An Agent-Based Forest Sector Modeling Approach to Analyzing the Economic Effects of Natural Disturbances

by

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

The Faculty of Graduate Studies

(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

December 2008

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Abstract

This dissertation describes the development of CAMBIUM, an agent-based forest sector model for large-scale strategic analysis. This model is designed as a decision support tool for assessing the effect that changes in product demand and resource inventories can have on the structure and economic viability of the forest sector. CAMBIUM complements existing forest sector models by modeling aggregate product supply as an emergent property of individual companies' production decisions and stand-level ecological processes. Modeling the forest products sector as a group of interacting autonomous economic agents makes it possible to introduce production capacity dynamics and the potential for mill insolvencies as factors in modeling the effects of market and forest inventory based disturbances.

This thesis contains four main manuscripts. The first manuscript describes the development and testing of a dispersal algorithm that projects aggregated forest inventory information onto a lattice grid. This method can be used to generate ecologically and statistically consistent datasets where high-quality spatial inventory data is otherwise unavailable.

The second manuscript utilizes this dataset in developing a provincial-level cellular automata resource dynamics model for assessing the timber supply effects of introducing weevil-resistant spruce. This model employs a stand-level approach to simulating weevil infestation and associated merchantable volume losses. Provincial-level impacts are estimated by simulating harvest activities over a 350 year time horizon.

In the third manuscript the focus shifts to interactions between forest companies. We analyze the effects of strategic decisions on sector structure by developing CAMBIUM, an agent-based model of competition and industry structure evolution. The forest sector is modeled as a group of autonomous, interacting agents that evolve and compete within the limitations posed by resource inventories and product demand.

In the final manuscript we calibrate CAMBIUM to current conditions in the British Columbia forest sector. Industry agents compete for roundwood inputs, as well as for profits in finished product markets for pulp, panel products, and lumber. To test the relevance and utility of this model, CAMBIUM is used to quantify the cumulative impacts of a market downturn for forest products and mountain pine beetle induced timber supply fluctuations on the structure of the forest sector.

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Acknowledgements

I would like to thank my co-supervisors Dr. Thomas Maness and Dr. Gary Bull for their continuous financial and moral support, discussions about modeling and economics, and the feedback and advice they provided on drafts of the model itself and the resulting papers. They have played a central role in getting me where I am today. I would like to thank my committee members Dr. John Nelson and Don Roberts for their sound and critical advice and the diversity of perspectives that they brought to the table.

I have also been fortunate to work with Dr. Clive Welham, Dr. Brad Seely, and Dr. Juan Blanco. Their expertise in ecological modeling has been critical in allowing me to trace small-scale ecological processes through to their large-scale economic implications. I would also like to thank Kate Maness for her work in collecting and collating the spatial databases that my work is based on.

Parts of this research have been funded by Genome Canada, FP Innovations, and the B.C. Forum on Forest Economics and Policy. I am grateful to Dr. Jörg Bohlmann, Dr. Kermit Ritland, Dr. Christopher Gaston, and Nicole Robinson for the opportunities to work with such a diverse group of researchers.

I would also like to thank Doris and Ludwig Schwab, Stefan Schwab, Dr. Susanne Frohriep as well as Nancy and Anthony Charbonneau for their encouragement throughout my studies. Finally, I would like the thank my wife Krista for her unwavering support, and our daughter Ella for providing some much needed distraction during the final months of writing and editing this dissertation.

To Ella and Krista

Co-authorship Statement

Chapter 2:

Title: *Building spatial forest inventories from aggregated data.*

Authors: Olaf Schwab and Thomas Maness

Role of co-author(s): Thomas Maness contributed to model development, data analysis, and manuscript preparation.

Chapter 3:

Title: *Modeling the timber supply impact of introducing weevil-resistant spruce in British Columbia.*

Authors: Olaf Schwab, Thomas Maness, Gary Bull, Clive Welham, Brad Seely, and Juan Blanco

Role of co-author(s): Thomas Maness and Gary Bull developed the grant proposal for funding this project and contributed to model development, data analysis, and manuscript preparation. Clive Welham, Brad Seely, and Juan Blanco developed the methodology for stand-level weevil impact modeling (Section 3.2.1).

Chapter 4:

Title: *Modeling structural development in the forest sector with the EWA-Lite algorithm.*

Authors: Olaf Schwab and Thomas Maness

Role of co-author(s): Thomas Maness contributed to model development, data analysis, and manuscript preparation.

Chapter 5:

Title: *Modeling the effect of changing market conditions on mountain pine beetle salvage harvesting in British Columbia.*

Authors: Olaf Schwab, Thomas Maness, Gary Bull, and Don Roberts

Role of co-author(s): Thomas Maness, Gary Bull, and Don Roberts contributed to model development, data analysis, and manuscript preparation.

1 Introduction

This dissertation describes the development of an agent-based forest sector model (CAMBIUM[1]) for large-scale strategic analysis. This model is designed as a decision support tool for assessing the effect that changes in forest product demand and resource inventory fluctuations can have on the structure and economic viability of the forest sector.

CAMBIUM complements existing forest sector models by modeling aggregate product supply as an emergent property of individual companies' production decisions and stand-level ecological processes. Modeling the forest products sector as a group of interacting autonomous economic agents makes it possible to introduce production capacity dynamics and the potential for mill insolvencies as factors in modeling the effects of market and forest inventory based disturbances.

1.1 Literature Review

1.1.1 Timber Supply and Natural Disturbance Modeling

Quantifying resource inventories and projecting growth and yield through time plays a central role in forest related planning. As Krünitz, and 18th century German economist stated:

> *"If forests are not cartographed in a thorough and geometrical manner, then forestry is only conducted by chance, and any subsequent planning of the forests, that may be performed, will always have an insecure and uncertain foundation, because it is only based on a rough guess."*
>
> Krünitz (1778), translated from German.

[1] The cambium is a layer of cells that contributes to the growth of both the wood and innermost bark of a tree. The name CAMBIUM was chosen for this agent-based forest sector model to reflect the critical role that forest sector agents play within the interdependent feedback loops between resource inventories and product markets.

Building on these inventory maps forest management models and planning systems began to evolve in a systematic manner as an analytical and decision support tool in Europe during the second half of the 19th century in response to an increasing scarcity of forest resources (von Gadow and Bredenkamp 1992). While most of the early applications of forest management planning were deterministic in nature, the role of disturbances in forest ecosystems became more widely recognized during the second half of the 20th century (Picket and White 1985). Significant efforts were made to develop predictive models of the size, frequency, and spatial distribution of disturbances such as wildfires and insect infestations. Disturbance models have been used to define forest management objectives, adjust harvest targets, and direct resources for disturbance suppression.

Natural disturbance patterns are widely used as a benchmark in assessing the sustainability of forest management plans and in designing the scope and pattern of harvest activities (Bunell 1995; Landres et al. 1999; Schwab 2008). Spatial benchmarks are usually developed based on regression analysis of remote sensing data or through inventory sampling procedures (DeLong 1998, Cumming and Wong 2003).

Probabilistic disturbance processes have been integrated into forest management models to quantify the effects of disturbances on timber supply. Forest fires and insect infestations are the dominant disturbance regime in Canadian forests (Stocks et al. 2003; Walton et al. 2007). They have therefore been used as the primary, and sometimes interchangeable, examples in the development of integrated forest disturbance and management models (see for example Routledge (1980)). An early stand level application was described by Martell (1980) who concluded that rotation periods should be shortened as fire probabilities increase. Van Wagner (1983) conducted a similar analysis at the forest level showing that the equilibrium harvest level is a non-linear decreasing function of the area affected by fire each year. These results were confirmed by Armstrong (2004), who argued that a probabilistic and highly variable fire regime makes it impossible to set a harvest level that would be sustainable over the long term with complete certainty. The challenges that probabilistic disturbance processes pose for forest management planning were also recognized by Reed and Errico (1986) and Grassmann (1989). Instead of conducting a simulation analysis of the probabilistic disturbance process, Reed and Errico (1986) used the mean expected disturbance rate as a proxy in calculating the effect of fire disturbances on timber supply. Grassmann (1989) expanded on this analysis by calculating the upper and lower harvest level bounds for a given probabilistic fire regime.

Disturbance models can also be used to direct human intervention in order to minimize timber supply losses. Alfaro et al. (1996) developed a stand-level model of spruce weevil infestation and use it to assess the cost effectiveness of management interventions in reducing merchantable volume losses. A similar approach was taken by MacLean et al. (2000) in a forest level analysis of spruce budworm infestations. In contrast Martin-Fernández et al. (2002) and MacLellan and Martell (1996) used spatial disturbance models to identify areas with high fire probabilities in order to effectively direct fire suppression resources. Armstrong and Cumming (2003) used shadow prices to estimate the economic impact of forest fires on long-term timber supply. They proposed to use these impact estimates as a benchmark in deciding whether it is economically beneficial to suppress specific fires.

The economic impacts of natural disturbances can extend beyond the value of the affected roundwood (Butry et al. 2001). Depending on the severity of damages it is often possible to recover some economic value by salvage harvesting affected stands (Prestemon and Holmes 2004). The continuing degradation of damaged or killed stands makes it necessary to conduct salvage operations within a relatively short time period following the disturbance (Prestemon et al. 2006). High rates of salvage harvesting can create an excess supply of roundwood, temporarily depressing stumpage market prices. Holmes (1991) developed and estimated an economic model of timber supply and demand that documents such a price reduction following a pine beetle epidemic in the southern United States. In a study of the effects of Hurricane Hugo, Prestemon and Holmes (2000) extended this economic model to include long-run effects. They concluded that the short-run price decrease can be followed by a subsequent price increase if the natural disturbance constrains timber supply by affecting a sufficiently large portion of the landbase.

1.1.2 Forest Sector Modeling

The interdependency of resource inventory dynamics, timber supply, and forest product markets is a key characteristic of forest sector models (Andersson et al. 1986; Buongiorno 1996). The first model incorporating both roundwood supply and finished product demand was published by McKillop (1967). This model derived equilibrium price levels from econometrically estimated supply and demand equations for solid wood and paper products. Subsequent studies have predominantly focused on integrating the spatial aspects of roundwood and forest products markets. Lönnstedt (1986) developed a two sector model of domestic and international production and applied it to the Swedish forest products sector. In a later study Lönnstedt and Peyron (1989) demonstrated how the same framework can be applied in analyzing regional markets. These small sector models require relatively few parameter inputs for estimation and can therefore be used as an initial approximation for directing subsequent implementations of larger, more complex models (Wibe 2005).

The Timber Assessment Market Model [TAMM] is an example of a national level forest sector model (Adams and Haynes 1980; 1996). This model computes equilibrium trade flows and price levels for 12 supply and 6 demand regions in the United States and Canada. Regional forest products industries are modeled using aggregate capacity estimates and econometrically estimated supply functions (Adams and Haynes 1996).

Other large-scale models include the global trade model [GTM] developed by Kallio et al. (1987). The EFI-GTM is a direct successor of this GTM, disaggregating data on supply regions and technologies (Kallio et al. 2004; 2006). Northway and Bull (2007) expand on this approach in the International Forest and Forest Products Trade Model [IFFP] by modeling resource availability using embedded country-specific forest estate models.

A common characteristic of these forest sector models is their macroeconomic approach, using aggregated data and linear functions for describing resource inventory dynamics, manufacturing processes, and product demand. While these models are spatial in nature, it is not possible to interpret modeling results at a scale that is finer than their constituent spatial and functional entities.

1.1.3 Agent-Based Modeling

Economies can be described as largely self-regulating and self-determining systems (Vanderburg 1985). In the case of the forest sector, the boundaries of self-regulation and self-determination are defined by resource inventory growth rates and market demand for finished forest products.

Multiple agent systems [MAS], and in particular agent-based computational economics [ACE] have been introduced as tools to model interdependencies and feedback loops between microstructures and macrostructures quantitatively (Lempert 2002; Tesfatsion 2002). An early example of using MAS for wood products allocation problems is Säaksjärvi (1986), who recognized that unequal cost allocations may make individual companies unlikely to cooperate and support a globally optimum wood allocation solution. Cooperative games are shown to be effective in determining fair compensation levels for wood sharing agreements. Gebetsroither et al. (2006) presented a model of self-organization in socio-economic and ecological processes to reduce the amount of uncertainty that conflicting objectives and complex interdependencies introduce into forest management planning. Modeling these processes as self-organizing subsystems eliminated the need for direct hierarchical control and made it possible to implement an adaptive management system for achieving desired conditions with minimum interventions. Moyaux et al. (2004) analyzed the effects of collaboration on supply chain performance using the Quebec forest products industry as the primary case study. This study demonstrated that selfish agents have an incentive to at least partially collaborate, and that, from a game theoretic perspective, no equilibrium existed when at least one agent does not collaborate. Gerber and Klusch (2002) presented an information and trading network that coordinates plans between producers, buyers, retailers, and logistics companies in the agriculture and forestry sectors. The network was designed as a MAS due to its inherent robustness, flexibility, and ability to self-organize in the absence of direct human interaction. D’Amours et al. (2006) developed a MAS approach to lumber production planning that offer significant time savings relative to manual planning.

1.2 Research Hypothesis

In contrast to macroeconomic forest sector models, an agent-based approach to economic modeling can generate detailed spatially and temporally differentiated information. An agent-based approach to modeling the economic effects of natural disturbance mitigation at the provincial level will therefore provide improved information for making policy and strategic investment decisions.

1.3 Dissertation Structure

The structure of this dissertation follows the guidelines for manuscript-based dissertations (University of British Columbia - Faculty of Graduate Studies 2008). Following this introduction are four manuscripts that form the main body of this dissertation. These manuscripts are formatted following the submission guidelines for the Canadian Journal of Forest Research (2008).

In the first manuscript (Chapter 2: *Building Spatial Forest Inventories from Aggregated Data*), I develop and test a dispersal algorithm that projects aggregated forest inventory information onto a lattice grid. This method is used to generate an ecologically and statistically consistent datasets for the province of British Columbia since large-scale and high-quality spatial data was otherwise unavailable. The resulting dataset is used as a model input for Chapters 3 and 5. This dataset contains approximately 370 000 records, covering the province of British Columbia with a 256 hectare resolution.

The second manuscript (Chapter 3: *Modeling the Timber Supply Impact of Introducing Weevil-Resistant Spruce in British Columbia*) utilizes this dataset in developing a provincial-level cellular automata resource dynamics model for assessing the long term timber supply effects of introducing weevil-resistant spruce. This model employs a stand-level approach to simulating weevil infestation and associated merchantable volume losses. Provincial-level timber supply impacts are determined by simulating harvest activities over a 350 year time horizon. Harvest targets are defined using the volumetrically sustainable annual allowable cut levels identified in the provincial timber supply review process (B.C. Ministry of Forests and Range 2008a; 2008b).

In the third manuscript (Chapter 4: *Modeling Structural Development in the Forest Sector with the EWA-Lite Algorithm*) I shift the focus to interactions between forest companies. I analyze the effects of strategic decisions on sector structure by developing CAMBIUM, an agent-based model of competition and industry structure evolution for the forest sector. The forest sector is modeled as a group of autonomous, interacting agents that evolve and compete within the limitations posed by resource inventory dynamics and market demand for finished products. Resource inventories are modeled as a randomly distributed normal forest in order to isolate the resulting industry structure as an emergent property of repeated agent interactions. Results from this chapter are used to initialize forest sector agents in chapter 5.

In the final manuscript (Chapter 5: *Modeling the Effect of Changing Market Conditions on Mountain Pine Beetle Salvage Harvesting in British Columbia*) I integrate research results from the previous three chapters by calibrating CAMBIUM to current conditions in the British Columbia forest sector. Resource inventory dynamics are modeled using the datasets and methods presented in Chapters 2 and 3. Modeling results from Chapter 4 are used as default parameters for initiating industry agents that are spatially located on the landscape. These agents compete for roundwood inputs, as well as for profits from the sale of pulp, panel and lumber products. To test the relevance and utility of this model, CAMBIUM is used to quantify the cumulative impacts of a market downturn for finished forest products and mountain pine beetle induced timber supply fluctuations on the structure of the British Columbia forest sector.

In the final chapter of this dissertation I summarize the main results and establish linkages between the four manuscripts and current research in the field. I also identify limitations of this dissertation research and discuss directions for future research that will increase the relevance of CAMBIUM for applied policy and economic analysis.

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2 Building Spatial Forest Inventories from Aggregated Data[2]

2.1 Introduction

Spatially heterogeneous data is one of the main inputs for forest planning models that are designed to identify potential resource utilization conflicts and generate location-specific outputs (Jansen et al. 2002). The objective of this paper is to develop and test a fast and cost-effective algorithm for generating spatially heterogeneous forest inventory datasets for areas where high-resolution data is not available. The algorithm generates a grid-based forest inventory dataset based on highly aggregated input information. The resulting dataset can be used as a proxy in large-scale forest planning applications while empirical datasets are under development, or where spatial data is otherwise unavailable. This algorithm was developed and tested as part of a larger project on agent-based forest sector modeling for British Columbia, where access to large-scale forest inventories remains restricted[3] (B.C. Integrated Land Management Bureau 2008).

First, the forest inventory parameters that are necessary for forest management modeling are identified and linked to publicly available data sources. Second, the methodology for projecting aggregated forest inventory statistics onto the landscape in an ecologically sensible and statistically consistent manner is introduced. This methodology adapts the concept of predictive vegetation mapping (Franklin 1995) to the particular information requirements for forest management modeling. Third, consistency checks for input and output data, as well as tests of agreement at the ecosystem level are conducted. Fourth, the

[2] A version of this chapter has been submitted for publication. Schwab, O. and T. Maness. *Building spatial forest inventories from aggregated information.* 19 pp.
[3] The BC Ministry of Forests and Range has published a new dataset on vegetation resources concurrently with this work.

utility and limitations for this dataset are discussed in detail. Fifth, and finally, directions for refining and augmenting this dataset are identified.

2.2 Methodology

Predictive mapping can be defined as the application of a conceptual model to a geographical database in order to produce the predictive map as a particular realization of the model (Franklin 1995). This methodology has been used to generate predictions of vegetation (Hamann and Wang 2006), stand structure attributes (Moisen and Edwards 1999), and habitat distribution (Guisan and Zimermann 2000). While these predictive ecological mapping models are more cost effective than traditional terrestrial ecosystem mapping (Olivotto and Meidinger 2001), processing costs and time requirements remain relatively high ($0.20/ha, and 2 million ha per person year) (MacMillan et al. 2007). The inventory dispersal algorithm presented in this paper substantially reduces costs by utilizing publicly available data sources, and by making tradeoffs between prediction accuracy and processing speed. Some location errors within a management unit were deemed acceptable for modeling applications at the regional and provincial level. For each tile, the resulting dataset contains information on tree species, stand age, and site quality. This information is sufficient for projecting timber volumes over time using growth and yield models such as the Variable Density Yield Prediction Model [VDYP] (B.C. Ministry of Forests and Range 2007a).

2.2.1 Data Sources

The underlying geographical database for this paper was developed by Hamann and Wang (2006) for their study of potential climate change effects on ecosystem and tree species distribution. This database provides information on latitude, longitude, and elevation for a 1600 m resolution grid covering the entire province with 373 176 tiles. For each of these grid points GIS data layers describing forest service administrative boundaries (B.C. Integrated Land Management Bureau 2004) and protected areas (B.C. Ministry of Sustainable Resources Management 2006) were queried to establish an association to either a Timber Supply Area [TSA], a Tree Farm License [TFL], or a protected area.

Data on the geographic envelope (Table 2.1) and tree species associations (Table 2.2) for each biogeoclimatic ecosystem classification [BEC] zone were collected from the Standards for Broad Terrestrial Ecosystem Classification and Mapping for British Columbia (Resources Inventory Committee (Canada) - Ecosystems Working Group 2000).

Table 2.1. Geographical biogeoclimatic ecosystem classification zone envelopes

BEC zone	Latitude		Longitude		Elevation	
	min	max	min	max	min	max
Boreal white and black spruce [BWBS]	53	61	110	140	230	1 300
	55	61	110	140	0	1 100
Coastal douglas fir [CDF]	48	61	110	140	0	150
Coastal western hemlock [CWH]	48	56	110	140	0	900
	54	61	110	140	0	300
Engelman spruce - subalpine fir [ESSF]	48	56	110	122	1 200	2 100
	48	56	122	140	1 500	2 300
	55	57	110	140	900	1 700
Interior cedar - hemlock [ICH]	48	55	110	140	400	1 500
	55	58	110	140	100	1 000
Interior douglas fir [IDF]	48	53	110	140	350	1 450
Montane spruce [MS]	48	54	110	140	1 100	1 700
Mountain hemlock [MH]	48	56	110	140	900	1 800
	54	61	110	140	400	1 000
Ponderosa pine [PP]	48	52	110	140	335	900
Spruce willow birch [SWB]	55	58	110	140	1 000	1 700
Sub boreal pine - spruce [SBPS]	48	56	110	140	1 100	1 500
	54	61	110	140	850	1 300
Sub boreal spruce [SBS]	50	59	110	140	0	900

Data source: Resource Inventory Committee (Canada) – Ecosystem Working Group (2000).

Table 2.2. Species associations by biogeoclimatic ecosystem classification zone

BEC Zone	Primary species	Secondary species
BWBS	white spruce	black spruce, subalpine fir, trembling aspen, balsam poplar
CDF	douglas fir	western redcedar, amabilis fir, red alder
CWH	western hemlock, douglas fir, western redcedar	lodgepole pine, western white pine, grand fir, red alder, sitka spruce, black cottonwood
ESSF	engelman spruce, subalpine fir	lodgepole pine, alpine larch, amabilis fir, western white pine, douglas fir, western hemlock western redcedar
ICH	western redcedar, western hemlock	amabilis fir, white spruce, subalpine fir, ponderosa pine, western larch, trembling aspen, black cottonwood
IDF	douglas fir	lodgepole pine, ponderosa pine, spruce hybrid, western redcedar, amabilis fir, trembling aspen
MH	mountain hemlock, amabilis fir, yellow cedar	western hemlock, western redcedar, douglas fir, western white pine, sitka spruce, lodgepole pine, subalpine fir, whitebark pine
MS	spruce, subalpine fir, lodgepole pine, douglas fir	white spruce, subalpine fir, lodgepole pine, western larch, western redcedar, trembling aspen
PP	ponderosa pine, douglas fir	trembling aspen, black cottonwood
SBPS	lodgepole pine	white spruce, trembling aspen
SBS	white spruce, spruce hybrid, subalpine fir, lodgepole pine	lodgepole pine, douglas fir, black spruce, trembling aspen
SWB	white spruce, subalpine fir	pine, black spruce, trembling aspen

Data source: Resource Inventory Committee (Canada) – Ecosystem Working Group (2000).

Aggregated forest inventory information was obtained from the timber supply review analysis reports published by the B.C. Ministry of Forests and Range (2007b). These reports presented information on the parameters of interest (total area by ecosystem, species, site quality, and age class) in graphical formats such as bar graphs and curve plots. The values of these parameters were digitized for both the timber harvesting landbase [THLB] and the non-timber harvesting landbase [NTHLB] in each TSA and TFL using the graph digitization software DigitizeIt v1.5.8 (Bormann 2006). The parameter values were stored in a hierarchical database (Figure 2.1).

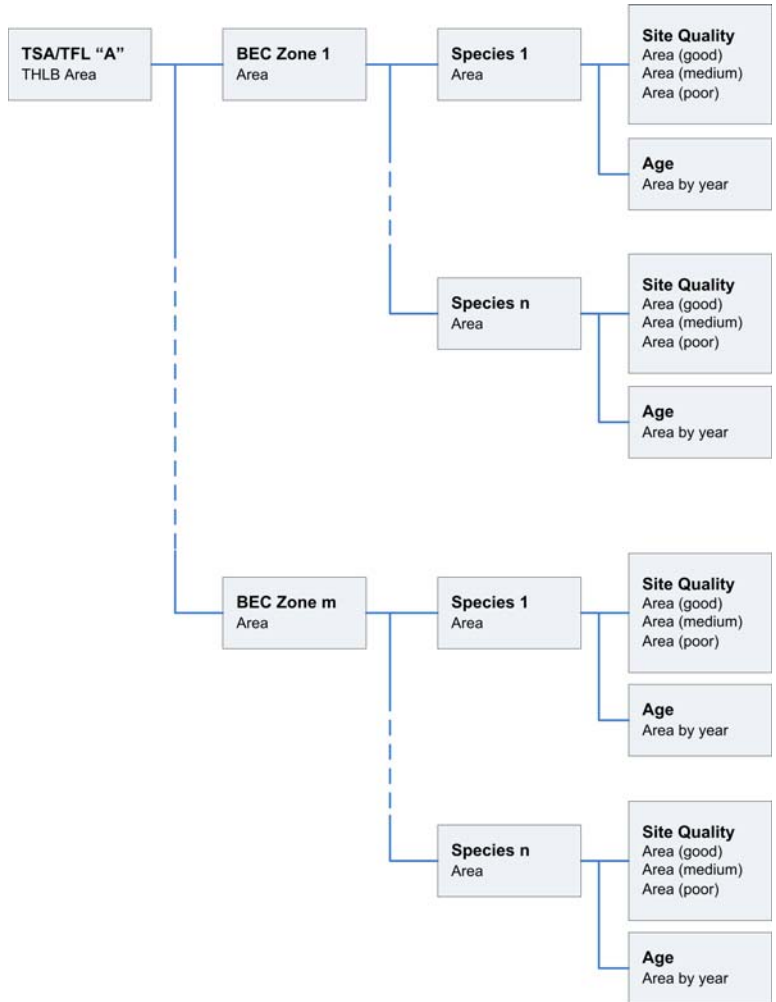

Figure 2.1. Hierarchical database structure

Within each TSA/TFL, this data structure was repeated twice: Once to describe the THLB, and once to describe the NTHLB. This type of hierarchical data structure can be directly translated into a series of nested arrays to facilitate classification tree searching (Flanagan 2005).

2.2.2 Data Processing

The inventory dispersal algorithm was designed to project the non-spatial forest inventory information that was collected from the timber supply review documents back onto the landscape grid. By using a sequential random draw procedure without replacement, it was possible to disaggregate the inventory data and to create a dataset that represents one possible spatial realization of the aggregated input information.

The inventory dispersal algorithm was programmed in Java using the Eclipse Platform 3.1.2 (Eclipse Foundation 2006). The search sequence in this algorithm is summarized in Figure 2.2 below.

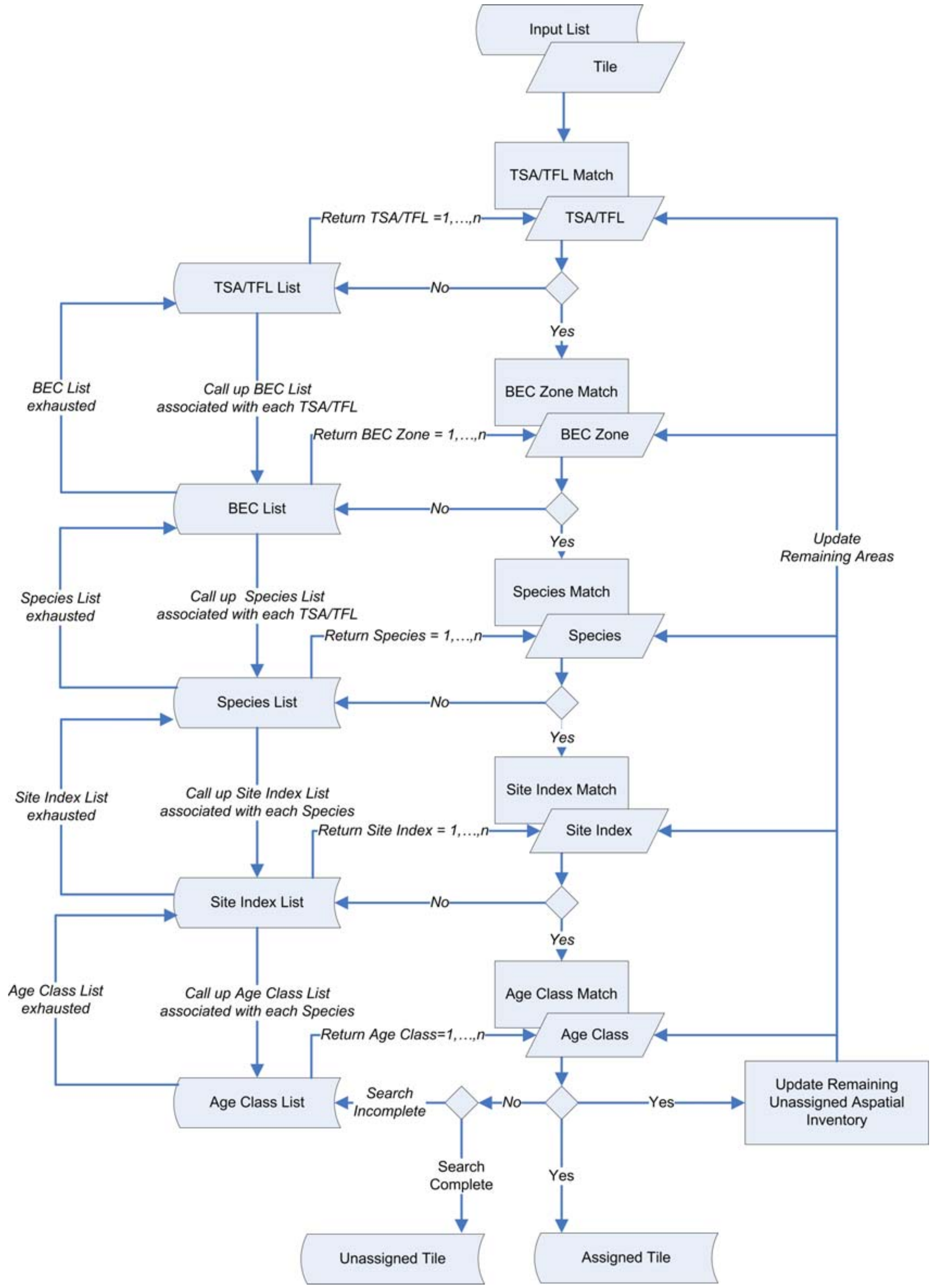

Figure 2.2. Flowchart for inventory dispersal algorithm

For each tile, the algorithm proceeded through four levels from identifying potential BEC zones, to species, site index, and age class assignment. At each level, the tile parameters were checked for consistency with the environmental envelope and tree species associations, as well as consistency with the remaining (unassigned) non-spatial inventory. If inconsistencies were detected, the search algorithm returned to the previous level and explored the next branch of the classification tree for a feasible solution. If a feasible solution was found for assigning a tile to the THLB or NTHLB, the TSA/TFL level area targets for the selected BEC Zone, primary species, site index and age class were reduced by 256 hectares each to reflect that a proportion of this inventory had now been placed on the landscape. If no solution was found during an exhaustive search of the entire tree, the tile in question was queued as temporarily unassigned. The search algorithm proceeded through the sequence described in Figure 2.2 four times using a net down procedure:

1. dispersal of timber harvesting landbase inventory;
2. dispersal of non-timber harvesting landbase inventory;
3. evaluation of protected area tiles for potential forest cover; and
4. evaluation of remaining tiles for assignment to non-forested BEC zones.

At each pass, tiles for which a feasible solution had been found were removed from the input list. Since no quantitative information on forest cover was available for protected areas, the assumption was made that the ecosystems and tree species in the park were likely to be similar to the ones found on the THLB and NTHLB outside the protected area. Therefore, tiles within protected area were tested for consistency with the ecological envelope of this subset of BEC zones, and randomly assigned to a primary and secondary tree species associated with this BEC zone. In the absence of empirical associations, site index and age class were also determined randomly.

2.2.3 Reliability Testing

The reliability of this inventory dispersal algorithm was assessed using site-specific and non site-specific accuracy measurements, depending on the availability of spatial reference data. For non site-specific accuracy measurements, the spatial forest inventory data was summarized into the same categories that were used for the input information, generating area distributions for ecosystem classifications, tree species, site index, and age classes. These input and output area distributions were plotted for BEC zones, primary tree species, site index, and age classes. These summary plots provide an indication of the extent to which the relatively aggressive search algorithm locks in on suboptimal inventory assignments that would limit the overall level of target achievement.

Second, the site-specific kappa statistics and confidence interval for BEC zone assignments were calculated using the broad ecosystem inventory dataset (B.C. Ministry of Sustainable Resources Management 2004) as a reference. The kappa statistic was developed as a reliability measure for nominal scale assignments in sociological and psychological studies (Cohen 1960). It has since also become standard for remote sensing applications (Congalton and Green 1999). The kappa statistic measures assignment accuracy as the proportion of agreement once chance agreement has been accounted for. The kappa statistic and associated confidence intervals were calculated following Cohen (1960) and Sim and Wright (2005).

2.3 Results

The inventory dispersal algorithm generated feasible forest inventory solutions for a timber harvesting landbase of 23 million hectares, and a non-timber harvesting landbase of 23.5 million hectares. Program run times were approximately 100 seconds, net of time for reading from/writing to databases. The provincial level inventory dispersal results are summarized in Table 2.3.

Table 2.3. Inventory dispersal results

Land use	Target Area (million hectares)	Projected Area (million hectares)	Number of Tiles
THLB	23.5	23.0	89 999
NTHLB	23.9	23.5	91 633
Non-forested		24.4	95 382
Cities and settlements		0.1	422
Protected areas		8.4	32 802
Not assigned		16.1	62 938
Total		95.5	373 176

The projected area reached 98% of the target for both the THLB and the NTHLB. TSA and TFL specific results varied between 65 and 100% for the timber harvesting landbase, and 0 and 100% for the non-timber harvesting landbase. High levels of variation mainly occurred in small TSAs and TFLs where each tile represents a relatively large proportion of the landbase. The economically most important areas on the timber harvesting landbase of large TSAs and TFLs generally showed the highest level of target achievement. Once the timber harvesting landbase and the non-timber harvesting landbase were established, 24.4 million hectares, or 17% of the remaining area fell within the elevation envelopes of bunchgrass [BG] and arctic tundra [AT] ecosystems. After cities, settlements, and protected areas were accounted for, 16.1 million hectares remained unassigned. These unassigned tiles represent an aggregation of line-based features such as roads, water bodies, and transmission lines that are not being captured by the grid based system used for this study, as well as additional areas in urban and agricultural uses that are not accounted for in the provincial timber supply review process.

The comparisons of input and output distributions for BEC zones, tree species, site quality, and age classes are shown in Figures 2.3-2.6.

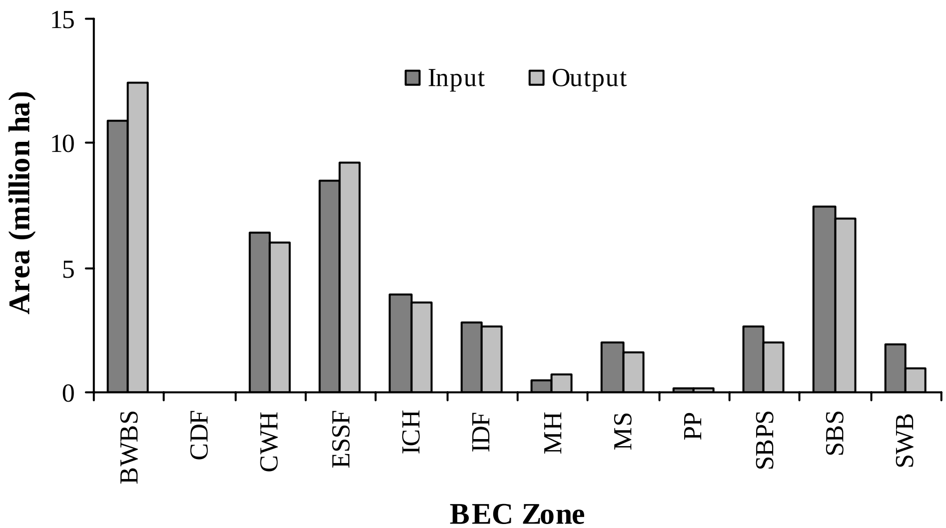

Figure 2.3. Biogeoclimatic ecosystem classification zone distribution

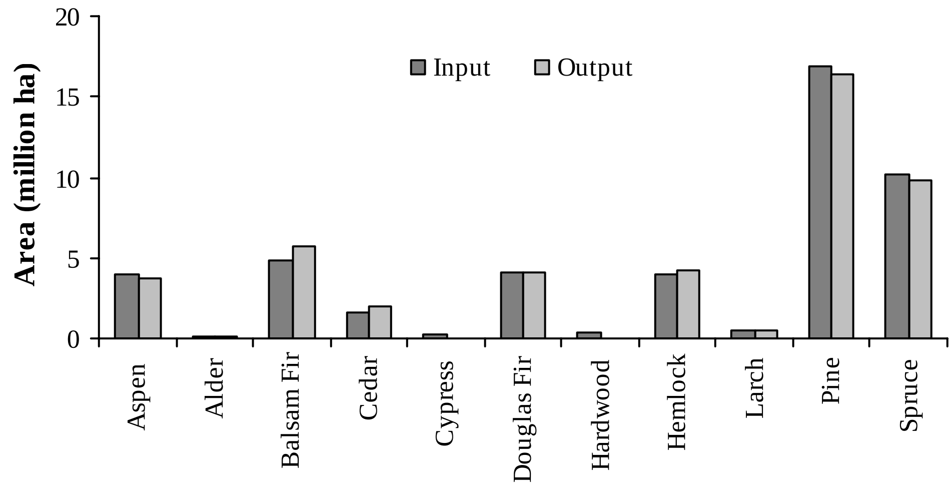

Figure 2.4. Species distribution

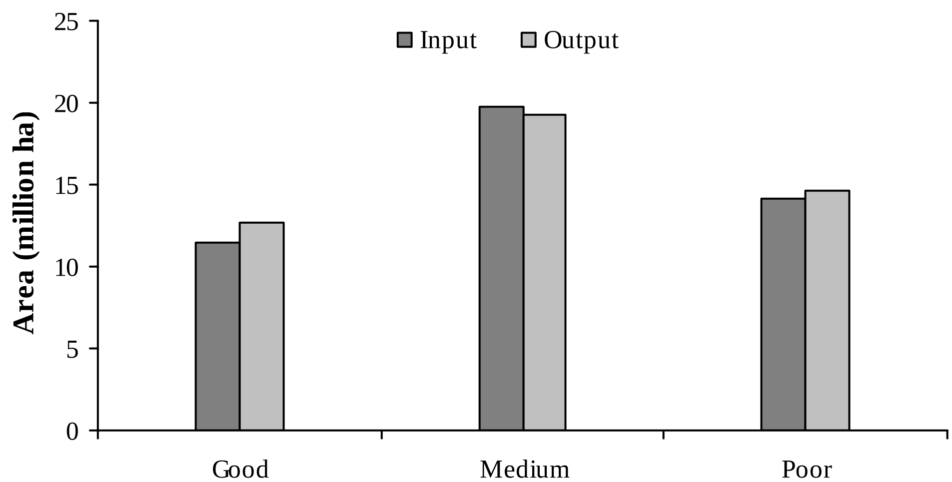

Figure 2.5. Site quality distribution

Figure 2.6. Age class distribution

As shown in Figures 2.3-2.6, the spatial forest inventory that resulted from the inventory dispersal process closely replicates the aggregated inventory information that was used to set dispersal targets. In some cases the spatial inventory exceeds target levels. This is caused by the grid based geographical database where each tile represents an area of 256 hectares. During the inventory dispersal process (Figure 2.2), the remaining area in any category may fall between zero and 256 hectares. Since partial assignments of tiles were not possible, a choice had to be made on whether to treat these positive remaining areas as zero or to allow allocated areas to exceed target levels. To avoid under-representation of ecologically and economically valuable categories, the methodological choice was made to allow for area over-representation. While the area in question is relatively small for each tile, the cumulative effect of these target overshoots is clearly visible in the graphical comparison of the input and output statistics. This situation was most frequently encountered in older age classes where target areas were relatively small.

Table 2.4 gives a detailed comparison of BEC zone classifications from the inventory dispersal algorithm and the broad ecosystem inventory dataset published by the B.C. Ministry of Sustainable Resources Management (2004). Correctly classified areas are shown on the diagonal in bold italics. Since ecosystem classification is conducted on a nominal scale, the distance between the off-diagonal fields and the diagonal does not relate to the size of the classification error.

Table 2.4. Comparison of biogeoclimatic ecosystem classification zone assignments

Area (1 000 ha)		**Reference Dataset**											
		CDF	**CWH**	**MH**	**ESSF**	**PP**	**IDF**	**ICH**	**MS**	**SBPS**	**SBS**	**BWBS**	**SWB**
Predicted BEC Zone	**CDF**	***199***	47	0	0	0	0	0	0	0	0	0	0
	CWH	33	***9,129***	67	25	1	33	111	0	1	33	57	0
	MH	0	453	***1,367***	92	0	68	182	2	4	19	58	0
	ESSF	0	30	94	***8,213***	0	172	517	683	376	1,382	822	18
	PP	0	0	0	0	***94***	99	66	1	0	0	0	0
	IDF	0	48	1	323	64	***1,884***	505	263	265	86	0	0
	ICH	0	89	14	467	26	393	***2,865***	96	66	168	26	0
	MS	0	0	3	584	0	260	127	***1,182***	345	5	0	0
	SBPS	0	11	4	47	0	297	103	171	***1,212***	175	1	0
	SBS	0	302	12	388	0	142	249	33	275	***5,231***	378	0
	BWBS	0	0	0	199	0	0	2	0	0	261	***10,190***	42
	SWB	0	0	0	150	0	0	1	0	0	224	2,761	***722***

The kappa coefficient for BEC zone classification using the inventory dispersal algorithm is 0.551, with a 99% confidence interval of 0.549 to 0.553. Kappa coefficients can range from -1 for complete disagreement to 1 for complete agreement. A value of zero indicates the level of agreement that could be expected by chance (Sim and Wright 2005). The rate of accurate classification is highest for the Coastal Western Hemlock [CWH], Boreal White and Black Spruce [BWBS], and Coastal Douglas Fir [CDF] zones (96, 95, and 81% respectively), and lowest for the Spruce Willow Birch [SWB], Ponderosa Pine [PP], and Montane Spruce [MS] zones (19, 36, and 47% respectively).

The following section will discuss the strengths and limitations of the inventory dispersal algorithm and the dispersed datasets in more detail. The concept of scale is then used to define the appropriate scope for using the current dataset, and to outline the implications that reductions in site-specific errors would have for forest management modeling.

2.4 Discussion

The inventory dispersal algorithm is capable of generating a spatial dataset that is consistent with the publicly available aggregated forest inventory data that was used to set dispersal targets. This dataset is one ecologically consistent spatial representation of the aggregated input data. The kappa coefficient of 0.551 indicates that some site-specific error is present within each TSA and TFL in determining BEC zone classifications. The highest rates of misclassification occur for tiles in the BWBS zone that the dispersal algorithm allocated to the SWB zone. Of the 10 784 tiles that were misclassified in this way, 44% had an elevation between 1 100 and 1 300 meters. This band represents the overlap between the BWBS and SWB geographical envelopes (Table 2.1) and results in a high likelihood of misclassification. An additional 2 768 (26%) of these misclassified tiles had elevations greater than 1 300 meters. In these cases, the geographical envelope for the BWBS zone is too narrow, thereby underestimating BWBS ecosystems occurring outside their typical range. A similar pattern can be found in analyzing misclassifications of Sub Borea Spruce [SBS] as Engelman Spruce – Subalpine Fir [ESSF], where an elevation threshold of 900 meters differentiates the two geographical envelopes. Of the 5 397 misclassified tiles in this category, more than 99% (5 366) had an elevation greater than the 900 meter threshold.

No spatial reference data was available for determining kappa statistics for tree species, site quality, and age class assignments. However, it is possible to make some inferences from these BEC zone classification errors. As shown above, prediction errors mainly occur in cases where environmental envelope associations are ambiguous, or where the environmental envelope does not capture the full empirical range of the BEC zone. The accuracy and exclusiveness of associations between parameter categories can therefore be interpreted as key factors determining the prediction accuracy of the inventory dispersal algorithm.

The accuracy of tree species predictions will vary depending on BEC zone. Some BEC zones such as Coastal Douglas Fir [CDF] and Interior Douglas Fir [IDF] have uniquely identified primary tree species, while others such as Coastal Western Hemlock [CWH] and Sub Boreal Spruce [SBS] have multiple primary tree species associations (Table 2.2). Higher prediction accuracy can therefore be expected based on narrowly defined tree species associations, while multiple associations will likely result in greater degrees of variation. It is expected that the accuracy of tree species classification in the spatial inventory dispersal dataset is better than random assignment, but lower than the accuracy level that was achieved for BEC zone classification. The algorithm is expected to perform better than random assignment since the BEC zone – tree species combinations shown in Table 2.2 limit the search algorithm to ecologically sensible associations. However, since classification errors for BEC zone and tree species can be cumulative, tree species classification accuracy will likely be lower than for BEC zone classification.

These types of direct and indirect associations to geographical parameters could not be established for site quality and age class parameters. The dispersal of these parameters therefore occurred as a random draw without replacement from the aggregated inventory data associated with each area. This method ensures that parameter distributions are consistent at the TSA/TFL level, but will result in kappa values close to zero. In the absence of additional data that could be used in predictive age class mapping (for example, remote sensing data), it is not likely that the site-specific error for age class assignments can be substantially reduced. However, at a later stage, it may be possible to reduce site-specific errors for site quality, by drawing on procedures developed by MacMillan et al. (2007), who integrated information on parent material texture and depth in predicting ecosystem distributions for a forest region in British Columbia.

The scale or resolution of a dataset not only describes what kind of information a dataset contains, it also determines what kind of analysis can be conducted (Goodchild 2001). The issues of site-specific errors and scale therefore have important implications for the use of the inventory dispersal algorithm in general, and more specifically for the use of the dispersed forest inventory dataset for British Columbia in modeling applications.

The inventory dispersal algorithm assigns a combination of BEC zone, tree species, site quality, and age class to each tile that is consistent with the TSA/TFL specific aggregated input information used to set dispersal targets (Figure 2.2). The current dataset is therefore most suitable for use in large-scale analyses and modeling applications, where results are reported at the TFL/TSA level or higher.

Disaggregating the TSA/TFL level inventory information into individual tiles creates a specific combination of attributes for each tile, and makes it possible to use standard growth and yield models such as VDYP to simulate forest growth over time.

The ability to track and process spatial and temporal data heterogeneity is a key characteristic in modeling complex systems (Strayer et al. 2003). The dispersed spatial dataset was sufficiently complex to serve as a default dataset in developing and testing an agent-based forest sector model that was designed to provide information emergent properties at a very large scale while also maintaining the ability to produce location specific outputs at a fine scale. To increase the accuracy and relevance of fine-scale outputs, future work is expected to focus on reducing site-specific errors. This error reduction can be achieved either through the integration of empirical data, or by refining the predictive modeling procedures of the inventory dispersal algorithm to take into account additional parameter associations.

2.5 Conclusion

The inventory dispersal algorithm can be used as a fast and cost-effective method for generating spatially heterogeneous forest inventory datasets where high-resolution spatial forest inventory data is not otherwise available. It projects aggregated forest inventory information onto a grid-based landscape in an ecologically sensible and statistically consistent manner. This dispersal procedure assigns specific combinations of BEC zone, tree species, site quality, and stand age parameters for each tile. These parameter combinations allow for the use of standard growth and yield modeling procedures in simulating forest growth over time. While some site specific prediction errors exist at finer scales, the dispersed dataset is sufficiently accurate for use in high-level forest sector modeling applications.

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3 Modeling the Timber Supply Impact of Introducing Weevil-Resistant Spruce in British Columbia[4]

3.1 Introduction

In 2007, the British Columbia forest industry shipped products valued at approximately $ 13.9 billion, accounting for 22% of all manufacturing outputs (BC Stats 2008). This significant contribution to the provincial economy is largely based on conifer inventories (B.C. Ministry of Forests and Range 2007a; 2007b). The ongoing mountain pine beetle infestation has focused attention on spruce inventories as sources of high quality green fibre for short and medium term timber supply. However, these spruce inventories are also being affected by damaging agents such as the spruce weevil (*Pissodes strobi).*

Weevil damage has been documented in British Columbia in Sitka spruce (*Picea sitchensis*), white spruce (*Picea glauca*) and interior spruce (*Picea glauca x Picea engelmanni*) (Heppner and Turner 2006; Alfaro et al. 2008). The spruce weevil causes reduced growth and tree deformations by killing or damaging the leading shoot of susceptible host trees (Alfaro et al. 2002). Since direct control methods were found to be of limited effectiveness, identifying and breeding weevil resistant spruce stock has been proposed as an alternative for minimizing damages (Alfaro 1994). Resistant stock has been identified for Sitka and interior spruce using conventional breeding programs and progeny tests (Alfaro et al. 2008). While supplies of these resistant stocks are currently limited by seed orchard capacity, they are being planted throughout the province (B.C. Ministry of Forests and Range 2008a; 2008b). The extent of damages that spruce weevil infestations can cause in individual trees and stands

[4] A version of this chapter will be submitted for publication. Schwab, O., T. Maness, G. Bull, C. Welham, B. Seely and J. Blanco. *Modeling the timber supply impact of introducing weevil-resistant spruce in British Columbia.* 23 pp.

is well documented (see for example van den Drissche (1997)). Alfaro et al. (2004) estimate weevil impacts at "*several million dollars per year*". No other information on the overall economic impact of spruce weevil on the British Columbia forest sector, and on the extent to which weevil damages can be avoided through forest management activities was found in the peer reviewed literature.

In order to address this gap in the resource economics literature, we developed an agent-based resource inventory model to quantify spruce weevil damages at the provincial scale. The long-term economic benefits of introducing weevil resistant planting stock are assessed by simulating harvest activities and determining the value of avoided merchantable volume losses over time. Results from this analysis can be used as background information for policy decisions on the economic returns and uncertainties associated with planning these types of large scale pest management activities.

3.2 Methodology

We first describe the methodologies for modeling weevil attack at the stand level. Since weevil damages accumulate as a stand ages, the time of harvest for each affected stand is an important factor in determining the timing and extent of spruce weevil related merchantable volume losses. We then implement the stand level weevil attack model as part of a province-wide agent based model of resource inventory dynamics and harvesting.

3.2.1 Stand-Level Weevil Impact Estimation

Endemic spruce weevil populations are present throughout British Columbia (Langor and Sperling 1995). The expected merchantable volume loss due to spruce weevil infestation is dependent on the duration and intensity of the attack (Alfaro 1994).

The duration of a weevil attack can be defined as its equilibrium phase, where the probability of an attack is higher than 85% of the maximum attack probability observed for a specific stand (Alfaro et al. 1996). These attack probabilities can be calculated using probability functions developed by McMullen et al. (1987). Figures 3.1 and 3.2 show the effect of total tree height and leader length on the probability of weevil attack.

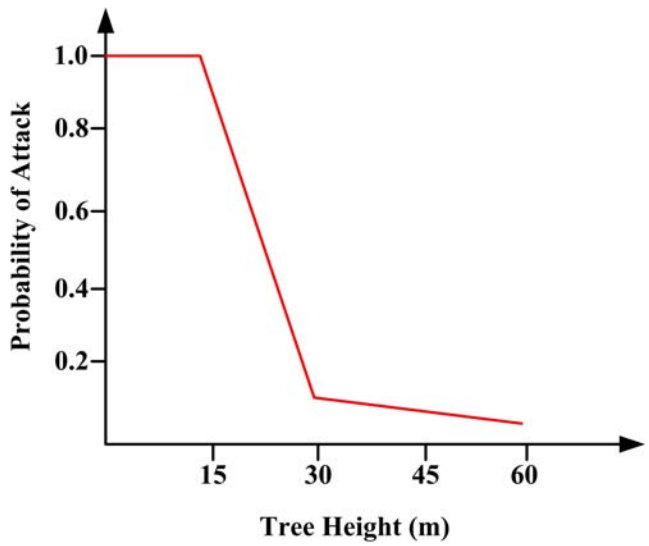

Figure 3.1. Weevil attack probability relative to tree height
Source: adapted from McMullen et al. (1987).

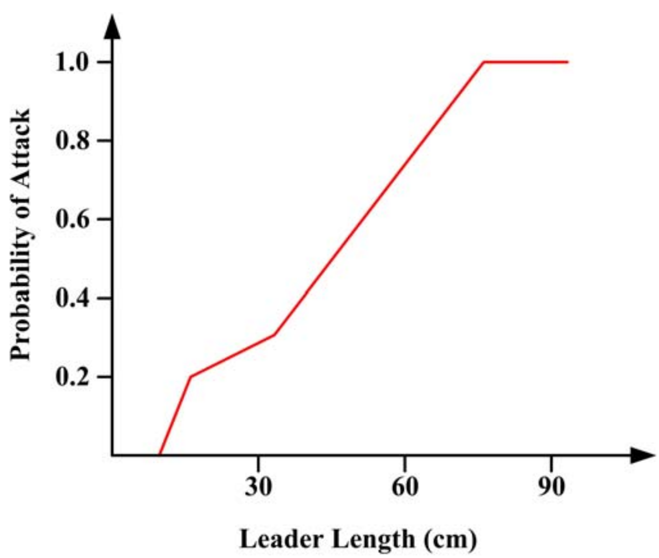

Figure 3.2. Weevil attack probability relative to leader length
Source: adapted from McMullen et al. (1987)

When a stand is scheduled for harvest, the relationship between tree height and leader length is used to calculate the cumulative attack probability for each year from planting to harvest. Parameter values for leader length and tree height are obtained by interpolation from the appropriate VDYP yield and height curves (B.C. Ministry of Forests and Range 2007c). This array of attack probabilities is then used to calculate the duration of the attack. A year is counted towards the duration of weevil attack if the current attack probability reaches 85% of the maximum attack probability observed for this stand.

Attack intensity is dependent on site quality, species composition, local climate, and genetic resistance (Ying 1991; Alfaro 1994; Alfaro et al. 2008). Based on calibration tests using the stand simulation model FORECAST (Seely et al. 2002), the current intensity of weevil attack (CA) can be calculated for any given year t as:

[1] $CA_t = 0.55 * SQ * SC_t * GF * SF$

Site quality (SQ) is inversely related to attack intensity (Lysack et al. 2006). SQ takes a value of 1.0 for good sites, 0.8 for medium sites, and 0.6 for poor sites. Species composition (SC) reflects the reduction in attack intensity when the leading spruce shoots are shaded by other trees (Taylor et al. 1996). SC ranges from 1.0 in cases where less than 25% of the stand are taller than spruce to 0.25 when at least 75% of the stand are taller than spruce. The genetic factor (GF) reflects whether a stand is stocked with weevil resistant spruce. It takes a value of 1.0 for stands that are not resistant, and 0.5 for stands that are weevil resistant. This reduction in attack intensity is consistent with values reported in the literature (King 1994). Additional sensitivity analysis was performed with genetic factor values of 0.25 and 0.75. The site factor (SF) describes the spruce weevil's dependence on sufficient heat sums to complete its development cycle (McMullen et al. 1987; Spittlehouse et al. 1994). Degree day thresholds, hazard ratings, and SF values are summarized in Table 3.1.

Table 3.1. Hazard ratings, degree day thresholds, and site factor values

Hazard rating	Degree days	Site factor (SF)
High	> 820	1.0
Medium	750 – 820	0.75
Low	660 – 749	0.5
None	< 660	0.25

When a stand is scheduled for harvest, equation 1 is used to calculate current weevil attack intensity values for each year that is counted towards the duration of the attack. This array of attack intensities is used to determine the average attack intensity during the equilibrium phase of the attack. The two parameter estimates on attack duration and intensity can then be used for estimating damage as a percentage of merchantable volume using the data matrix published by Alfaro (1994) (Table 3.2).

Table 3.2. Merchantable volume loss percentages

Attack duration (years)		5	10	15	20	25	30	35	40
Attack Intensity (%)	**5**	2.6	3.8	5.0	6.6	7.2	7.9	8.5	9.0
	10	4.2	7.8	10.3	13.1	14.6	15.7	16.6	17.0
	15	5.8	11.7	14.1	16.8	19.5	19.7	20.6	21.6
	20	8.1	13.5	16.1	21.3	23.8	25.6	27.2	28.2
	25	10.9	14.6	20.0	24.6	27.9	31.3	32.5	33.9
	30	12.3	18.0	24.8	28.9	32.6	35.3	37.2	38.5
	35	10.9	16.6	22.6	29.3	32.8	35.4	37.9	39.6
	40	10.6	16.0	20.6	25.8	28.8	32.2	36.0	37.6
	45	11.5	18.7	24.9	30.7	33.4	36.4	39.3	40.8
	50	11.1	16.2	22.5	27.7	31.5	34.6	36.8	38.6

Data source: Alfaro (1994)

3.2.2 Provincial-Level Modeling

3.2.2.1 Data Sources

The distribution of climate based hazard ratings is largely determined by geographic location and elevation. Degree days were calculated and recorded for each area using a 7.2°C threshold in the ClimateBC model (Wang et al. 2006). Areas with high hazard ratings are mainly located on Vancouver Island, lower elevation ranges throughout southern and central British Columbia, and in the plateau regions around Fort Nelson and Fort St. John (Figure 3.3).

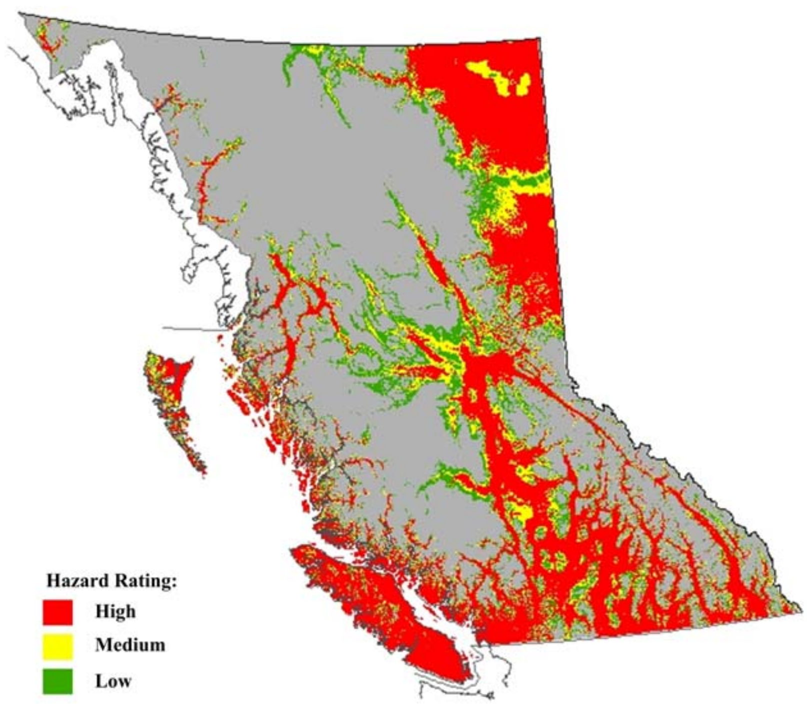

Figure 3.3. Weevil hazard rating based on 7.2° degree day threshold

Intersecting these hazard ratings with the distribution of spruce inventories in the province provides a first indication on the extent and location of areas at risk. Tree species distribution is shown in Figure 3.4. Areas with spruce inventory are shown in blue, while forested areas without a spruce component are shown in green.

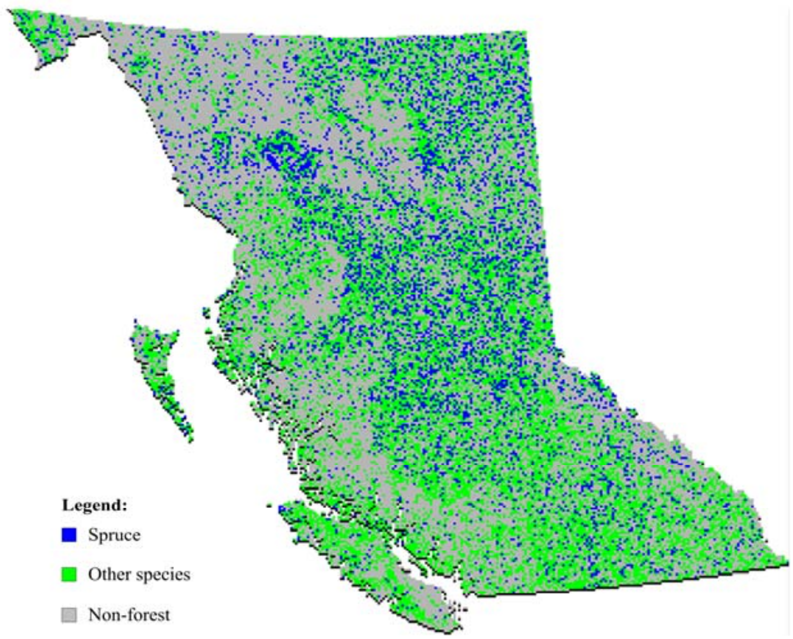

Figure 3.4. Tree species distribution

Based on these two maps, the highest level of spruce weevil damage can be expected in the northeastern, and to a limited degree in south central regions of British Columbia. The coast has relatively little spruce inventory and therefore a lower level of expected damage.

As outlined above, spruce weevil damages depend on the site-specific interaction of local climate, site characteristics, and forest structure. An object-oriented approach to simulation analysis was used for this study since it allows for the translation of site-specific ecological processes into large-scale changes in timber supply (He 2008). The resource inventory model was programmed in Java using the Recursive Agent Simulation Toolkit [Repast J] program libraries (ROAD 2008). This modeling environment was chosen for its ability to interface with geographical information systems, cross platform transferability of program code, and well-documented program libraries.

For this analysis, the province of British Columbia was modeled as a lattice grid with a 256 hectare resolution, or 370 000 tiles in total. Each tile is identified by its association with either a tree farm license [TFL] or timber supply area [TSA].

Modeling the large-scale effects of site-specific ecological processes requires high-resolution spatial forest inventory data. Since no suitable forest inventory dataset was available, we used an inventory dispersal algorithm to project aggregated forest inventory data from the provincial timber supply review process onto this lattice grid[5]. Aggregated forest inventory information was obtained from the timber supply review analysis reports published online by the B.C. Ministry of Forests and Range (2008c). These reports provide information on total area distributions by ecosystem, species, site quality, and age class for a specific forest management area. Data on the geographic envelope and tree species associations of forested biogeoclimatic ecosystem classification [BEC] zones were collected from the Standards for Broad Terrestrial Ecosystem Classification and Mapping for British Columbia (Resources Inventory Committee (Canada) - Ecosystems Working Group 2000).

The objective of the inventory dispersal process is to characterize each tile with a specific combination of tree species, site quality, and stand age. The algorithm uses predictive mapping (Franklin 1995) to create a dataset that is both statistically and ecologically consistent. Ecological consistency is achieved by restricting ecosystem and tree species parameter assignments to combinations identified in the BEC classification system. Within each forest management unit, statistical consistency between aggregated and dispersed forest inventory information is achieved by implementing parameter assignments as a random draw without replacement from area targets for each parameter. Using this information on tree

[5] Schwab, O. and T. Maness. Building spatial forest inventories from aggregated data. Chapter 2, pg. 16-35.

species composition, site quality, and stand age, forest growth for each individual tile can be simulated using data obtained from the variable density yield prediction model [VDYP] (B.C. Ministry of Forests and Range 2007c).

3.2.2.2 Model Structure

In this cellular automata resource dynamics model, both individual tiles and groups of tiles act as autonomous agents according to specified schedules and methods. Such a decentralized structure allows for a great amount of flexibility in adding additional modules and adapting the model to different research questions such as industry structure development following natural disturbances[6].

The sequence of modeling steps is summarized in the following section. At the beginning of each time step, each tile increments its age and updates timber volumes by interpolating values from the associated VDYP yield curves. At this stage, overmature stands are exposed to random mortality using a user specified attrition rate and threshold age. Following this growth step, the TSA/TFL agents proceed through the sequence of harvest simulation steps shown in Figure 3.5.

[6] Schwab, O., T. Maness, G. Bull, and D. Roberts. The effect of changing market conditions on mountain pine beetle salvage harvesting in British Columbia. Chapter 5, pg. 94-138.

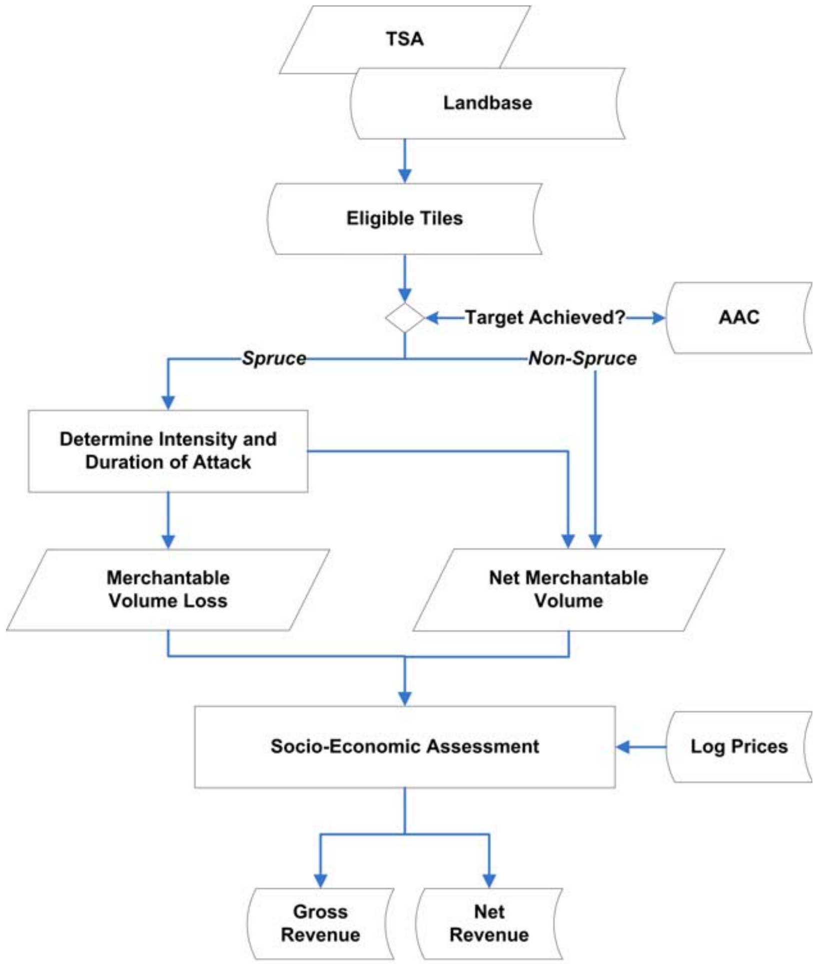

Figure 3.5. Model structure for assessing spruce weevil impacts

As described earlier, each TSA and TFL consists of a group of tiles. The timber supply review documents for each TSA and TFL were reviewed to collect information on annual allowable cut [AAC] determinations (B.C. Ministry of Forests and Range 2008c; 2008d). Tiles are scheduled for harvest using an 'oldest first' harvesting rule that is constrained by minimum harvest age requirements. The minimum harvest age is automatically set as the age at which each individual tile reaches its maximum mean annual increment. All tiles that are part of the timber harvesting landbase and meet minimum harvest age requirements are placed on a list of eligible tiles. Tiles are then scheduled for harvest until either the annual allowable cut for the management unit has been reached, or until no additional tiles are eligible for harvest during the current period. For harvested tiles with a spruce component, the intensity and duration of weevil attack are calculated using the methodology previously described. These two parameter estimates are then used to obtain the merchantable volume loss percentage from the Alfaro (1994) volume loss matrix (Table 3.2). The gross merchantable harvest volume is adjusted for weevil losses to calculate net merchantable volumes. To provide a baseline economic valuation of spruce weevil impacts, merchantable volume losses are valued using average species specific log prices for the coast and interior (B.C. Ministry of Forests and Range 2007a; 2007b). All output parameters (gross harvest volume, net harvest volume, spruce proportion of total harvest, and the value of gross and net roundwood harvests) are compiled at the TSA/TFL level and recorded to a database file at each simulation time step. At the end of each time step harvested stands are regenerated by setting their stand age to zero, and marking newly established spruce stands as weevil resistant. This approach reflects the gradual introduction of weevil resistant spruce as part of regular harvesting activities. Given this gradual introduction of weevil resistant stock, benefits will only begin to accrue as these stands reach maturity. A baseline estimate of the economic impact of introducing weevil resistant stock was developed by discounting the annual value differential between net harvests levels with and without damage reductions. Present value (PV) calculations can be used to directly compare scenarios with varying revenue streams over time. Interest rates used for assessing long-term land management issues typically vary in the range of 2 % to 4 % (Breinard et al. 2006; Heinonen and Pukkala 2007; Zhou et al. 2008), with sensitivity analyses extending this range from 1% to 5% (Pearce 2003; Garcial-Gonzalo et al. 2007).

3.3 *Results*

Simulations were conducted with a cellular automata resource dynamics model using a resource inventory consisting of approximately 370 000 tiles and a 350 year time horizon. This long time horizon was chosen to ensure that the full effect of weevil resistant stock on merchantable volume losses is captured by the model. Results were recorded annually, and compiled into 10 year averages for analysis. Average simulations speeds of approximately 2.4 years/second were observed. A comparison of annual allowable cut and realized harvest levels is shown in Figure 3.6.

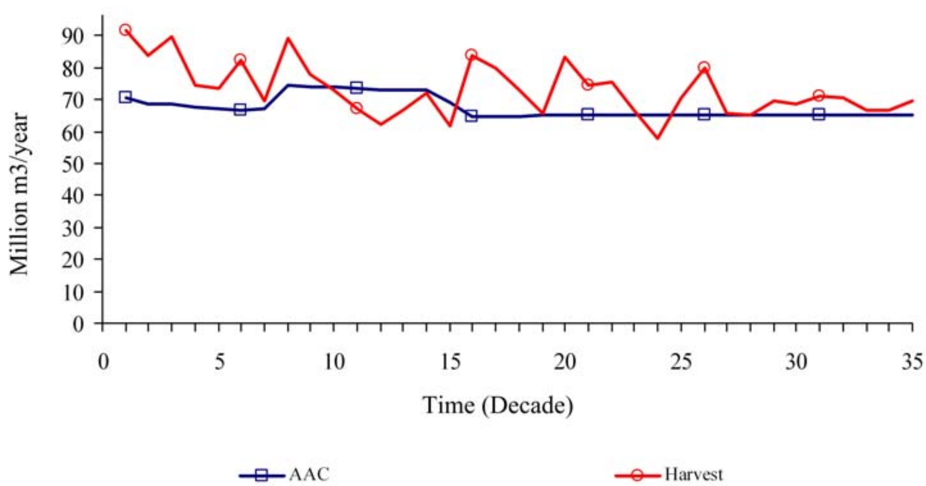

Figure 3.6. Annual allowable cut and realized harvest volumes

In this model configuration, AAC levels do not pose a firm upper limit to harvesting activities. Harvesting decisions are constrained to clearcutting entire 256 hectare tiles. Each TSA and TFL continues to harvest tiles until the AAC volume has been achieved. Excess harvest occurs in cases where the merchantable volume of the next tile in the harvest queue is larger than the remaining target volume. Allowing excess harvest ensures that realized harvest levels do not continuously fall short of target values. In general, the forest sector model was able to achieve or exceed AAC levels throughout the simulation run.

The effect of weevil resistant stock on merchantable volume loses is shown in Figure 3.7.

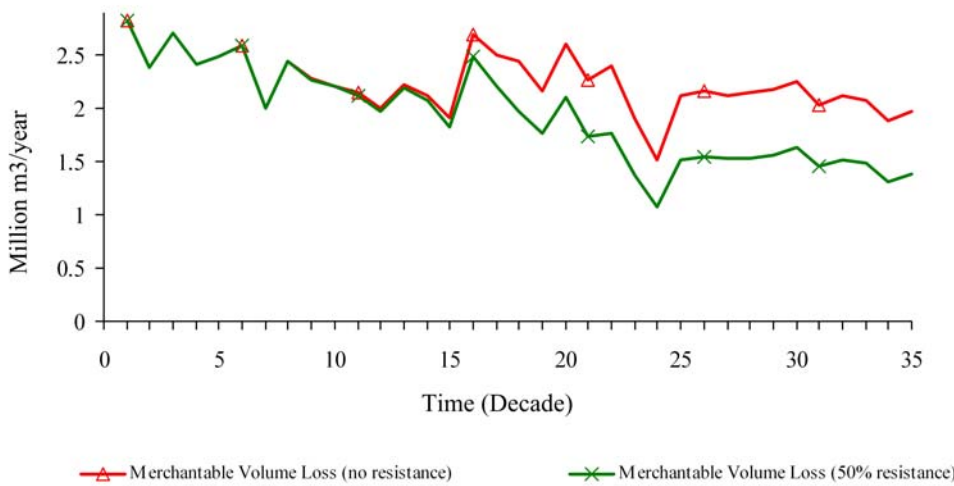

Figure 3.7. Effect of genetic resistance on merchantable volume losses

On average, spruce inventories support a gross annual harvest volume of 14 million m^3 (19% of provincial total). In the absence of weevil resistant stock, merchantable volume losses due to spruce weevil damages amount to approximately 2.3 million m^3/year. If weevil resistant stock is introduced as spruce stands are harvested and replanted, the average annual merchantable volume loss over this 350 year time horizon drops by 13% to 1.9 million m^3/year. This effect becomes more pronounced if the comparison is limited to decades 26 to 35, once the full benefits of harvesting weevil resistant stock become apparent. During these 10 decades, average damage levels drop by 28%, from 2.1 million m^3/year to 1.5 million m^3/year.

Spruce weevil impacts vary throughout the province, depending on the percentage of spruce in annual harvest volumes and the intensity of weevil damage. TSAs and TFLs were assigned to the three different regions following the definitions used by the BC Ministry of Forests (2008c; 2008d). As shown in Figure 3.7, the full benefits of introducing weevil-resistant spruce become apparent from year 250 onwards. Average annual spruce weevil impacts for years 250 to 350 of the simulation run are shown in Table 3.3.

Table 3.3. Regional spruce weevil impacts

	Coast	**Northern Interior**	**Southern Interior**	**Province**
Spruce proportion (% of total harvest)	4.9	26.7	15.3	18.5
Weevil loss – no resistance (% of spruce harvest)	18.5	14.4	20.0	16.3
Weevil loss – 50% resistance (% of spruce harvest)	14.3	10.1	14.6	11.6

Harvesting activities rely most heavily on spruce inventories in the northern and southern interior of British Columbia, with 26.7% and 15.3% of total harvest volumes respectively. On the coast, spruce harvest accounts for less than 5% of total volumes. However, although harvesting activities in the northern interior rely heavily on spruce inventories, merchantable volume losses due to spruce weevil damages are relatively low, with only 14.4 % of the spruce volume harvested. Damage levels are substantially higher on the coast and in the southern interior, with 18.5% and 20% of merchantable spruce volume respectively. These differences in merchantable volume loss rates can be attributed to clustering of the site-specific hazard factors identified in equation 1.

The results of the present value analysis are summarized in Table 3.4. These calculations are based on merchantable volumes and current market prices for logs, and do not take into account costs for harvesting, replanting, and other forest management activities.

Table 3.4. Present value of avoided merchantable volume losses

		Present Value ($ million)		
Discount Rate		**1%**	**3%**	**5%**
Increase in weevil resistance	25%	195.2	4.3	0.2
	50%	562.3	13.4	0.8
	75%	1 123.3	30.0	2.3

The present value of avoided losses is sensitive to both the level of weevil resistance and interest rate assumptions. As described earlier, a 50% increase in weevil resistance has been reported for selected stock (King 1994). In this case, the present value of avoided losses varies from $ 0.8 million using a 5% discount rate, to $ 562 million when discounting at 1%.

Under the most favorable conditions, with a 75% increase in resistance and a 1% discount rate, avoided losses are valued at approximately $ 1.1 billion. In contrast, under the least favorable conditions, with a 25% resistance increase and a 5% discount rate the present value of avoided losses is close to zero.

3.4 Discussion

The results of this study confirm the importance of spruce inventories for the British Columbia forest sector. While species composition varies from year to year, spruce harvest account for an average of 19% or 14 million m^3 of annual harvest volumes. In the absence of weevil-resistant spruce stock, approximately 2 million m^3 of merchantable volume are lost per year due to defects caused by spruce weevil infestations. Based on current log prices, these losses represent a gross value of approximately $ 120 million per year. These figures provide some support to the perception of spruce weevil damage as a major economic threat to the British Columbia forest products industry. However, the 2.3 million m^3 of merchantable volume that are lost due to spruce weevil damage only represents approximately 3.1% of the total provincial harvest.

The interpretation of these modeling results is dependent on the assumption that the simulated spatial distribution of spruce inventories shown in Figure 3.4 is a sufficiently accurate approximation of actual inventories. Data on climate-based infestation risk shows strong spatial clustering (Figure 3.3), since it was obtained from an elevation and location driven climate model (Wang et al. 2006). In contrast, the resource inventory dataset for this study was generated by disaggregating forest inventory statistics available at the TSA/TFL level. This disaggregation procedure randomly distributes tiles within the geographic and elevation ranges specified by the Biogeoclimatic Ecosystem Classification System[7]. Some estimation errors may therefore be present, depending on the degree of overlap between high climatic risk areas and spruce inventories.

From a policy perspective, the most important issue is how much of this damage could be avoided, and how soon any management intervention would become effective. First, as shown in Figure 3.5, the benefits of replanting harvested spruce stands with weevil resistant stock begin to occur from year 110 onwards, once second growth weevil resistant spruce stands are being harvested. This time lag is due to two factors. First, minimum harvest ages are relatively high due to the late culmination of average growth rates. Second, the 'oldest first' harvesting rule may delay the harvest of second growth stands beyond the rotation ages

[7] Schwab, O. and T. Maness. Building spatial inventories from aggregated data. Chapter 2, pg. 16-35.

associated with optimum economic returns or fibre yield. The extent of this initial delay is determined by the amount of existing older inventories. Over the course of several rotations this delay will become shorter as average yields decrease. The maximum loss reduction effect is achieved in year 250, and stabilizes at this level for the remainder of the simulation horizon. At this point, all existing spruce inventories have been harvested and regenerated at least once. Second, even weevil resistant spruce stands are likely to sustain some damage if local environmental conditions are favorable and endemic weevil populations are sufficiently high (Alfaro et al. 2004). This effect is taken into account in equation [1] by integrating the genetic factor [GF] as a multiplicative parameter that will lower the maximum attack intensity [MA] without reducing it to zero. Therefore, assuming that weevil resistant stock would sustain a 50% lower maximum attack intensity, only up to 30% of the $ 120 million per year in merchantable volume losses could be avoided by planting weevil resistant spruce.

The relatively low percentage of avoidable volume losses and the long lag time until benefits accrue have a major effect on the economic assessment of weevil resistant stock as a pest management option. As shown in Table 3.4, the present value of avoided merchantable volume losses is sensitive to variations in interest rates as well as the effectiveness of weevil resistant stock in reducing maximum attack intensities. Under median assumptions (3% interest, 50% increase in weevil resistance) the present value of avoided merchantable volume losses is $ 13.4 million. This relatively low median value, as well as the high sensitivity of present values to changes in resistance levels and interest rates suggest that investments into identifying, propagating, and planting weevil resistant spruce stock should be considered with caution. At the same time, the economic benefits from introducing weevil resistant spruce can extend beyond the immediate value of avoided roundwood losses.

Harvesting and processing roundwood creates economic benefits to the province through direct and indirect employment, as well as through taxation on forest sector expenditures and earnings (Horne 2004).

Under current model settings, the merchantable volume that is damaged by spruce weevil is treated as a total economic loss. However, some economic value may be recoverable, for example by using damaged timber as feedstock for bioenergy generation, or for pulp and paper production. Lysack et al. (2006) also found that visible damages were concentrated in the upper parts of the tree, while defects in the lower bole have healed over time. They conclude that while some internal defects are likely to remain, it is possible to produce high quality clear wood in areas with high weevil infestation risks. Daoust and Muttet (2006) report similar findings for weevil infestations in Norway spruce (*picea abies [L.] Karst.*) plantations in Quebec, where defect-free lumber could be produced despite high rates of weevil infestation.

Downward pressures on the present value of avoided losses may be partially offset by the effect of the current mountain pine beetle infestation on long term harvest scheduling. Second growth spruce stands may be harvested sooner than expected, since the temporary uplifts in AAC levels for mountain pine beetle salvage harvesting may deplete mature inventories of non-spruce stands at a substantially faster rate. The reliance of harvest activities on these spruce inventories is therefore likely to increase in the future.

Harvest targets for this simulation analysis were defined using AAC levels determined by the B.C. Ministry of Forests during periodic timber supply reviews. This timber supply reviews process is inventory driven. AAC levels are determined by adjusting maximum sustainable yield levels for ecological and social factors such as habitat conservation and stable levels of fibre flows and local employment (B.C. Ministry of Forests and Range 2008e). A central assumption to this approach is that domestic and international markets for logs and finished lumber products remain relatively stable, and that the Canadian forest products industry will be able to maintain its current market share. Given current developments in the U.S. housing market (Blackstone 2008), and the emergence of South America as a major competitor in commodity lumber markets, future work should focus on integrating market scenarios when assessing the economic implications of large-scale forest management activities.

3.5 Conclusion

The agent-based forest sector model presented in this paper is capable of projecting the expected economic effects of introduction spruce weevil resistant planting stock over large spatial and temporal scales. While spruce weevil damages are significant (2.3 million m^3/year, valued at approximately $ 120 million per year), only a relatively small percentage of these losses can be avoided by planting resistant stock. Losses only begin to decline after a lag time of approximately 150 years, and do not reach their maximum reduction of 30% until year 250. Given the small percentage of avoidable losses, the introduction of weevil resistant stock is too slow to make an immediate difference for the economic viability of the forest sector in British Columbia. However, the economic benefits from introducing weevil resistant spruce can extend beyond the immediate value of avoided roundwood losses since harvesting and processing of roundwood creates economic benefits to the province through direct and indirect employment, as well as through taxation on forest sector expenditures and earnings.

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4 Modeling Structural Development in the Forest Sector with the EWA-Lite Algorithm[8]

4.1 Introduction

The forest products sector in British Columbia faces a range of ongoing economic challenges; from diminishing product demand due to the U.S. housing crisis to uncertain raw material supplies in the aftermath of the current mountain pine beetle epidemic (Watson 2006; Blackstone 2008). Both of these challenges contribute to a need for a better understanding of how primary manufacturing industries evolve and respond to change.

Equilibrium models have most frequently been used in assessing the economic impacts of disturbances and in predicting the effects of strategic industry decisions (see for example Alavalapati et al. (1998) and Lundmark (2007)). Neo-classical economic theory largely relies on axioms to define economic problems that are relevant and analytically tractable. Analysis and interpretation of these problems are usually done by deduction. In well-specified cases, such as resource allocation in a competitive market with optimizing behavior and freely available information, the expected results can be readily identified. While this is of great value in determining the long-term implications of proposed strategic decisions, little information is available on adjustment processes during transition between equilibrium states. However, when economic agents are either incapable of, or unwilling to optimize it becomes impossible to deduce market outcomes (Axelrod 1997; Rammel et al. 2007). Reasons for this type of non-optimal behavior include irrational or bounded rational agent behavior, a dynamic and continuously changing environment, and competing objectives among different agents.

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[8] A version of this chapter has been submitted for publication. Schwab, O. and T. Maness. *Modeling structural development in the forest sector with the EWA-Lite algorithm.* 33 pp.

These types of comparative statics models can be improved upon in two areas. First, the limiting effects of commonly made assumptions such as the existence of a market clearing mechanism, rational behaviour, common knowledge, and the use of representative market participants have been recognized in the theoretical and applied economic literature. Second, by definition, comparative statics focuses on equilibrium states. Agent-based computational economics is a method for developing and exploring economic models as complex adaptive systems. ACE therefore makes it possible to observe transition processes between equilibria. Using object-oriented programming techniques, it is possible to model economies as systems of autonomously interacting agents that do not necessarily act perfectly rational, or possess complete information about their environment.

Multiple agent systems [MAS], and in particular agent-based computational economics [ACE] have been introduced as tools to model these interdependencies and feedback loops between microstructures and macrostructures quantitatively (Lempert 2002; Tesfatsion 2002). An early example of using MAS for wood products allocation problems is Säaksjärvi (1986), who recognized that unequal cost allocations may make individual companies unlikely to cooperate and support a globally optimum wood allocation solution. Cooperative games are shown to be effective in determining fair compensation levels for wood sharing agreements. Gebetsroither et al. (2006) presented a model of self-organization in socio-economic and ecological processes to reduce the amount of uncertainty that conflicting objectives and complex interdependencies introduce into forest management planning. Modeling these processes as self-organizing subsystems eliminated the need for direct hierarchical control and makes it possible to implement an adaptive management system for achieving desired conditions with minimum interventions. Moyaux et al. (2004) analyzed the effects of collaboration on supply chain performance using the Quebec forest products industry as the primary case study. This study demonstrates that selfish agents have an incentive to at least partially collaborate, and that, from a game theoretic perspective, no equilibrium exists when at least one agent does not collaborate. Gerber and Klusch (2002) presented an information and trading network that coordinates plans between producers, buyers, retailers, and logistics companies in the agriculture and forestry sectors. The network was designed as a MAS due to its inherent robustness, flexibility, and ability to self-organize in the absence of direct human interaction. D'Amours et al. (2006) developed a MAS approach to lumber production planning that offer significant time savings and efficiency gains relative to manual planning.

In this paper, we develop CAMBIUM[9], an agent-based forest sector model that is capable of simulating how strategic decisions and inter-agent competition affect the emergence of industry structures, firm survival, and industry resilience. Following this introduction, background literature on agent-based computational economics [ACE] and decision modeling using evolutionary learning algorithms are reviewed and summarized. The next section describes the parameters and methods used in modeling forest inventory, product markets, industry agents, production strategies and strategic choices are described in detail. The third section presents sample outputs from a 200 year simulation of 15 sawmilling agents on a hypothetical 3.3 million hectare landbase consisting of 13 000 tiles, followed by a sensitivity analysis of model outputs. Finally, the distinguishing features of the CAMBIUM model will be summarized.

[9] The cambium is a layer of cells that contributes to the growth of both the wood and innermost bark of a tree. The name CAMBIUM was chosen for this agent-based forest sector model to reflect the critical role that forest sector agents play within the interdependent feedback loops between resource inventories and product markets.

4.2 Methodology

Tesfatsion (2002) describes ACE as "(…) the computational study of economies modeled as evolving systems of autonomous interacting agents." ACE models are commonly driven by two objectives: 1) descriptive research on why certain market structures and dynamics evolve and persist despite the absence of centralized planning and control in market economies; and 2) normative research on mechanism design, assessing the role of existing and new market factors on the performance of the economy as a whole (Tesfatsion 2002).

ACE is part of a third developmental stage in socioeconomic modeling, where agent interactions are explicitly incorporated to improve the explanatory power of earlier macrosimulation and microsimulation models (Macy and Willer 2002). Key features of this approach are its ability to: 1) provide useful information on systems that are out of equilibrium (Arthur 2006); and 2) integrate interdependent systems from different disciplines (Andersson et al. 1986).

Economies can be described as largely self-regulating and self-determining systems (Vanderburg 1985). While each individual process within such a model may be quite simple, their simultaneous and repeated implementation creates 'artificial histories' that make it possible to study processes of interest, such as patterns of resource utilization and industrial organization (Axelrod 1997; Bonabeau 2002). The CAMBIUM model concentrates on the descriptive aspects of ACE, which will provide the foundation for future normative work. A specific industry structure in this model is the result of exogenous and endogenous factors. Exogenous factors include parameters like consumer demand for specific products, the available supply of raw material and in the case of oligopolistic or perfectly competitive producers to a large extent the market price. Endogenous factors are defined within the model and include feedback from interactions with other agents, probabilistic processes within the model and each firm's competitive position and production costs. Systems approaches such as agent-based modeling are uniquely suited for exploring how phenomena such as a specific industry structure emerge. The emphasis on autonomously interacting agents allows for a departure from a purely mechanistic world view that has historically characterized the majority of quantitative studies (Vanderburg 1985).

The agent-based forest sector model presented in this paper is similar to a model described by Gebetsroither et al. (2006), but expands on it by integrating a mechanism for learning and individual strategic choice. The importance of inertia and limited memory have long been recognized as important factors in decision making processes (see for example Lindblom (1959), and March (1978)). Optimum choices that are being made based on such a limited subset of decision options can be classified as boundely rational (Dieckmann 1995). The concept of procedural rationality shifts the emphasis from the decision outcome to the process of how a decision is being made (Simon 1976, Dean and Sharfman 1996), allowing for greater heterogeneity in strategic choices at the agent level.

Decision processes in the CAMBIUM model were simulated based on the self-tuning experience weighted attraction learning algorithm [EWA-Lite] (Ho et al. 2001). This procedurally rational decision algorithm combines each agent's repeated assessment of expected strategy payoffs with information on how each strategy performed in previous periods and how drastically the learning environment is changing. The EWA-Lite algorithm allows agents to adjust their learning behavior along a continuum between reinforcement learning (for stable environments) and belief learning (for instable environments). This algorithm has been found to correspond well to human behavior (Nawa 2006) and consistently performs equivalent or better than other learning algorithms (Camerer and Ho 1998; Ho et al. 2001). The unique feature of EWA-Lite is that it only requires the a-priori estimation of one parameter that describes the sensitivity of an agent's decisions to changes in its learning environment. An agent with a high response sensitivity parameter value would switch to a belief learning model when faced with a relatively small change in the learning environment. An agent with a low response sensitivity would continue with a reinforcement learning model when faced with the same change in the learning environment. All other parameters are being determined and adjusted endogenously, making this decision model uniquely suitable for the requirements of 'no modeler intervention' (Tesfatsion 2002) and the minimal set of necessary processes and parameters in agent-based modeling (Macy and Willer 2002). These requirements ensure that a model is fully specified and capable of generating the phenomena of interest endogenously, while still being sufficiently abstract to support the analysis of potential causal relationships.

The EWA-Lite algorithm was adapted to the particular structure of the decision problem facing each agent in the forest sector model. The components and structure of the decision process are summarized in Figure 4.1 and described in detail below.

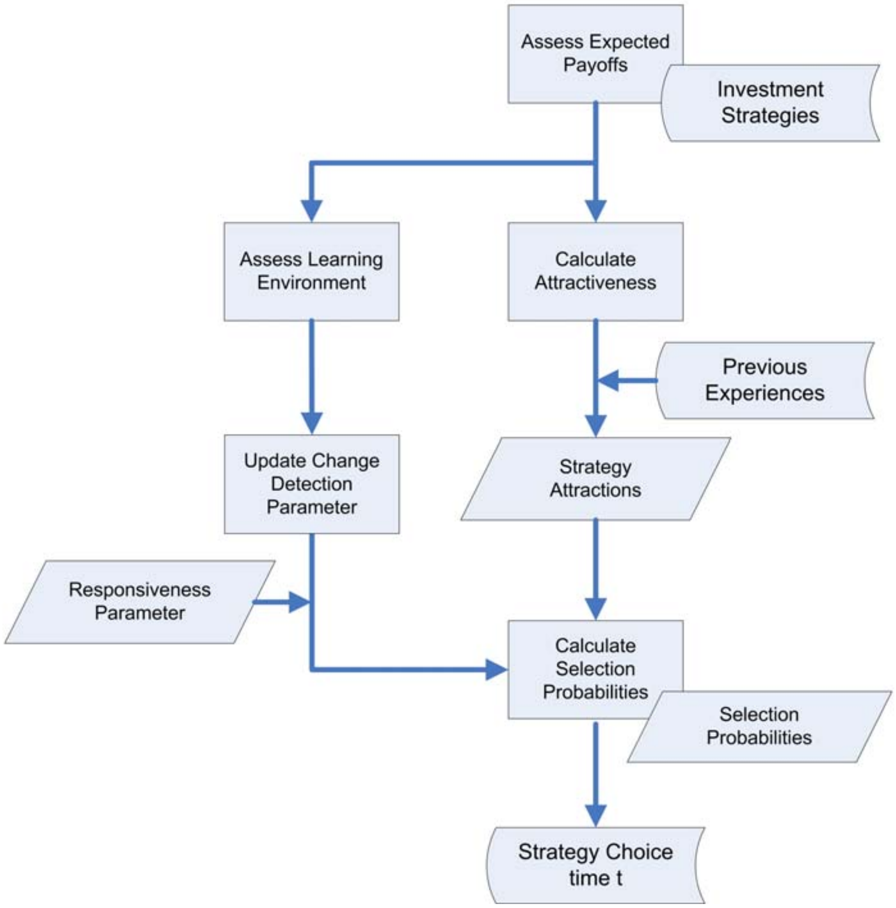

Figure 4.1. Modeling decisions with experience weighted attraction learning

Based on their perception of the learning environment in any given period firms can choose from three district investment strategies. These are: 1) endogenous growth through capacity expansion; 2) improving product recovery through process innovation; and 3) sustaining current operations by periodically replacing outdated equipment.

An expected payoff is calculated for each available strategy using infinite horizon net present value calculations. The expected payoffs are translated into attractiveness values based on the agent's previous experience with implementing each strategy, placing the highest emphasis on recent experiences. Positive previous experiences increase the current attractiveness of a strategy, while negative experiences decrease attractiveness.

At this stage, the agent assesses the stability of its learning environment. The change-detection parameter plays a critical role in adjusting decision behavior. The learning environment is stable when the parameters of interest change relatively little. Depending on model settings, the change detection parameter reflects either the frequency with which competitors choose specific strategies, or the quantities and price range of products traded in the market. In stable environments past experiences are a good predictor for future conditions, allowing agents to exploit well performing strategies with little risk. In contrast, past experiences are a poor predictor of future conditions in rapidly changing environments, and are therefore less relevant for current decisions. This allows agents to enter an exploration phase, where decisions are once again mainly based on the expected payoff for each strategy.

The probability that a firm selects a given investment strategy is determined using a logit response function that takes into consideration each agent's individual response sensitivity. The strategy choice for a specific period is then determined by random draw. Equations for calculating and updating the decision parameters are described by Ho et al. (2001). It is expected that over time economic agents will settle into a stage of dynamic equilibrium where occasionally firms revise their strategic choices and displace another firm, but where the overall industry structure remains relatively stable (Camerer and Ho 1998).

A review of the economic literature indicated that capacity expansion and process innovation are some of the primary means by which companies achieve specific competitive positions (Besanko and Doraszelski 2004; Hansen et al. 2007). A third strategy, sustainment, was added to accommodate conditions where neither continuing innovation nor capacity expansion are technologically and economically feasible. These three distinct investment strategies were sufficient for achieving agent differentiation and an associated dynamic industry structure equilibrium.

The agent-based forest sector model was coded in Java using the Recursive Agent Simulation Toolkit [Repast J] program libraries (North et al. 2006; ROAD 2008). The modeling environment was chosen based on reviews and comparisons by Tobias and Hofmann (2004) and Railsback et al. (2006). Important factors in this decision were the ability to interface with geographical information systems, cross-platform transferability of the resulting model, and well-documented open access program libraries.

Industry structure is tracked using two closely related measures: 1) a capacity-based industry concentration curve, and 2) the Herfindahl-Hirschman Index [HHI]. The HHI is calculated as the sum of squared market shares for all firms in an industry, thereby providing a measure of the overall shape and position of the industry concentration curve. When market share is measured in percentage points, the HHI can range from 1/n (with n being the number of companies in the market) to 10 000. A small HHI represents competitive markets without dominant players, while higher HHI values indicate increasing market concentration. Commonly used interpretation thresholds relate to no market concentration (HHI<=1 000), moderate concentration (1 000<HHI<=1 800), and high levels of market concentration (HHI>1 800) (Calkins 1983; U.S. Department of Justice Antitrust Division 2007).

4.2.1 Model Structure

The CAMBIUM model consists of three main components: the forest model, the market model, and the economic agent model. Each of these components will be described in detail in the following section.

The geographical range of the forest model is defined by a rectangular grid, with forest stands being represented by individual lattice tiles. Both the size and the number of tiles can be defined by the model user. Default settings are 13 000 tiles of 256 hectares each, but the model has been successfully tested with landscapes of up to 1.4 million tiles. The forest inventory on each tile is described by stand age and merchantable volume. Stand growth is modeled using a sigmoid growth curve (Pretzsch 2001). The default forest inventory is modeled as a randomly distributed normal forest, where each age class is represented with an equal area. The use of this normal forest model removes the effects that an unbalanced age class structure and resulting timber supply shortages may have on industry structure development.

At this stage of model development, the market for lumber products is modeled using a linear demand function with a demand elasticity of -0.5 (Abt and Ahn 2003). Forest growth and lumber demand constrain the maximum size of the forest sector. The number and relative size of competitors in the forest sector is determined by repeated agent interactions, and can be interpreted as an emergent property of this inventory, industry and market system.

Economic agents are defined by their location on the landscape, production capacity, product recovery factor, innovation success rate, strategy response sensitivity and an initial capital endowment. The user defined number of agents is placed on the landscape randomly, establishing a starting industry configuration with uniform production capacities. Figure 4.2 shows how the economic agents (centre column) act and interact with each other, as well as with the forest inventory (left column) and the lumber products market (right column).

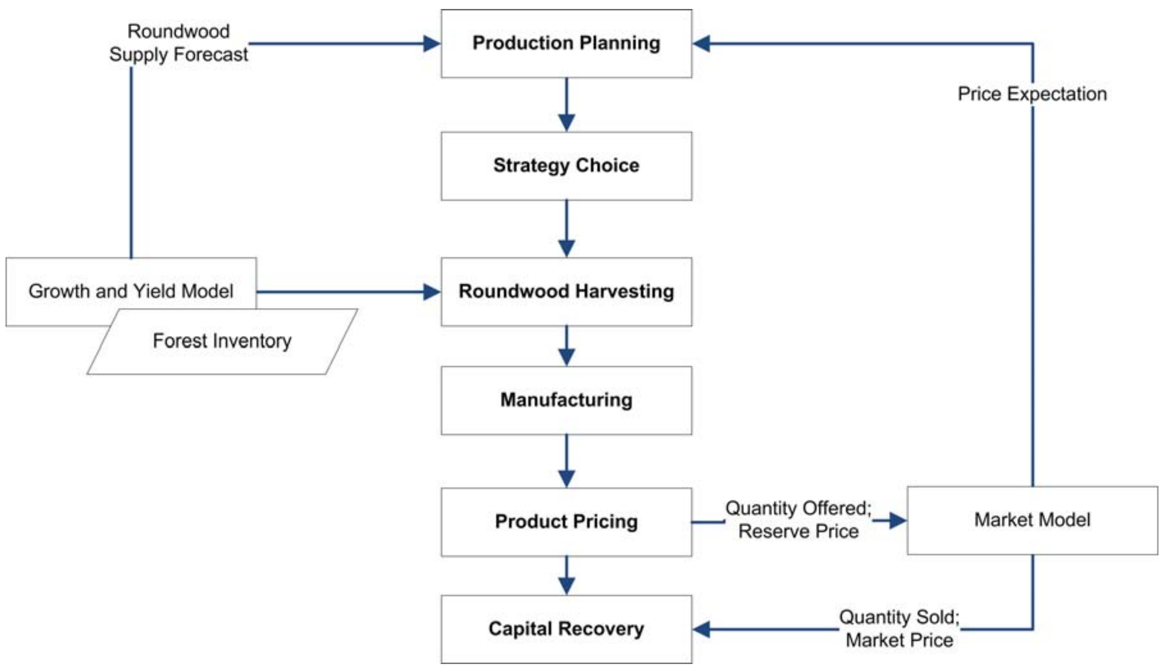

Figure 4.2. Information flow between agents, markets, and resource inventory

At each time interval, the sawmill agent proceeds through the sequence of planning and implementation steps shown in bold. Agents become insolvent as soon as their working capital falls to zero. These agents become inactive immediately and are removed from the simulation environment upon completion of the current time step. During production planning, agents form price expectations for their finished products based on predicted product demand and the observed production capacity of competing sawmills. This forecast is not necessarily equivalent to the period's realized market price, since competitor's choices regarding capacity expansion and capacity utilization cannot be observed until the following period.

Tentative production targets are developed for all three investment strategy options as a function of predicted market demand and price levels, as well as each agent's production costs and capacities. Production targets are set in an iterative procedure by adjusting targets downwards until a solution is found that is expected to be financially feasible over an infinite horizon given current expected market conditions.

Financial feasibility is defined as the ability to meet projected cash flow requirements for equipment amortization, as well as stumpage and other production costs. Agents become inactive and are removed from the simulation if no financially feasible strategy can be found.

4.2.1.1 Strategy Definitions

Capacity expansion is one of the means by which companies achieve their relative competitive position in developing markets (Reynolds 1987). In this model, the endogenous growth strategy is designed to achieve maximum production capacity subject to constraints posed by the availability of capital and roundwood. Capital availability is dependent on the agent's profitability and cumulative net earnings. Capacity expansion occurs in multiples of a user-defined increment and is restricted to cases where previous manufacturing equipment investments have been fully amortized.

Companies also have the ability to remain competitive through innovation, by introducing new or improving existing products, processes, and business systems (Hovgaard and Hansen 2004). The commodity orientation of the Canadian forest products industry has resulted in a very strong focus on achieving high levels of production efficiency (Crespell et al. 2006). Therefore, successful innovation is modeled as improving product recovery while lowering variable manufacturing costs. Innovation can occur within an industry specific user defined range of product recovery factors. Default values for the sawmilling sector are a lower bound of 5.32 m^3 per thousand board feed [mbf] and an upper bound of 3.32 m^3/mbf (Haynes 2003). The expected payoff from implementing an innovation strategy was calculated based on the user-defined costs per innovation initiative and the agent-specific innovation success rate. Multiple innovation initiatives can be undertaken in a single period. This expected payoff can differ from the realized payoff at implementation since the success of each innovation initiative was modeled using a random draw from a uniform distribution.

A sustainment strategy was included to account for situations where neither innovation nor endogenous growth would generate a positive payoff. For the sustainment strategy, agents replace equipment only at the end of its user defined lifespan. Production targets are determined within the bounds set by the current production capacity. Lumber recovery rates increase and production costs decrease by a user defined percentage (default: 5%), reflecting improvements in manufacturing technologies that have occurred since the previous equipment purchase.

4.2.1.2 Stumpage Rates, Roundwood Harvesting, and Lumber Production

Stumpage charges are modeled based on a competitive bidding process. To establish a stumpage base rate, each agent submits a maximum bid net of road access costs. Access costs are user-defined as a fixed rate per kilometer and cubic meter (default $0.20 per km and m^3). The maximum stumpage bid is based on each agent’s individual cost structure and profit targets, as well as expected and historical market prices for finished products. The base stumpage rate for the current period is then set using a weighted moving average of the current maximum bid and stumpage rates for the previous 4 years.

Tiles are queued for harvest using an oldest-first harvesting rule, and allocated to mills based on minimum transportation distance. For each harvested tile, the resource owner receives stumpage revenues that are calculated as the product of the tile's roundwood volume and the transportation cost adjusted stumpage base rate. Agents continue harvesting until the roundwood demand for the current period is met or no additional roundwood is available without exceeding sustainable harvest levels. Agents also incur costs for harvesting and transporting roundwood. During the manufacturing process harvested roundwood is converted into dimensional lumber and chips based on each agent's lumber recovery factor. Variable operating costs are then deducted from the agent's working capital.

4.2.1.3 Product Pricing and Market Trading

At the end of the manufacturing step, agents set a minimum sales price for their current lumber production. The reserve price is based on average production costs for the period, as well as expected and observed market prices. The lowest price they will accept for lumber produced during the current period is one that just covers their cost and an agent-specific minimum profit expectation. Unsold inventory from previous production periods may be sold at a loss once reserve prices have been adjusted accordingly.

During this pricing process, unsold inventory from previous periods is discounted by a user-defined percentage and offered on the market. Trading units are defined by an owner (the producing agent), a product category, a reserve price, and a quantity offered.

Market trading occurs once all agents have submitted their trading units. These trading units are sorted with ascending reserve price, and matched to the market demand. The trading result for a non-saturated market is shown in Figure 4.3, while a trading in a saturated market is shown in Figure 4.4. Trading units are shown as grey rectangles, with the width indicating the volume offered, and the height indicating the reserve price.

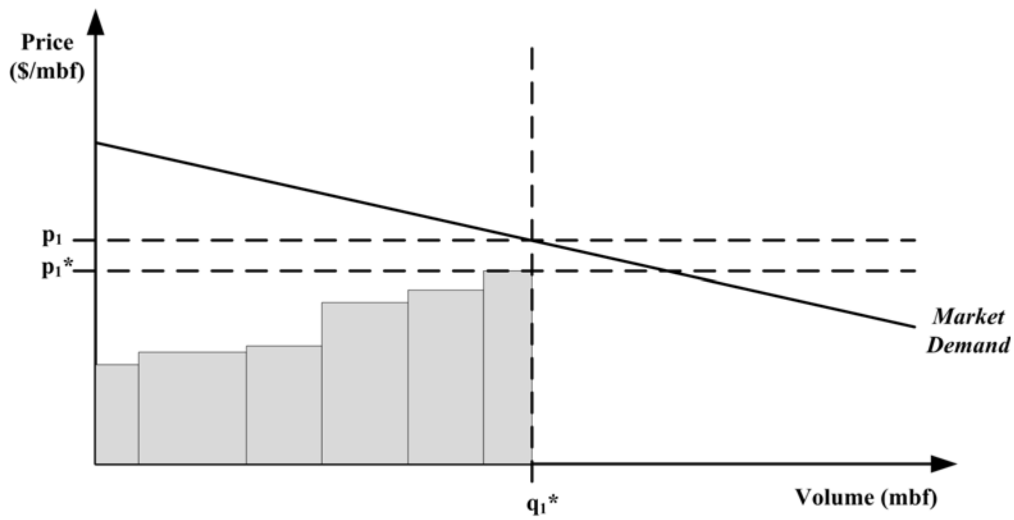

Figure 4.3. Trading in an unsaturated market

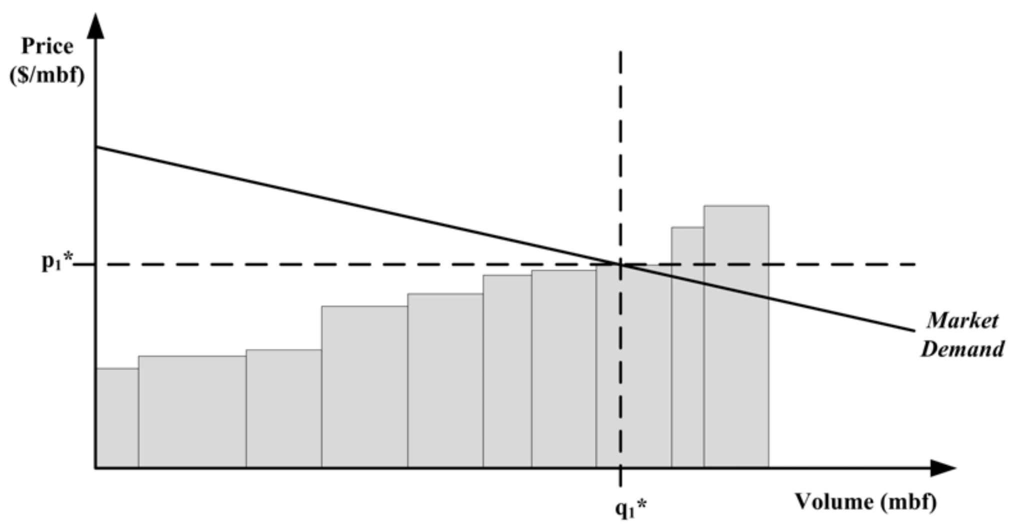

Figure 4.4. Trading in a saturated market

As shown in Figure 4.3, all trading units offered in the market are traded, with the last trading units' reserve price determining the current market price p_1*. Companies observe the difference between the realized market price p_1* and the predicted market price p_1, and adjust profit targets and production plans accordingly. In contrast, in Figure 4.4 market supply exceeds demand. Only the first seven trading units and a portion of the eighth are traded at price p_2*, for a total volume of q_2*. For each traded unit, the owning agent realizes a gross revenue defined by the market price p* and the volume sold. The remaining trading units are returned to the producing agents as unsold inventory.

The elements outlined in Figure 4.2 are implemented for each modeling time step. Simulation speed is mainly affected by the number of tiles in the landscape and the number of companies that are being modeled.

4.3 Model Output

Figure 4.5 shows a screenshot of the model with 15 companies on a hypothetical uniform landbase consisting of 13 000 tiles. An average simulation speed of 10 years per second was observed for this configuration, enabling model users to rapidly test the effects of different configurations on emerging industry structures.

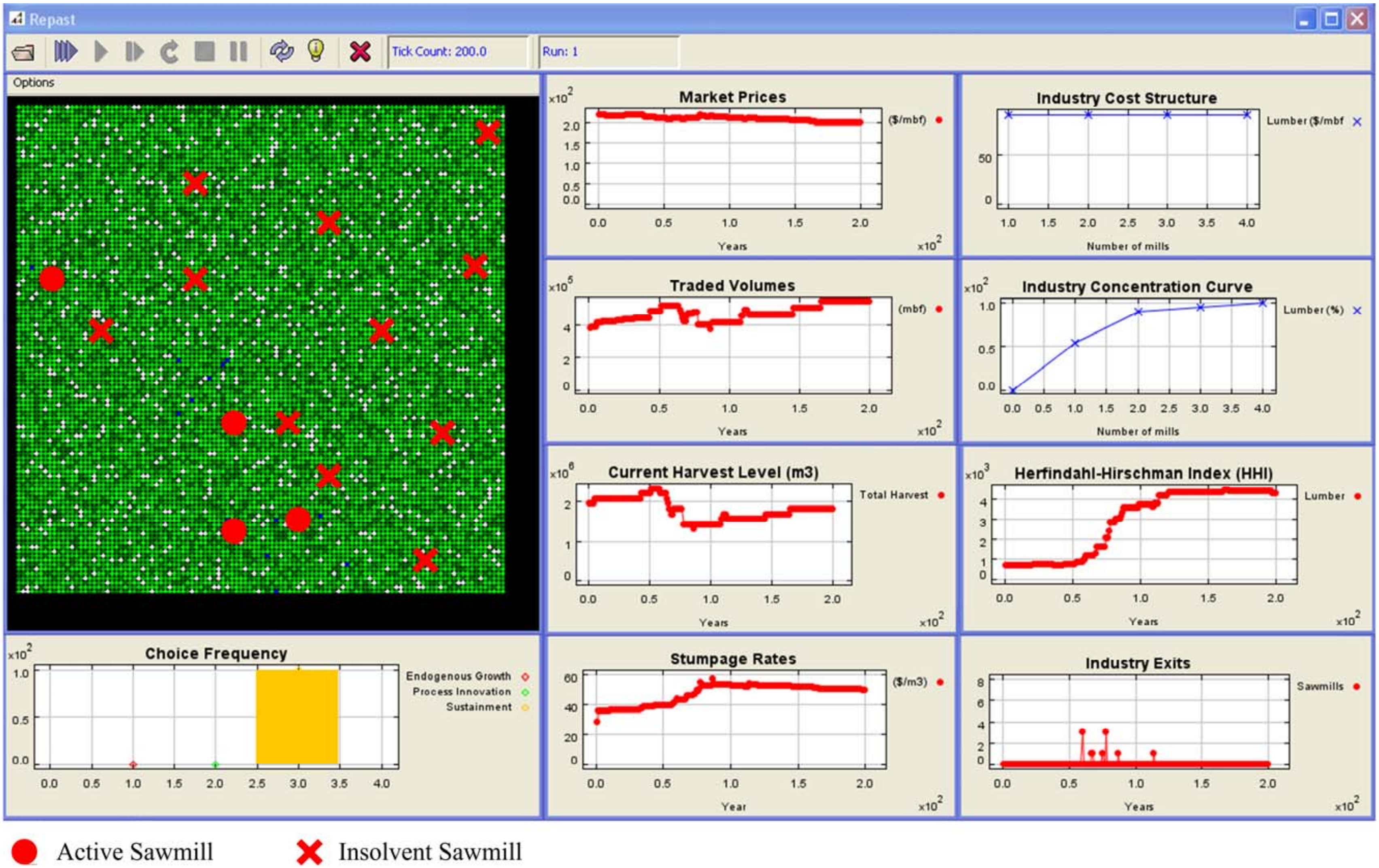

Figure 4.5. CAMBIUM model screenshot

The display window in the top left corner of Figure 4.5 shows the model landscape as a network of tiles in a grid pattern. Light colored tiles indicate young stands and darker colors indicate mature stands. Active sawmilling agents are shown as red dots, while insolvent agents are shown as red crosses. The bar graph below the grid displays the frequency with which each investment strategy (endogenous growth, innovation, sustainment) was chosen in the current period. The graphs in the centre column track market prices ($/mbf), traded volumes (mbf/year), harvest levels (m^3/year), and stumpage rates ($\$/m^3$) respectively. These graphs provide a high level summary of harvesting activities and market outcomes.

The graphs in the right column address issues related to current industry structure. The topmost graph shows current production costs for individual agents ($/mbf) from lowest to highest. It reflects the realized costs for production, harvesting, and transportation for the current time step. The industry concentration curve below shows each agent's market share (%), ordered from largest to smallest. This concentration curve provides a snapshot of the current industry structure. The graph below tracks the Herfindahl-Hirschman Index [HHI], providing a measure of how industry structure is changing over time. The final graph on the bottom of the right column indicates when agents became insolvent and exited the simulation.

Overall, the graphs in Figure 5 belong to two distinct groups. The first group consists of the overview map, industry cost structure, choice frequency, and industry concentration curve. This group provides continuously updated snapshots of current conditions in the simulation model as it is running in real time. The second group consists of market prices, traded volumes, harvest level, stumpage rate, HHI, and industry exits. This group of charts is cumulative over the entire simulation run in order to provide information on how a specific industry structure was attained. The use of simulation time as the common x-axis for the second group also facilitates cross-comparison for identifying effects that may have a causal relationship.

A Monte-Carlo analysis of 100 simulation runs was conducted to assess the sensitivity of model results to the stochastic components of the model. The stochastic components are the location of the agents on the landscape, the location of forest inventory age classes, as well as the parameters describing each agent's response sensitivity and innovativeness. For this analysis, all random parameters were drawn from a uniform distribution within the appropriate range of values. For each 200 year simulation run a population of 15 sawmilling agents was randomly placed on a forested landscape consisting of 13 000 tiles. Each of these sawmilling agents has an initial production capacity of 20 000 mbf/year and sufficient working capital to operate for the first year.

4.4 Results

Output parameters were recorded at the end of every year. Modeling results are presented in box-and-whisker plots. Median, quartiles, minimum and maximum values were calculated for 10 year intervals. For each time interval, the whiskers indicate minimum and maximum values, the top and bottom of the box show the 1^{st} and 3^{rd} quartile, and the bold horizontal line bisecting the box locates the median observation value. Figure 4.6 shows the number of active mills over the course of the simulation.

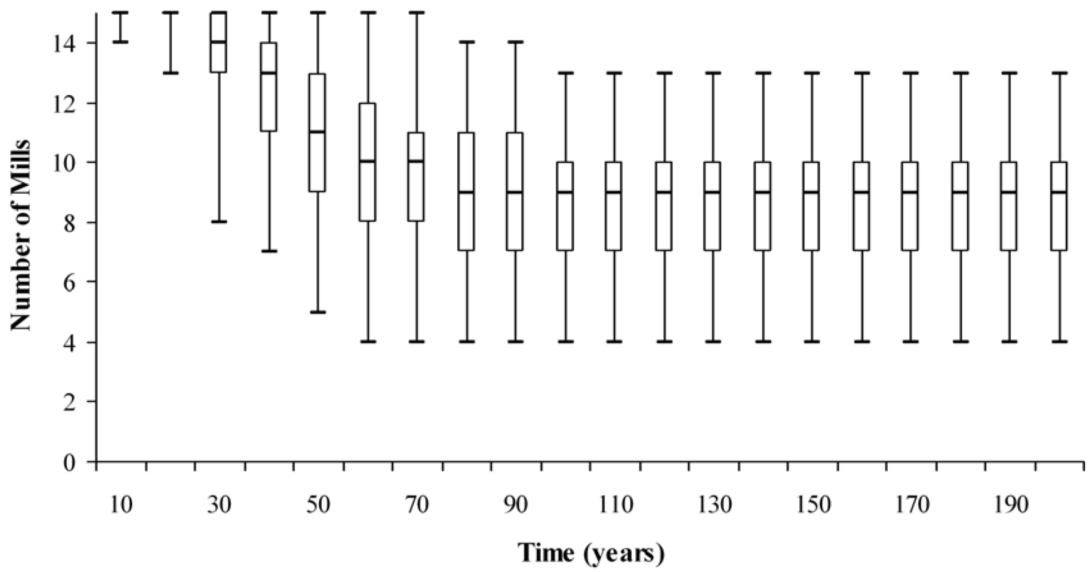

Figure 4.6. Number of active mills remaining

For most simulation runs, the industry structure reaches equilibrium with nine active mills, with a minimum of four and a maximum of thirteen active mills. These observations show a tight clustering around the median, identifying this as the most likely industry size given the current model size and specification. Industry consolidation mainly occurs over a 50 year period between years 21 and 70 of the simulation. The majority of mill insolvencies was observed between years 31 and 60. These insolvencies are closely linked to the average production cost structure of the industry (Figure 4.7).

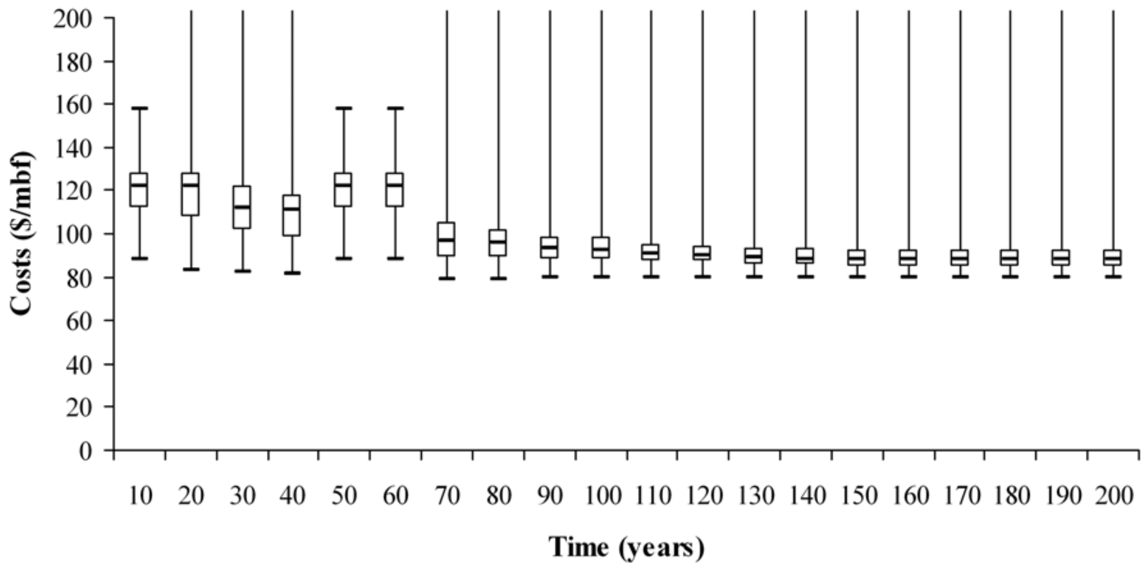

Figure 4.7. Average production costs

These production cost values allocate both fixed and variable costs to the realized production volume. Over the course of the 200 year simulation horizon, median production costs fall by 28% from 122 $/mbf to 88 $/mbf. The distribution of production costs also changes over the course of the simulation horizon. During the first decade, production costs are distributed in an almost symmetrical bell curve. As the simulation progresses, the cost distribution becomes increasingly skewed towards the minimum value of 80 $/mbf. Outliers with very high production costs are caused by low capacity utilization levels in mills that are facing cash flow constraints. Low capacity utilization allocates a relatively large share of a mills fixed costs to each unit of output. The overall downward trend in production costs is driven by two processes. First, intensive cost competition occurs throughout each simulation run, with high-cost producers becoming insolvent as they are being undercut in the market. Second, mills with a high level of innovation potential are able to lower their production costs through investments in process innovation, or through the replacement of outdated equipment at the end of its lifespan.

The convergence in production costs coincides with the period of industry concentration that lasts until year 70 of the simulation. During this period, capital reserves and existing production cost advantages are the most important factors in determining which mills are capable of outlasting their competitors. On average, this shakeout phase eliminates 75% of the competitors and redistributes their market share among the remaining mills (Figure 4.8).

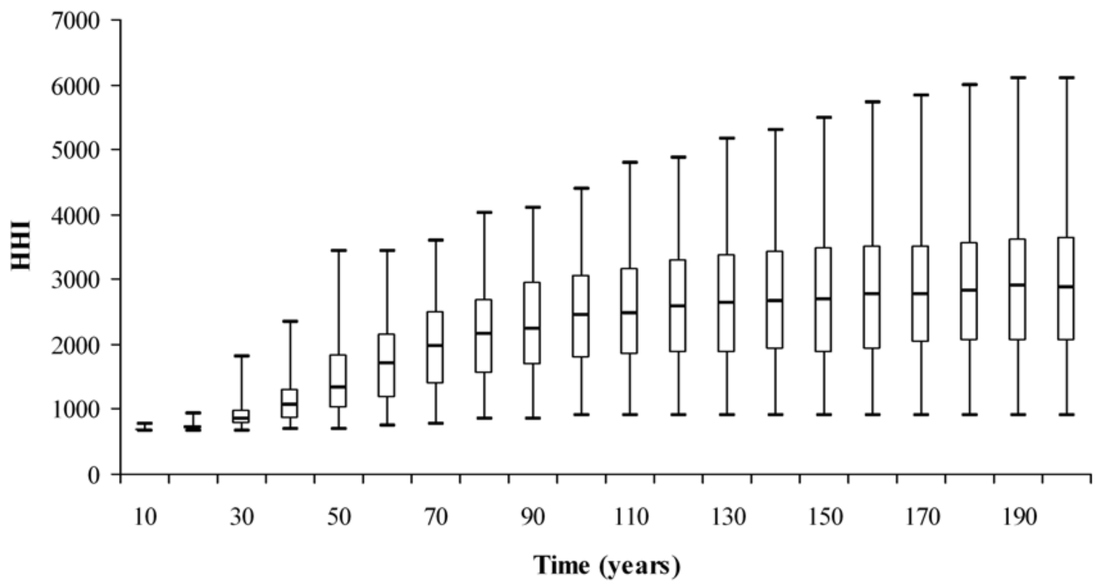

Figure 4.8. Herfindahl – Hirschman Index (HHI)

The Herfindahl-Hirschman Index (HHI) a measure of industry concentration reflects both the number and the relative size of firms active in a specific market. As shown in Figure 4.8, industry concentration mainly occurs between years 30 and 100 of the simulation. This period of increasing HHI only partially overlaps with high rates of insolvencies (Figure 4.6). Industry concentration is therefore not only caused by redistributing market shares as mills become insolvent. Especially during the later stage of the concentration process, from years

70 onwards, strategic choices become an important factor in size differentiation among the remaining mills. Individual mills emerge as dominant large-capacity producers while the remainder of the market is occupied by smaller profitable producers. Since mills are able to make suboptimal decisions it is not possible to establish a direct causal link between mill characteristics and their ability to become a dominant player.

The industry structure that emerges during these simulation runs is the result of agent interaction within the boundaries defined by both the underlying resource inventory and the lumber market. Using a 120 year rotation with a maximum volume of 500 m^3/ha, the maximum sustainable yield for the model area is 12.8 million m^3/year. The highest observed roundwood harvest was 4.4 million m^3/year, or approximately one third of the maximum sustainable harvest. This underutilization of available resources indicates that under current model settings market demand is acting as the limiting factor. The volume of lumber traded per year is shown in Figure 4.9.

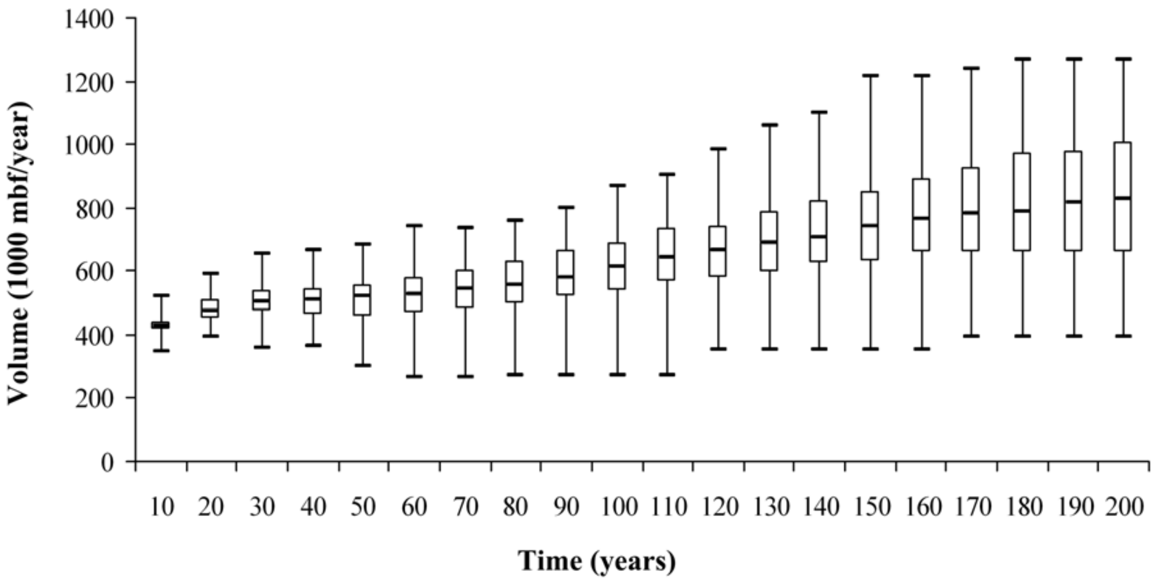

Figure 4.9. Annual lumber trade volume

Over the first 80 years of the simulation, the 50% of the observations occur within a narrow band between 410 000 to 540 000 mbf/year. This clearly defined peak disappears during the subsequent years, resulting in an almost uniform distribution at the end of the simulation horizon. A similar pattern can be observed for the distribution of lumber prices over time (Figure 4.10).

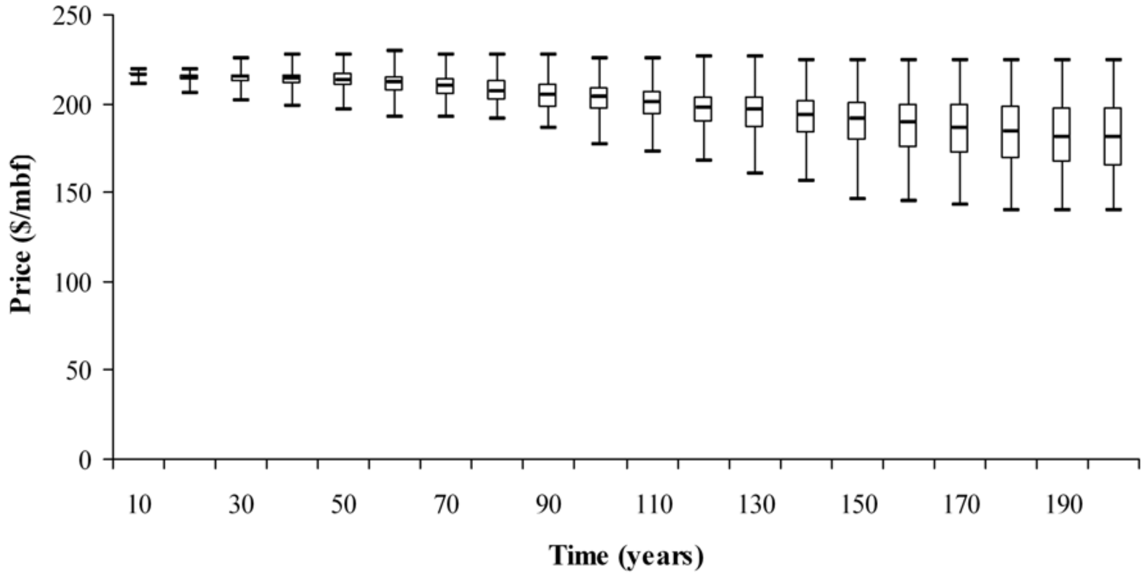

Figure 4.10. Annual market price for lumber

The median, minimum, maximum and quartile values for lumber prices are a horizontal mirror image of the corresponding values in the traded volume graph (Figure 4.9). This close tracking between volumes and price suggests that trades are occurring on the market demand curve, and that mills are successful in adjusting profit expectations to changing market conditions. The average stumpage rate that is being paid to the resource owner is shown in Figure 4.11.

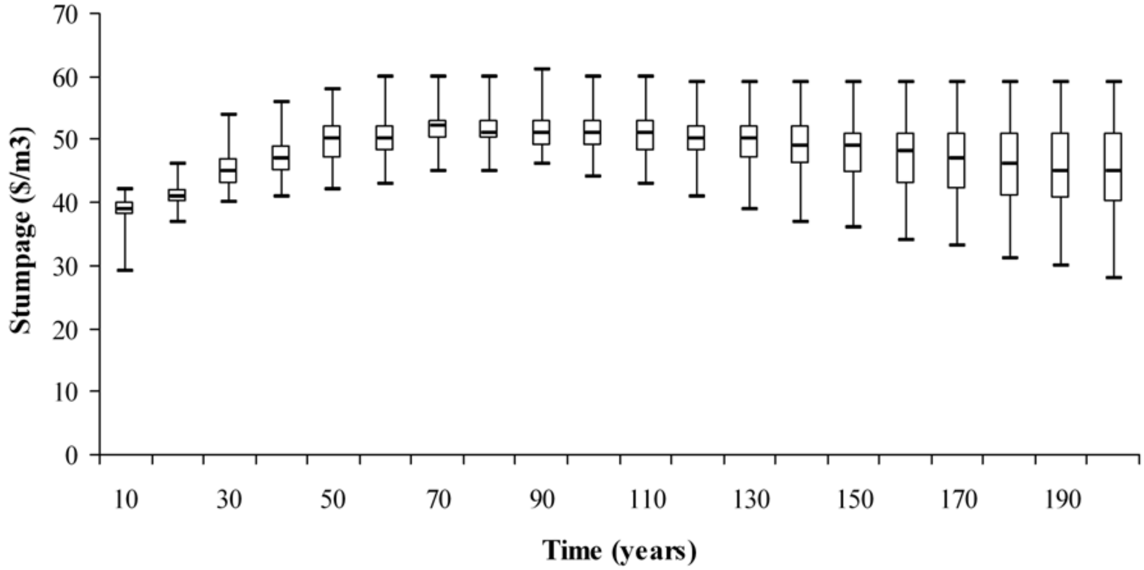

Figure 4.11. Annual stumpage rates

While lumber prices remain relatively flat during the first 70 years of the simulation, median stumpage rates increase by more than 40% from 39 $/m^3 to 52 $/m^3. At the same time, the median annual harvest volume increases from 1.9 million m^3 to 2.1 million m^3 before once again decreasing to 1.7 million m^3 (Figure 4.12).

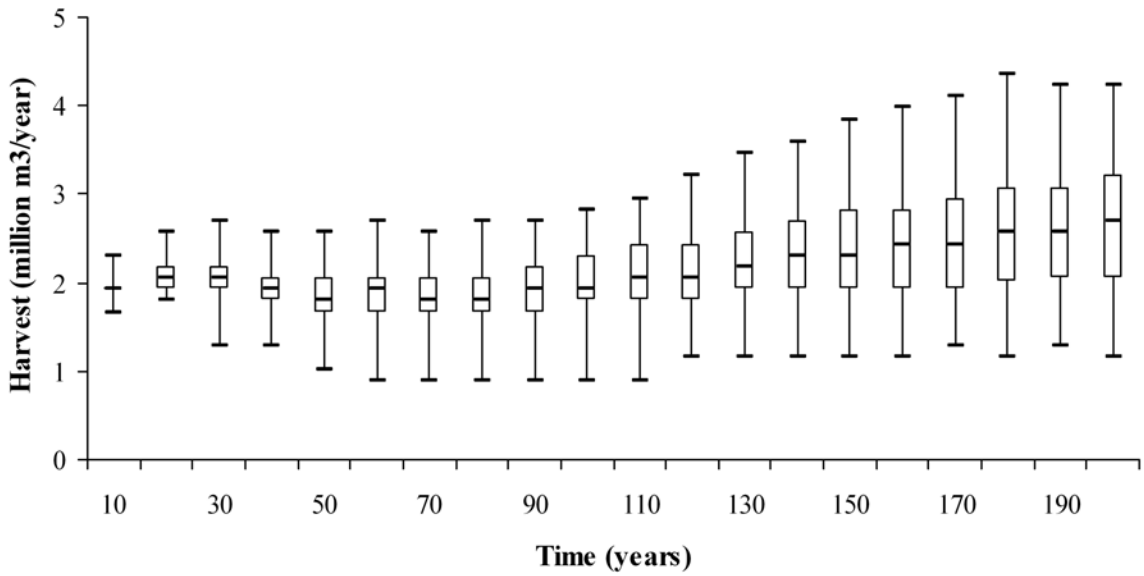

Figure 4.12. Annual harvest volume

Combining these observations on market price, traded volume, stumpage rates, and roundwood harvest with information on industry cost structure (Figure 4.7) provides an indication of the distribution of market power between the forest products industry and the owner of the timber inventory. Over the first 70 years of the simulation mills are getting more efficient, producing an increasing volume of lumber from a decreasing amount of roundwood. Lumber prices remain stable, and mills realize a substantial reduction in their production costs. However, mills are not able to capture the full value of these efficiency gains due to the competitive bidding process that is being used in determining stumpage rates. Profit allocation between sawmills and the resource owner is shown in Figure 4.13.

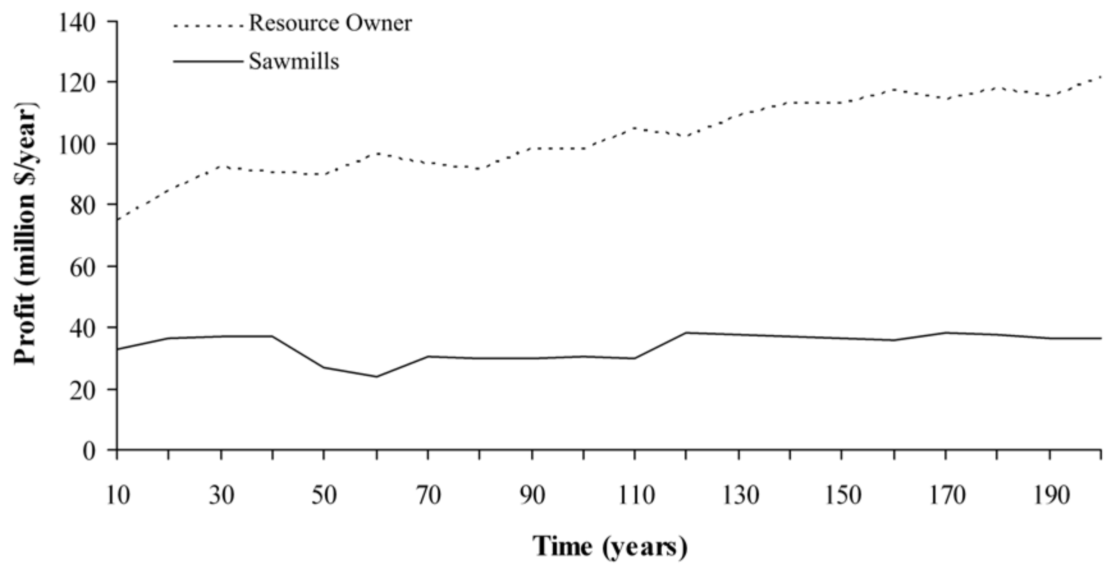

Figure 4.13. Profit allocation between resource owner and sawmills

The profit values in Figure 4.13 are based on median values for production costs, harvest volume, stumpage, and traded volume. Average expenditures on stumpage increase from 75 million $/year to more than 120 million $/year over the course of the simulation. Forest industry profits only increase by about 4 million $/year over the first 20 years of the simulation before entering a prolonged slump between years 40 and 110. Since the number of active firms remains relatively constant from year 70 onwards, the total profit per firm increases slightly over the second half of the simulation.

4.5 Conclusion

The agent-based forest sector model presented in this paper is capable of modeling agent differentiation and industry structure development. Decisions in the CAMBIUM model are based on agents' individual measures of innovativeness and risk aversion, expected payoffs and experiences with the different strategy options, and competition with other agents for raw material inputs and profits in a competitive lumber market. Agent interactions occur both directly and indirectly. Direct interactions play a major role in modeling the decision making process using the evolutionary learning algorithm EWA-Lite, where changes in other agents' behavior are observed to assess the stability of economic conditions. Indirect interactions occur in the allocation of roundwood, market trading of lumber, through market signals in forming price expectations for lumber products, as well as during the stumpage bidding process with the highest bidder determining base rates for the current period.

At the current stage of development, the CAMBIUM model provides a useful framework for studying industry interactions and strategic decision making in an environment that is characterized by continuously changing conditions in both the underlying resource inventory and finished product markets. The frequency and scale of these environmental changes will determine for how long companies continue to adjust to a specific impulse before having to address new challenges.

The modular setup of the model allows for further developments and adaptations of this model to specific research questions. Potential areas of research include studying the effects of unbalanced age class structures, product differentiation for dimensional lumber products, the inclusion of quality indicators in growth and yield modeling, further differentiation of business strategy options, and the introduction of different manufacturing technology choices. Future research should also include econometric analysis, for example of potential functional relationships between profitability, strategic choices, and an agent's innovativeness.. Identifying functional relationships would make it possible to more closely calibrate this model to specific regional industries and assess the performance of potential industry configurations.

The market module described in this model is relatively simple, consisting mainly of price intercept and demand elasticity. Currently demand is modeled as a linear function. More sophisticated models of demand could be integrated as data becomes available. Given estimates of cross-product elasticities, finished product markets can be modeled as a series of market modules, where the supply of a trading unit to one of these submarkets would in turn affect the potential benefits of trading in other markets as well. Ultimately, it will also be possible to disaggregate the market module from a single function into a number of interdependent ‘purchasing agents’, with market demand becoming an emergent property.

Any attempt at understanding how companies pursue different markets and manufacturing strategies leads directly to the need to better understand timber quality and grade in the forest. Timber quality information is an important factor in log merchandizing, and in determining the appropriate manufacturing strategy to obtain maximum value from each log. In the absence of differentiating information on wood quality, manufacturing strategies cannot be selected for matching specific roundwood resources to specific markets. However, with differentiation on all three levels, it would be possible to achieve a very high degree of information integration throughout harvesting, manufacturing, and product marketing.

4.6 References

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5 Modeling the Effect of Changing Market Conditions on Mountain Pine Beetle Salvage Harvesting in British Columbia[10]

5.1 Introduction

The forest products industry in British Columbia is facing an uncertain future. The mountain pine beetle outbreak in the interior of the province has affected mature lodgepole pine inventories at an unprecedented scale. To date, the epidemic has affected more than 700 million m^3 and over 13.5 million hectares (B.C. Ministry of Forests and Range 2008a). These killed or damaged stands are deteriorating rapidly, creating pressure to recover economic value from these stands through intensive salvage harvesting (B.C. Ministry of Forests and Range 2006; Watson 2006).

The timber supply impacts of the mountain pine beetle infestation have been relatively well documented (Timberline Forest Inventory Consultants Ltd. 2006; Walton et al. 2007), while economic research has mainly focused on optimizing value recovery from damaged wood (Wagner et al. 2006). Examples include studies on pulping (Hu et al. 2007), lumber recovery (Orbay and Goudie 2006; Chow and Obermajer 2007), and bioenergy production (Kumar et al. 2008). In contrast, only limited information is available on the impact of the mountain pine beetle on the provincial economy as a whole, and on the economic viability and performance of the forest sector in particular. Patriquin et al. (2007) employ a computable general equilibrium [CGE] approach to estimate the sensitivity of regional economies in the interior of British Columbia to changes in forest

[10] A version of this chapter has been submitted for publication. Schwab, O., T. Maness, G. Bull, and D. Roberts. *Modeling the effects of changing market conditions on mountain pine beetle salvage harvesting in British Columbia.* 44 pp.

sector exports. Using the same methodological approach, Patriquin et al. (2008) conclude that wood sharing agreements across regions may be able to reduce the impact of mountain pine beetle related timber supply shortages. This static method provides information on the expected maximum extent of changes, but does not address adjustment processes while local economies are in transition.

Agent-based computational economics is a method for developing and exploring economic models as complex and evolving systems. Agent-based models typically focus on interdependencies and feedback loops between microstructures (such as individual agent's production decisions) and macrostructures (such as aggregate market supply). These models decentralize decision making to the agent level, thereby eliminating the need for central coordination mechanisms such as market clearing and perfect rationality (Tesfatsion 2006).

This paper calibrates and applies the dynamic agent-based forest sector model CAMBIUM[11] to current conditions in the British Columbia forest sector. CAMBIUM is designed to generate continuous, location specific information on the interdependencies between resource inventories, product markets, and the primary wood processing sector during adjustment periods following a natural disturbance. The abstract homogenous landbase that formed the foundation for the analysis in Schwab[12] is replaced by a spatial resource inventory model that covers the province of British Columbia with a 256 hectare

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[11] The cambium is a layer of cells that contributes to the growth of both the wood and innermost bark of a tree. The name CAMBIUM was chosen for this agent-based forest sector model to reflect the critical role that forest sector agents play within the interdependent feedback loops between resource inventories and product markets.

[12] Schwab, O. and T. Maness. Modeling structural development in the forest sector with the EWA-Lite algorithm. Chapter 4, pg. 60-93.

resolution[13]. CAMBIUM models the interdependencies and feedback loops between resource inventory dynamics and changing market conditions for finished products using an intermediate layer of autonomously interacting forest industry agents.

The following section provides an overview of the parameters and methods used in modeling forest inventory, product markets, economic agents, and strategic decision making. The model is then applied to assess the effects of the current market downturn in the U.S. forest products market on salvage harvesting of mountain pine beetle affected stands, and on structural changes in the B.C. forest products industry. The final section discusses strengths and limitations of this modeling approach and identifies directions for future research.

5.2 Methods

The model was coded in Java using the Recursive Porous Agent Simulation Toolkit [Repast J] program libraries (North et al. 2006; ROAD 2008). This modeling environment is able to interface with geographical information systems and provides for easy cross-platform transferability of model applications.

The forest sector is modeled as a group of spatially located autonomous economic agents that interact and compete for raw material inputs and profits from finished product sales. Sector structures evolve based on interactions within the boundaries defined by the resource inventory, harvest restrictions, and market conditions. Strategic decision processes are modeled using an implementation of the self-tuning experience weighted attraction learning algorithm EWA-Lite (Ho et al. 2001). This algorithm allows agents to

[13] Schwab, O. and T. Maness. Building spatial forest inventories from aggregated data. Chapter 2, pg. 16-35.

respond to changes in their environment by switching between reinforcement learning, where past experiences are assumed to be a good predictor of future conditions, to belief learning, where past experiences are discounted in favor of expected benefits.

5.2.1 Data Sources

The resource inventory was modeled as a lattice grid of 256 hectare tiles, covering the entire province of British Columbia. There are approximately 370 000 cells in total. Since no provincial-level spatial forest inventory dataset was available, aggregated forest inventory data from the timber supply review process was projected onto this lattice using an inventory dispersal algorithm[14]. This dispersal process generates a dataset where each tile in the grid is described by a specific combination of primary and secondary tree species, site quality, stand age, and growth region. This parameter set makes it possible to simulate forest growth using the growth and yield model VDYP (B.C. Ministry of Forests and Range 2007a). For each tile, information on the severity and timing of mountain pine beetle infestations was queried from the BCMPB.v4 model dataset (B.C. Ministry of Forests and Range 2008b). This dataset covers the timeframe from 2007 to 2026, and provided annual data on the cumulative percentage of pine killed by the mountain pine beetle.

Once the pine component of a stand has been killed by the mountain pine beetle, the value of the standing pine timber begins to deteriorate as staining fungi colonize the sapwood and drying cracks develop throughout the log (Trent et al. 2006; Chow and Obermajer 2007). The duration of this commercial shelflife largely depends on local site

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[14] Schwab, O. and T. Maness. Building spatial forest inventories from aggregated information. Chapter 2, pg. 16-35.

characteristics and ranges from approximately 5 years on wet sites to 15 years on dry sites. The relative distribution of wet, medium, and dry sites was collected for 18 timber supply areas in the interior of British Columbia (Timberline Forest Inventory Consultants Ltd. 2006).

The timber supply review documents for each timber supply area [TSA] and tree farm license [TFL] were reviewed to collect information on annual allowable cut [AAC] determinations and temporary AAC uplifts for mountain pine beetle salvage harvesting. The annual allowable cut is determined by the province's chief forester based on estimates of current and future timber supply, as well as ecological and social considerations. The AAC is generally set to provide a continuous, sustainable volumetric flow of fibre from a TSA or TFL (B.C. Ministry of Forests and Range 1996; Rayner 2001). Although these documents continue to be updated periodically, a common cutoff date of July 31, 2007 was used for this analysis. The most recent documents can be obtained online from the B.C. Ministry of Forests (2008c; 2008d).

Information on the current structure of the forest products sector was obtained from the 2005 primary wood processing sector survey published by the BC Ministry of Forests and Range (2008e). This dataset contains information on the processing capacity and location for 22 pulpmills, 37 panelmills, and 194 sawmills. The capacity distribution for these mills is shown in Table 5.1.

Table 5.1. Current capacity distribution

	Number of Mills		
	<33% Cumulative Capacity	33-67 % Cumulative Capacity	>67% Cumulative Capacity
Lumber	143	31	20
Panel	20	11	6
Pulp	12	6	4

Additional information on working capital per unit of output, product recovery factor, fixed and variable production costs, as well as decision patterns for both the agent itself and its competitors was needed for modeling production and decision making processes. Since no empirical data was publicly available, the additional parameters were obtained from repeated simulations of industry differentiation processes using this agent-based forest sector model with an abstract landscape and randomly distributed normal forest inventory[15]. The abstract uniform landbase was used to ensure that industry differentiation was driven by interagent competition rather than resource endowments. The processes used in initializing and calibrating the economic agents for this model are shown in Figure 5.1.

[15] Schwab, O. and T. Maness. Modeling structural development in the forest sector using the EWA-Lite algorithm. Chapter 4, pg. 60-93.

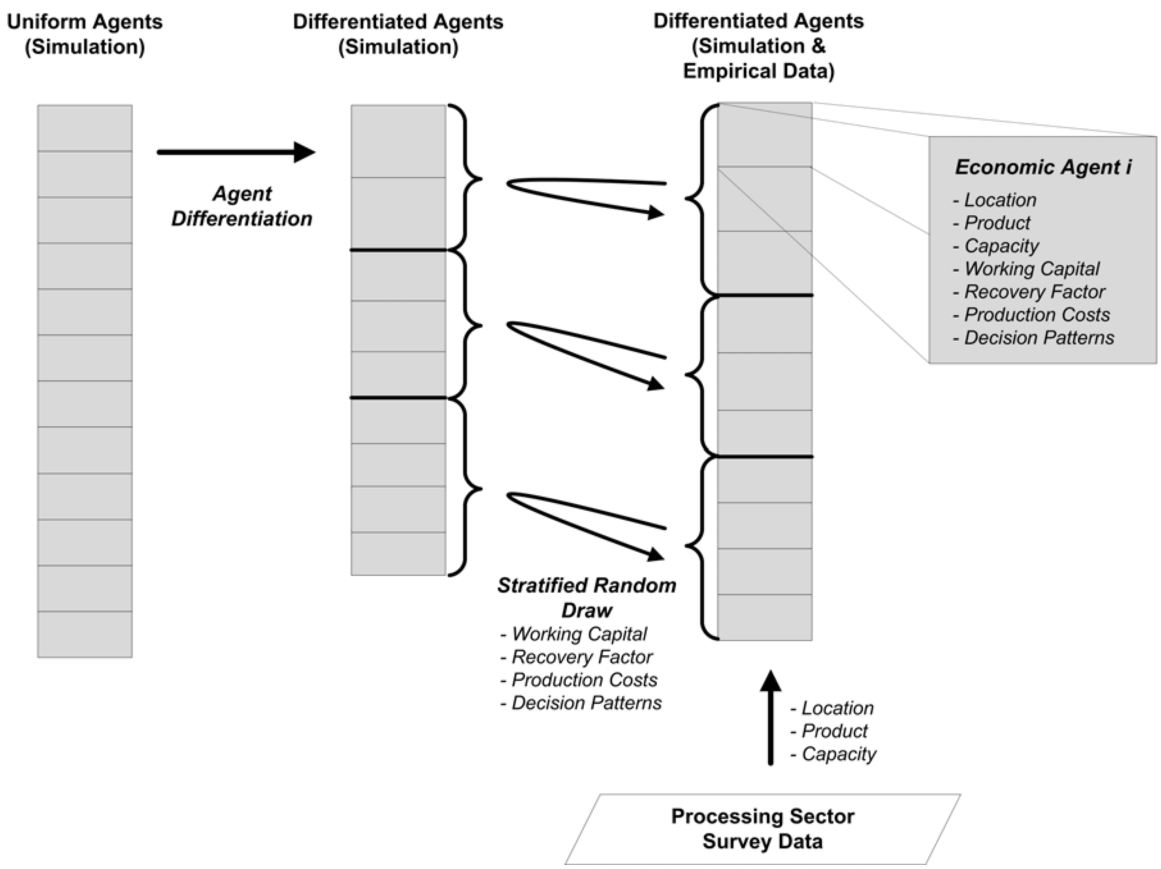

Figure 5.1. Initialization and calibration of economic agents

Competition among uniform agents on a homogenous landscape results in capacity differentiation and industry concentration processes as agents adopt different competitive strategies. This differentiation process is shown on the left of Figure 5.1. Each grey rectangle represents an economic agent, with the height of the rectangle indicating the agent's total production capacity. The resulting industry structures are consistent with the current capacity distribution in the British Columbia forest products sector (B.C. Ministry of Forests and Range 2008e)[16]. At the end of the simulated differentiation process, the remaining agents were sorted according to increasing capacity and assigned to three capacity groups: small producers (<= 33% of cumulative capacity), medium producers

[16] Schwab, O. and T. Maness. Modeling structural development in the forest sector with the EWA-Lite algorithm. Chapter 4, pg. 60-93.

(33 – 67% of cumulative capacity), and large producers (> 67% of cumulative capacity). The specific parameter combination of working capital, product recovery factor, production costs, and decision pattern was then recorded as a blueprint for initializing spatially located economic agents.

Stratification based on production capacity was also applied to the primary wood processing facilities contained in the 2005 sector survey (Figure 1, third column). For each processing facility, parameter values for working capital per unit of output, product recovery factor, production costs, and decision pattern were obtained by randomly drawing a blueprint from the corresponding capacity group (Figure 1, second and third column). The additional parameters that were obtained from the initialization blueprints serve as default values. It is expected that these default values will be replaced with empirical data in future research projects.

The stratified random drawing procedure ensures that large mills are initialized with default values that were typical for large mills in the simulation experiment, and that small mills received default values typical of smaller manufacturers. Each of these processing facilities was modeled as an autonomous economic agent that was located in the appropriate geographic position on the provincial lattice grid system. Since mill location and capacity were obtained from empirical data, the resulting set of economic agents (Figure 1, third and fourth column) reflects the current structure of the British Columbia forest products sector.

The production cost and product recovery rates of the initialization blueprints were calibrated using industry averages and parameter ranges reported in the literature (Table 5.2).

Table 5.2. Production costs and product recovery rates

	Roundwood Requirements	Production Costs	Source
Lumber	3.32 – 5.32 m^3/mbf	165 $/mbf	Haynes (2003), Schuler (2005)
Panel	1.76 – 2.01 m^3/1000 sq ft	230 $/1000 sq ft	Haynes (2003), Montrey and Utterback (1990)
Pulp	2.43 – 5.66 m^3/ton	220 $/ton	Cambers and Borralho (1999), Smook (2002), Haynes (2003),

The lattice grid system with the year 2007 forest inventory and primary wood processing facilities is shown in Figure 5.2. The province of British Columbia is represented using approximately 370 000 tiles of 256 hectares each.

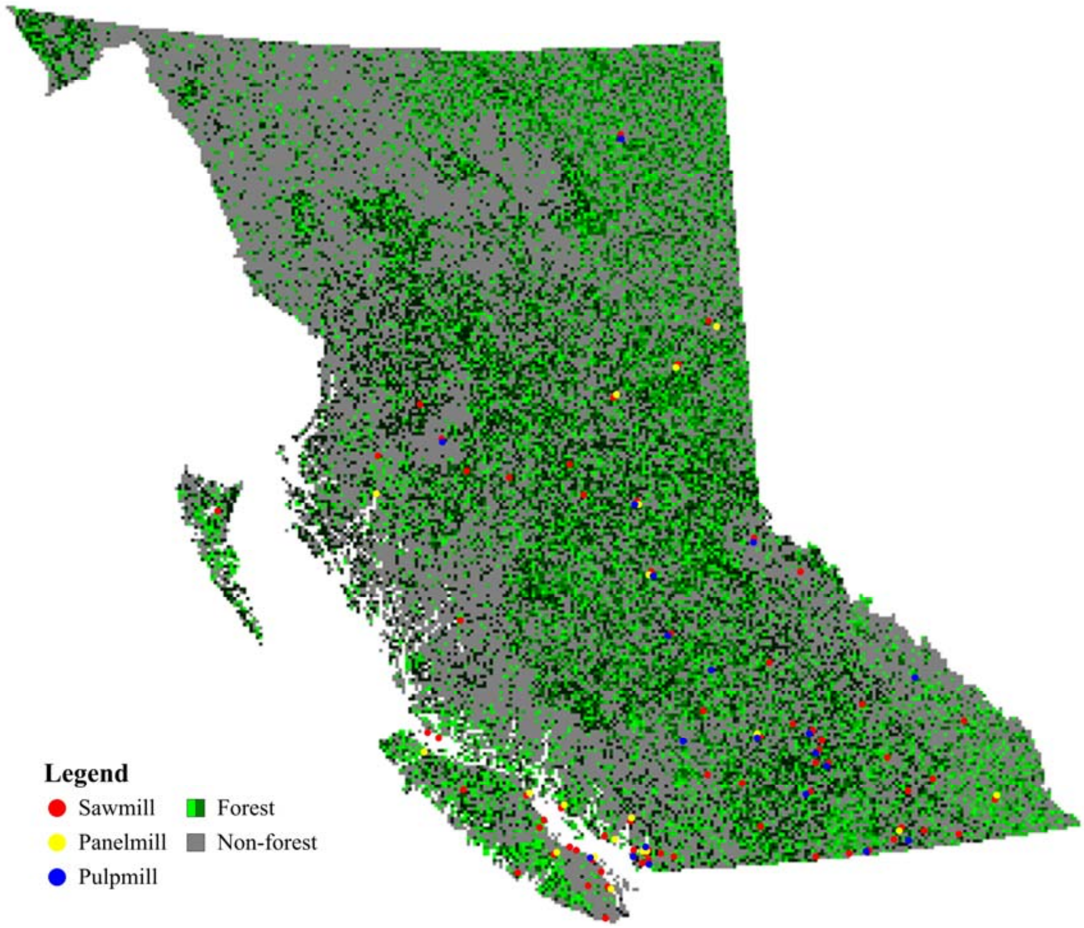

Figure 5.2. Provincial overview of forest inventory and primary processing facilities

5.2.2 Model Structure

This agent-based forest sector model consists of three major modules: a resource inventory module, an economic agent module, and a market module. Figure 5.3 provides an overview of the linkages and information flows between the different model components.

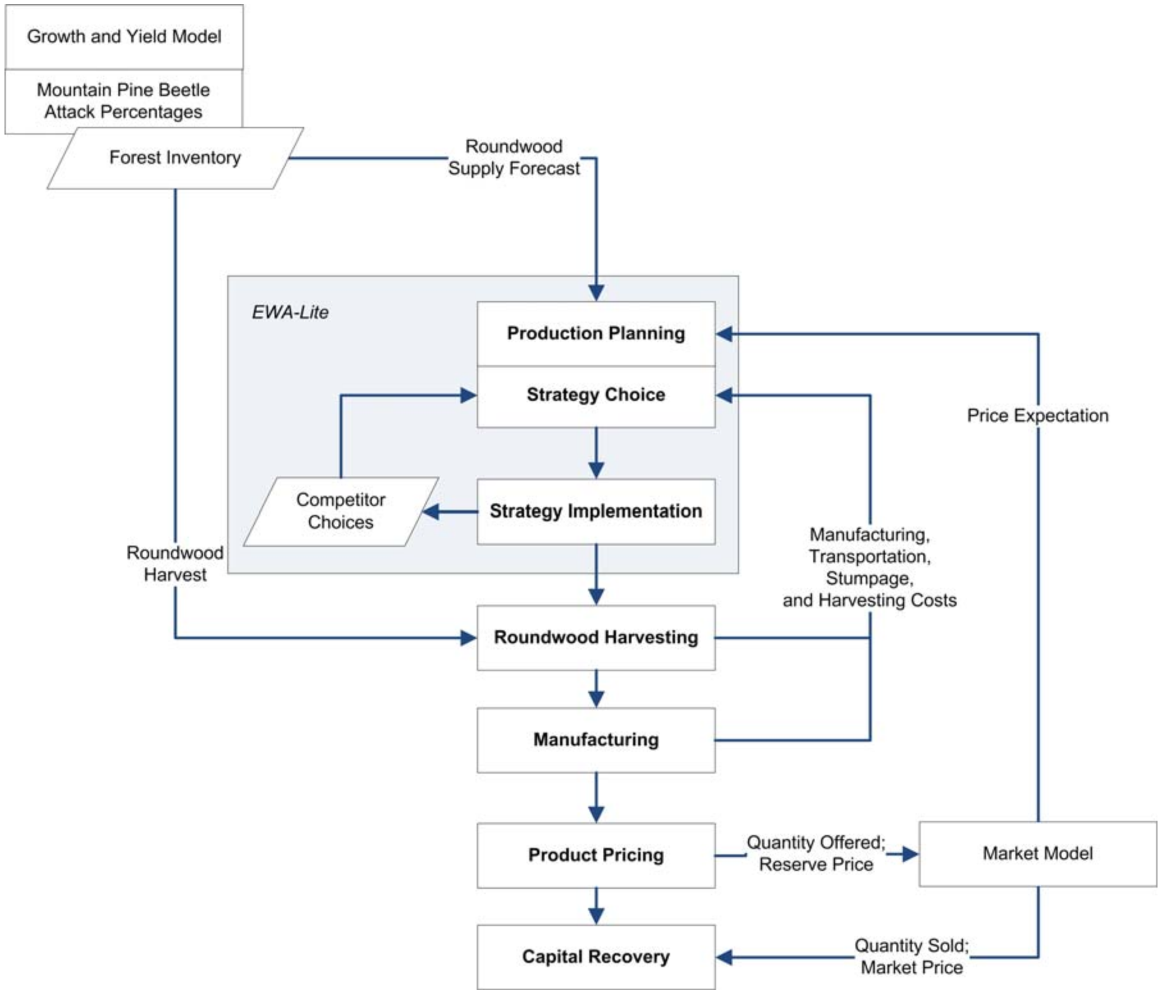

Figure 5.3. CAMBIUM model structure

For each simulation year, the model proceeds from growth and yield modeling (Figure 5.3, left column), over production planning, harvesting, and manufacturing (Figure 5.3, centre column), to product pricing and market trading (Figure 5.3, centre and right column). The next four sections will describe these model steps in detail.

5.2.2.1 Forest Growth and Mountain Pine Beetle Impacts

At the beginning of a time step (model year), the resource inventory for each tile is updated. If the current cumulative mountain pine beetle kill percentage for a tile exceeds zero, the pine portion of the tile is marked as 'damaged' and assigned a commercial shelflife using a random draw from the shelflife distribution associated with the surrounding TSA or TFL. The non-pine component of the tile will continue to grow. As trees deteriorate, the development of drying cracks decreases the merchantable volume within the affected stand. The merchantable volume degradation of pine beetle killed stands is modeled as a stepwise process (Figure 5.4).

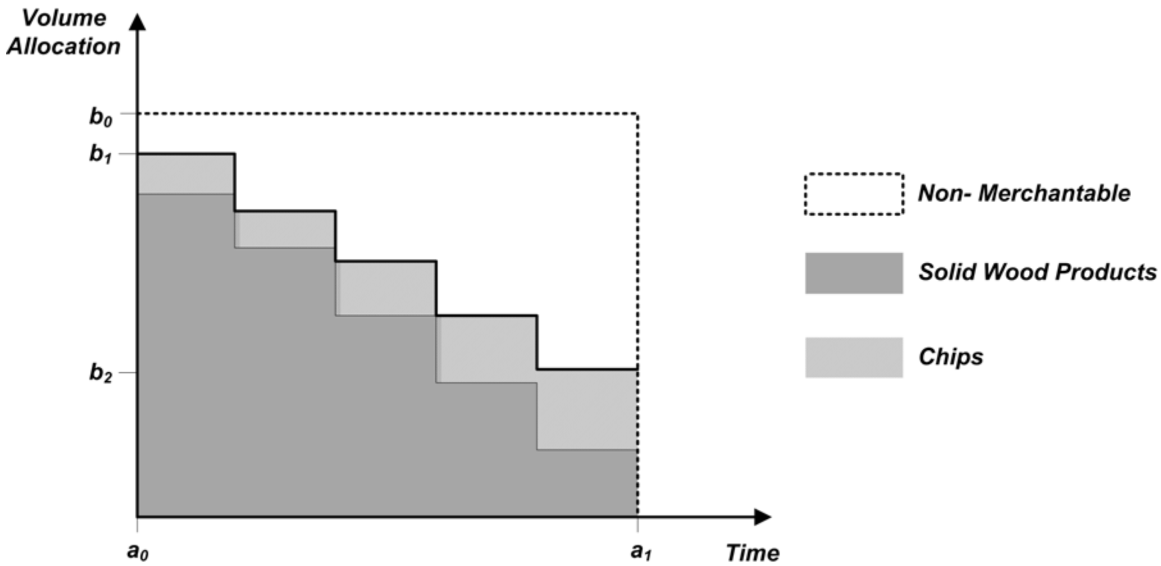

Figure 5.4. Volume allocation for pulp and solid wood products production as a function of shelflife for mountain pine beetle killed stands

The merchantable volume degradation occurs within user-defined limits. Default values for the maximum merchantable volume (b_1) were obtained from VDYP yield curves. Minimum merchantable volume (b_2) default values were set as 40% of b_2. Over the course of the commercial shelflife (a_0 - a_1), the merchantable stand volume decreases from the initial value (b_1) to the minimum value (b_2) in a stepwise fashion. The allocation between solid wood products and chips depends on the product recovery factor and product type for each individual mill. In general, the recovery efficiency for solid wood products decreases as the roundwood deteriorates, thereby increasing the volume of chips that becomes available to pulp processors. If the stand has not been harvested by the end of its commercial shelflife, it is regenerated using the original species distribution. The roundwood volume of stands that are part of the timber harvesting landbase is recorded as a non-salvaged loss. As the final step in the resource inventory module, each tile increments its age and updates timber volumes by interpolating volumes from the associated yield curves. Overmature stands are exposed to random mortality based on a user-defined attrition rate and threshold age (10% mortality, 150 years minimum age).

5.2.2.2 Production Planning and Strategic Investment Choice

Following this initial growth step, the model proceeds through a sequence of planning and implementation steps within the economic agent module (Figure 5.3, centre column). If an agent's working capital falls below zero, the agent becomes insolvent and exits the simulation.

Production planning and strategy choice are modeled as an integrated process using probabilistic decision making based on the experience weighted attraction learning algorithm (Ho et al. 2001). In each period, agents choose from three investment options: endogenous growth through capacity expansion, improving product recovery through process innovation, and maintaining current operations by periodically replacing outdated equipment. These three strategies were found to be sufficient for modeling agent differentiation[17].

Each agent determines current production targets based on production capacity, capital and roundwood availability, production costs, expected market prices, and the expected outcomes of implementing the three available investment options. The choice of investment option is dependent on the perceived stability of the business environment.

[17] Schwab, O. and T. Maness. Modeling structural development in the forest sector with the EWA-Lite algorithm. Chapter 4, pg. 60-93.

The environment is assumed to be stable when the investment options chosen by competitors remain unchanged from period to period. In this case, agents employ reinforcement learning and favor strategies that have provided positive returns in the past. In cases where competitors have changed their choices in recent periods, agents employ belief learning and determine choice probabilities almost exclusively based on the expected payoff of each investment option.

5.2.2.3 Harvest Scheduling, Harvest Allocation, and Stumpage System

Stumpage charges are determined using a bidding process model of the British Columbia market pricing system (B.C. Ministry of Forests and Range 2007b; 2007c). To establish a base rate, each agent submits a maximum bid based on individual cost structure and profit targets, as well as expected and historical market prices for finished products. The base stumpage rate for the current period is then set to the weighted average value of the current maximum bid and base rate values for the previous 4 years. Low quality salvage stands are valued at a minimum stumpage rate of $0.25/m^3 (B.C. Ministry of Forests and Range 2008f). For each harvested tile, the resource owner receives stumpage revenues that are calculated as the product of the tile's roundwood volume and the transportation cost adjusted stumpage base rate.

All tiles that meet minimum harvest age requirements are queued in a harvest eligibility list. If salvage harvesting is permitted, all tiles with mountain pine beetle damage are added to this eligibility list as well. Harvest allocation occurs based on minimum transportation distance; it does not differentiate between salvage and non-salvage tiles. Allocation begins with the random selection of a solid wood processing mill (sawmill or panel mill). The harvest eligibility list is then sorted with ascending distance relative to the location of this economic agent. This agent then searches through the harvest eligibility list until it identifies a suitable tile. Tiles can be harvested if their volume does not exceed the remaining annual allowable cut for the TSA or TFL it belongs to, and if it is possible to deliver the wood to the agent's location at a reasonable cost. For each agent, the cost limit for roundwood transportation costs is calculated as the maximum amount that still allows the agent to break even under current processing cost and market conditions. Transportation cost limits are updated during the planning stage at the beginning of each time step. If the roundwood volume of a harvested tile exceeds the remaining demand of the economic agent, the remainder is allocated to the next closest agent. This sequence of mill selection and tile selection is repeated until either no more tiles remain in the harvest eligibility list, or until the roundwood demand of all solid wood processors has been met. This repeated random selection process ensures that no economic agent is favored during harvest allocation.

Once a solid wood processor obtains roundwood from a harvested tile, it calculates the volume of chips that will result from processing (Figure 5.4). This chip volume is then traded at cost to the closest pulpmill. Once roundwood volumes have been allocated, each economic agent incurs stumpage costs, as well as costs for harvesting and transporting roundwood to the mill gate. During the manufacturing process roundwood is converted into finished products based on each agent's product recovery factor. Variable production costs increase by a user-defined percentage for processing mountain-pine beetle damaged wood (default: 15%). Remaining roundwood inventories can be used in subsequent periods. Fixed and variable production costs are deducted from the agent's working capital.

5.2.2.4 Product Pricing and Market Trading

At the end of the manufacturing step, agents define a reserve price for the current production volume. Their reserve price is based on their total production cost and profit target, as well as expected and observed market prices. Depending on observed and realized market prices this target profit can vary in user-specified increments between an agent-specific minimum profit and infinity. Agents act conservatively in their pricing behavior to avoid being priced out of the market during any given period. The lowest price they will accept for products manufactured during the current period is one that just covers their cost and a minimum profit. Unsold inventory from previous production periods may be sold at a loss once reserve prices have been adjusted accordingly. This flexible pricing structure allows agents to capture additional economic rent during favorable market conditions, while being able to adjust expectations downwards if price competition develops.

During this pricing process, unsold inventory from previous periods is discounted by a user-defined percentage and also offered on the market. Trading units are defined by an owner (the producing agent), a product category, a reserve price and a quantity offered.

The final component of the forest sector model is the market module. Market trading occurs once all agents have submitted their trading units. These trading units are sorted with ascending reserve price, and matched to the market demand. For each of the three product categories (lumber, panel products, and pulp), market demand is modeled as a continuous function of demand elasticity and price. For any given point in time, the current market demand curve can be described by its elasticity and a single point on the demand curve. The market demand curves can therefore be shifted along a user defined trajectory by defining a sequence of these parameter combinations (quantity, price, elasticity) for each of the product markets. Default settings are summarized in Table 5.3:

Table 5.3. Default settings for modeling market demand

	Price	Quantity	Elasticity
Lumber	350 $/mbf	17 million mbf	-0.5
Panel	360 $/1,000 sq ft	6,7 million sq ft	-0.5
Pulp	800 $/ton	7.5 million ton	-0.5
Source	Kosman and Heartwood (2008), PaperAge (2008), Random Lengths (2008)	B.C. Ministry of Forests and Range (2008b)	Abt and Ahn (2003)

At the end of the market modeling step the owner realizes a gross revenue for each traded unit defined by the current market price and the volume sold. Unsold units are returned and will be offered at a discount in subsequent periods.

The sequence of steps outlined in Figure 5.3 is executed for each time step during the simulation run. Neither the Repast J simulation toolkit nor the forest sector model itself impose limitations on the time horizon of the analysis. Modeling up to 350 autonomous economic agents, three product markets, and a resource inventories consisting of 370 000 tiles resulted in processing speeds of approximately 15 second per simulation year.

Figure 5.5 shows a snapshot of the CAMBIUM model interface at the end of a 150 year simulation run.

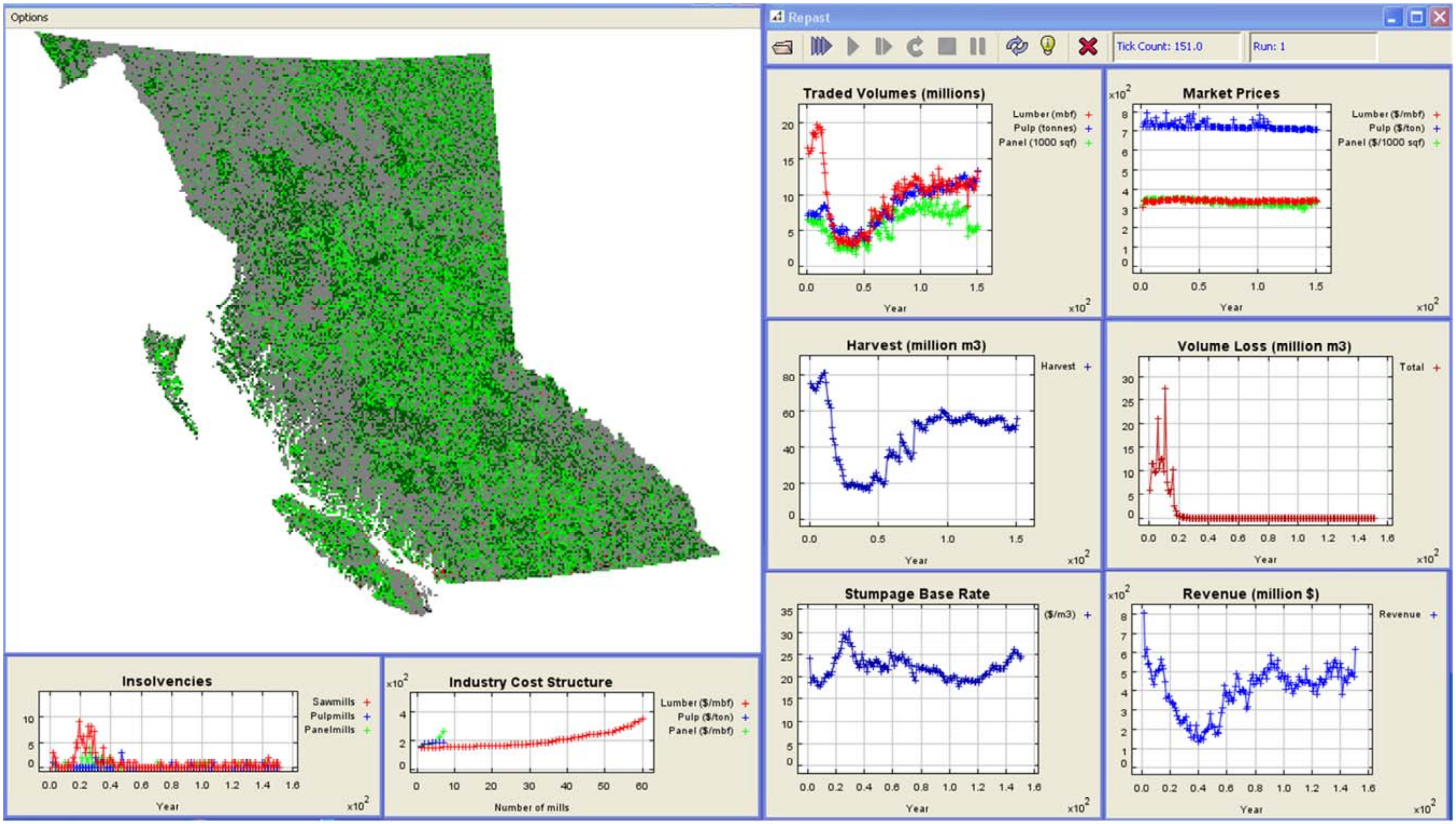

Figure 5.5. CAMBIUM model interface at the end of a 150 year simulation run

The interface components belong to two distinct groups. The first group consists of area overview and industry cost structure. It provides continuously updated snapshots of current conditions during the simulation run. The display window in the top left corner of Figure 5 shows the model area as a lattice network of tiles in a grid pattern. Forested areas are shown in green, with lighter shades indicating young stands and darker shades indicating older stands. Non-forested areas are shown in grey, and mill locations are indicated by red tiles. The second grouping consists of traded volumes, market prices, harvest volume, volume losses, stumpage rate, stumpage revenue, and insolvencies. This group tracks parameters of interest over the entire simulation run. The use of time as the common x-axis makes it possible to identify phenomena that may have a causal relationship.

Subsequent sections of this paper will present the application of the CAMBIUM model to assessing the effects of the current downturn in the U.S. forest products market on salvage harvesting, as well structural changes in the British Columbia forest products industry.

5.2.3 Scenario Analysis

Depending on the scale of the natural disturbance, salvage harvesting can exacerbate both short-run and long-run effects in regional roundwood markets. Short-run price reductions in stumpage markets and increased long-run values for non-damaged stands have been documented following hurricane damages (Prestemon and Holmes 2000; 2004) and infestations of the southern pine beetle (Holmes 1991). The number of U.S. housing starts has fallen drastically over the last two years, indicating a potentially prolonged downturn in British Columbia's main export market for finished wood products (Blackstone 2008).

For the first scenario (baseline), prices for finished forest products are modeled at pre-recession levels for the duration of the 150 year simulation run (Table 5.3). In the second scenario market prices increase from current levels to pre-recession levels in two steps (Table 5.4).

Table 5.4. Price settings for market downturn scenario

Year	Lumber ($/mbf)	Panel ($/1,000 sq ft)	Pulp ($/ton)
2007 – 2016	250	310	800
2017 – 2022	290	295	800
2022 - 2156	350	360	800
Source	Kosman and Heartwood (2008), Random Lengths (2008)	Kosman and Heartwood (2008), Random Lengths (2008)	PaperAge (2008)

In both scenarios, maximum volumes for regular and salvage harvesting were set for each TSA and TFL using information obtained from the provincial timber supply review process. The long simulation time horizon was chosen to test if the forest products industry would attain a new dynamic equilibrium following the market downturn and mountain pine beetle salvage harvesting. The realization of this long-term equilibrium depends on the timing and scale of disturbances that are exogenous to the CAMBIUM model.

5.3 Results

Approximately 330 million m^3 of standing pine will have been killed or damaged due to the mountain pine beetle infestation between 2007 and 2035. Non-salvaged losses will peak in 2017 at approximately 41 million m^3/year. Secondary peaks occur in 2012 and 2022 at 21 million m^3 and 12 million m^3 respectively. These peaks occurs 7, 12, and 17 years after the area of newly affected stands reached its maximum in 2005 (B.C. Ministry of Forests and Range 2008g). The effect of salvage harvesting and changing market conditions on volume losses is shown in Figure 5.6.

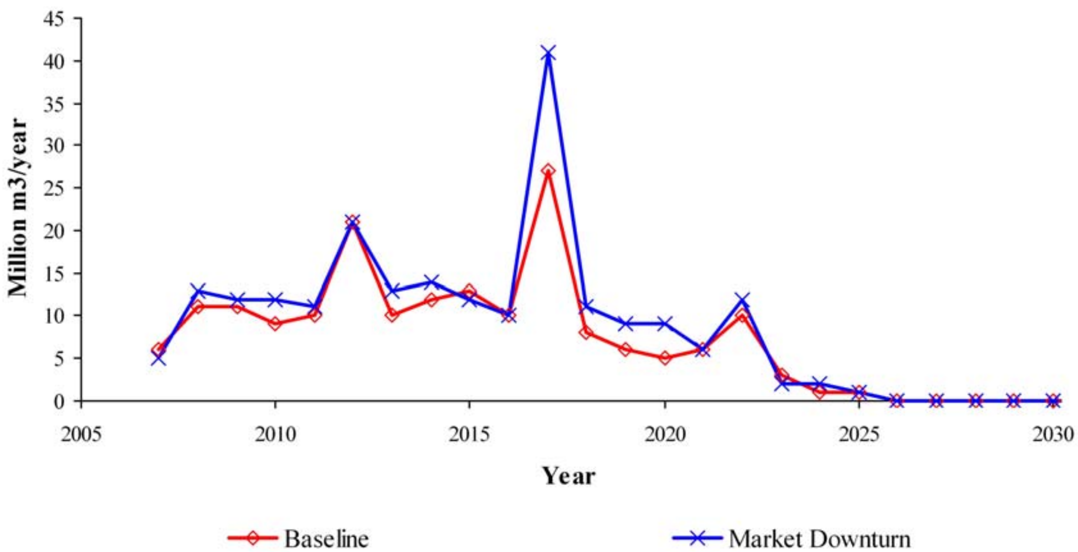

Figure 5.6. Unsalvaged roundwood losses for 2007 to 2030

Under pre-recession market conditions, salvage harvesting will recover approximately 45%, or 148 million m^3 of the total affected volume. Salvage volumes will be significantly lower under market downturn conditions. In this case, only 112 million m^3, or 34% of the affected volume will be recovered. The distribution of roundwood harvest volumes over time is shown in Figure 5.7.

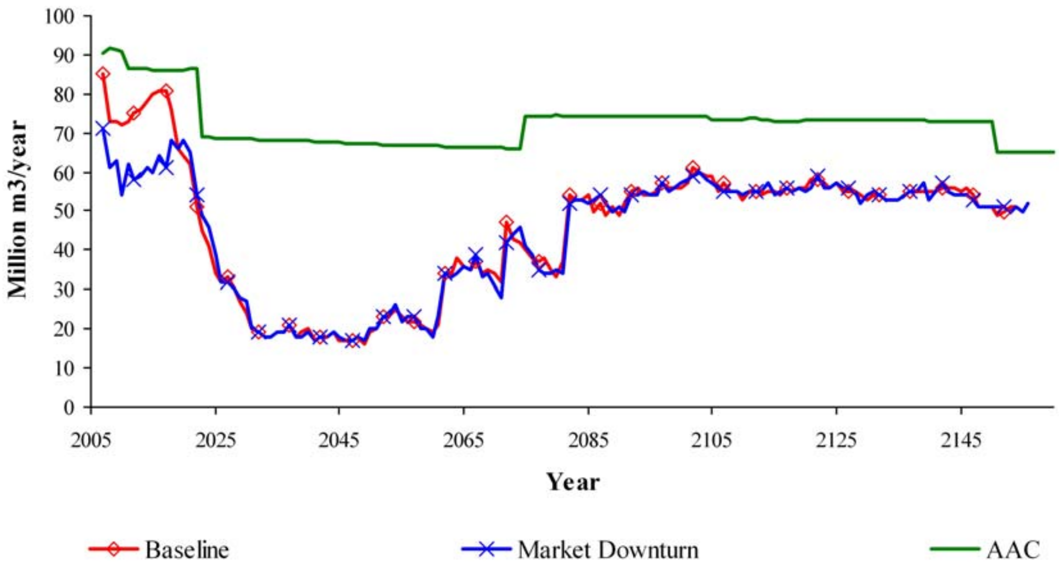

Figure 5.7. Cumulative effects of mountain pine beetle attack and changing market conditions on roundwood harvest

In this figure, AAC levels are shown in green. Under current cost and market assumptions, roundwood harvest levels remain well below AAC levels throughout the entire 150 year simulation horizon. Under baseline market conditions, an average annual harvest of 77 million m^3 can be sustained until 2017. This harvest level conforms well with the approx. 75 million m^3 that have been harvested annually in the province since the 1980s (Pedersen 2003). A market downturn for finished forest products shifts roundwood harvest levels downwards by 20%, or approximately 16 million m^3 of roundwood per year. Roundwood harvests decline drastically over the medium term. This decline begins in 2018 under baseline market conditions, and in 2021 under market downturn conditions. Roundwood harvests are almost identical for both scenarios for the rest of the simulation horizon. The medium-term decline in roundwood harvests persists between 2031 and 2060 and reaches a minimum of approximately 20 million m^3 per year. Harvest levels begin to recover in 2061 and stabilize at an average level of 54 million m^3 per year from 2082 onwards.

Following harvest, the roundwood supply is converted into lumber, pulp, and panel products. These products are offered in the market at a reserve price that reflects each agent's production costs, profit targets, and market forecasts. The annual trade volumes for the lumber market are shown in Figures 5.8.

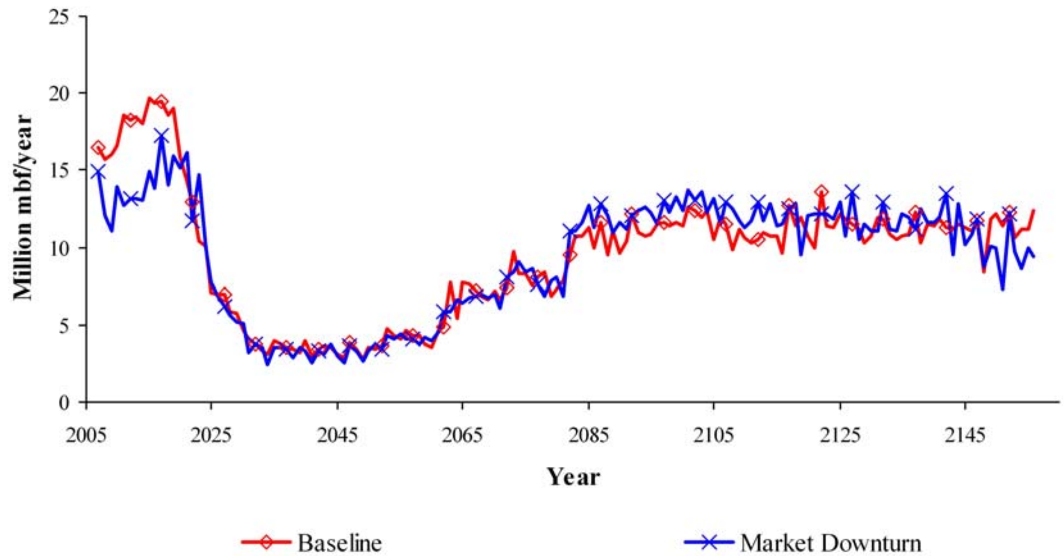

Figure 5.8. Annual trade volume for lumber (2007 – 2156)

Annual trade in lumber follows closely with roundwood harvests (Figure 5.7). Traded lumber volumes increase during the first 10 years of the simulation for both scenarios. Under baseline market conditions, trade volumes peak at 19.7 million mbf/year in 2015. This trade volume is higher than the initial sawmill sector capacity, indicating that some capacity expansion has taken place in order to utilize the overabundance of fibre from salvage harvesting operations. Under market downturn conditions, annual trade in lumber products is reduced by approximately 20%, or 4.2 million mbf/year. Traded lumber volumes do not differ significantly between the two market scenarios from 2021 onwards. The medium-term decrease in lumber trade between 2031 and 2060 reflects the medium-term reduction in roundwood harvests (Figure 5.7). Since market conditions for lumber products do not change during this period, the reduction in lumber processing and trade can be attributed to a timber supply shortage. Lumber trade recovers once more roundwood becomes available from 2060 onwards, and stabilizes at a level of approximately 10.4 million mbf/year. Trade in panel products is somewhat more volatile (Figure 5.9).

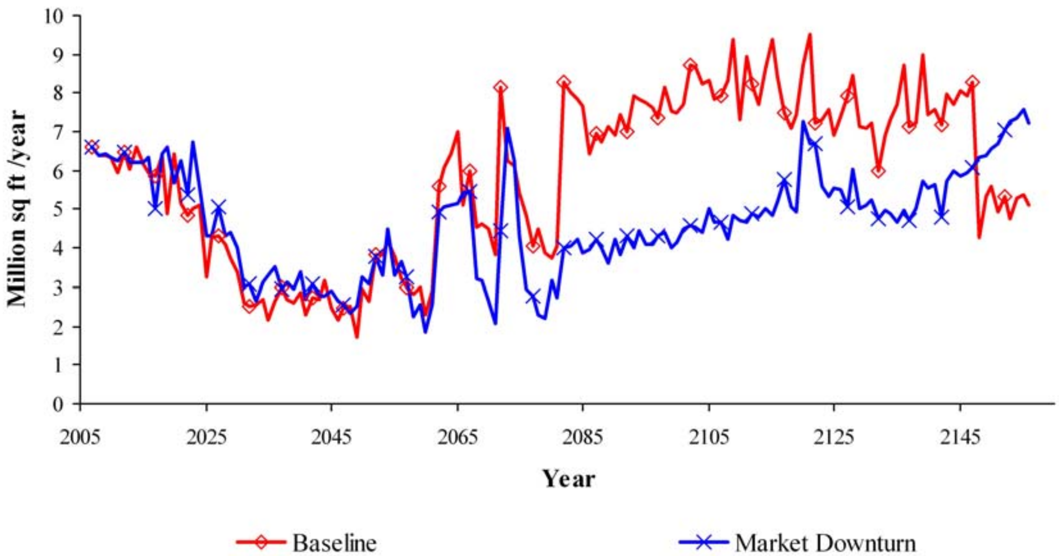

Figure 5.9. Annual trade volume for panel products (2007 to 2156)

Following an initial period of relative stability, trade in panel products declines by approximately 50% from approximately 6.5 million sq ft/year to 3.2 million sq ft/year. Similar to trade in lumber products, this decline coincides with the medium-term timber supply shortage (Figures 5.7 -5.8). It is interesting to note that panel trade volumes is not sensitive to reduced market demand during the initial years of the simulation run. Results from the two scenarios begin to diverge at the end of the timber supply shortage. Between 2061 and 2082, trade in panel products is very volatile, fluctuating by up to 4 million sq ft/year. Trade levels then enter a relatively stable period until 2145, with an average of 7.8 million sq ft/year for the baseline scenario, and 4.9 million sq ft/year for the market downturn scenario. During the last 10 years of the simulation run, panel products trade decreases to 4.2

million sq ft/year for the baseline market scenario, while trade increases to 7.6 million sq ft/year under the market downturn scenario. The corresponding figures for the pulp market are shown in Figure 5.10.

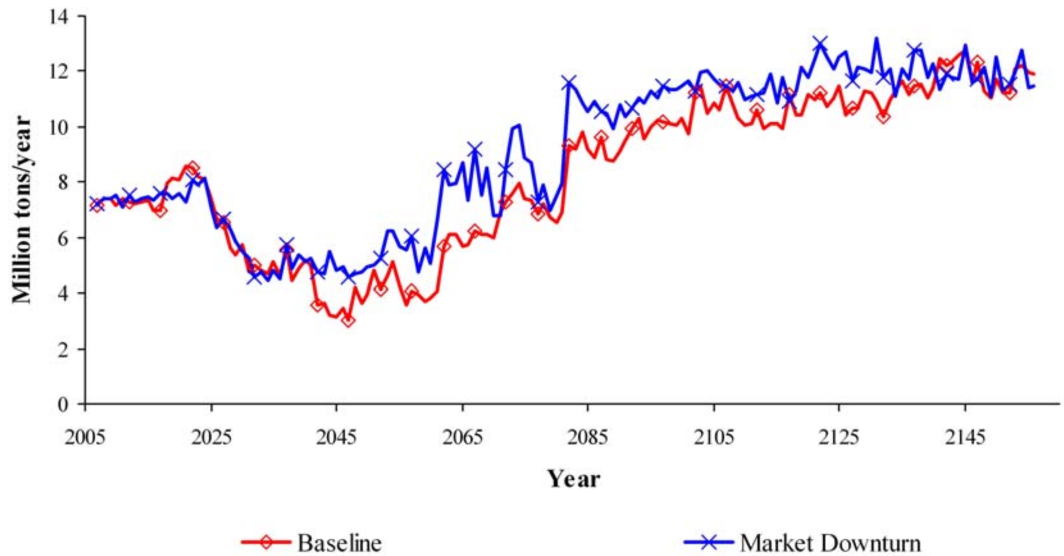

Figure 5.10. Annual trade volume for pulp (2007 – 2156)

Similar to panel products, traded pulp volumes are not sensitive to the reduced demand in the lumber and panel markets during the initial years of the model run. Between 2007 and 2022, the pulp sector is operating at approximately 95% of its 7.5 million tons/year capacity. Pulp trade also reflects the timber supply shortage between 2031 and 2060, declining to a minimum of 3 million tons/year. Over the long term, pulp trade stabilizes at approximately 10.7 million tons/year for the baseline scenario, and 11.6 million tons/year for the market downturn scenario.

Market prices for lumber, panel products, and pulp did not vary significantly between the two scenarios. Annual averages are shown in Figure 5.11 below.

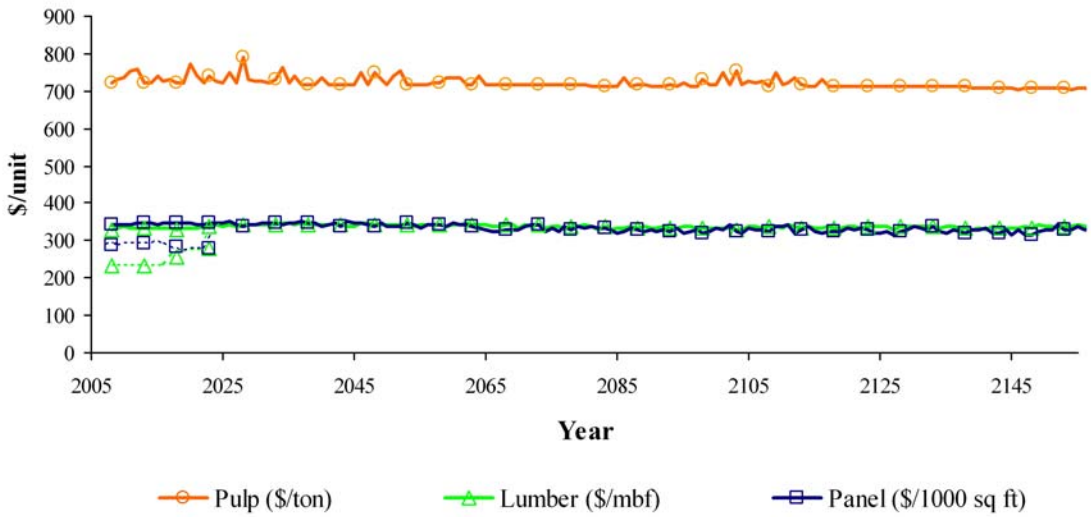

Figure 5.11. Annual market prices for lumber, panel products and pulp (2007-2156)

In all three markets, trade consistently occurred below the respective market demand curves specified in Table 5.3. Pulp prices remain unchanged at approximately 722 $/ton throughout the simulation horizon. Market prices for lumber and panel products temporarily decrease between 2008 and 2025 due to the exogenous shift in market demand for the market downturn scenario (dashed lines). In the case of the lumber market, this price shift results in a corresponding reduction in traded volumes that can be seen in Figure 5.8. Such a volume response was not observed in the panel market (Figure 5.9). However, changing market conditions for finished products did have an effect on stumpage base rates (Figure 5.12).

Figure 5.12. Annual stumpage rates (2007 -2156)

Stumpage rates are primarily sensitive to roundwood availability and finished product prices. For the period of 2007 and 2017, economic agents bid an average of \$16.10 / m^3 for stumpage, approximately 12% or \$ 2.20 /m^3 below bids under baseline market conditions. From 2018 onwards, the increasing scarcity of roundwood overshadows the effect of finished product prices. During the medium-term timber supply shortage, stumpage bids almost double, reaching a peak value of \$ 32 per m^3 in 2025. This increase in stumpage bids reflects the higher value that economic agents now place on roundwood as a relatively scarce resource. However, stumpage rates begin to decline well before the end of the medium-term timber supply shortage, as companies search for opportunities to increase profit margins. The market downturn therefore primarily affects the revenue accruing to the province of British Columbia as the owner of the provincial forest inventory. The cumulative effects of salvage harvesting and fluctuating stumpage rates on provincial revenue are shown in Figure 5.13.

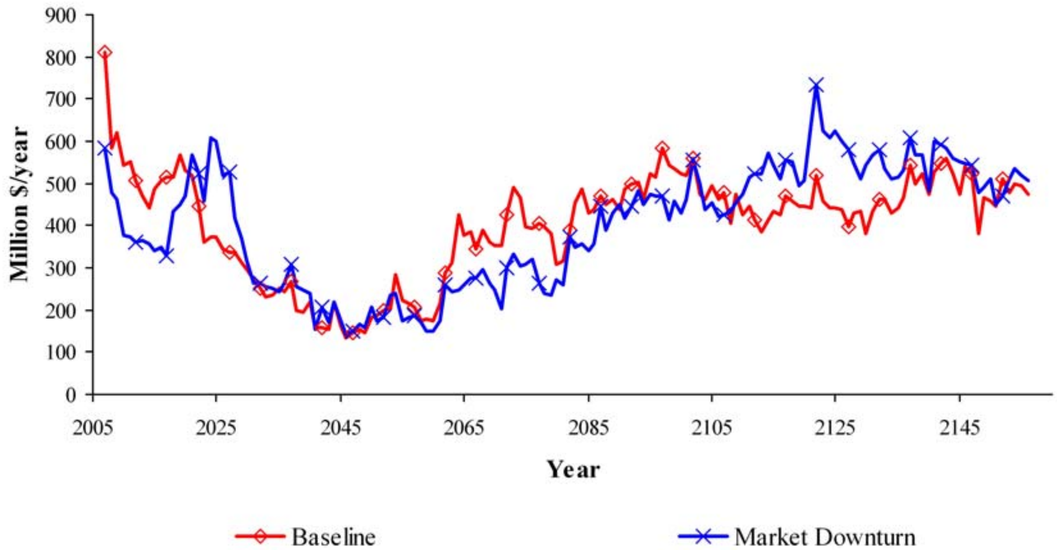

Figure 5.13. Effects of salvage harvesting and market conditions on gross stumpage revenue (2007 – 2156)

In addition to harvest volumes and stumpage rates, gross stumpage revenue can also be affected by the proportion of the harvest originating in mountain-pine beetle affected stands. Low quality salvage stands are valued at a minimum stumpage rate of $\$0.25/m^3$ to compensate for increased processing costs and to encourage salvage harvesting (B.C. Ministry of Forests and Range 2008f). During the first 10 years of the simulation run, the difference in gross stumpage revenues between the two scenarios remains relatively constant at an average 27%, or $150 million per year. This difference can be attributed to the relative changes in stumpage base rate and harvest volume, suggesting that the proportion of salvage harvests remains unchanged between the two scenarios shown in Figures 5.7 to 5.12. Gross stumpage revenues decline to a minimum of $140 million/year during the medium-term timber supply shortage. Over the long term, revenue stabilizes at approximately $490 million/year. Present value (PV) calculations can be used to directly compare scenarios with varying revenue streams over time. Interest rates used for assessing long-term land management issues typically vary in the range of 2 % to 4 % (Breinard et al. 2006; Heinonen and Pukkala 2007; Zhou et al. 2008), with sensitivity analyses extending this range from 1% to 5% (Pearce 2003; Garcial-Gonzalo et al. 2007). The effect of the downturn in the U.S. housing market on the present value of gross stumpage revenues is summarized in Table 5.5.

Table 5.5. Effects of salvage harvesting and market conditions on the present value of gross stumpage revenues

	PV (billion $)		
Interest Rate	**1%**	**3%**	**5%**
Baseline	30.4	12.6	9.0
Market Downturn	29.2	11.6	7.9

For all three interest rates, a market downturn decreases the PV of gross stumpage revenues by approximately $1.1 billion. This constant change in PV is due to the fact that gross stumpage revenues for the two scenarios primarily vary during the early years of the simulation run.

According to the 2005 survey of primary wood processing facilities, the forest products industry in British Columbia consists of 194 sawmills, with annual production capacities ranging from 150 mbf to 492 000 mbf, 37 panel mills with capacities between 7 and 460 million square feet, and 22 pulpmills with annual capacities from 31 000 to 776 000 metric tons (B.C. Ministry of Forests and Range 2008e).

Table 5.6 provides an overview of the number of lumber, panel, and pulp manufacturers that are active in years 1, 50, and 150 of the simulation run.

Table 5.6. Effect of market conditions on industry sector size

Sector	Lumber			Panel			Pulp		
Year	2007	2056	2156	2007	2056	2156	2007	2056	2156
Baseline	194	90	61	37	15	7	22	11	6
Market Downturn	194	81	55	37	17	9	22	16	9

Insolvencies were observed in all three product sectors. Under baseline market conditions, 58% of sawmills, 73% of pulp mills, and 81% of panel mills became insolvent by the end of the simulation run. For the sawmilling sector, the market downturn increased the insolvency rate to 72%. In contrast, the market downturn reduced the number of insolvencies in the panel and pulp sectors by 6% and 14% respectively. In the pulp and panel products sectors, the distribution of insolvencies over time did not differ between the two scenarios. However, a market downturn did have a noticeable effect on the timing of insolvencies in the lumber sector (Figure 5.14).

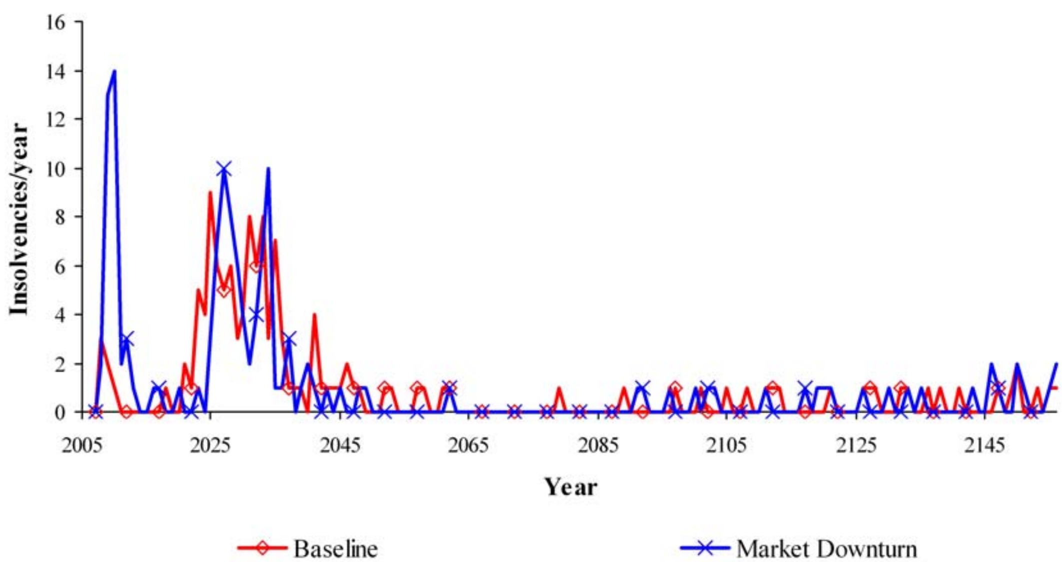

Figure 5.14. Distribution of lumber sector insolvencies over time

For both scenarios, the majority of insolvencies occur as provincial roundwood harvests decline between 2020 and 2030. A market downturn accelerates the lumber sector shakeout during the first decade of the simulation run. Under baseline market conditions, insolvency rates peak at 3 mills in 2008, affecting 6 mills in total. In contrast, 36 mills become insolvent during the same period under market downturn conditions, with insolvency rates peaking in 2009 and 2010. Insolvencies in the panel and pulp sectors occur mainly between 2025 and 2060.

Following this shakeout period during the medium-term timber supply shortage, the remaining mills enter a period of rapid capacity expansion as roundwood supply improves. Changes in average manufacturing costs highlight the effects of capacity reallocation within each product sector. Table 5.7 provides an overview of average manufacturing costs for lumber, panel, and pulp manufacturers in years 1, 50, and 150 of the simulation run. Costs include stumpage charges and are reported as production volume weighted averages.

Table 5.7. Average manufacturing costs in the lumber, panel products, and pulp sectors

Sector	Lumber ($/mbf)			Panel ($/1000 sq ft)			Pulp ($/ton)		
Year	**2007**	**2056**	**2156**	**2007**	**2056**	**2156**	**2007**	**2056**	**2156**
Baseline	173	213	243	158	192	238	178	178	182
Market Downturn	181	223	238	161	188	207	181	186	193

Inefficient, high-cost mills are more likely to become insolvent and exit the simulation during the shakeout period. However, average manufacturing costs increase over time for all product sector and market scenario combinations. As shown in Figures 5.8-5.10, the remaining mills take full advantage of improving conditions by expanding production capacities once the medium-term roundwood supply shortage ends in 2060. This concentration of production capacities in relatively few manufacturing facilities increases average roundwood transportation distances, resulting in an upward trend in average manufacturing costs.

5.4 Discussion

Resource inventory dynamics play a critical role in determining the economic opportunities available to the forest sector over the course of the simulation horizon. The CAMBIUM model projected mountain pine beetle related total volume losses of approximately 330 million m^3 on the timber harvesting landbase between 2007 and 2030. Compared to figures published by the B.C. Ministry of Forests and Range (2008b), this projection underestimates affected volumes by approximately 34%, or 174 million m^3. However, the CAMBIUM estimate of affected volumes on the entire landbase falls within less than 3 million m^3 of the B.C. Ministry of Forests and Range estimate. Our underestimation of mountain pine beetle impacts on the timber harvesting landbase is at least in part attributable to the use of different data sources for inventory volumes and cumulative attack data. As described in the methodology section, it was not possible to directly obtain a provincial-level spatial forest inventory dataset for this study. The resource inventory dataset used for this study was generated by disaggregating forest inventory statistics available at the TSA/TFL level. This disaggregation procedure randomly distributes tiles within the geographic and elevation ranges specified by the Biogeoclimatic Ecosystem Classification system[18]. Data on infestation intensities however was obtained directly from a spatial dataset (B.C. Ministry of Forests and Range 2008b). If infestation intensities are clustered, the result would be a systematic underestimation of total affected volumes in the agent-based forest sector model.

[18] Schwab, O. and T. Maness. Building spatial forest inventories from aggregated information. Chapter 2, pg. 16-35

This uncertainty could be resolved by replacing the current model-based forest inventory dataset with empirical data.

The distribution of impacts over time varies between the CAMBIUM model and the B.C. Ministry of Forests and Range (2008b) data due to methodological differences. As outlined in the methodology section, the CAMBIUM model tracks mountain pine beetle impacts in the form of non-salvaged volume losses. These non-salvaged losses occur once an infested stand reaches the end of its commercial shelflife, 5 to 15 years after the initial infestation. In contrast, the B.C. Ministry of Forests and Range uses the stage of ‘red attack’ as the common reference point for reporting observed and projected impacts. ‘Red attack’ occurs one year after the initial infestation, once the needles of beetle-killed trees have changed their color. The B.C. Ministry of Forests and Range reports an annual attack rate of 100 million m^3 for 2007, which then decreases to zero by 2020 (B.C. Ministry of Forests and Range 2008b). This trajectory is consistent with the estimates generated using the CAMBIUM model. Peak volume losses were observed in years 7, 12, and 17 of the simulation run, accounting for a total of 129 million m^3 of salvage harvests and unsalvaged losses. The differences in total peak volumes are caused by the variations in the commercial shelflife among stands on wet and dry sites.

Due to the systematic underestimation of the total volume affected by the mountain pine beetle infestation, the scenario analyses presented in this paper should be interpreted as very conservative estimates. However, since this underestimation is systematic across both scenarios, the results are suitable for assessing the effect of salvage harvesting and harvest restrictions on the British Columbia forest sector. Non-salvaged volume losses are an important indicator for the ability of the forest sector to recover economic value during the current mountain pine beetle infestation. As shown in Figure 5.6, the forest industry is not able to utilize all damaged fibre by the end of its commercial shelflife. Under baseline market conditions, the forest sector was able to recover approximately 45% of the volume affected by the mountain pine beetle, while a downturn in the lumber and panel products markets reduced salvage rates by 36 million m^3 to 34%. Due to the overabundance of fibre relative to the processing capacity of the forest sector, it is not possible to salvage all affected stands before value deterioration occurs. Since economic agents are trying to minimize their production costs, they will not salvage damaged stands if other roundwood supplies are available at a lower total cost. Other factors contributing to the underutilization of damaged fibre are harvest restrictions and the limited processing capacity of the forest sector.

The British Columbia forest products industry is entering a shakeout period due to the combined effects of the current mountain pine beetle epidemic and a downturn in the markets for lumber and panel products. A period of limited roundwood supply between 2031 and 2060 will force the majority of manufacturers to operate well below their respective production capacities. Not all manufactures will be able to sustain operations throughout this industry downturn. An economic agent’s ability to survive this downturn depends on the ratio between fixed and variable operating costs, as well as working capital reserves. Actual insolvency rates are likely to vary since simulation-based default cost data was used for this analysis. Based on this scenario analysis, up to 113 sawmills, 22 panel mills, and 11 pulp mills are expected to become insolvent by 2052 (Table 5.6). These results are consistent with current industry observations. It has been reported in the Vancouver Sun (Hamilton 2008a) that 34 sawmills and 5 panel mills in British Columbia closed permanently in 2007. In addition, 16 sawmills reduced operating hours to account for lower than expected consumer demand. This trend of temporary and permanent closures is continuing into 2008 (Deutsch 2008; Fahey 2008; Hamilton 2008b; Hoekstra 2008).

In addition to reducing the salvage percentage for mountain pine beetle affected stands, the downturn in the U.S. housing market results in a stumpage revenue shortfall of approximately $150 million/year. Assuming a 3% discount rate, this market downturn reduces the net present value of gross stumpage revenues by $1.1 billion, or 8%. In addition to stumpage revenue, harvesting and processing roundwood creates economic benefits to the province through directly and indirect employment, as well as through taxation on forest sector expenditures and earnings. In the socio-economic assessment that is part of the provincial timber supply review process, these economic benefits are estimated using a series of regional impact coefficients (B.C. Ministry of Forests 2003; Horne 2004). Using this broad approximation, the U.S. housing market downturn would have additional negative effects on economic activity throughout the province since it reduces short-term harvests by approximately 16 million m^3 per year (Figure 5.7).

The simultaneous shifts in stumpage rates and market prices for lumber and panel products provide an indication of the distribution of market power in this agent-based forest sector model (Figures 5.11-5.12). As described earlier, the stumpage rate is determined using a competitive bidding process, where each economic agent’s bid reflects production costs, profit targets, as well as current and expected market prices for finished products. Since anticipated changes in product prices are incorporated in current stumpage bids, changing market conditions will primarily affect provincial stumpage revenue. The competitive bidding process used in determining stumpage rates enables the BC forest products industry to predominantly act as price-takers with regard to changes in finished product markets.

However, companies were not able to reduce stumpage rates below a minimum threshold of 0.25 $\$/m^3$ net of harvesting and transportation costs.

Although the same set of market demand curves was used, traded volumes for lumber, pulp, and panel products varied considerably between the two scenarios. Once changes in roundwood supply are accounted for, industry sector size has a major effect on fluctuations in traded volumes. Due to the large number of competitors, each sawmill contributes a relatively minor share of the overall product supply (Table 5.6, Figure 5.8). In the pulp and panel products sectors, each competitor represents a much larger share of aggregate supply (Table 5.6, Figures 5.9-5.10). Therefore, traded volumes are much more sensitive to individual companies' investment and production decisions. An example of this type of sensitivity can be seen in Figure 5.10, where the insolvency of a single mill in 2042 shifts traded volumes downwards for the remainder of the simulation run.

5.5 Conclusion

The mountain pine beetle infestation is a significant driver for medium to long-term changes in the structure of the British Columbia forest products. The combined effects of both salvage and regular harvesting activities, as well as the natural regeneration of non-salvaged stands will result in a disproportionally large share of immature stands in the provincial forest inventory. The effects of this imbalanced age class structure will become most pronounced between 2030 and 2060, with annual roundwood harvests declining by more than 40 million m^3/year. This timber supply shortage and the resulting intense cost competition are expected to result in a large number of insolvencies in all three product sectors.

The effects of the downturn in the U.S. housing market are limited to the short term, since medium term dynamics are being dominated by the mountain pine beetle induced roundwood supply shortage. This market downturn will result in an accelerated industry shakeout in the lumber sector. The associated reduction in stumpage rates and roundwood harvests will result in a $ 1.1 billion stumpage revenue shortfall, and reduce the proportion of mountain pine beetle damaged stands that can be salvaged by 36 million m^3.

The agent-based model CAMBIUM complements methodologies such as computable general equilibrium analysis by generating continuous data on the economic effects of harvest restrictions on the forest sector as it responds to changing market conditions and the current mountain pine beetle epidemic. This model is designed to account for the feedback loops and interdependencies that exist between resource inventories, product markets, and the primary wood processing sector. Modeling the forest products sector as a group of interacting autonomous economic agents makes it possible to introduce production capacity dynamics and the potential for mill insolvencies as factors in modeling the effects of market and forest inventory based disturbances.

In its current stage of development, this model is most suitable for provincial level analysis. Since the model utilizes spatial data on the distribution of resource inventories and processing capacities throughout the province, it will be possible to use this model for setting the context for smaller-scale analyses. In the case of the mountain pine beetle infestation, the severity of timber supply impacts varies among the affected TSAs and TFLs (B.C. Ministry of Forests and Range 2008g). The timing and extent of expected mill insolvencies can therefore be of critical importance in assessing the implications of provincial-level policy changes on specific forest-dependent communities. However, before this model can be used for smaller-scale analysis, it is necessary to replace the current forest inventory information with an empirical dataset. In addition, the parameters and methods used in modeling individual processing facilities would need to be calibrated to account for local conditions.

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6 Conclusion

6.1 Overview and Chapter Linkages

In this dissertation, I develop and test an agent-based forest sector model for analyzing transition processes as companies adjust following large-scale natural disturbances. The four manuscript chapters (Chapter 2-5) represent different components and developments stages of the meta-model CAMBIUM[19]. The linkages between the four manuscript chapters are shown in Figure 6.1.

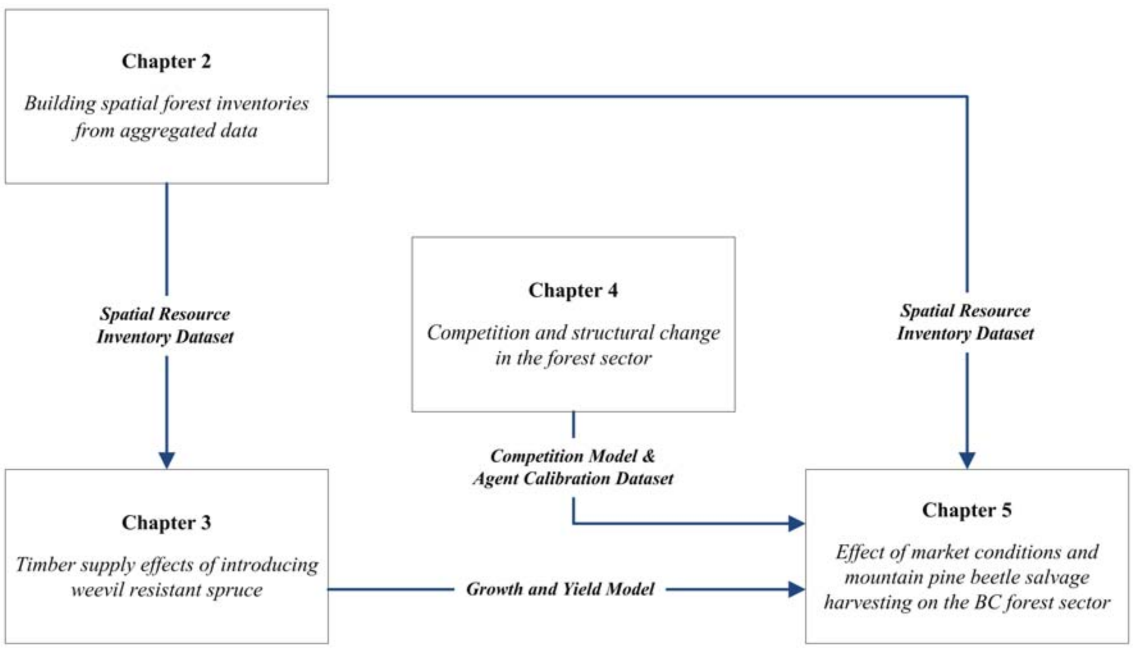

Figure 6.1. Linkages between the four manuscript chapters

In the following section I provide an overview of the key methodologies, results, and linkages from each of the four manuscript chapters.

[19] The cambium is a layer of cells that contributes to the growth of both the wood and innermost bark of a tree. The name CAMBIUM was chosen for this agent-based forest sector model to reflect the critical role that forest sector agents play within the interdependent feedback loops between resource inventories and product markets.

The ability to track and process spatial and temporal data heterogeneity is a key characteristic in modeling complex systems (Strayer et al. 2003). The scale and resolution of a dataset also affect what kinds of analyses can be conducted (Goodchild 2001). The first manuscript develops and tests an algorithm for generating ecologically and statistically consistent high-resolution spatial forest inventory datasets based on high-level aggregated data. This algorithm can be used as a rapid, low cost method for generating spatial datasets where such information is under development or otherwise unavailable.

The dispersal algorithm implements a predictive mapping procedure (Franklin 1995) to assign information on primary and secondary tree species, stand age, and site quality for each polygon. The algorithm is structured as an exhaustive classification tree search, intersecting information on polygon elevation and location with geographic ecosystem boundaries and information on the total area by tree species, age class, and site quality within a management unit. Area targets were defined for each Tree Farm License [TFL] and Timber Supply Area [TSA] using information obtained from the provincial timber supply review process (B.C. Ministry of Forests and Range 2007). Implementing the dispersal process as a random draw without replacement from these area targets ensures that the resulting spatial inventory dataset is consistent with the aggregated input information on area distributions for tree species, age classes, and site quality. At the same time, the use of geographical ecosystem envelopes and tree species associations ensures that forest inventory assignments are ecologically plausible.

The resulting dataset covers the province of British Columbia with approximately 370 000 tiles of 256 hectares each. Reliability testing using kappa statistics indicated that some location error was present in the high-resolution spatial dataset. The dataset should therefore be interpreted as one possible spatial representation of the aggregated input information.

As shown in Figure 6.1, Chapter 3 draws on this spatial inventory dataset to quantify the timber supply impacts of introducing weevil resistant spruce in British Columbia by developing an cellular automata model of resource inventory dynamics. The spatial assignment of specific combinations of tree species, stand age, and site quality in the inventory dispersal process (Chapter 2) makes it possible to simulate forest growth for each tile using stand level yield tables and growth curves.

Similar to simulation models such as HARVEST (Gustafson and Crow 1996), LAMPS (Bettinger and Lenette 2002), and FPS-ATLAS (Nelson 2003), this resource dynamics model uses a rule-based harvest scheduling algorithm. Harvest simulation models do not necessarily generate optimum solutions since they do not make intertemporal tradeoffs (Baskent and Keles 2005). They are not as computationally complex as mixed integer and heuristics optimization techniques that have also been used in spatial harvest scheduling (Lockwood and Moore 1993).

These models are typically applied at the management unit or landscape level, ranging from thousands to hundreds of thousands of hectares. The resource dynamics model described in Chapter 3 expands the modeling scale to a landbase of approximately 96 million hectares, 49 % of which are forested.

Spruce weevil infestations can significantly reduce the merchantable volume of affected stands. Volume losses are due to stem defects that are being caused by repeated weevil damages to the leading shoots (Heppner and Turner 2006). Since direct control of weevil populations was found to be ineffective, identifying and planting weevil resistant spruce has been suggested as an alternative for minimizing damages (Alfaro 1994). While tree breeding programs for propagating resistant planting stock are provincial in scale (B.C. Ministry of Forests and Range 2008a; 2008b), research has mainly focused on individual trees (Alfaro et al. 2002) and stands (Alfaro and Omule 1990). Therefore, very little is known on the overall impact that spruce weevil infestations have on provincial timber supply.

The resource dynamics model described in Chapter 3 bridges this gap between stand-level weevil infestation models and their large-scale timber supply effects. The timber supply effects of introducing weevil resistant spruce are limited by the relatively low percentage of avoidable merchantable volume losses and the long time lag before these benefits begin to accrue. Based on simulation results, merchantable volume losses will begin to decline from year 110 onwards, as second growth weevil resistant spruce stands are beginning to mature. The maximum loss reduction of 600 000 m^3 per year will be realized from year 250 onwards, once all spruce stands on the timber harvesting landbase have been replanted with weevil resistant planting stock.

In Chapter 4, I shift the focus to forest companies as a central link between resource inventories and forest products markets. Economies can be described as largely self-determining and self-regulating systems (Vanderburg 1985). In the case of the forest sector, these processes occur within the boundaries set by resource inventory dynamics, market demand for forest products, and policies affecting the use of natural resources. Since human decision making behavior is rarely optimal or completely rational (Lindblom 1959; Mintzberg 1994), it becomes difficult to define axioms that would allow for the deduction of market outcomes using neo-classical economic theory. Agent-based modeling is a methodology that is capable of modeling macroeconomic outcomes as an emergent phenomenon of repeated interactions of microeconomic entities (Tesfatsion 2002; 2006).

In this fourth chapter I developed CAMBIUM, an agent-based model of competition and structural change in the forest sector using a hypothetical landbase. In this model agents interact and compete autonomously within the broad boundaries defined by resource inventory dynamics and market demand for finished forest products. Strategic decisions were modeled using the self-tuning experience weighted attraction learning algorithm EWA-Lite (Ho et al. 2001). This algorithm allows for suboptimal decisions by modeling choice as a probabilistic process. Agents continuously monitor how rapidly their environment is changing and adjust decision behaviors accordingly. In cases where the environment is stable, previous experiences are a relatively good predictor of future conditions. Agents therefore exploit their experiences by favoring strategies that have performed well in the past. If conditions are changing rapidly, agents discount previous experiences in favor of predicted strategy payoffs. This exploration phase ensures that agent decisions remain reasonably close to the economic optimum.

The initial development and testing of CAMBIUM was carried out using an abstract, uniformly structured landbase and agents that were competing in a single product market. This high degree of abstraction made it possible to eliminate the effects that resource endowments may have on the competitive success of a company and to isolate the resulting industry structure as an emergent property of agent interactions and competition.

Modeling three distinct strategies (capacity expansion, process innovation, and sustainment) was found to be sufficient for initiating processes of agent differentiation and industry consolidation. The resulting industry structures were consistent with observations of the primary wood processing sector in British Columbia, where relatively few companies control the majority of processing capacities (B.C. Ministry of Forests and Range 2008f).

Chapter 5 integrates research results and modeling methods from the previous three manuscript chapters as shown in Figure 6.1. In this final manuscript chapter we calibrated CAMBIUM (Chapter 4) to conditions in the British Columbia forest sector and applied it in a scenario analysis of the cumulative effects of a market downturn and mountain pine beetle salvage harvesting.

In Chapter 5, we replaced the abstract uniform landbase that was used in Chapter 4 with the spatial forest inventory dataset developed in Chapter 2. This increased the model scale from approximately 3.3 million hectares (13 000 tiles) to more than 95 million hectares (370 000 tiles).

Resource inventory growth was simulated using the methods developed in Chapter 3. In Chapter 3, annual harvest targets were defined using the annual allowable cut levels that were published as part of the provincial timber supply review process (B.C. Ministry of Forests and Range 2008d; 2008e). This process is volume driven, maximizing even flow timber harvest levels subject to ecological and social constraints and objectives (Pedersen 2003; B.C. Ministry of Forests and Range 2008f). However, annual allowable cut levels are a relatively poor predictor of future harvesting behavior. Timber harvests on public forest land in British Columbia are licensed to private forest companies (Howlett 2001). Since these companies depend on their ability to sell the forest products that they manufacture, actual roundwood harvest levels may fluctuate depending on market conditions.

This limitation was addressed in Chapter 5 by modeling the harvesting behavior of individual mills as they compete and adjust to changes in roundwood availability and market demand for finished forest products. Instead of being used as harvest targets, annual allowable cut levels now form an upper bound for the roundwood volume that individual agents may harvest in a management unit within a given year.

In contrast to the single product market used in Chapter 4, agents now also competed in three distinct markets for lumber, pulp, and panel products that were calibrated to current market conditions using price data published by Kosman and Heartwood (2008), PaperAge (2008) and Random Lengths (2008).

The more than 250 agents (194 sawmills, 37 panel mills, and 22 pulp mills) that constitute the primary wood processing sector in British Columbia were initiated using a combination of empirical and simulation data. As shown in Chapter 4, modeling strategy and production decisions for individual mills required information on parameters that are not covered in the 2005 census on primary wood processing facilities that was compiled by the B.C. Ministry of Forests and Range (2008c). Default values for the remaining parameters were therefore obtained from repeated simulations of industry differentiation processes using the abstract landbase and uniform industry starting conditions described in Chapter 4.

Based on the scenario analysis conducted in Chapter 5, the structure of the British Columbia forest products sector is expected to change substantially over the short to medium term as companies adjust to the effects of the mountain pine beetle epidemic and reduced product demand in the U.S. housing market. Reciprocal wood flow arrangements between areas affected by the mountain pine beetle and unaffected areas have been suggested as an option for mitigating timber supply shortages (Patriquin et al. 2008). However, the CAMBIUM scenario analysis indicates that the cumulative effect of regular harvesting activities and mountain pine beetle salvage harvesting will result in severe medium term timber supply shortage throughout the province. This timber supply shortage will initiate a phase of intense cost competition in the primary wood processing industry, with large numbers of insolvencies occurring in all three product sectors.

CAMBIUM complements existing forest sector models by modeling aggregate product supply as an emergent property of individual companies' production decisions and stand-level ecological processes. In its present form, CAMBIUM can be used by stakeholders in government, industry, and academies as a decision support tool for provincial-level economic and policy analyses, in particular in the context of managing transition processes following large-scale natural disturbances.

6.2 Limitations

The limitations of this dissertation research have also been identified and discussed in the appropriate sections of the manuscript chapters.

The spatial dataset that was developed in Chapter 2 contains some location errors, in particular for age class and site quality assignments. These location errors can occur in cases where the inventory dispersal algorithm is not able to parse the list of possible inventory parameter combinations down to a single, unique combination of ecosystem, tree species, age, and site quality. Since dispersal results were statistically consistent at the management unit level, the high resolution spatial dataset was sufficiently accurate for higher level analyses. However, the location errors in the dispersed dataset introduced a degree of uncertainty into the quantitative scenario modeling results for assessing the timber supply impacts of introducing weevil resistant spruce (Chapter 3) and for modeling salvage harvesting of stands affected by the mountain pine beetle (Chapter 5). In the case of Chapter 5 the location errors in the spatial resource inventory dataset result in an underestimation of mountain pine beetle impacts. This underestimation can be observed directly by comparing the estimate of 330 million m^3 of affected volume by 2030 from the CAMBIUM model runs to the remote sensing based estimate of 475 million m^3 published by the B.C. Ministry of Forests and Range (2008g). In the case of Chapter 3 it is not possible to predict whether the location errors in the spatial forest inventory dataset resulted in an overestimation or underestimation of the timber supply impacts of introducing weevil resistant spruce. A comparison of Figures 3.4 and 3.5 indicates that the climate-based weevil hazard zones show a higher degree of clustering than the distribution of spruce inventories in the dispersed forest inventory dataset. If there is a negative correlation between high climate-based risk and spruce inventories weevil impacts would have been overestimated; while underestimation would have occurred if there is a positive correlation between climate based infestation risk and the distribution of spruce inventories. As discussed in the previous section, the use of annual allowable cut levels as harvest targets may have resulted in an overestimation of future roundwood harvest volumes. The estimated timber supply impacts of introducing weevil resistant spruce should therefore be interpreted as the maximum benefit that could be attained assuming a continuation of current conditions.

The agent-based structure of the CAMBIUM model makes it possible to assess the effects of large-scale phenomena such as insect infestations and changing market conditions on individual companies. However, at the current stage of development of CAMBIUM, the quality of the input and calibration data does not support this level of analysis. As shown in Figure 5.1, the economic agents in the provincial forest sector model were initiated using a combination of empirical and simulation data. The use of empirical information on the location, name, and processing capacity of each economic agent makes it tempting to draw location and company specific conclusions. However, parameter values for working capital per unit of output, fixed and variable production costs, and product recovery factors were obtained from simulation runs with the simplified forest sector model presented in Chapter 4. It is therefore not possible to draw location and company specific conclusions until these parameter values have been verified against, or substituted with, empirical data.

In addition, CAMBIUM currently does not incorporate information on species, log size, and log quality distributions in modeling harvesting decisions, product manufacturing, and trading of finished forest products. The relevance of these parameters is highlighted by the spread in average roundwood prices, currently ranging from less than \$ 10 per m^3 for Y grade western red cedar to more than \$ 360 per m^3 for D grade Douglas fir (B.C. Ministry of Forests and Range 2008h). The absence of these parameters from the current version of the CAMBIUM model is due to the lack of sufficiently detailed input information on forest inventories.

6.3 Future Research

Future research building on the agent-based forest sector model CAMBIUM is expected to focus on two broad areas: 1) data acquisition and model calibration, and 2) methodological improvements.

Work on data acquisition and model calibration would directly address some of the limitations outlined above and increase the relevance of the CAMBIUM model for applied policy and economic analysis.

In the case of British Columbia, it would be possible to substitute more accurate remote sensing based forest inventory data for the approximated inventory dataset used in this dissertation in order to improve the quantitative modeling results presented in Chapters 3 and 5. At the same time, additional research could focus on integrating more detailed models of associations between geographic features, ecosystems, and tree species into the inventory dispersal algorithm, thereby reducing location errors in the resulting datasets.

The collection and integration of empirical mill-level data on manufacturing technologies and cost parameters would make it possible to interpret CAMBIUM modeling results at the level of individual processing facilities. Once the input and calibration data is sufficiently accurate for mill-level analysis, the CAMBIUM could be used by forest products companies for assessing the expected benefits of introducing alternative manufacturing technologies, business strategies, or product lines.

The CAMBIUM model currently describes markets for finished forest products using user-defined demand curves. It would be possible to determine product demand endogenously by linking CAMBIUM to larger-scale forest products trade models such as the EFI-GTM developed by Kallio et al. (2004) or the IFFP developed by Northway and Bull (2007).

The harvest scheduling methods used in Chapters 3 and 5 are rule-based and do not include intertemporal tradeoffs. Harvest schedules are therefore not necessarily optimal. This limitation could be addressed by integrating alternative approaches such as the cellular automata planning model developed by Mathey et al. (2008) into CAMBIUM.

A significant area for methodological improvements exists in modeling the entrance of new competitors into existing markets. In the current stage of development, CAMBIUM focuses on the effects of competition and insolvencies among existing companies. However, new industry entrants can play a significant role in the development of a product sector or market (Spence 1979; Maggi 1996; Malerba et al. 1999; Amir and Lambson 2003). In the context of CAMBIUM, entry of new competitors and construction of new processing facilities could be modeled using facility location optimization algorithms such as the ones developed by Schulman (1991), Current et al. (1997), and Vila et al. (2006). Such a spatial industry entry model could then also be used for assessing the effects of emerging industries based on alternative fibre uses such as bioenergy (Kumar et al. 2003; Roberts 2008; Kumar 2009).

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