rotation, then a yield table is assigned depending on management objectives and constraints. Areas can be transferred between crop types / development types (and assigned the "new" yield tables) at prescribed ages (e.g. post thinning) and not just at the end of the rotation following clearfelling.

Type I Model versus Type II Model

The sequence of treatments on a given hectare over multiple rotations are predetermined in a Type I Model. A Type II Model covers the treatments only over the life of one hectare (stand). Each time a hectare is clearfelled in a Type II Model, it may be combined with other areas belonging to the same development type to form a new age class for the next rotation.

When the Type I Model structure is used for modeling the enumeration of all rotation combinations is usually incomplete, so there is a higher probability of resulting in infeasible and suboptimal solutions than a Type II Model. Under a Type I Model structure it may be infeasible to meet harvest flow constraints in periods simply due to the lack of complete rotation enumeration (called "rotation inflexibility"). A major advantage of a Type II Model is the flexibility that they can generate all rotation combinations from the base number of yield tables, and so reduce model size. Type II Model formulations are ideally used when there are multiple choices for regeneration in terms of the intensity and timing of operation and rotation length, and this is accentuated when rotations are short.

Type II Model formulations enable the following:

- At the time of clearfelling the forest area may be transferred to one development type class, or split and transferred to many different development types. In each case the areas will be assigned to a new age class beginning with the age of zero.

- An area of forest can be transferred to alternative during the rotation e.g. thinned c.f. Unthinned regime.

- In some models forest areas can be passed to regeneration classes any time during the rotation (due to mortality), up to the time of regeneration harvest.

D.2.3.2 Area and stratum based modeling

There are two basic approaches to classifying the land are within forest estate models - stratum based and area based modeling. Composites of the two procedures can be used.

Stratum Based Modeling

Stratum based modeling involves classification of the resource into homogenous units of forest characterized by unique strata level yield tables. The forest crop attributes and silviculture are defining characteristics. The physical (administrative, management) boundaries are not. The areas may be non-contiguous (discontinuous) and transcend the whole estate. While each stratum has a unique set of attributes, pieces of the stratum may be scattered geographically throughout the forest estate or across the region. No spatial relationships and spatial constraints are modeled.

Stratum based modeling has a role in strategic wood supply assessments as it provides an indicative forecast of the wood supply capacity overtime. Strategic modeling often covers an extensive and extremely heterogeneous area, detailed level area-based modeling is not necessarily a suitable option for two reasons:

- the level of supplementary data required for area based modeling can be prohibitive, and
- a model encapsulating all of the data can be difficult or impossible to solve with certain modeling technology (viz LP programming). In stratum based modeling an advantage is a smaller number of analysis areas used, resulting in a smaller number of rows in the LP matrix and faster solution time.

Two disadvantages arise from stratum based modeling:

- When analysis areas are split through harvesting at different ages or are allocated to different schedules of silvicultural treatments it is not possible to know which piece of the analysis area should be harvested when and which part should receive a particular silvicultural treatment.
- Wood supply forecasts are typically overestimated because they omit a range of constraints (adjacency, minimum area) and the associated sub-optimal stand management (the need to apply alternative silviculture such as not thinning or thinning heavier/lighter or harvest earlier/later) reduces volume forecasts. When an irregular resource is regulated using stratum based modeling (i.e. strata transcend range of geographical areas and many stands) the harvest scheduling model will effectively pick out areas and proportions of areas in an order across the estate to best achieve the overall objectives (e.g. maximise sawlog volume).

Area Based Modeling

Area based modeling involves defining discrete and contiguous geographic portions of land which may be characterized by heterogeneous forest (multiple inventory strata or forest types in varying proportions). Yield tables used are linked to the unique blocks of land. Spatial relationships are preserved and spatial constraints may be applied.

Area based modeling is necessary for tactical scheduling to identify precisely where harvesting operations should be scheduled and in which period. This approach requires substantial modifications to the area definitions, yield table structure, level and types of constraints, and the planning horizon and period length.

With area based modeling each analysis area is a contiguous piece of land. An analysis area may comprise multiple GIS polygons (patches) separated by physical or administrative factors (e.g power lines, riparian buffers and other inoperable areas). In this approach two or more analysis areas may have the same set of land attributes (same development type or development type class) but have different names

identifying the discrete land unit e.g. coupe number. An advantage is that the specific location of the scheduled harvesting events or the allocation of silvicultural options to specific areas are known. A disadvantage is the increased number of analysis area (LP matrix rows and columns) which will increase model processing time.

If LP models are applied, area based modeling can be used effectively for a large resource for a short time frame. The longer the time frame the smaller the number of discrete units that can be modeled. This situation is compounded by the number and type of yield tables used. If time dependent yield tables are used then more options are typically required than if age dependent yield tables are used. Conversely, if age-dependent yield tables are used then many more constraints may be required.

D.3 Spatial Forest Planning

"A planning problem is spatial if the decision about each spatial cell requires data specific to that cell's state and other cell's in its neighborhood." (Crowley, 2006)

Increasingly the spatial location of activities is included in forest estate models because they affect wildlife habitat, aesthetics, and other environmental concerns. Spatial forest planning addresses issues including:

- maximum harvest opening size
- harvesting discrete units
- road building
- ecological corridors/fragmentation
- visual impact

Developments in quantitative analysis approaches that integrate spatial constraints enable forest managers to provide more accurate wood supply forecasts and to better achieve goals of forest management within financial, environmental, social, legal, certification or policy constraints.

D.3.1 Factors contributing to the inclusion of spatial considerations in forest planning

Harvest scheduling on both public and private land has progressively included spatial planning issues. Factors identified by Bettinger and Sessions (2003) for making spatial forest planning desirable or necessary in North America include:

(a) Regulations

Regulations in North America often necessitate the use of spatial planning, as guidelines are imposed on the size of clear-cuts, the minimum buffer width between harvest openings, and the minimum time interval between cuts of adjacent areas (green-up intervals) to maintain forest cover or connectivity. The planning regulations vary between public or private tenure, and by state in the USA or province in Canada.

Examples of Pacific North West legislation include:

- Oregon State Legislation (2001)
- Oregon Secretary of State (2002)
- Washington State Legislation (2002) requires 70 acres around spotted owl nesting site
- British Columbia (Canada) Ministry of Forests (2002)
- National Forest Management Act (1976) limits clearcut to 60 acres or less

A comprehensive regulatory approach to spatial planning has been implemented in Ontario Canada where natural disturbance patterns are emulated in forest management (OMNR, 2001). Detailed guidelines exist for the size, frequency, temporal and spatial separation of planned clearcuts.

(b) Published Forest Plans

Public lands are experiencing increasingly complicated land use demands. As competing land use demands have grown, forest managers are including many more constraints in forest modeling programs, including spatial factors. For example, the Canadian government and USDA Forest Service national forests are managed under forest plans that contain guidelines on managing for timber, wildlife, water and other non-forest, social and environmental requirements. Some of the forest management plans outline spatial restrictions on forest management activities such as the maximum clearcut size and dispersion of openings that must be separated by a minimum distance separated by uncut or sufficiently regenerated stands. Some forest plans limit the number and size of harvest openings that are adjacent to forest reserves.

Some plans contain guidelines for reserve designs to achieve effective wildlife habitat. Features include:

- requiring forest patches be distributed across the landscape and connected by corridors
- forest patches may have to contain certain seral stages (or stand types) and possibly in certain complex arrangements
- maintaining large contiguous area of forest (200 – 500 acres) of late seral stage forest to enhance interior forest habitat
- monitoring the rate of movement of contiguous interior forest habitat across the landscape.

(c) Management efficiency

Spatial planning can also increase management efficiency as public and private organizations include spatial restrictions in forest planning to more accurately predict and optimize future wood supply levels, harvest schedules, and the extent and type of habitat.

There is a preference to link strategic with tactical and operational level planning to ensure that forecasted harvest levels are achievable using the most profitable management strategy. Strategic planning without spatial relationships overlooks restrictions that occur over the landscape and implementation at a tactical level may not enable strategic goals to be achieved.

Optimal management of forests at landscape level that include spatial constraints such as non-adjacency of harvest areas, green-up intervals or combinations of stand types, will still typically result in some sub-optimal stand level decisions. The level of sub-optimality depends on the degree of forest and stand irregularity and characteristics. In general, sub-optimality results in lower wood supply forecasts or limitations in meeting landscape goals.

(d) Landscape planning

Spatial landscape planning can also help evaluate the level of potential activity across multiple ownerships in terms of impacts on visual aspects of the landscape, forest cover and habitat, as it enables the analysis of alternative management approaches and forest land-use zoning across the landscape of a given tenure or multiple ownerships.

(e) Voluntary program guidelines

Voluntary programs may require the use of spatial planning, such as in the case of forest certification schemes and habitat conservation plans.

Certification schemes enable industrial and small private forest managers and owners to demonstrate the sustainability of forest management (in terms of social, environmental and economic factors) and compliance with regulations such as average clearcut size, minimum green-up periods, landscape spatial patterns and diversity.

Habitat Conservation Plans are voluntary programs implemented by some large forest owners to demonstrate effective habitat management for wildlife. Spatial forest planning enables the spatial layout of forest activities and stands meeting habitat conditions to be demonstrated temporally.

(f) Visualization of management alternatives

Spatial planning enables forest managers to produce management plans as maps that illustrate the proposed location of harvesting operations and ecological or habitat reserves over time. This enables managers and stakeholders to better understand the impacts of forest management plans on the landscape and to monitor changes. This also helps build trust among groups with an interest in forest management.

D.3.2 Types of Spatial Constraints

D.3.2.1 Adjacency Constraints in Harvest Scheduling

Adjacency constraints are spatial restrictions that prohibit the harvesting of adjacent management units larger than a specified value within a given time period. The restrictions are imposed to limit the size of contiguous forest openings created during harvesting. The minimum time period between harvesting of adjacent management units is referred to as a "greening up" constraint and is the time necessary to replant or regenerate a harvested area to develop forest cover. The adjacency constraint results in increasing forest fragmentation since the harvest opening as are dispersed across the landscape.

Regulating spatial disturbance is now standard practice in public and private forest management throughout North America, though the maximum size of contiguous openings and green-up periods vary significantly. In the United States these regulations are stipulated at the state and federal level; in Canada they are stated at the Provincial level.

Computer models have been developed to model spatial constraints in two different ways – either as a Unit Restriction Model or an Area Restriction Model (Murray, 1999; Murray and Weintraub, 2002). Both models have the same basic goals, but the distinguishing characteristic is the issue of scale and spatial unit representation.

Unit Restriction Model

Unit Restriction Models (URM) restrict concurrent harvesting on all adjacent units, regardless of area. The management units are typically less than a maximum area and greater than a minimum area, but often assumed to be near maximum opening size. The management units are formed *a priori* by the forest planner using forest characteristics to form cutting units by blocking basic cells. When a management unit is scheduled for harvest in a given period, none of its neighboring units can be harvested in that period or in a number of succeeding periods until regeneration in the harvested unit has progressed for a defined minimum period of time to satisfy green up requirements. (Davis et al, 2001)

This modeling problem can be formulated by various approaches that have all been relatively successful. The URM can be formulated as either an integer programming or mixed integer programming problem and exact methods used to solve the problem, but heuristics have mostly been used due to the size of the problem (Öhman ,2002).

- Exact techniques include Integer Programming, dynamic programming (Hoganson and Borges 1998), column generation (Barahona et al. 1992), and formulation strengthening (Murray and Church 1996, 1997).

- Heuristics such as Tabu search (Murray and Church 1995), simulated annealing (Murray and Church 1995), Monte Carlo simulation (O'Hara et al. 1989, Nelson and Brodie 1990)

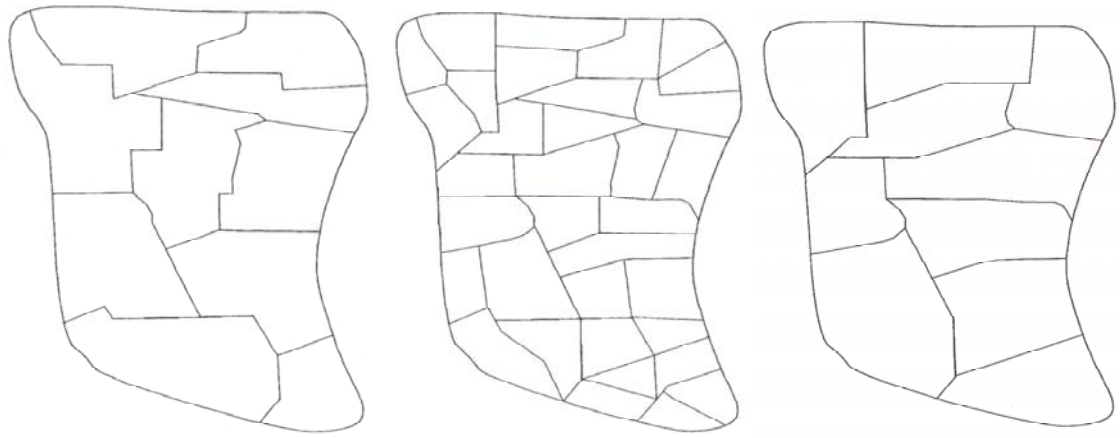
The URM is been the most commonly utilized approach in harvest scheduling and continues to be the focus of research aimed at improving solution capabilities and reducing solution time (Weintraub et al., 2000; McDill and Braze, 2000).

Area Restriction Model

Area Restriction Models (ARM) allows the simultaneous harvest of groups of contiguous management units whose combined areas are less than some predefined limit. Constraints prevent concurrent harvesting of groups of contiguous stands only when the combined area of a group exceeds the harvest area restriction. Harvest planning units are typically composed of smaller management cells well below the maximum harvest opening size. In the URM approach the harvest units are predefined aggregates of the smaller management cells. The ARM finds more efficient ways of combining (aggregating or "blocking") basic cells of a harvest unit to solve harvest scheduling problems with adjacency constraints. These groups of contiguous management units whose combined areas do not exceed the maximum contiguous harvest area limit are called Generalized Management Units.

The ARM has not been widely used for harvest scheduling problems because of its inherent computational complexity as it is not possible to decide in advance all the possible combinations of harvested units. For this reason URM has been more commonly applied to solve adjacency constraint planning problems. The ARM formulations usually result in larger models and take longer to solve, but allow for higher objective function values than otherwise similar URM formulations.

Figure 59: Forest Management Unit Delineation



(a) Spatial harvest units = average maximum opening area. Pre-blocked. URM. Harvesting adjacent unit would violate harvest opening size restriction

(b) Subsets of harvest unit. Adjacent units can be harvested simulataneously if contiguous area does not exceed maxium area limit. ARM approach.

(c) Alternate management unit realization of pre-blocked units units using patches in (b)

Source: Murray (1999)

Approaches proposed to solve this problem include:

- Heuristics are more suitable due to non-linear characteristics of the area constraint. (Hokans 1983, Lockwood and Moore 1993, Barrett et al. 1998, Clark et al. 2000, Richards and Gunn 2000, Boston and Bettinger 2002).

- Exact solution approaches – these are limited (McDill et al. ,2002; Crowe et al. ,2003; Martins et al.,1999, 2000)

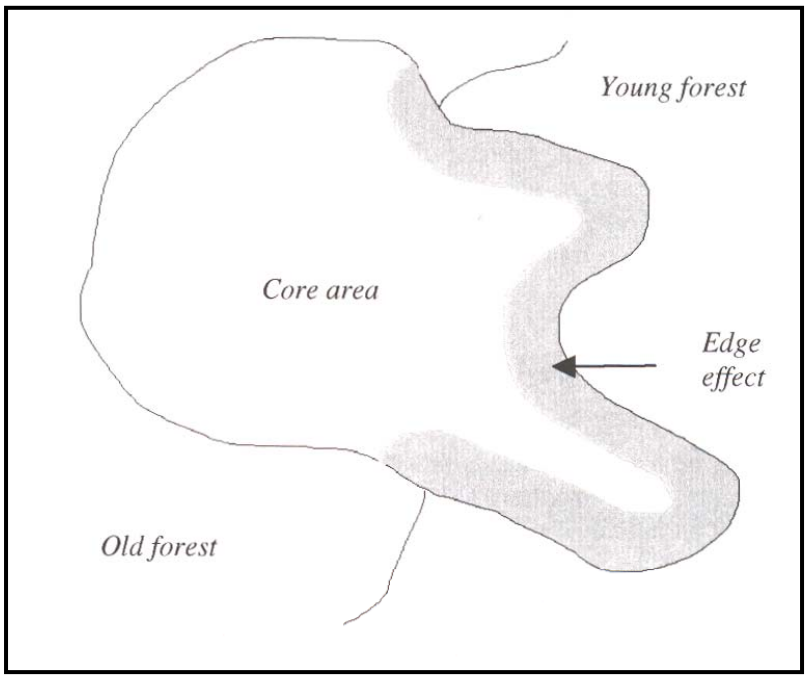
A comprehensive review of combinatorial problems induced by spatial forest harvesting planning has been published by Weintraub and Murray (2006).

D.3.2.2 Preserve Connectivity and Minimize Fragmentation

Spatial planning methods have also been developed to create connectivity in the landscape to maintain forest biodiversity and wildlife habitat by minimizing fragmentation of old growth (late successional reserve) forest. Adjacency methods focus on keeping harvest activity separated by time and space, and increase forest fragmentation since the harvest openings are dispersed over the landscape. Connectivity focuses on trying to aggregate stands with similar conditions to create a contiguous area of old growth forest to minimize fragmentation.

Öhman (2002) discusses how maximizing the core area of undisturbed forest (minimize edge effect where disturbance occurs. Figure 60) rather than maximizing old growth forest would be better for species that need interior forest conditions. It could be better to cluster harvesting over time and spatially across the landscape rather than reducing the harvest intensity over a greater area of the landscape, as it would provide more interior forest habitats, and this would also enhance financial performance as it is less expensive to harvest in clusters rather than dispersed areas.

Figure 60: Core Forest Area Description



The core area of a stand is the area that is not influenced by edge effects from surrounding stands. The stand in the figure is surrounded partly by young forest that causes edge effects and partly by old forest that does not causes edge effects. As a result only a part of the stand consists of core area.

Source: Öhman (2002)

Examples of how the forest management problem of aggregating forest has been addressed include:

- Hof and Joyce (1993) who provide a mixed integer linear programming approach for spatially optimizing wildlife and timber in managed forests.
- Clements et al (1999) provide a reserve design for species preservation
- Nalle et al (2002) outline a method of designing compact and contiguous reserve networks with a hybrid heuristic algorithm.

D.3.3 Approaches to Modeling Spatial Constraints

Spatial considerations can be modeled from either an exogenous or endogenous approach. The exogenous approach involves building pre-determined constraints into the modeling such as excluding riparian buffers, special ecological zones, and threatened species habitat from the forest area. Endogenous approaches, which are the focus of the discussion in this report, involve specifying the spatial relationships and constraints that are processed by the model, such as the amount of core area to retain, maximum and average contiguous clearcut area. The solution algorithm determines the spatial layout that optimizes the objectives. (Öhman, 2002). The endogenous approach can also be used for certain spatial considerations in addition removing exclusion areas or zoning by management intent from the net harvestable area. Öhman (2002) points out that the endogenous approach is particularly important in long term planning, so there is potential for biodiversity zones to change over time (not fixed *a priori*) with future development of the forest to provide plans that are more effective ecologically and economically.

Strategic forest planning (whole forest estate) has traditionally excluded consideration of spatial relationships and has been undertaken with non-spatial data. Some spatial concerns are either treated exogenously (non-production zones are delimited and excluded from the model) or ignored. Spatial considerations have been excluded from many models as they are considered unnecessary for long term planning, there are insufficient data, or are too complex to model, or the processing time is impractical. In this situation, the harvest and silvicultural operations are scheduled to meet spatial constraints in the tactical level harvest planning.

It is important that spatial considerations (relationship between neighboring management units) are included in long term planning and not just tactical level modeling, because omission of spatial objectives and constraints can lead or misleading results and make implementation of plans impossible. The production of an aggregate volume harvested from an area without consideration of the layout can result in overestimates of the wood supply capacity if the need for harvesting discrete area, non-adjacent area, and minimum economic sized areas are not addressed. (Öhman, 2002; and authors' personal experience with NSW native forest timber supply forecasts). Similarly, Johnson et al (2001) notes that retention of minimum aggregate habitat area, without consideration of the patch shape, size and distance between habitat patches can result in over estimates of harvesting possibilities or the amount of habitat that is actually suitable.

The level of spatial detail incorporated needs to be appropriate to the required use of the strategic modeling. Nelson and Davis (2002) point out that "Strategic planning models for large forest estates can become very inefficient if proper care is not taken in defining the appropriate level of spatial detail necessary to answer the strategic questions. There is a tendency to carry spatial detail appropriate for operational and tactical planning to the strategic level, which results in cumbersome databases and models. In addition, there is a tendency to treat all inventories within GIS as though they share the same accuracy, which results in numerous resultant polygons. The overall effect is that these large databases and models discourage sensitivity analysis and strategic thinking." They present a case study comparing the effectiveness of detailed and generalized polygons in a strategic planning model.

Many forest planners conduct long term planning (strategic wood supply forecasts) using an exogenous approach to spatial issues (exclusion zones), and explicitly address spatial issues in tactical level scheduling. This has partly been the result of commercial software availability (that corresponds to emerging demands for this functionality), financial and practical organizational factors (e.g. level of information on future road networks, cost of preparing information for detailed long term spatial planning, appropriate resolution of data for planning needs), plus the level of awareness of the importance and impacts of spatial factors on strategic forecasts.

Integration of spatial relationships into long term planning dramatically increases the complexity of the modeling and dictates the approaches that can be used. Changes necessary for endogenous implementation of spatial relationships include:

- Area based modeling is necessary. Strata based modeling is inadequate because strata transcend multiple management unit boundaries and may not coincide with whole management units. Geographic location specific data are required to model the relationship between individual units.

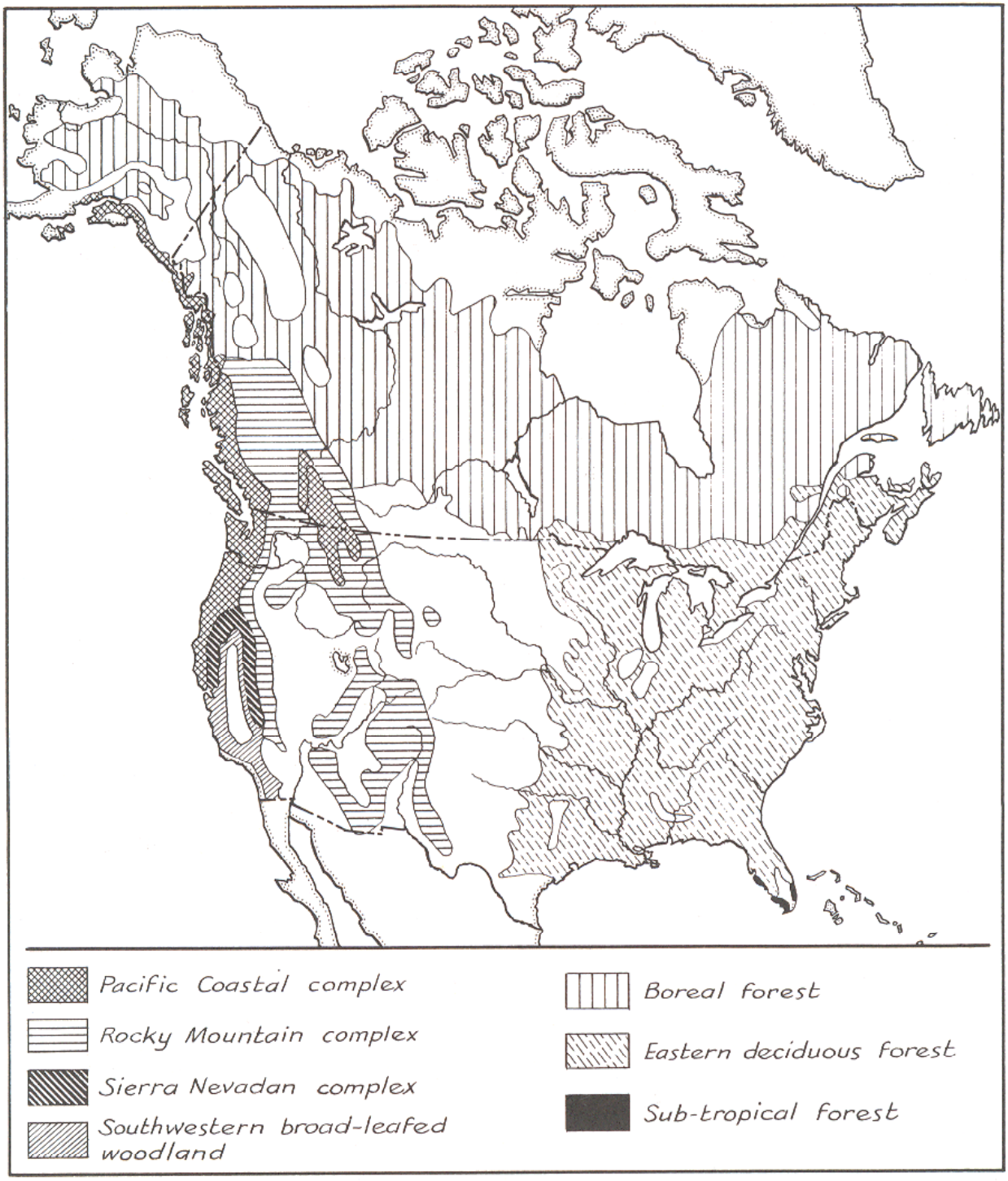
- Integer variables are necessary to model spatial relationships and the harvesting of discrete management units. The divisibility of management units as in linear programming is not appropriate.

- Interdependencies between neighboring individual management units are important. Different spatial configurations of management actions affect harvest volumes in spatial area-based modeling as the output of one management unit is dependent on the adjacent unit treatment. The timing of operations may need to be scheduled together or offset by a green-up delay that is not optimal for some, or all, of the individual management unit.

Solutions to hierarchical planning framework problems are outlined by Gunn (1991), Weintraub and Davis 1996, Cogswell and Feunekes (1997) and Martell et al (1998).

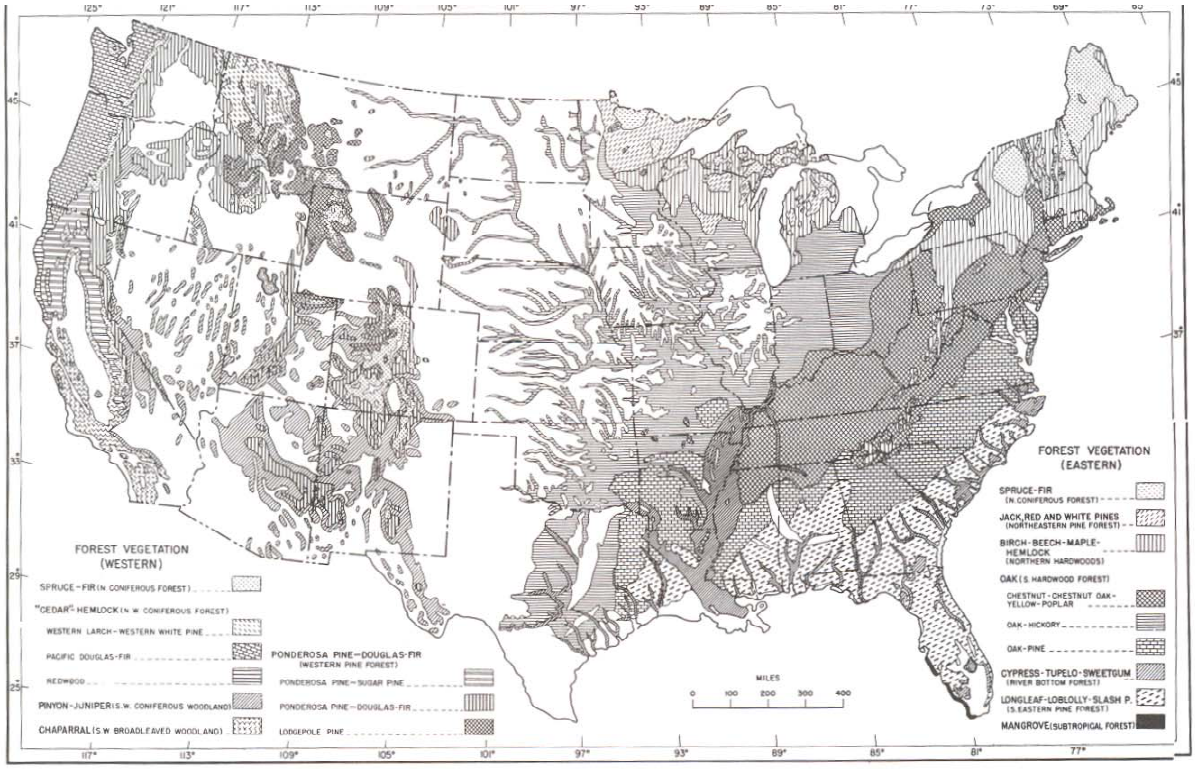
Appendix E North America Forest Distribution and Major Tree Species

Figure 61: The Major Formations of Original Forest Vegetation of the United States and Canada



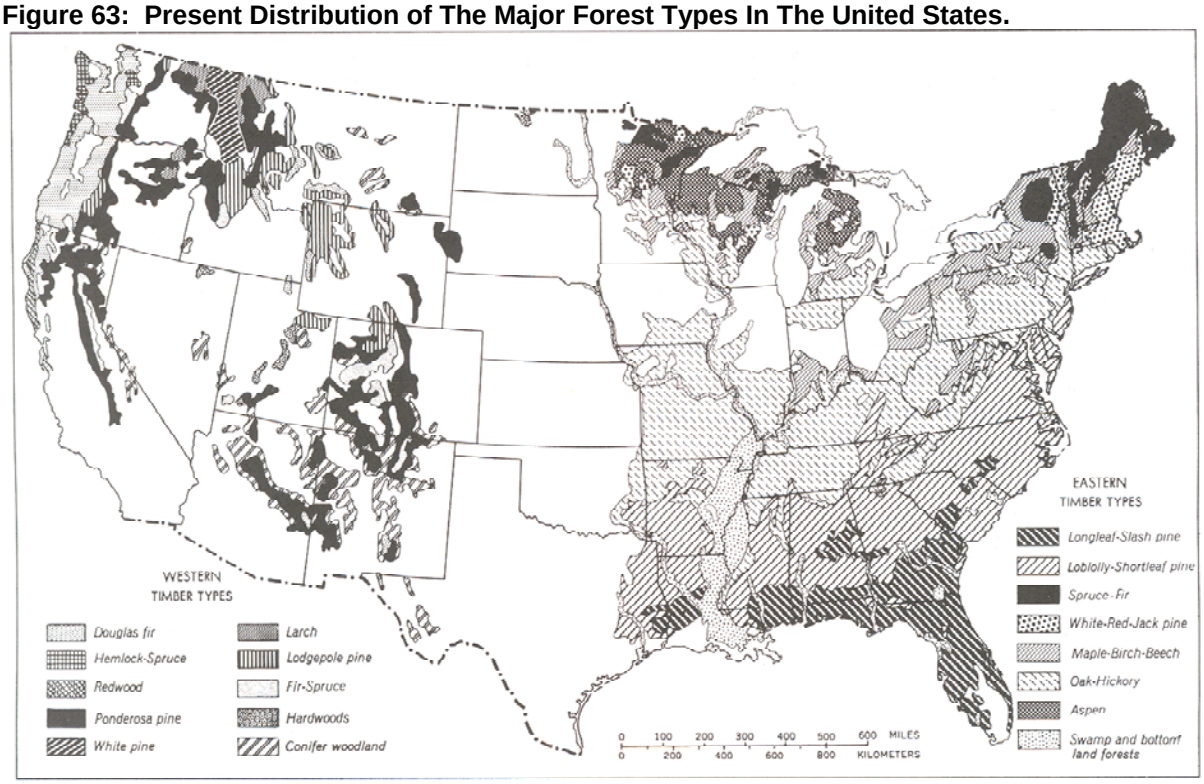
Source: Barrett, 1995.

Figure 62: Distribution of the major types of natural forest vegetation in the United States prior to settlement.



Source: Barrett, 1995.

Figure 63: Present Distribution of The Major Forest Types In The United States.



Source: Barrett, 1995.

Table 12: Common and Scientific Names of Major Tree Species - USA

Common name	Scientific name	Common name	Scientific name
Eastern Softwoods:		Chinkapin oak	*Q. muehlenbergii* Engelm.
True firs	*Abies* Mill.	Water oak	*Q. nigra* L.
Balsam fir	*A. balsamea* (L.) Mill.	Pin oak	*Q. palustris* Muenchh.
Fraser fir	*A. fraseri* (Pursh) Poir.	Willow oak	*Q. phellos* L.
Eastern redcedar	*Juniperus virginiana* L.	Chestnut oak	*Q. prinus* L.
Tamarack	*Larix laricina* (Du Roi) K. Koch	Northern red oak	*Q. rubra* L.
Spruce	*Picea* A. Dietr.	Shumard oak	*Q. shumardii* Buckl.
Jack pine	*Pinus banksiana* Lamb.	Post oak	*Q. stellata* Wangenh. var. *stellat*
Shortleaf pine	*P. echinata* Mill.	Black oak	*Q. velutina* Lam.
Slash pine	*P. elliottii* Engelm.	Willow	*Salix* L.
Longleaf pine	*P. palustris* Mill.	Basswood	*Tilia* L.
Red pine	*P. resinosa* Ait.	Elm	*Ulmus* L.
Eastern white pine	*P. strobus* L.	**Western Softwoods:**	
Loblolly pine	*P. taeda* L.	True firs	*Abies* Mill.
Baldcypress	*Taxodium* Rich.	Pacific silver fir	*A. amabilis* Dougl. ex Forbes
Northern white-cedar	*Thuja occidentalis* L.	White fir	*A. concolor* (Gord. & Glend.) Lindl. ex Hildebr.
Eastern hemlock	*Tsuga canadensis* (L.) Carr.		
Eastern Hardwoods:		Grand fir	*A. grandis* (Dougl. ex D. Don) Lindl.
Maple	*Acer* L.		
Red (soft) maple	*A. rubrum* L.	Subalpine fir	*A. lasiocarpa* (Hook.) Nutt.
Sugar (hard) maple	*A. saccharum* Marsh.	Juniper	*Juniperus* L.
Birch	*Betula* L.	Incense-cedar	*Libocedrus decurrens* Torr.
Yellow birch	*B. alleghaniensis* Britton	Engelmann spruce	*Picea engelmannii* Parry ex Engelm.
Paper birch	*B. papyrifera* Marsh.		
Gray birch	*B. populifolia* Marsh.	Blue spruce	*P. pungens* Engelm.
Hackberry	*Celtis occidentalis* L.	Sitka spruce	*P. sitchensis* (Bong.) Carr.
American beech	*Fagus grandifolia* Ehrh.	Lodgepole pine	*Pinus contorta* Dougl. ex Loud.

Source: Smith et al, 2004. www.ncrs.fs.fed.us