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Canada's Timber Supply: Current Status and Future Prospects under a Changing Climate

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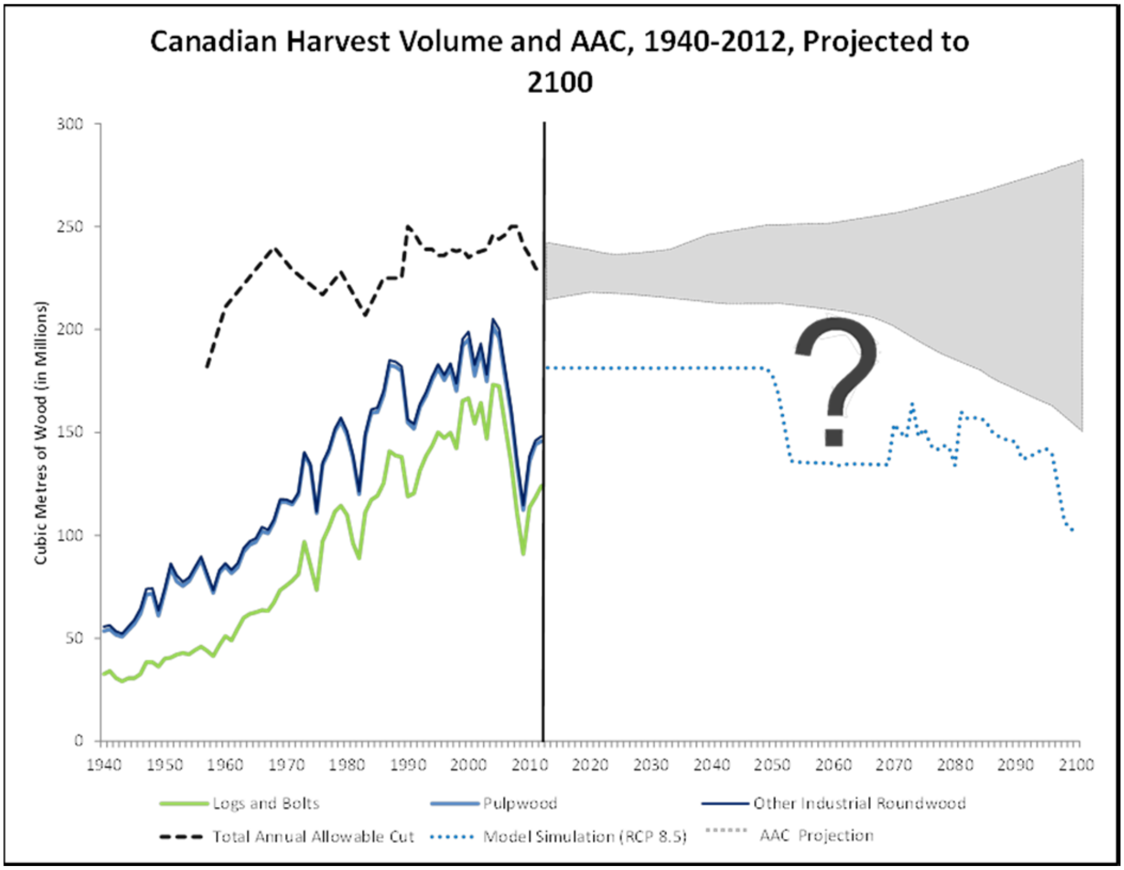

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Summary

This report contains an update of certain sections of the 1991 Forestry Canada Information Report Canada's Timber Supply: Current Status and Outlook and preliminary results of a computer-based national timber supply study examining potential impacts of climate change. We first review historical harvests and allowable cut levels, place Canada's forests in an international context, and briefly review global timber market studies that examine the implications of a changing climate. Many of those studies find that consumers may gain and producers may lose under a changing climate, but this is often predicated on sweeping assumptions about positive forest growth responses and little or no changes in disturbance regimes such as wildfire return intervals.

The second part of this report uses bioeconomic modelling to examine the national timber supply question from the growing and delivery-to-mills perspective. This analysis, which represents the first effort of its kind at this scale in the country, attempts to model changes in delivered wood supply costs, taking into account the current forest inventory (at a ~500 metre grid resolution) and projected changes in growth and yield and fire disturbance regimes under climate change. Although the analysis must be considered preliminary due to various data and computational challenges, it would appear that significant increases in delivered wood costs are plausible over the course of the century under the Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP) 8.5 greenhouse gas emission pathway. While this represents one of the more extreme IPCC scenarios, current global greenhouse gas emissions are arguably tracking along this path.

British Columbia and Quebec appear most likely to bear the brunt of the changes, with many mills potentially facing delivered wood shortages and/or cost increases of greater than 25% - even by mid-century. While this analysis identifies numerous challenges for forest managers, ranging from allowable cut determinations to developing climate change adaptation strategies, we note that significant

research efforts are required to increase confidence in the results, particularly in refining the inventory and growth and yield components. Disturbance regime changes will always remain challenging to forecast with specific spatial or temporal precision. Actual outcomes in the future will of course be highly influenced by such specifics.

1.0 Introduction, Motivation and Background

The sustainability of Canada's timber supply has been a recurring topic of interest over the last century. Almost 100 years ago two articles appeared in the Canadian Forestry Journal raising questions about pulpwood supplies in Eastern Canada (Campbell, 1919; Leavitt, 1919). In 1925, C.D. Howe provided an insightful perspective on the "forestry problem", foreshadowing many of the management challenges that some may argue still remain (How much timber do we have and how long will it last?; Howe, 1925).

In the late 1980s, there was renewed federal interest in the sustainability of Canada's forest sector which culminated in a Forestry Canada Information Report by Ken Runyon in 1991 titled Canada's Timber Supply: Current Status and Outlook. Runyon (1991) synthesized several historical studies and reported on the state of knowledge regarding issues such as forest area, volumes, growth rates, harvests and allowable cuts across the country. He also provided data and perspectives on a number of "Problems and Opportunities" seen to be facing the forest sector at the time, including institutional arrangements, forest protection, silvicultural investments and technological change, among others.

Runyon (1991) reported:

> The conclusions are that there is substantial hardwood supply available, but that current softwood harvest is approaching the maximum sustainable level given current biological, economic, and technological conditions. However, as shown in the study, these conditions are changing. Increased effort is being put into more intensive management including forest renewal and protection. Utilization is improving through more effective harvesting and processing, and demand for finished products is changing. These and a variety of other factors will affect the sustainable level of timber available for harvest.

Twenty five years have passed since the Runyon report was published. Since then, climate change has emerged as a key challenge in assessing the sustainability of timber supplies and forest management in general. Scientific insights, the increased availability of important and relevant data, and improved technology now allow us to more quantitatively examine timber supply questions in this context. In fact, many of the concerns and questions raised in the Runyon report are of heightened interest today. This is especially true in the context of a climate that is changing at the rate suggested by the most recent IPCC scenarios.

- How will climate change impact timber supply (quantity, quality, species mix and location)?
- Which forested areas in Canada are most sensitive to the effects of climate change on timber supply?
- Should we attempt to breed trees that are better suited to future climate conditions? What would be the return on this investment?

- How will climate change affect the nature of fibre for industry? What impact will it have on the location of mills?
- How is climate change impacting timber supply in other countries (both our competitors and our markets)? How does it impact their ability to compete with or buy from us?
- What are the sources and implications of uncertainty in climate change related timber supply studies?
- What are the implications of a decrease in timber supply for the forest industry, communities, consumers (domestic and foreign), taxpayers and producers?
- What is the optimal level of investment in forest management under a changing climate?

Several studies have examined the effects of climate change on Canadian forests; Lemprière et al. (2008), and more recently Price et al. (2014) provide summaries of trends in climate across Canadian forest ecozones and examples of recent and possible pending impacts on Canadian forests (see also Pedlar et al., 2015). However these are very complicated questions and there is significant uncertainty around how climate will change – including the formation of "novel" climates (Williams and Jackson, 2007) – and how forests will be impacted in terms of growth, mortality, and disturbance patterns (e.g. wildfire return intervals, new and spatially extensive insect and disease outbreaks, extreme weather). For example, the relatively recent mountain pine beetle outbreak in British Columbia that has now moved east into parts of Alberta is an example of a significant, broadly-scaled climate-related impact on Canadian forests (Kurz et al., 2008). While disturbance regimes are typically implicitly embedded in the growth and yield projections and expectations used by forest planners, the concern now is that climate change will affect forests well beyond the boundaries of historical outcomes.

Our objectives here are to: 1) provide a brief overview of Canada's forest resources and summarize recent trends in the timber supply situation, and 2) present preliminary findings from a modelling exercise on the effect of climate change in the coming century on timber supply. Section 2 provides an overview of the components affecting timber supply in Canada, including forest industry, inventory, products, and international competition; it concludes with a brief review of studies that have examined the projected effects of climate change on the forestry sector in Canada/North America. Section 3 provides early results of new computer-based modelling which integrates data on current forest condition and mill attributes with projected forest yields and fire regimes to estimate timber supply through the end of the current century. The results must be viewed with caution because of their preliminary nature, but we hope they also provide motivation for more efforts on the subject.

Canada's forests extend across the country from Newfoundland and Labrador to British Columbia providing a wide range of services from ecological, spiritual, recreational and commercial needs.

Photo credits: Denys Yemshanov (top); Michael Hoepting (middle left and middle); Mark Primavera (middle right); and Mark Primavera (bottom) Natural Resources Canada

2.0 Canada's Timber Supply

Timber supply modelling means different things to different people. Runyon (1991), as do others, distinguish between economic and physical timber supply; economic being the "rate at which timber will be made available for harvesting in response to a range of product prices" and physical timber supply being "the rate at which timber can be harvested (usually at a sustained level) without consideration of prices". Indeed, many may think of timber supply calculations as a forest planning exercise where the achievement of harvest targets are simulated using growth and yield models integrated with forest inventories. As computing power and data availability of forest condition and growth have increased, so too has the complexity of forest planning models; furthermore, the task of forest planning has become much more complex in recent decades as the demand on forests to provide more than just wood fibre has increased. In Canada, simulation and optimization planning models such as Patchworks and Woodstock (Spatial Planning Systems, 2009; Remsoft, 2014) have become widely used at the forest management unit level to support timber supply and forest planning. These models can be and are often used to estimate the flow of both wood and non-wood values from forests.

For others, the idea of timber supply has much more of a forest products market orientation. Wear and Pattanayak (2003) describe it as a "…means of formalizing the production behavior of heterogeneous landowners managing a wide variety of forest types and vintages within a region". In these cases, the linkages between landowners who grow and manage forests and final products firms can be direct or complex, with each responding to their own perceptions of economic and policy signals. The distinction between economic and physical timber supply is especially important for a large country like Canada where most forest lands are publically owned. Geography plays an important role in influencing economic timber supplies and public forest management is influenced by more than economic efficiency considerations in timber growing and acquisition. This complicates not only actual management decisions but also modelling exercises that attempt to integrate biophysical conditions and human responses to economic and policy signals. For the modelling work described below, our focus is on timber supply from the forest to the mill gate from the perspective of a mill; as a result, delivered wood cost is the primary metric.

2.1 Forest Industry and Inventory

Canada's forests and forest products industry are in a state of change. Government and industry are transitioning from managing and harvesting primary forests to investing in and managing second-growth forests. As primary forests are depleted, transportation costs become more significant. Harvesting firms go farther and farther afield to access their wood supply. Recent years have seen major structural changes in the Canadian forest product sector, partly driven by global market forces and drastic changes in consumer preferences. The biophysical realities of current inventories and the ever increasing pressures on forests to provide a wide range of non-timber values are also changing the way forestry industry approaches the forest. The recent Canadian Boreal Forest Agreement serves as an illustrative example (http://cbfa-efbc.ca/).

Krueger forest products mill in Newfoundland.
With the downturn in the forest products sector, mills are innovating and modernizing to stay viable.

Photo credit: Michael Hoepting, Natural Resources Canada

Figure 1 shows industrial roundwood production in Canada from 1940 to 2014 and highlights some of the changes the forest industry has been facing. From 1940 to the early 1970s, roundwood production (logs and bolts, pulpwood and other industrial roundwood) increased at a steady pace, from about 6.00×10^{7} m^3 in 1940 to 1.41×10^{8} m^3 produced in 1973. From the early 1970s onwards, the production of roundwood continued to increase but experienced more variation, with years of high production closely followed by sudden decreases. This historical volatility has been driven by market demands more than the physical availability of wood fibre. Production peaked in 2004, with slightly over 2.00×10^{8} m^3 produced. Since that time, there has been a 44% decrease in total production; less than 1.20×10^{8} m^3 were produced in 2009, following the global financial crisis of 2008. This decline was due to a number of factors, including drops in demand for Canadian wood products, downward swings of the business cycle, strong competition from Asia and Brazil, and rising energy costs (Canadian Senate, 2011). The production of industrial roundwood has recovered somewhat in the past few years; as of 2014, 1.48×10^{8} m^3 of roundwood was produced, similar to levels in the early 1980s and late 1970s (see Table 1 for further details).

Numerous lumber and forest product mills have closed throughout Canada in recent years. From 2000 to 2008 direct employment in the forest sector dropped by almost 40%, equating to roughly 100,000 jobs (Canadian Senate, 2011). Numerous large and small mills have been closed across the country with a loss of more than 20 major mills nationally since 2000 (Keenan et al., 2014; Hyslop, 2014; Marowits, 2014). The decline in roundwood production and subsequent closure of multiple mills has spillover effects to the communities and families whose incomes rely on this industry.

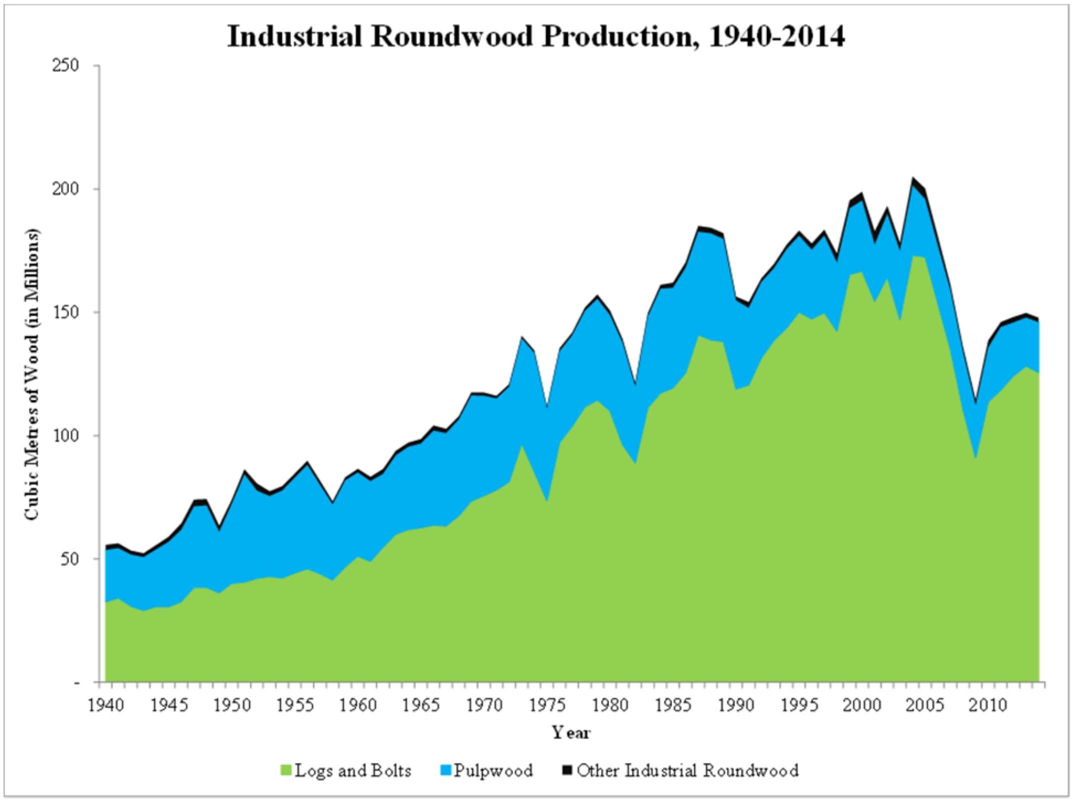


Figure 1: Annual Canadian roundwood production from 1940 - 2014 (National Forestry Database 2016a).

However, as noted, roundwood production has begun to increase since the 2009 downturn. Growing demand from non-US markets for forestry products has likely contributed to the increase in production (Parkinson et al., 2014). Periodic declines in the exchange value of the Canadian dollar often help the competitive position of forest product exports by making Canadian lumber relatively less expensive in comparison to competitors' products. The species composition of Canadian forests, which are predominantly coniferous, also provides a key advantage to the industry. These species have wood quality attributes that are ideal for pulp and paper production; in particular, the longer fiber length in softwood coniferous trees provides extra strength to pulp and paper products (PaperOnline, 2014).

Table 1 provides a breakdown of the distribution, amount and relative magnitude of roundwood production by province/territory and land ownership for 2014. British Columbia is by far the largest supplier of roundwood, producing almost three times more than the next province (Quebec) and approximately five times greater than Ontario (the next largest). Most of this production takes place on provincial crown lands; with production on federal lands being essentially negligible. Private lands accounted for about 2.40×10^7 m^3 of the 1.53×10^8 m^3 produced across the country in 2014, with British Columbia, Quebec and New Brunswick accounting for over 75% of the private land production. Roundwood production is further broken down into softwood and hardwood species; the production of softwood is significantly higher in most provinces, reflecting the higher demand for softwood derived products. Saskatchewan is the exception, with hardwood production making up almost two thirds of total production.

2.1.1. Canada's Annual Allowable Cut

Canadian forests have supported significant levels of commercial harvesting in a continuous manner for many decades, although the actual level of harvest has fluctuated widely over time as noted above. Forest management programs attempt to sustain the flow of timber harvests and other values given the dynamics and influences of factors such as growth, wildfire, and insect and disease depletions. Forest management is a provincial responsibility in Canada; each province sets what is essentially an Annual Allowable Cut (AAC) or harvest level that can be removed in a region. These harvest levels are reviewed periodically and indicate the volume of wood that each jurisdiction believes can be harvested in both an economically and biologically sustainable fashion.

AAC levels are determined for both softwood and hardwood species. As noted, the high proportion of coniferous species in Canadian forests provides producers with a comparative advantage over areas dominated by less desirable tree species. Any changes in the species mix could significantly affect the forest product sector's competitive position.

Forest harvesting in Canada is increasingly mechanized.
Photo credit: Michael Hoepting, Natural Resources Canada

The process of determining AAC quantities are summarized for each province in a Canadian Council of Forest Ministers report: "Wood supply in Canada" (CCFM, 2005). Table 2 provides an aggregate, national summary of the AAC for both hardwoods and softwoods from 1957 to 2014. Since 1990, the AAC has fluctuated between approximately 230 and 250 million cubic meters per year. Approximately 70% of the AAC is allotted to softwood species.

Although Table 2 stretches back to 1957, it is difficult to develop definitive historical estimates of actual forest conditions due to changes in record keeping that have occurred over time. This makes comparisons between historical conditions and present day conditions challenging. Table 3 provides a series of national snapshots of the volume and area of timber in various maturity classes from 1981 to 2006. The mature and overmature groups held constant (or increased) in volume levels over this period, even with an increase in overall harvest levels as indicated in Figure 1(total roundwood production). Table 3 also illustrates changes in the area an age class occupies, from 1986 to 2006. Similar to the volume measurements, most of the forested area in 1986 was devoted to mature and overmature stands. In more recent years there have been declines in the relative proportions of the overmature classes with increases in mature and uneven age classes. However this interpretation should be viewed with some caution as the "unclassified" category has disappeared from the 2006 summary.

A healthy spruce seedling in the regeneration phase.
Spruce are among the mostly widely distributed species in all of Canada.
Photo credit: Michael Hoepting, Natural Resources Canada

Table 1: Roundwood production by ownership and species, 2014 (Thousands of Cubic Metres)

Ownership and Species	NL	PE	NS	NB	QC	ON	MB	SK	AB	BC	YT	NT	NU	CA
Provincial Crown land														
Softwoods	1,056	8	727	3 720	17,502	10,822	872	1,358	14,227	58,298	23	15	..	108,627
Hardwoods	93	-	168	1 956	4,132	3,544	624	2,359	6,712	1,216	-	-	..	20,805
Total	1,149	8	895	5,676	21,634	14,366	1,496	3,717	20,939	59,514	23	15	..	129,432
Private land														
Softwoods	546	119	2,210	2,886	3,192	-	..	-	671	6,766	-	2	..	16,392
Hardwoods	1	244	538	1,438	5,396	-	..	-	1,427	197	-	..	..	7,442
Total	547	363	2,748	4,472	6,788	-	..	-	2,098	6,964	..	2	..	23,982
Federal land														
Softwoods	..	..	..	8	5	..	..	..	..	22	..	..	..	35
Hardwoods	..	..	..	12	3	..	..	..	..	-	..	..	..	15
Total	..	..	..	20	8	..	..	..	..	22	..	..	..	50
Total														
Softwoods	1,602	127	2,937	6,614	20,700	10,822	872	1,358	14,897	65,086	23	17	..	125,055
Hardwoods	94	244	706	3,406	7,731	3,544	624	2,359	8,140	1,414	..	-	..	28,262
Total	1,696	371	3,643	10,168	28,430	14,366	1,496	3,717	23,037	66,500	23	17	..	153,464

Source: National Forestry Database (2016b)

Table 2: Potential harvest/AAC for Canada, 1957-2012 (Millions of cubic metres)

	Canadian Annual Allowable Cut		
Year	Softwoods	Hardwoods	Total
1957	127	55	182
1960	155	57	211
1968	-	-	240
1971	196	33	229
1976	177	40	217
1979	174	54	228
1983	167	40	207
1986	166	59	225
1988	175	59	233
1989	166	59	225
1990	188	62	250
1991	185	62	247
1992	182	60	242
1993	180	60	239
1994	179	60	239
1995	176	60	236
1996	176	60	236
1997	177	62	239
1998	176	62	238
1999	177	62	239
2000	174	61	235
2001	177	60	237
2002	177	60	238
2003	179	60	239
2004	186	60	246
2005	183	61	244
2006	186	60	246
2007	190	60	250
2008	190	60	250
2009	184	57	241
2010	180	56	236
2011	175	56	230
2012	172	55	227
2013	170	54	224
2014	170	57	227

Source: National Forestry Database (2016c, 2016d)

Table 3: Volume and area of gross merchantable wood on inventoried, stocked, productive, and non-reserved forest land, 1981-2006

Maturity class	1981		1986		2001		2006	
	Volume (m^3x10^6)	Percent of Total	Volume (m^3x10^6)	Percent of Total	Volume (m^3x10^6)	Percent of Total	Volume (m^3x10^6)	Percent of Total
Regeneration	180	0.9%	140	0.6%	155	0.6%	245	1%
Immature	6,738	34.3%	5,625	24.3%	6,787	24.7%	891	2%
Mature	6,918	35.2%	5,766	24.9%	6,943	25.2%	21,147	45%
Overmature	11,030	56.1%	13,621	58.8%	14,360	52.2%	11,881	25%
Uneven-aged	23	0.1%	34	0.1%	3,426	12.5%	13,155	28%
Unclassified	896	4.6%	1,618	7.0%	-	-	-	-
Total Volume	19,644		23,154		27,501		47,320	

Maturity class	1981		1986		2001		2006	
	Area ($hax10^6$)	Percent of Total	Area ($hax10^6$)	Percent of Total	Area ($hax10^6$)	Percent of Total	Area ($hax10^6$)	Percent of Total
Regeneration	-	-	19.8	9.1%	16.7	6.4%	9.8	3%
Immature	-	-	77.7	35.9%	66.3	25.4%	14.16	4%
Mature	-	-	97.5	45.1%	83	31.8%	166.6	51%
Overmature	-	-	85.3	39.4%	81.5	31.3%	44.9	14%
Uneven-aged	-	-	0.4	0.2%	4	1.5%	91.6	28%
Unclassified	-	-	22	10.2%	77.4	29.7%	-	-
Total Area			216.4		260.6		327.2	

Source: Compiled from: Canadian Forestry Service, 1985; Forestry Canada 1991; National Forest Inventory, N.D

2.1.2. Forestry Inventory Systems

In the early 1980s, a national inventory system known as Canada's Forest Inventory (CanFI) was developed to help summarize forest inventory data collected by forest management agencies across the country. Because of differences and changes in standards and definitions across the provinces/territories, interpretation of changes in forest condition was problematic at times. CanFI was updated in 1981, 1986, 1991, and most recently in 2001(Power and Gillis, 2001). CanFI was, until recently, widely used for State of the Forest Reporting and to support other types of forest-related research (e.g., Yemshanov et al. 2009; Yemshanov et al. 2012a).

To help address some of the limitations with CanFI, a new National Forest Inventory (NFI) is now being implemented throughout Canada (Gillis et al., 2005). The NFI consists of two parts; a number of ground-based plots and a set of aerial photos. Currently, there are approximately 1,1161 ground-based plots in which forest characteristics have been physically measured. These ground-based plots provide a reference for aerial photo interpretation. A much larger set of aerial photos 13,148 across the country), along with remote sensing data, capture and help quantify numerous forest inventory attributes such as species composition and biomass volume estimates. Plans are in place to update the NFI once every ten years to ensure relevant forest inventory information and to support forest condition change estimates.

The new NFI allows for volume and age class estimates to be generated and summarized more consistently (see: http://nfi.nfis.org). Although detailed comparisons with CanFI are not possible due to the differences in collection procedures over time, the national data do provide a rough approximation of Canadian forest demographics for 2006.

Besides supporting various national ecozone level reporting needs, the new NFI database has also allowed for the development of higher resolution maps of forest attributes that can be used in various modelling exercises (Beaudoin et al., 2014). These spatial depictions of forest attributes can be used to address issues such as the evaluation of timber losses from fires, or the spread of insects based on host tree species abundance. Many evaluations of forest attributes require spatially explicit, continuous and standardized coverage of forest properties across provincial boundaries, including the current national timber supply study. Further details on the forestry inventory dataset are provided in Section 3.

2.2 Forest Products

Canadian forests are a source of many products and services, ranging from lumber to non-lumber goods and alternative non-lumber forest uses. Bioproducts, defined as marketable products from the forest (Wetzel et al., 2006), can include bioenergy feedstocks, agroforestry products, pharmaceuticals, and decorative items. These products have been shown to have significant growth potential within Canada's forest sector (Wetzel et al., 2006).

Table 4 shows the quantity (and value) of a select set of forest products from 1989 to 2014. The quantity of lumber produced in Canada increased steadily from 1989 to 2004, and fell to a minimum in 2009, reflecting the economic impacts of the global slowdown noted above. In fact, all listed products, excluding maple syrup and Christmas trees, produced significantly lower quantities in and around 2009 when compared to previous years. Although the production of both softwood and hardwood lumber has started to increase (2010 period and onwards), the production of newsprint, wood pulp and printing and writing paper has continued on a downward trend, reflecting a shift away from traditional advertising and communication to a digital medium (Natural Resources Canada, 2010) . The non-lumber products, maple syrup and Christmas trees, do not follow the trend associated with lumber products, offering diversification options.

Depending on local markets some lower quality harvested logs are now sometimes being used for chips and energy production.
Photo credit: Jeff Fera, Natural Resources Canada

Table 4: Production and value of lumber and select Canadian forest products, 1989-2014

	Lumber (1,000 m^3)		Wood Products				Maple Products		Christmas Trees	
Year	Softwood	Hardwood	Newsprint (1,000 tonnes)	Wood Pulp (1,000 tonnes)	Structural Panels (1,000m^3)	Printing and Writing Paper (1,000 tonnes)	Litres	Dollars ($1,000)	Number of Trees (1000's)	Dollars ($)
1989	59,200	-	9,640	23,700	-	-	-	-	-	-
1990	54,900	-	9,100	22,800	-	-	-	-	-	-
1991	52,100	-	9,000	23,300	-	-	-	-	-	-
1992	55,700	-	8,900	22,800	-	-	-	-	-	-
1993	59,800	-	9,100	22,900	-	-	-	-	-	-
1994	61,500	-	9,300	24,600	-	-	-	-	-	-
1995	-	-	-	-	-	-	-	-	-	-
1996	62,800	-	9,000	24,400	-	-	-	-	-	-
1997	64,800	-	9,200	24,900	-	-	-	-	-	-
1998	65,100	-	8,600	23,500	-	-	-	-	-	-
1999	68,400	-	9,200	25,300	-	-	-	-	-	90,000
2000	69,600	-	9,200	26,800	-	-	-	-	-	-
2001	69,900	-	8,300	24,900	-	-	-	-	4,100	-
2002	73,000	-	8,500	25,500	-	-	-	163,968	-	-
2003	77,600	-	8,500	25,900	-	-	31,300,000	-	4,100	64,100
2004	81,700	-	8,200	26,200	-	-	26,900,000	152,900	3,900	62,200
2005	81,200	-	7,800	25,200	12,200	6,700	28,100,000	-	3,200	-
2006	79,200	1,600	7,100	23,500	12,400	6,100	27,000,000	-	-	-
2007	70,600	1,400	6,600	22,100	10,200	6,000	23,339,240	167,449	1,926	34,259
2008	56,139.4	1,110.9	6,004	20,300	6,592.505	5,239	27,010,899	263,216	1,843	37,507
2009	44,436	813	4,378	17,095	6,008.471	3,602	41,274,309	353,801	1,878	39,407
2010	52,356.3	954.9	4,640	18,530	5,967.766	4,064	42,742,625	285,250	1,796	35,833
2011	52,743.9	865.7	4,382	18,287	6,239.43	3,772	50,109,000	349,504	1,838	39,438
2012	54,722.6	1,297.6	3,874	17,079	6,695.153	3,319	-	-	-	-
2013	57,687.7	1,306.2	3,972	17,254	7,132.294	3,466	-	-	-	-
2014	58,158.3	1,459.5	4,014	16,962	7,687.126	3,268	-	-	-	-

Note: Natural Resources Canada, The State of Canada's Forests: Annual Reports 1990 to 2015

Forest-related food products, which include honey, berries, wild plants and mushrooms, (as well as maple syrup) contributed over $725 million (2006 CND) to the Canadian economy in 2006, and are thought to have the potential to provide over $2 billion per year in the future (Wetzel et al., 2006). Other forest-related industries in Canada are expected to continue growing; Wetzel et al. (2006) project that the combined benefit to the Canadian economy from the production of biofuels and bio-chemicals alone could well exceed $23.7 billion. Additional growth derived from the growing nutraceutical and pharmaceutical markets, as well as demand for recreational activities, will only increase the value and importance of Canadian forests. Aesthetic items, consisting of Christmas trees and greenery for floral arrangements, contribute a small amount to the value of forest products. Table 4 includes the dollar value and number of Christmas trees produced in Canada from 2002 to 2011. The production and value of Christmas trees has steadily declined over the examined time period.

2.3 Canada's Forests in an International Context

Examining forests in an international context helps illustrate their relative scale and certain aspects of Canada's competitive position. The United Nations Food and Agriculture Organization (FAO) reports various global forest statistics on a biennial basis (FAO, 2014). In Canada, the National Forest Information System (CCFM, 2013) and various federal State of the Forest reports (Natural Resources Canada, 2013) synthesize Canadian information. Canada remains one of the world's largest "forest" nations. Total Canadian land area is estimated to be 9.98×10^8 hectares (Statistics Canada, 2005), with approximately 3.47×10^8 hectares classified as "forest land" (Natural Resources Canada, 2016), although land used for forestry extraction activities is restricted to about 2.50×10^8 ha (see Table 5). In comparison, Europe contains approximately 5.25×10^8 ha of productive forest land and Africa contains 1.86×10^8 ha (see Appendix 1, Table 1). In per capita terms, these forest area numbers translate to roughly 1.5 people per hectare of forest land in Africa, 4.8 in Asia/Pacific, 0.7 in Europe, 0.5 for Latin America and 0.7 in North America (see Appendix 1, Table 1).

Over the period of 1990 to 2010, Canada reported no change in total forest area (FAO, 2013). However, the cumulative area planted has increased over that period from approximately 1.36×10^6 ha to 8.96×10^6 ha, indicating both the changing nature and age structure of the nation's forests.

Forest growth rates in Canada are, with some exceptions, relatively low when compared to other parts of the world (see Table 6). This has longer term implications on wood supply and affects the economics of growing and managing forests in Canada (Sedjo, 1990; Sedjo and Lyon, 1983). For example, it tends to take longer for forest stands in Canada to reach commercial viability and rates of return for silvicultural are generally low (Anderson, 1979; Yang et al., 2015). Bickerstaff et al. (1981) suggest a range of mean annual increments (MAI) of 0.3 m^3/year for slow growing species on poorer sites to over 10.5 m^3/year on very good sites. Greater MAI values have been documented for intensively managed fast growing poplar plantations in certain circumstances (Dominy et al., 2010); however, the area of fast growing poplar plantations remains low and the economic rates of return on investing in such plantations are also low due to their high establishment cost (see Yemshanov et al., 2005). Furthermore, much harvested land in Canada is allowed to regenerate naturally. For example, from 2000 to 2012, approximately half of the harvested area in Canada was regenerated through planting, with the remainder left to regenerate naturally according to established standards. In 2000, 43% of the harvested area was replanted, and in 2012, 58% was replanted (Compiled from the National Forestry Database, 2014).

Table 5: Land use in Canada (2001)[2]

	Land use (thousand hectares)	Percentage of Total
Agriculture	62,154	9.6%
Conservation	83,509	12.9%
Forestry	258,604	39.9%
Industrial	473	0.1%
Infrastructure	8,052	1.2%
National Defence	2,314	0.4%
Recreation	70,444	10.9%
Settlement	4,453	0.7%
Unknown	158,351	24.4%
Total	648,354	100.0%

[2]The Arctic Cordillera, Northern Arctic, Southern Arctic, Taiga Plains and Hudson Plains are not included in this inventory.
Source: National Forest Inventory (2013)

2.4 Climate Change effects on Global Timber Markets

A changing climate is likely to directly and indirectly affect the forest products sector by influencing both the demand for final products and the supply of raw fibre. Clearly this could result in a complex set of biophysical, ecological and economic interactions with outcomes very difficult to predict, especially further into the future, which is subject to both biophysical and economic uncertainties. Nevertheless the possible effects of climate change on global timber markets have been investigated by a number of research groups in recent years (see Table 7 for a summary of several of these studies).

Most of the studies divide the world into major wood producing regions and make various assumptions on markets and growth effects under a changing climate. Typically, metrics include Gross Domestic Product effects and/or changes in producer and consumer surpluses. These economic measures are sometimes used to evaluate the impact of a change in price or supply quantity on the economic welfare of society. While the studies summarized in Table 7 come to numerous conclusions, there are a number of consistent findings.

Generally, the studies suggest an increase in global physical timber supply as a result of climate change. Although Canada is expected to see some benefits from this, other regions will also experience increases in supply. This may reduce Canada's share of the global timber market, especially if fast growing plantations in subtropical countries become more prevalent.

Table 6: Mean Annual Increments of selected plantation species, by major world region

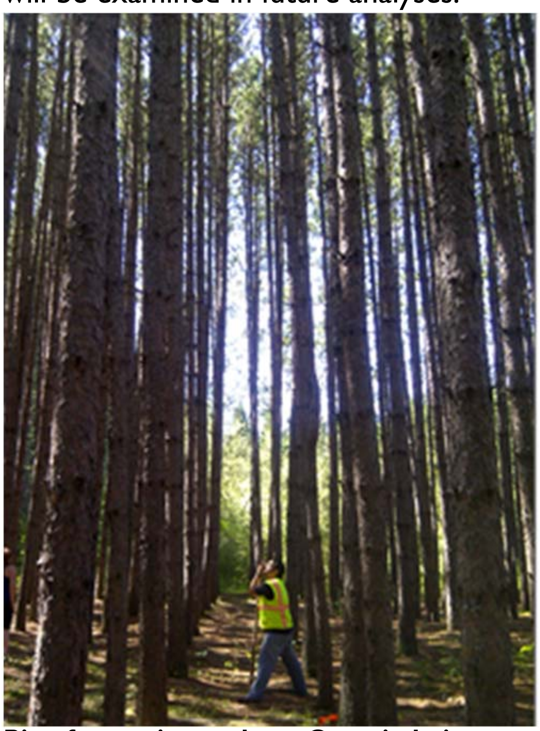
Region	Species	Mean Annual Increments (m^3/year)
Africa	*Acacia* spp.	9-26
	Eucalyptus grandis	16-24
	Pinus elliottii	12-15
	Pinus patula	12-15
Asia	*Acacia* spp.	8-30
	Eucalyptus spp.	11-25
Europe and Former Soviet Union	*Picea* spp.	1-6
	Pinus sylvestris	3-8
North and Central America	*Picea* spp.	2-6
	Pinus spp.	7
	Pseudotsuga spp.	2-12
Oceania	*Eucalyptus nitens*	14-32
	Pinus radiate	12-26
	Pinus caribaea	13-26
	Eucalyptus globulus	15-38
	Acacia mangium	20-60
	Swietenia macrophylla	7-10
South America	*Pinus* spp.	10-25
	Eucalyptus spp.	15-30

Source: Adapted from ABARE and Poyry, 1999

Domestically, Canadian consumers and producers are expected to experience welfare increases and decreases respectively. The change in producer welfare is primarily due to increased global timber supply, lower timber prices and increased competition from other countries. The magnitude of the increase in consumer welfare caused by reduced timber prices is projected to be larger than the loss experienced by producers, resulting in an overall increase in total welfare within Canada. Increases in timber supply are estimated as a result of a projected expansion in forested areas and improved growing conditions.

However, many of the studies examined make the critical assumption that growth rates and disturbance regimes will not change significantly from current conditions or that growth rates will increase due to warming. We note that this may be an unlikely assumption, and is not the case in the analyses presented in Section 3, which attempt to account for changes in forest growth rates and wildfires as a result of climate change.

The studies within Table 7 make varying assumptions about what a changed climate would look like. Some authors simply assume a doubling of CO2 content within the atmosphere, while others make use of more specific climate change scenarios. For the analyses presented in Section 3, we use the IPCC Representative Concentration Pathway (RCP) 8.5 (IPCC, 2013). RCP 8.5 reflects the IPCC's current more extreme prediction for the future, assuming the emission of CO2 into the atmosphere is not abated. Under this pathway, global average temperatures are expected to increase the most, sea ice will experience the greatest decrease, and oceans will become acidic (IPCC, 2013). Other scenarios will be examined in future analyses.




Pine forests in northern Ontario being examined.
Photo credit: Dan McKenney, Natural Resources Canada

Table 7: Market studies on the impacts of climate change on the forest products sector

Study[i,ii,iii]	Model Type/Description	Projected Implications for Canada
1. Solomon, 1996	BIOME: static model to assess geographic distribution of vegetation based on plant functional types IMAGE: Combines BIOME with population and land use practices and models effects of climate change	**Boreal Region** • Climate change effects on boreal region uncertain; evidence for both increased and decreased timber supply • By 2050, forested area projected to decrease 20 to 50% based on BIOME model; IMAGE model projects an increase of 10% • BIOME projects based on expansion of agricultural area and displacement of boreal species by temperate species; IMAGE model assumes limited expansion of agricultural area
2. McCarl et al., 2000	FASOM (Forest and Agricultural Sector Optimization Model): dynamic economic model with endogenous prices used to simulate timber markets and resource management responses over a 100 year period Effects of climate change included through modification of timber yields	**US Timber Markets** (US softwood timber consumption is of Canadian origin) • Model results uncertain; effects of the wide range of existing climates and timber yields within North America likely to exceed the effects of climate change • Increases in yields benefit consumers while decreases in yield benefit producers • Producer benefits were found to be more sensitive to changes in timber yield in comparison to consumer benefits; no real change in total welfare observed
3. Irland et al., 2001	Review of multiple models: FASOM (Burton et al., 1998) and TAMM/NAPAP/ATLAS (Joyce et al., 1995)	**North America** (US consumption is directly linked to Canadian production) • Adaptation of forestry sector is expected to mitigate negative effects of climate change • Growth rates are projected to increase 1 to 3% causing an increase in supply and increased benefit to consumers at the expense of producer welfare

4. Sohngen and Mendelsohn, 2001	VEMAP (Vegetation Ecosystem Modelling and Analysis Project): model predicts new ranges for plant species based on climate change, harvest, replanting and ecological effects	**US Timber Markets** • Model results predict increase in net welfare based on climate change projections until 2060; aggregated, losses to producers are projected to be smaller than gains to consumers • Producers are expected to adapt to climate change, reducing benefit loss • Various impacts for consumers and producers depending on location
5. Sohngen et al., 2001	Model developed combines BIOME3 (global model of changes in vegetation due to climate change) and global economic model	**Global Markets** • Global timber supply increases and prices decrease under all scenarios investigated • Largest losses to mid-latitude producers due to decreased supply and decreased global price
6. Alig et al., 2002	FASOM (Forest and Agricultural Sector Optimization Model): dynamic multi-period market optimization model that stimulates economic resource management in forest and agricultural sectors	**US** (with implications for Canada) • Land use shifts between forestry and agriculture likely based on comparative advantage caused by climate change • Productivity of forests expected to increase, while rate of land conversion from agriculture to forest expected to decrease • Increase in total welfare resulting from climate change and land conversions, but decline in producer welfare
7. Perez-Garcia et al., 2002	TEM (Terrestrial Ecosystem Model) generates vegetation responses to climate change scenarios: TEM results entered into CINTRAFOR Global Trade Model to evaluate forestry sector economic response to climate change	**Canada** • Climate change projected to increase timber growth, resulting in lower producer welfare, increased consumer welfare, and decreased total welfare • Producers expected to minimize surplus losses by decreasing harvest amounts

8. Haynes, 2003	TAMM/NAPAP/ATLAS (Timber Assessment Market Model/North America Pulp and Paper Model/Aggregate Timberland Assessment System) used to evaluate bioeconomic systems for modelling timber assessments	**US Timber Products** (With implications for Canadian timber product production) • US demand for timber products expected to increase; increase in domestic production and imports expected to meet demand to 2050 • Canada is a primary source of US imports (paper and paperboard products), but importance of exports to US expected to decrease • Harvest levels in Canada to peak in 2010 and slowly decline to achieve a steady state in 2050
9. Lee and Lyon, 2004	Method developed includes TSM (Timber Supply Model) to represent global timber markets, integrated with BIOME3 (ecological model) and the Hamburg general circulation models to evaluate changes to timber markets with a doubling of atmospheric carbon dioxide	**Global by Regions** • Projected increase in global timber supply due to increased growth rates and larger area of fast growing species; supply outstrips demand, driving prices down • Simulation results with climate change from 1995 to 2085 indicate a 2.8% decline in total wood volume produced for eastern Canada and a 50.9% decline for western Canada
10. Sohngen and Sedjo, 2005	Literature review and analysis of established economic-ecological models	**North America** • Climate change is expected to increase forest productivity in North America and reduce timber prices; consumers benefit and producers lose • Softwood production in Canada is projected to increase 20 to 50% over the next 50 years
11. Turner et al., 2006	GFPM (Global Forest Products Model): Spatial equilibrium model to estimate wood supply based on derived equations for wood supply, forest stock growth, and change in forest area	**Global** • Global forest area is projected to decline from 2000 to 2030 • Global forest stock is expected to increase over the same period, with the largest increases occurring in the Americas (North, Central and South) • Stock growth is expected to compensate for forest area loss

12. Joyce, 2007	Qualitative review of analysis tools used to evaluate the effect of climate change scenarios on forest sectors	**US** (with global implications) • All analysis models conclude a small increase in forest productivity, a subsequent decline in price, and a loss for producers • The magnitude of the impacts are very small when the effect of CO_2 fertilization is removed from the analysis • The impact of stochastic events (fire, pest, and weather) on the forest sector is likely to be significant, but is difficult to model
13. Daigneault et al., 2008	Model built on Sedjo and Lyon; dynamic model of timber markets that maximizes net present value based on changes in exchange rates	**North America** • Global timber prices expected to rise at a rate of 0.3% per year from 2000 to 2050 • Timber production in Canada and US projected to decline over the same time period, assuming constant exchange rates • Most timber supply expected to originate from tropical, fast growing regions
14. Williamson et al., 2008	Can-IBIS (Canadian Integrated Biosphere Simulator): dynamic vegetation model to simulate changes in forest vegetation with climate change Results of Can-IBIS combined with projections of future harvests to generate estimates of harvest potential in 2055	**Vanderhoof, BC** (Case Study) • Model projects increases in productivity and total wood volume per hectare, but does not account for natural disturbances; predictions are uncertain • Climate change effects on local economy are thought to be variable in the long run • Community is projected to be worse off in the long run
15. Williamson et al., 2009	Quantitative analysis of the impacts of climate change on Canada's forests	**Canada** • Impacts of climate change on productivity varies; large variation in timber supply can have negative impacts on industry • Canadian forest sector uniquely vulnerable to climate change due to heavy reliance on forest sector and climate change benefits accruing to forest product competitors • Canadian forest product market share expected to decline

16. Eboli et al., 2010	CGE (Computable General Equilibrium): Comparative static model to assess effects of climate change on world economy	**Global** • Model predicts global decrease in land productivity • Global model broadly defined for regions suggests reductions in the forestry industry
17. Ince et al., 2011	USFPM (US Forest Products Module): A partial market equilibrium model, accounting for forest product demand, production, timber harvest and regional markets used to generate long-term market predictions	**US Regions** • Demand for forest products and by-products for the production of energy is projected to increase from 2020 to 2060 • Projections of US market effects (supply, demand and trade) depend on the assumptions made about future US and global wood demands • US forest product prices are expected to remain consistent or decline; consumption is also projected to decline gradually
18. National Round Table on the Environment and the Economy (Canada), 2011	CGE (Computable General Equilibrium): Predict economic trends based on demand, factors of production, and markets	**Canada** (6 regions) • Effects of climate change on timber quantities (fires, productivity and pests) expected to vary across the country, with larger impacts in western Canada • Impacts of climate change on timber supply likely to increase over time • Strategies to mitigate the effects of climate change could reduce many of the negative impacts Canada would be subject to
19. Ochuodho et al., 2012	CGE (Computable General Equilibrium): Static economic impact model accounting for 15 individual forestry related sectors	**Canada** (6 regions) • Results suggest marginal changes (increase or decrease) to forest productivity due to climate change impacts from 2010 to 2080 • Climate change impacts investigated include forest fires, changes in productivity and forest pests • Most regions experience negative impacts from climate change without adaptation measures
20. Ochuodho and Lantz, 2013	CGE (Computable General Equilibrium): Optimization model used to account for the forestry sector, the agricultural sector, and a combination of the two sectors	**Canada** (by province and territory, and rest of world) • Model examining only forestry suggests variation in total welfare, depending on province, over a 45 year time horizon • Model examining both forestry and agriculture finds that total welfare increases in many provinces • Results suggest that individual analysis of sectors leads to

		underestimation of the effects of climate change
21. Hanewinkel et al., 2013	EFISCEN (European Forest Information Scenario): A forest forecast model used to estimate timber production, accounting for silvicultural treatments at five year intervals under projected temperature increases	**Europe** • Model examines changes in commercial tree species ranges in Europe • Results suggest that the commercial coniferous species will lose approximately 50% of their current range as currently suitable area becomes uninhabitable for these species • Results imply that loss of productive forestry land will reduce industry productivity and impact the forest sector
22. Ochuodho and Lantz, 2014	CGE (Computable General Equilibrium): Optimization model inclusive of single region and multiple Canadian regions, trade impacts and the rest of the world	**Canada** • Models examining single regions predicts smaller climate change impacts than models examining multiple regions • Model examining multiple regions predicts larger, more negative effects on capital, labour and production from climate change on Canadian forestry sector • All model results show larger impacts under more extreme climate change scenarios

[i] Buongiorno et al. 2011 used a GFPM (Global Forest Products Model) to evaluate the global effects of increasing fuelwood demand under IPCC scenarios. Authors found that world wood prices would increase to reflect increase in demand; increase in fuelwood demand increases price of roundwood, sawn wood, and pulp and paper. Results suggest increases in Canadian production of wood products due to increase in fuelwood demand, and spillover trade benefits.

[ii] Raunikar et al. 2010 use a Global Forest Product Model to evaluate the impacts of increased biofuel production in IPCC scenarios on a global scale with focus on specific regions. Fuelwood production grows fastest in North and South America and Europe. Model results suggest increase in all wood prices to 2060.

[iii] Johnston and van Kooten, 2014 examine the economic effects of an increased bioenergy demand in the form of wood pellets. Significant benefits accrue to pellet producing countries, including Canada. Results suggest an increase in the price of logs due to the increased demand for pellets, causing a price increase and loss of consumer welfare. The effects on producer welfare are uncertain.

3.0 The development of a computer-based National Timber Supply simulation model for Canada

3.1 Overview of the National Timber Supply Modelling Problem

The exercise undertaken here is very different from the operational timber supply planning typically done at the forest management unit scale. In Canada, while forest planning varies somewhat across jurisdictions, it is driven by numerous similar factors such as land-use designations, forest management objectives, minimum harvest-age rotation lengths, and various environmental sustainability guidelines (such as slope restrictions on timber harvests, designated no-harvest zones along streams, and wildlife habitat retention). At the operational scale, planners attempt to incorporate these types of considerations as well as detailed biological and economic considerations into harvesting plans over near-to-medium term decades (e.g. 20 – 100 years). Such efforts require significant time and resources to address objectives in a manner that satisfactorily informs decision makers of options and trade-offs for their management units. Developments in computing power over the last two decades have made it possible to model more detailed representations of timber supply through time at both local and larger scales.

Our objective was to generate a broad-scale assessment of the ability of Canada's forests to meet current mill wood demands under changing climate at costs similar to today (given the current distribution and capacities of mills and wood processing facilities). A secondary goal was the development of geospatial datasets and modelling capacities for use in ongoing and future timber supply analyses and climate change research. An operational-scale analysis of timber supply at the national level, inclusive of all the factors noted above, is not currently possible, nor desirable. We recognize that infrastructures, technologies, and even geographic locations of mills can change dramatically over the course of the century – even in the absence of any climate change. The intent here is to provide a narrative of possible outcomes against the benchmark of current mill distributions and processing capacities.

The primary metric is delivered wood cost at the mill gate (under scenarios with and without climate change). In this case the forest stand-to-mill gate cost, includes a harvest cost ($\$/m^3$) and a transportation cost ($\$/m^3/km$) as detailed below. We note that other indicators, such as changes in the age class structure of forest stands through time, could be used to monitor the available timber supply and support the pursuit of conservation values in forest management. However at this stage, for simplicity, we only report on changes in delivered wood costs here.

The following sections describe the key components of the Canadian Forest Service-Forest Bioeconomic Model (CFS-FBM) used in the current study. Section 3.2 details the data used within the model, while Section 3.3 provides a brief description of the model, key assumptions and harvest rules. Results and discussion are presented in Sections 3.4.

3.2 Data Sources

Our national modelling effort required data sources that characterized the area examined, starting conditions for the analysis of the forest, forest growth and yield, fire regimes, and harvest activities across the study region.

3.2.1 Harvest Base

Figure 2 shows Canada's forested area and a general outline of the managed forest that forms the geographic basis for our modelling effort (Lee et al., 2004; http://www.globalforestwatch.ca). Our analysis encompassed the entire managed forest. Some forest drivers such as fire regimes occur at broad scales and are stochastic (meaning both uncertain and variable in nature), thus examining their influences at the national scale is ecologically appropriate and arguably more realistic given the first objective. Additionally, in the longer run forest products firms are likely to adjust to stochastic disturbances by traveling further to obtain the required wood fibre; a broad geographic scope allows the model to account for this.

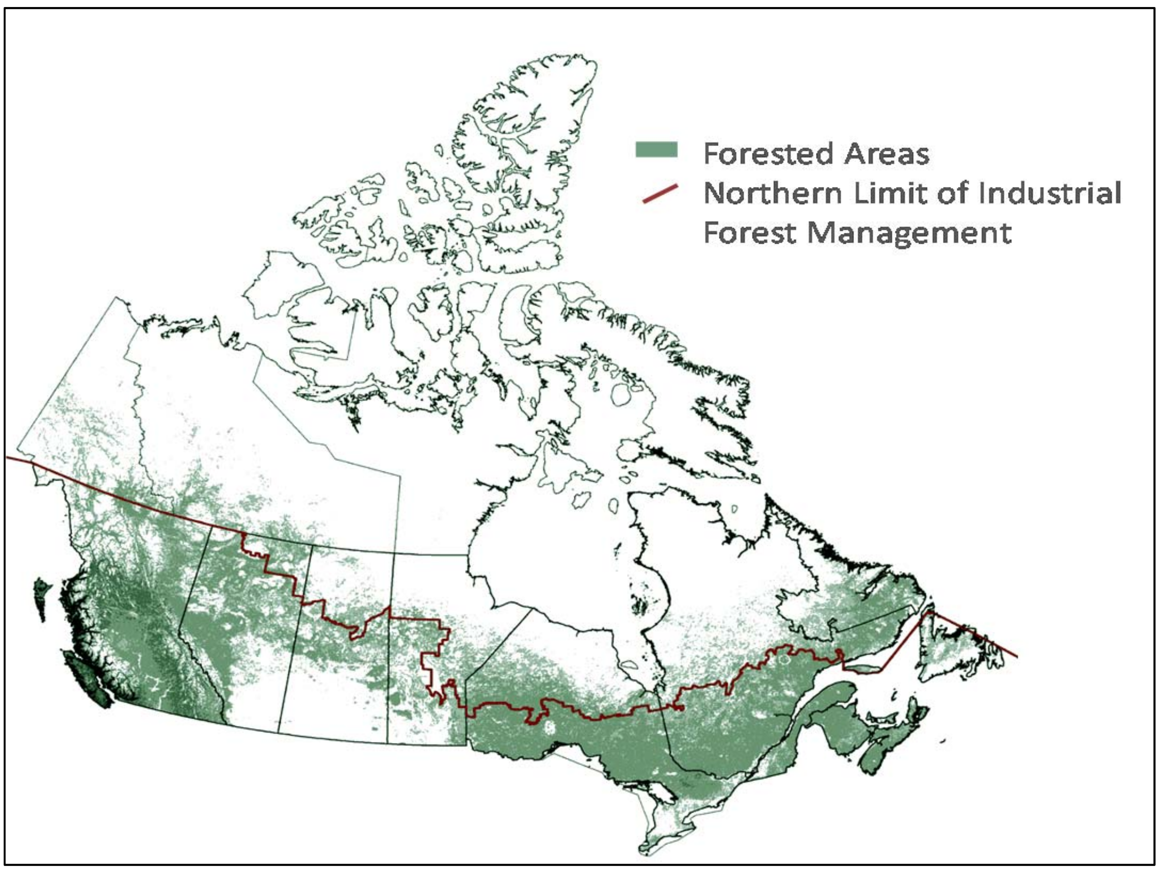


Figure 2. Canadian forested areas and northern limit of industrial forest management.

The land base available for harvest was estimated from the geospatial product generated by Global Forest Watch Canada (Lee et al., 2004; http://www.globalforestwatch.ca), which delineates the timber harvest licence areas within each province. It should be noted that our analyses include crown lands and the possibility of harvesting private lands (industrial freehold and fee simple), which may also be used in commercial logging operations in several provinces. However, our representation of the land available for harvest does not incorporate information on province-specific forest management guidelines and harvest regulations (e.g., particular ecological sustainability guidelines that vary province to province) that might further limit or expand the land base where harvest operations could potentially occur. Parks and protected areas have been excluded and are not recognized as part of the harvestable land base.

3.2.2 Tree Species Groups

Canadian forests cover a broad range of ecological and climatic conditions and are characterized by a diverse species composition. To help make the analyses more manageable and still reflect current mill needs, seven species groups were identified (Table 8). These groups, inclusive of coastal firs and spruces, coastal cedars and hemlocks, pines, spruces, firs, boreal hardwoods, and temperate hardwoods, were used as the basis for harvesting and growing the forest as detailed below.

3.2.3 Starting Forest Inventory

Starting values for forest attributes (such as stand age and percent cover of each species group) used in the simulations described below were derived from the spatial products of Beaudoin et al. (2014). These products made use of the k^{th} nearest neighbour (KNN) approach to impute 127 forest attributes measured at a network of survey plots to a regular grid at a 250 m resolution (see Beaudoin et al., 2014 for further details). These grids were coarsened to a 500 m resolution to improve computational efficiency during the simulations.

For the current work, we employed a subset of the 127 forest attribute grids, including: 1) a land cover grid to select forested areas, 2) a forest stand age grid (in years), and 3) percent abundance grids for each species group. As noted, the original species composition maps from Beaudoin et al. (2014), which characterized 112 tree and shrub species, were grouped to the seven broad tree species groups, shown in Table 8.

Table 8: Species groups used in the timber supply analysis and climate-driven equations used to generate yields for each group (modified from Ung et al., 2009).

Species Group	Main Species	Yield Equation
Coastal firs and spruces	*Pseudotsuga menziesii, Abies amabilis*	$Y = e^{(5.7+0.0636\cdot MAT-0.0001\cdot PCP+(\frac{-173.859+14.5291*MAT}{Age})} \cdot 1.0423$
Coastal cedars and hemlocks	*Chamaecyparis nootkatensis, Thuja plicata, Tsuga heterophylla, Tsuga mertensiana*	$Y = e^{(5.7+0.0636\cdot MAT-0.0001\cdot PCP+(\frac{-173.859+14.5291*MAT}{Age})} \cdot 1.0423$
Pine Species	*Pinus contorta, Pinus ponderosa, Pinus banksiana, Pinus resinosa, Pinus strobus*	$Y = e^{(6.4755+0.1271\cdot MAT-0.0008\cdot PCP+(\frac{-67.4993+2.6486*MAT+0.0119*PCP}{Age})} \cdot 1.0777$
Spruce Species	*Picea engelmannii, Picea glauca, Picea mariana, Picea rubens*	$Y = e^{(6.443+0.0981\cdot MAT-0.0013\cdot PCP+(\frac{-37.4046+7.5551*MAT+0.0362*PCP}{Age})} \cdot 1.2127$
Fir Species	*Abies balsamea, Abies lasiocarpa,*	$Y = e^{(4.8421+0.0007\cdot PCP+(\frac{-74.8932+4.3921*MAT}{Age})} \cdot 1.2453$
Boreal Hardwoods	*Populus tremuloides, Populus grandidentata, Populus balsamifera, Betula papyrifera*	$Y = e^{(6.6358-0.0004\cdot PCP+(\frac{-55.6634+0.8537*MAT}{Age})} \cdot 1.0289$
Temperate Hardwoods	*Acer saccharum, Fagus grandifolia, Acer rubrum, Quercus rubra, Betula alleghaniensis*	$Y = e^{(6.605-0.0009\cdot PCP+(\frac{-47.1154+1.6253*MAT}{Age})} \cdot 1.0819$

The Beaudoin et al. (2014) grids were representative of the forest condition in 2001; thus, the dataset was updated to reflect a 2011 age structure by incorporating forest losses due to harvests and fires from 2001 to 2011 using the spatial products of Guindon et al. (2014). We also incorporated the mountain pine beetle (MPB) outbreak in western Canada using 2 spatial products: 1) a grid showing cumulative forest attacks as of 2011 (Walton, 2014); and 2) grids of the year that grid cells were attacked by MPB (Natural Resources Canada, 2014a). After these modifications were complete, the starting endowment of merchantable timber on each pixel was calculated using the yield curves described below in combination with the updated age grid and the percent composition of each species group.

3.2.4 Growth and Yield Data

Provincial Yield Data

We collected data on forest yields on a province-by-province basis (Table 9), with an end goal of generating tables that provided annual yield estimates (m^3/ha) for up to 250 years of age for each species group and province. Since British Columbia encompasses such a wide range of climates and forest growth rates, we further divided this province into four separate ecozones for which yield data were gathered; similarly, we developed two sets of curves for two ecozones in Alberta (Table 9). The yield data varied significantly between provinces with respect to form (e.g., equations versus tables), age interval and maximum age (in the case of tables), and treatment of old age classes (e.g., inclusion of 'old growth tails' on some provincial curves). As a result, a significant amount of processing was required to standardize the data for use in this national modelling exercise (as detailed below and summarized in Table 9).

Tree seed, nurseries and tree improvement facilities in Canada produce high quality stock for forest regeneration.
Photo credit: Dan McKenney, Natural Resources Canada

Yield values were in the form of net merchantable volume, with typical utilization specifications of 30 cm stump height and 12.5 cm top (17.5 cm for coastal British Columbia species). All values were based on natural forest growth (i.e., no silvicultural inputs) and 70% stocking. Since provincial agencies did not typically report yields for the species groups used here (Table 8), we gathered data for major commercial species in each province and generated tables for each species group using weighted averages based on the relative abundance of each contributing species as depicted in the forest composition maps of Beaudoin et al. (2014). For each province and species, we gathered 'low', 'average', and 'high' yield estimates at each age step based on the reported range of site productivity classes. For example, site index at black spruce growth and yield plots in Ontario ranged from 0 to 32 m at age 50 (Penner et al., 2008), however, the majority of stands fell between 5 and 20 m at age 50 with an average of 12 m; thus we gathered yield estimates associated with site indices of 5, 12, and 20 m.

To make the provincial yield data suitable for modelling, several standardization procedures were required (Table 9). For provinces for which yield tables were obtained, values often needed to be interpolated within age steps (to obtain annual estimates) and extrapolated to 250 years of age. These requirements were met by fitting a Chapman-Richards growth equation (Liu and Li, 2003) to the yield table data, which was then used to estimate the annual yields for the desired range of ages. These fitted equations generally had a very high coefficient of determination (i.e., $R^2 > 0.95$ in most cases). We further incorporated age-dependent cull equations (Penner et al., 2008) to make the old-growth tails of the yield curves consistent across provinces. We recognize that there are widely varying approaches to treating yield at older stand ages (i.e., over 150 years), with some models simply holding yield constant and others rapidly reducing yield to zero. Our approach is intermediate between these extremes and reflects the species-specific loss of merchantable wood as stands age beyond an optimal harvest age. The impacts of this decision are relatively minor given the very small portion of the land-base in these older age classes. Yield estimates were not readily available for some provinces (specifically Saskatchewan, Manitoba, New Brunswick and Newfoundland and Labrador); for these provinces, yields were taken from the nearest province with comparable forest cover. For example, yield data from the Alberta boreal plains region was used to represent yields in Saskatchewan.

Table 9: Growth and yield data sources and standardization steps for various provinces/regions across Canada

Province/Region	Source of Yield Data	Productivity Stratifier	Standardization steps
British Columbia (Pacific Maritime)	WinVDYP7 (BCMOF, 2009a,2009b)	Site Index	Interpolation to obtain annual estimates
British Columbia (Montane Cordillera)	WinVDYP7 (BCMOF, 2009a,2009b)	Site Index	Interpolation to obtain annual estimates
British Columbia (Boreal Cordillera)	WinVDYP7 (BCMOF, 2009a,2009b)	Site Index	Interpolation to obtain annual estimates
British Columbia (Plains)	WinVDYP7 (BCMOF, 2009a,2009b)	Site Index	Interpolation to obtain annual estimates
Alberta (Foothills)	GYPSY (Huang et al., 2009)	Site Index	none
Alberta (Boreal Plains)	GYPSY (Huang et al., 2009)	Site Index	none
Ontario	Penner et al., (2008) Payandeh (1991)	Site Index	Averaging Penner and Payandeh values for certain species; applying old growth tails
Quebec	Sylva II (Lessard, 1998)	Site Index	Fitting yield curves; extrapolating yield curves; applying old growth tails
Nova Scotia	NS G&Y 2.1.0 (MacPhee and McGrath, 2006)	Combination of Land Capability and Site Index	Fitting yield curves; extrapolating yield curves; applying old growth tails

National Yield Equations

National-scale growth and yield equations (Ung et al., 2009) provided a second source of yield information that was used to adjust the provincial yield estimates to local climatic conditions. These equations incorporated mean annual temperature (MAT) and annual precipitation (PCP) to modify yield trajectories according to climate conditions at a given site. The original Ung et al. (2009) equations were developed for individual tree species; for the current effort, these equations were refitted for the seven tree species groups of interest (see Table 8). To generate yield tables from these equations (the required input format for the bioeconomic model described below), we identified common MAT-PCP combinations (or bins) that occurred in the study area. A normal yield table was then generated for each of these combinations using the midpoint MAT and PCP values for the bin. The end result was a set of normal yield tables for each combination of species group and province/ecozone that reflected the climate-based variation of growth rates.

Combining Provincial and National Sources of Yield Data

Our efforts to gather provincial yield data produced tables of low, high, and average yields for each species group and province/ecozone. These estimates appear to provide reasonable bounds on the yield estimates for each species group within each province. Alternatively, the national yield equations provided a number of yield estimates for each species group that varied according to the climate conditions across each province / ecozone. While these equations provided valuable information on how climate modifies forest yield, we were less confident in these estimates – particularly at older ages where the shape of the yield curves for some species/ecozones implied that yields would continue to incrementally increase indefinitely. To combine these two sources of information, we assumed that the range in yields (i.e., low and high values) provided by the provincial estimates was reasonably accurate and scaled the climate-driven estimates derived from the national equations to fall between the provincial bounds. To do this, the highest and lowest yields from the national equations were set equal to the minimum and maximum provincial estimates and the remaining yields were scaled proportionately between these bounds (for an example see Figure 3).

3.2.5 Climate Change Yield Modifiers

To incorporate the impact of climate change on forest growth, we used productivity modifiers (provided by Cyr and Bernier). These modifiers were based on outputs from a net primary productivity (NPP) model (called StandLeap) described in Bernier et al. (2010). For each species group, a representative species was identified; the model was then parameterized and run for each of the selected species under current (1970-2010) and future (2011-2100) climate conditions (RCP 8.5 scenario). The end result for each species was a series of coarse grids (0.25 x 0.25 degree) – one for each future 10-year period – that provided the ratio of NPP under climate change to the NPP under current conditions. Thus, a species that was projected to experience NPP declines for a given location and time period would have an NPP ratio less than one for that grid cell. We used these ratios to modify the yield estimates described in Section 3.2.3; note that the modifiers were incorporated such that the growth for each time period was added onto the growth that had been accumulated in previous time periods (under the climate conditions for that period).

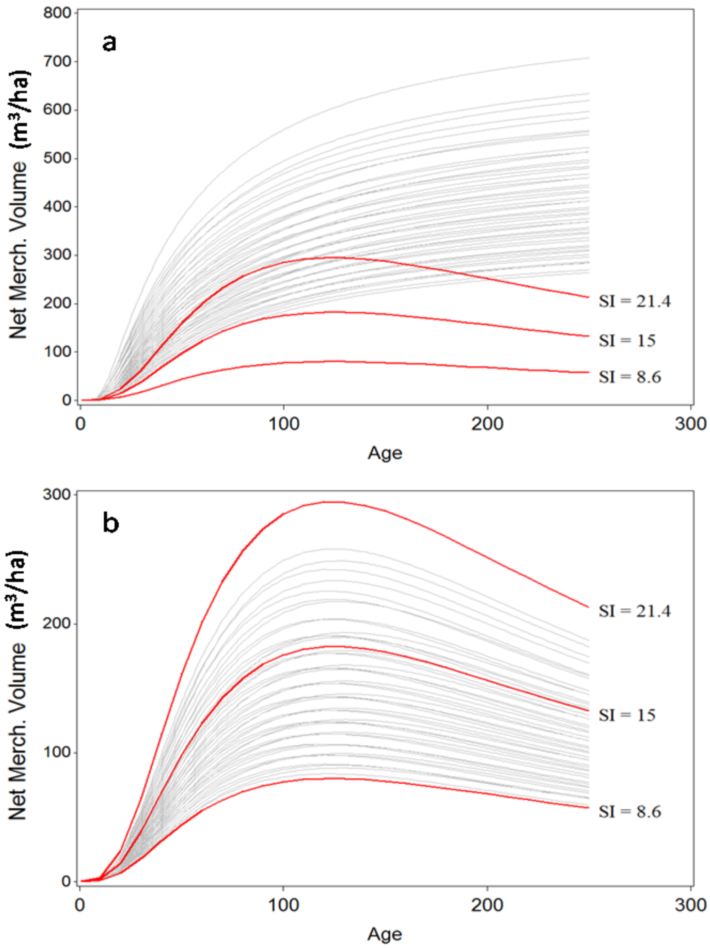


Figure 3. Plots showing: a) low, medium, and high yield curves for *Pinus* species in Ontario (red lines; derived from Penner et al., 2008) overlaid by curves derived from national yield equations (gray lines; Ung et al., 2009) for 49 combinations of temperature and precipitation across the province; and b) the same curves, but with the values derived from the national equations scaled within the range of the provincial estimates.

3.2.6 Fire Regime Data

To include the effect of wildfire on Canada's forests and timber supply, historical and future estimates of annual area burned and fire frequency were obtained for homogenous fire regime zones across the country (Boulanger, 2014). These zones were created through a spatially constrained clustering analysis, which aimed to connect adjacent cells into distinct regions based on their similarity with respect to local fire regime attributes (Figure 4; see Boulanger et al., 2014 for details). Fire regime attributes for each zone were then modelled as a function of monthly climate over the 1959-1999 period using Multivariate Adaptive Regression Splines (MARS). These models were then used to estimate future fire regime attributes using climate projections based on the Canadian Coupled Global Climate Model (CanESM2 GCM) and the Representative Concentration Pathway (RCP) 8.5 greenhouse gas emissions scenario (see Boulanger et al., 2014 for details; see IPCC, 2013 for additional descriptions of RCP scenarios).

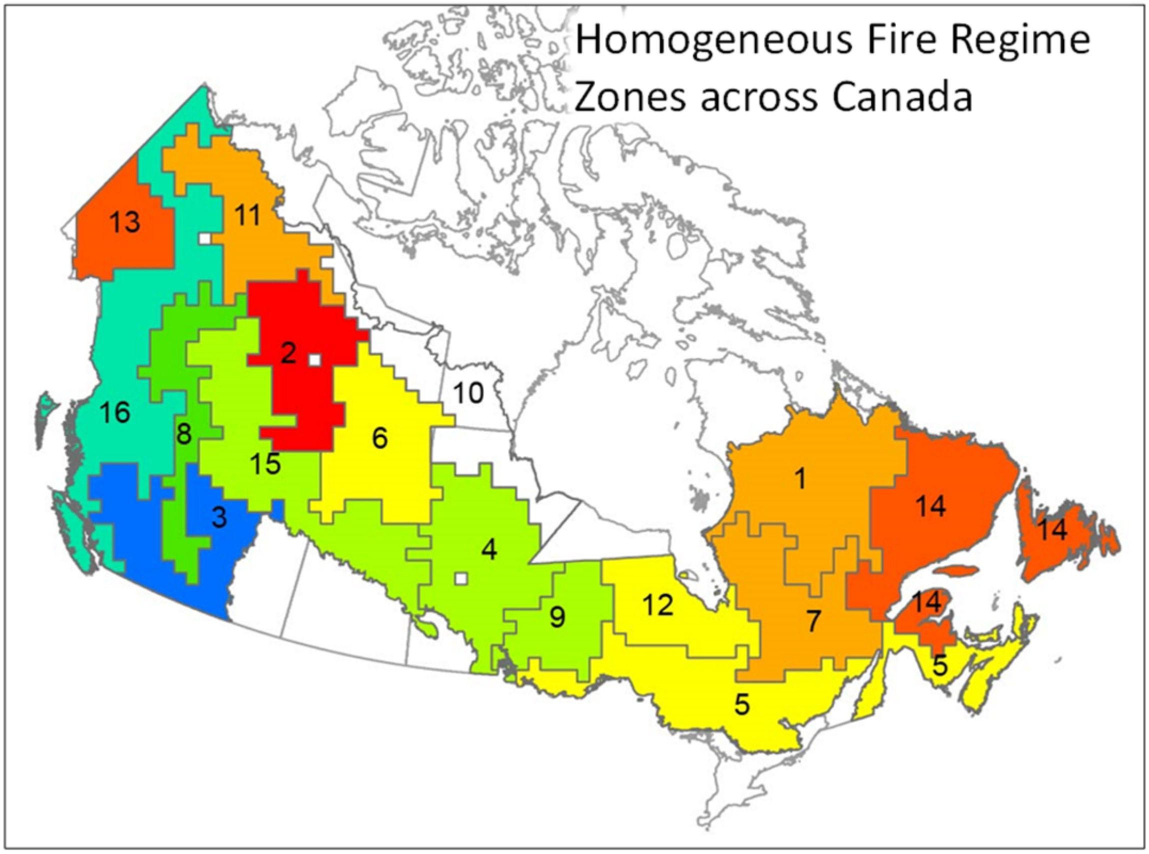


Figure 4. Homogeneous fire regime zones across Canada (Boulanger et al., 2014)

3.2.7 Forest Mills

Mill capacities and locations were collected from several data sources and reflected the state of Canada's forest sector as of 2014. The dataset was assembled and provided by Mathey as part of an integrated assessment examining the impacts of climate change on various aspects of the Canadian forest sector. Several other data sources were combined to provide further mill information for the model runs. Data from the Forest Economics Advisor (FEA, 2011) for softwood lumber, oriented strand board and plywood producers was used to obtain mill name, ownership, location and capacity. The Madison Lumber Directory (2011) was used to gather further information about lumber and panel mills. A third database was compiled by a research group at the University of Toronto (Krigstin et al., 2012) that tracked lumber mills in eastern Canada. Finally, a dataset provided by FisherSolve (Fisher International, 2013) contained detailed information on pulp and paper manufacturers. Because most pulp and paper mills use forest residues as their primary input, only mills that used raw log timber as a direct input in their operations were considered for that dataset. The current national capacity of the mills, after filtering out very small mills with annual capacity below 2500 m^3/year, was estimated to be approximately 180 million m^3, which is above the average nationwide harvest levels over the last 20 years. Nevertheless, because the policy interest behind this modelling activity was the degree to which harvests could supply "current" mill capacities, this was the target used in the modelling. All interpretations should keep this in mind.

Forest fires disturbances have always been a natural and essential part of boreal forest ecosystems. A warming climate may produce challenges at the interface of communities and forests.
Photo credit: Bo Lu, (left); CFS (right) Natural Resources Canada

3.2.8 Forest Succession

Changes in forest succession were not incorporated into the current set of model simulations, thus tree species composition was assumed to be unchanged after harvest or fires. We recognize that this is somewhat unrealistic, but note that the timber harvests for the time horizon in the study would, for the most part, be driven by forests already in existence unless there were significant forest management policy changes. Our modelling framework could be easily adapted to include succession rules in the future, when such information becomes available.

3.2.9 Forest Insects and Diseases

Similar to forest succession, we did not represent any climate change-driven impacts from insects and diseases on forest growth and yield. We note that impacts of forest insects and diseases are already implicitly embedded into growth and yield models used in forest planning. While numerous studies have examined potential range shifts associated with these taxa due to climate change (e.g., http://gmaps.nrcan.gc.ca/bmid/index.php?action=intro&lang=e), generating credible estimates of future impacts on forest growth is very challenging. Incorporating these kinds of effects will be the subject of future efforts.

3.3 CFS Forest Bioeconomic Model (CFS-FBM)

CFS-FBM model is a bioeconomic spatial simulation tool that performs biophysical and economic calculations in a grid-based spatial domain (Yemshanov et al., 2009; 2012a; 2014). It was originally developed to undertake economic assessments of carbon sequestration in forest stands, so it uses basic partitioning of biomass pools and forest growth concepts from the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3, Kurz et al., 2009). The model has been used in the past to estimate the costs of carbon sequestration (Yemshanov et al., 2005, 2012a), the economic impacts of exotic pest invasions (Yemshanov et al., 2009, 2012b) and economics of land use change (Yemshanov et al., 2015). The model is described in detail in the references provided above; here we provide a brief overview of the features germane to the current effort. Conceptually, the model can be thought of as a coarse-scale simulator of tree biomass growth and disturbances (fire), linked to a relatively simple rules-based harvest allocation and cost-benefit model. Here we use the model to simulate forest growth, fires and harvests in 1-year time steps for the period from 2011 to 2100, with and without climate change and using the CanESM2 RCP 8.5 climate change scenario (Chylek et al., 2011). The impact of climate change on wood supply was estimated by comparing delivered wood costs assuming current climate conditions to the scenario assuming climate change. Our choice of the RCP 8.5 scenario reflects our desire to explore the impacts of the most severe climate change scenario on timber supply. We note the analyses presented here used only the CanESM2 model. Future analyses will examine other models and other RCPs.

3.3.1 Forest Yields and Disturbances

To estimate merchantable volume for any given map cell, the CFS-FBM model employed the cell's age and PCP-MAT identifier which both refer to an appropriate yield curve to obtain per hectare volume estimates (m^3/ha) for each species group from the set of merchantable volume tables described in Section 3.2.4. These estimates were then multiplied by the size of the cell (i.e., 500 x 500 m) and the proportional composition (i.e., within a 0-1 interval) of each species group to arrive at a final volume (m^3) estimate. To account for adjustments to tree productivity under the climate change scenario, these volume estimates were multiplied by the NPP modifiers described in Section 3.2.4.

Fire disturbance was simulated with a fire regime model that assumed an exponential distribution of fire return intervals and used regional estimates of fire regime parameters (see Section 3.2.6) to generate fire disturbance events. Note that the fire regime model did not try to fit the particular size distribution or the number of individual fires to expected distribution shape as some other fine-scale landscape disturbance models have done; rather, the model essentially tracked the impact of fire regime changes at a regional level. Under the climate change scenario, fire return intervals are generally expected to get shorter due to longer fire seasons and periods of dryer and hotter conditions.

Note that, each year, the model first simulated tree growth from the normal yield curves and then implemented the occurrence of fire disturbances via stochastic random draws from the exponential fire regime model.

3.3.2 Timber Allocation and Harvest

In our study, the allocation of harvest regions around individual mills and wood processing facilities (wood sheds) was done in a dynamic fashion, on an annual basis (described further below). These regions provide the bulk of the wood supply for forest mills and industrial wood users. This approach provides more flexibility in the search for areas to harvest for individual mills than a static or fixed wood shed (e.g., based on administrative units). Since our intention was to use the mill-specific harvest levels only as a reference point for local wood demand, our preference here was to use simple heuristic harvest allocation algorithms (Bettinger et al., 2002) rather than optimization techniques. The heuristic approach is arguably better suited to deal with the coarse-scale model assumptions and processes.

The wood shed allocation algorithm was designed as follows: the model first estimated the current landscape's total wood supply given the current forest age, map of recent disturbances and species composition. Each spatial location (map cell) was assigned with the amount of wood that could potentially be harvested in the given year. The map cells in the forest management area were then allocated among individual mills in an iterative process, one cell at a time, starting from the locations closest to the mills and proceeding until the specified portion of the landscape's wood supply is allocated among all mills. To ensure that clustered mills get their share of wood supply, the area was divided into the random subsets and the allocation was done iteratively, one subset at a time and so on, until the entire supply of standing wood was apportioned among mill-specific wood sheds. The allocation algorithm has also ensured that the wood supply in the wood sheds is proportional to the distribution of individual mill wood consumption capacities.

Once each mill was assigned its wood shed area at a given simulation year, the second stage selected the map cells to be harvested within a given wood shed based on the mill's wood consumption capacity. We used a scoring method that prioritizes the selection of each mill's harvesting locations based on the present value of timber revenues, net of harvest and transportation costs:

$$NPV = (MV \cdot MGP) - (MV \cdot DIST \cdot TC) - (MV \cdot HC) \quad [1]$$

where NPV is the net present value of the stand from the mill's perspective, MV is net merchantable volume of the stand (in m3), MGP is the assumed mill gate price ($40/m^3), DIST is the distance from the stand to the mill, TC is the transportation cost ($0.32/m^3/km for British Columbia and Alberta, and $0.22/m^3/km for the rest of the country (Forrester et al., 2006)), and HC is the fixed tree-to-truck harvest cost ($20/m^3). Royalty or stumpage fees, silvicultural and/or regeneration costs are not explicitly included in the current study.

The harvest allocation starts from the map cells that had the highest present value of net timber revenues and continues until the harvest target (identified by mill capacity) is reached or until all potential harvest sites within the wood shed have been allocated. During the allocation of harvest sites, the model tracks the costs of the harvest and wood delivery, as well as "wood shortages" which occur when the amount of harvestable wood in a wood shed is insufficient to cover the mill demand. In this case, the assessments of changes in timber supply costs need to be carefully interpreted because the harvest level is lower and actually occurs on a smaller harvest footprint, therefore the estimate of the changes in the transportation costs may not be accurate. Hence a wood shortage is reported rather than a change in delivered wood cost. We also report "harvest failures", which occur when a mill is unable to harvest any wood in a given year; such a phenomenon is invariably accompanied by massive wood shortages in the years preceding and following the failure or high frequency of disturbances so that the stands cannot reach the minimum harvest age. The impact of climate change on delivered wood cost and availability of wood supply was estimated as the difference between the simulation based on the current climate and the simulation accounting for climate change according to the RCP 8.5 scenario.


Forest management continues to need people who are passionate about forests and their profession.
Photo credit: Dan McKenney, Natural Resources Canada

Note that, due to computing constraints, the model simulations were undertaken at the provincial level. This does limit the area that the model may extract wood from for mills located close to provincial boundaries and hence affects results by restricting the opportunity for cross-provincial border harvests.

3.4 Results and Discussion

The CFS-FBM simulations were run using a 500 x 500 m spatial resolution and a total of 9,260,209 map cells that were allocated to mills over the simulation period. This is equal to approximately 231,505,225 ha of forested area, which is nearly identical to the area of managed forest as defined by the 2014 State of Canada's Forests Annual Report, when Prince Edward Island and the territories are excluded (Natural Resources Canada, 2014b). Table 10 summarizes the harvest parameters used in the CFS-FBM on a provincial basis. The table depicts provincial totals, the number of mills, and the area of forest allocated.

Table 10: CFS-FBM provincial harvest assumptions

Province	Total quantity of hardwood required (m^3)	Total quantity of softwood required (m^3)	Number of mills*	Area of forest allocated (ha)
Alberta	3,454,265	15,129,681	33	27,744,175
British Columbia	14,378,756	62,978,957	105	73,575,000
Manitoba	74,510	326,352	5	16,517,038
New Brunswick	1,149,404	5,034,392	25	4,066,025
Newfoundland and Labrador	102,567	449,241	11	4,263,562
Nova Scotia	624,234	2,734,147	37	5,082,200
Ontario	1,971,213	8,633,912	57	43,547,563
Quebec	14,523,015	47,181,880	187	42,250,938
Saskatchewan	235,041	1,029,478	7	14,458,738
Total	**36,513,005**	**143,498,040**	**467**	**231,505,239**

***Note:** Number of mills with capacity greater than 2,000m^3

To provide general context, Figure 5 shows the 2011 updated mill capacities, overlaid by the 2071-2100 RCP 8.5 fire regime zones of Boulanger et al. (2014). Also shown is the northern boundary of the zone of industrial forest management (sometimes referred to as the zone of undertaking). The map shows two main groups of mills. One group is in British Columbia and northern Alberta; many of these mills have capacities beyond 1.50×10^5 m^3 per year and a number of mills with capacities beyond 1.5 million m^3 per year. These mills are mostly located in the least severe fire regime zone. The other large group of mills spans from eastern Ontario to New Brunswick; the capacity of these mills is typically 1.50×10^5 m^3 or less. Most of the mills in eastern Canada are also located within the least severe fire regime zone, although there are a number of mills located in northern Quebec where fire regimes are expected to be severe under future climate scenarios.

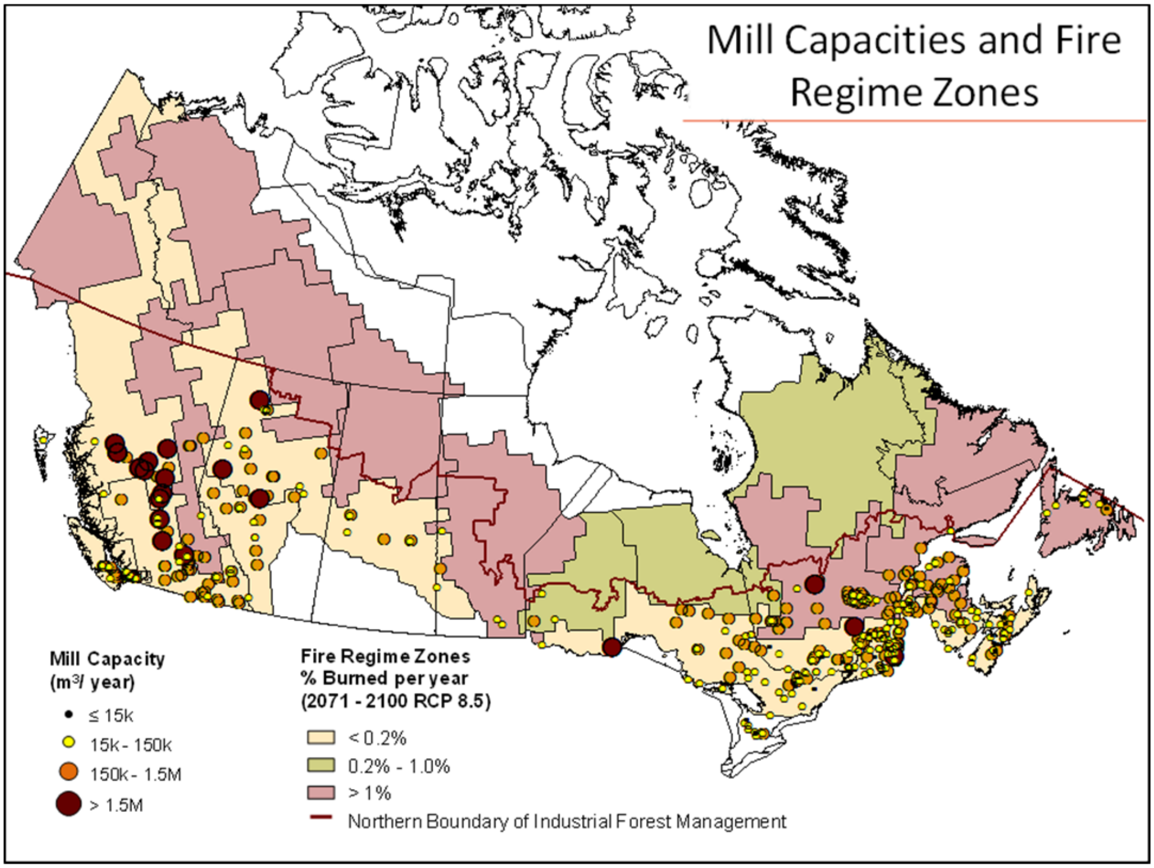


Figure 5. Mill capacities and fire regime zones across Canada.

Figure 6 provides a summary of changes in delivered wood costs at the level of individual mills, by province. Each cell within a band represents a mill; the three layers in each band represent different forecast horizons based on the RCP 8.5 scenario. Two bands are provided for each province, demonstrating changes in delivered wood costs for softwood and hardwood species. The colour of the individual cell reflects the magnitude of the increase in costs, with blue representing almost no change, and red representing large positive changes; grey areas indicate wood supply shortages (i.e., where the amount of standing wood appears insufficient to meet the existing forest mill capacities). Near-term forecasts to 2040 suggest that many mills will see some level of wood supply cost increase. British Columbia hardwood mills would see larger increases in wood supply costs. Under the 2070 projection, softwood mills in British Columbia would experience ongoing increases in wood supply costs. Softwood mills in Quebec may also experience wood supply shortages, while hardwood mills would experience ongoing increases in supply costs. Mills in the other provinces may also be subject to moderate increases in costs. The longer-term forecast horizon (2100) suggests larger increases in wood supply costs for both softwood and hardwood mills in British Columbia, with timber shortages likely for select hardwood mills. Similarly, hardwood mills in Quebec may also experience large cost increases and supply shortages, while softwood mills could face some shortages, but lesser cost increases. The remaining mills in other provinces may experience moderate increases in wood supply costs.

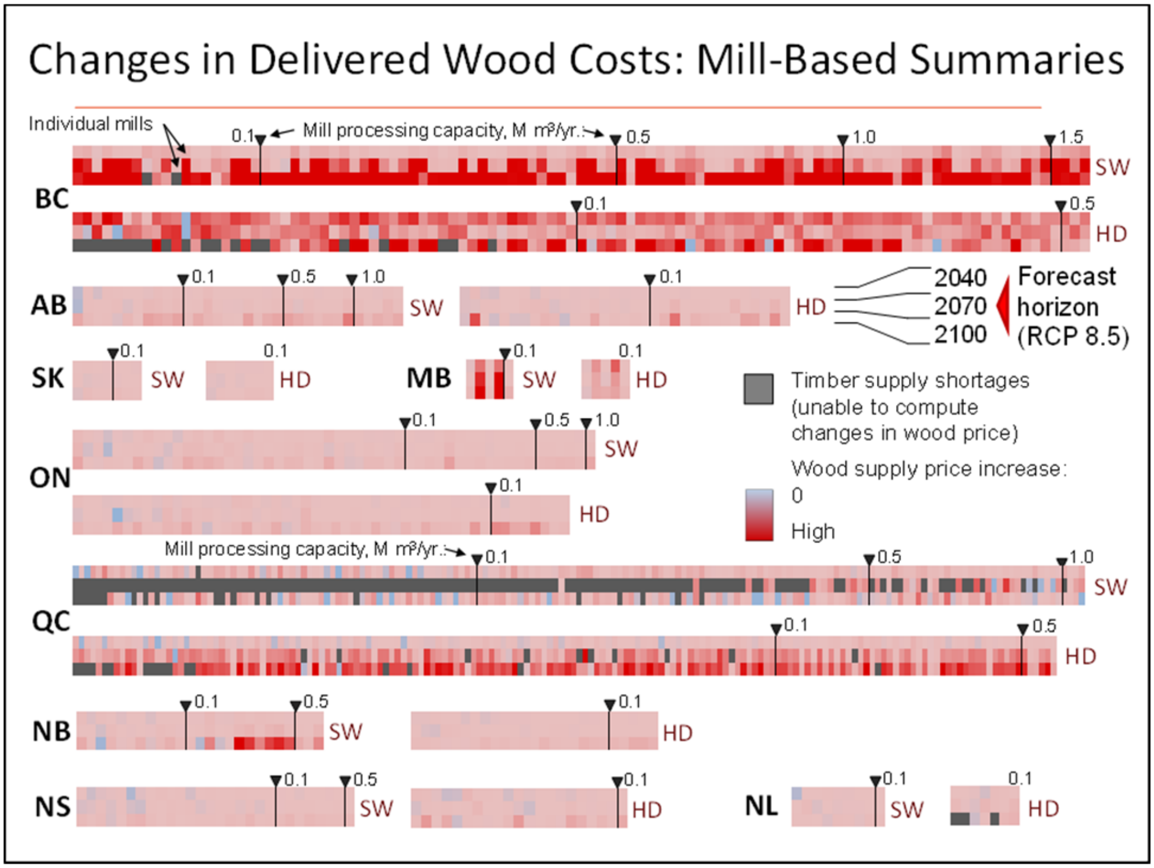


Figure 6. Changes in delivered wood costs at mill gate for three future time periods under RCP 8.5. The highest increases are shown in bright red and wood supply shortages are shown in gray.

Figures 7 and 8 illustrate the changes in softwood supply costs from 2041 to 2070 and from 2071 to 2100 respectively, as the difference between the scenario with no climate change effects and the RCP 8.5 climate change scenario. For the 2041-2070 period, mills in British Columbia and Manitoba are projected to experience significant climate change impacts, with some mills experiencing cost increases of more than \$25/m^3 (> 25%). Furthermore, many mills in Quebec are projected to experience wood supply shortages during this time period. Mills in Alberta, Ontario and the Maritime Provinces may see modest increases in wood supply costs of up to \$10/m^3 (< 10%).

Figure 8 indicates that, for the 2071 to 2100 period, British Columbia and Manitoba are projected to experience continued climate change impacts, with many mills facing wood supply cost increases beyond \$25/m^3 (>25%). Wood supply in Quebec is projected to recover somewhat by this period, with the majority of mills experiencing wood supply cost increases of \$10/m^3 or less (<10%). The remaining mills across the country continue to experience relatively moderate increases in supply costs of less than \$10/m^3 (<10%), though a number of mills show cost increases relative to the 2041-2070 period.

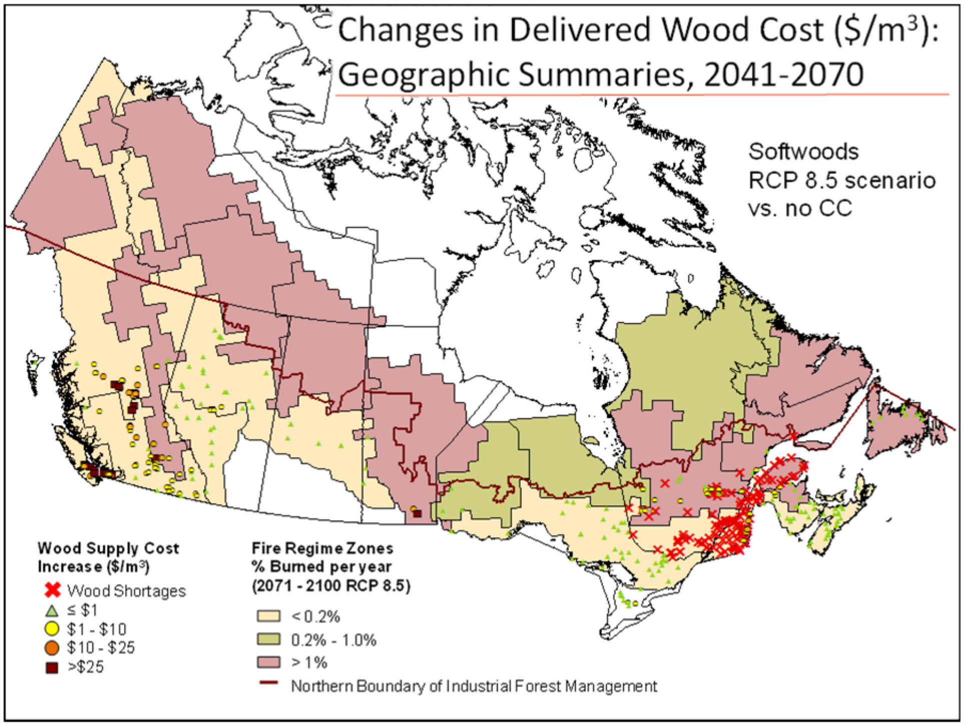


Figure 7. Projected changes in softwood supply costs at Canadian mills for the 2041-2070 period with 2071-2100 fire regime zones.

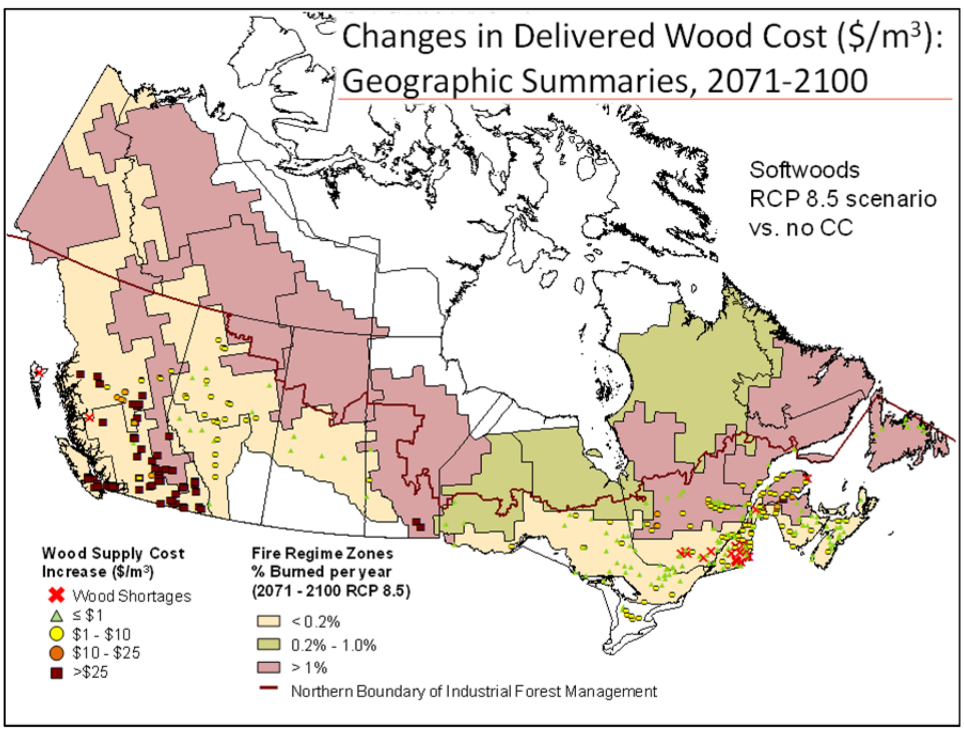


Figure 8. Projected changes in softwood supply costs at Canadian mills for the 2071-2100 period with 2071-2100 fire regime zones.

Figures 9 and 10 illustrate climate change impacts on hardwood supply costs for the 2041-2070 and 2071-2100 periods respectively. Generally, climate change impacts on hardwood supply appear less severe than those described above for softwood supply. For the 2041-2070 period, mills in British Columbia could face increases in wood supply costs, ranging from less than $1/m^3 to approximately $25/m^3 (<25%). In Quebec, many mills may see cost increases in the $1-$10/m^3 (1% - 10%) range; while a limited number in the eastern portion of the province are projected to experience wood supply shortages. Across the remainder of the country, mills could see increases of up to $10/m^3 (<10%). For the 2071-2100 period (Figure 10), a number of mills in British Columbia are projected to experience wood shortages or increases in supply costs of greater than $25/m^3 (>25%). These impacts are largely restricted to mills in the southern portion of the province. Similarly, many mills in the southern and central regions of Quebec are projected to experience hardwood shortages or significant cost increases (>25%). Note, however, that our assessment does not include potential wood imports from the northeastern US, which may help to reduce these shortages. Mills outside of these key regions are mostly projected to experience wood supply cost increases of <$10/ m^3 (<25%) though several mills in Newfoundland could experience wood supply shortages.

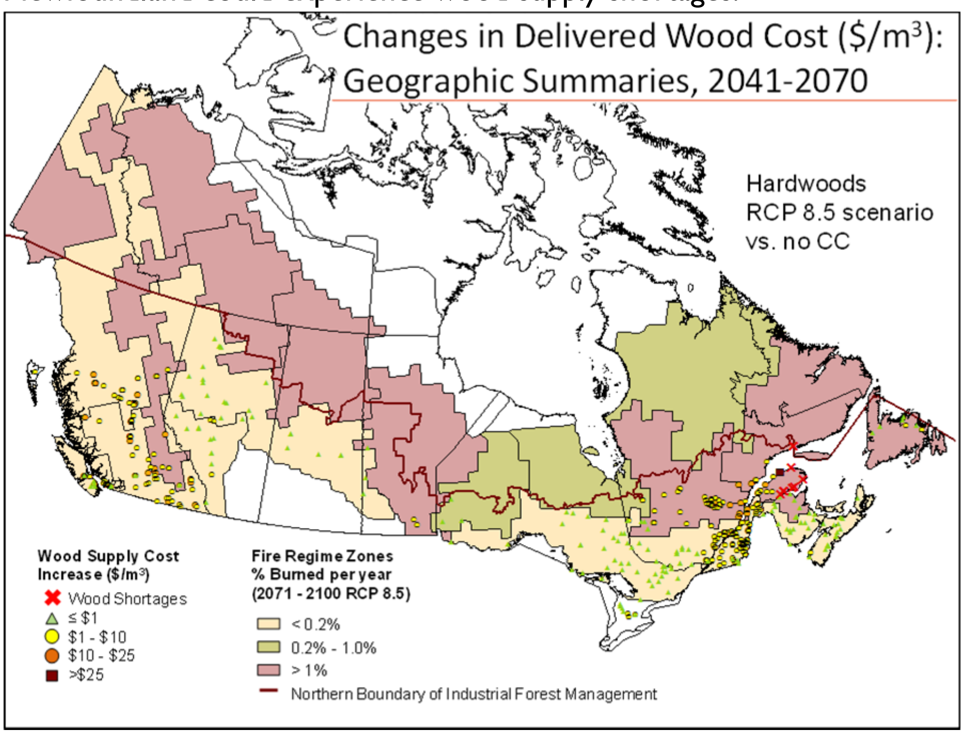


Figure 9. Projected changes in hardwood supply costs at Canadian mills for the 2041-2070 period with 2071-2100 fire regime zones.

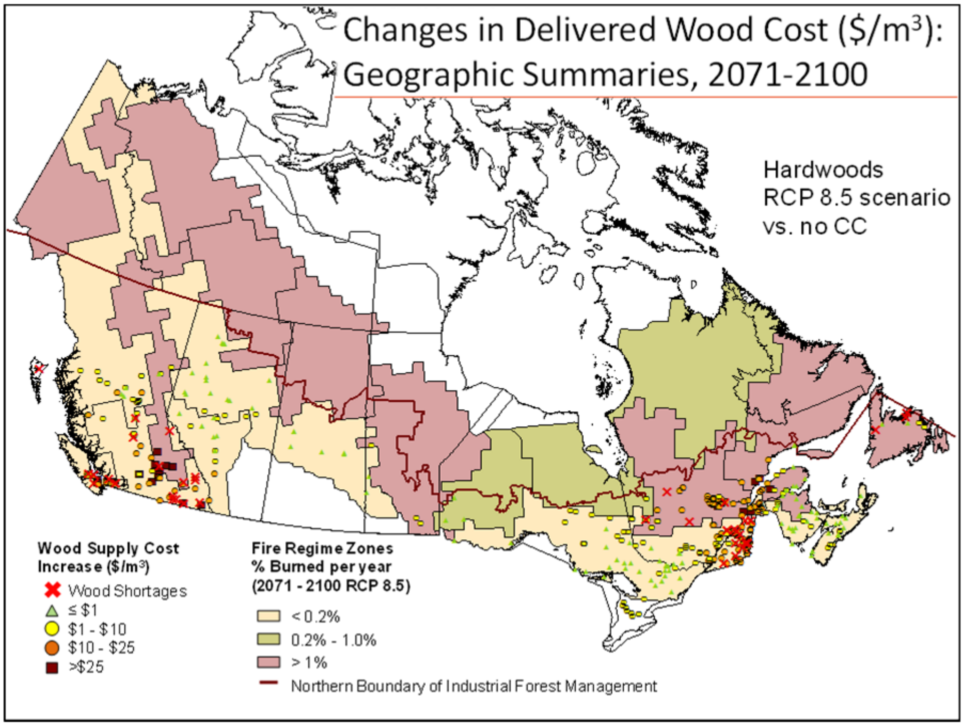


Figure 10. Projected changes in hardwood supply costs at Canadian mills for the 2071-2100 period with 2071-2100 fire regime zones.

Figures 11 and 12 illustrate softwood supply shortages for the 2041-2070 and 2071-2100 periods respectively. As noted above, wood supply shortages refer to reduced wood volumes available for harvest under the climate change scenario (expressed as a percentage of the wood volume available under the no climate change scenario), while wood failures refer to years in which little or no wood is available for harvest. Softwood supply failures are projected for the majority of mills in Quebec during the 2041-2070 period (Figure 11). Most mills outside of Quebec are projected to experience relatively minor softwood shortages during this period – generally less than 2% of mill capacity. For the 2071-2100 period (Figure 12), many mills in British Columbia could experience moderate (10% – 25%) to severe (>25%) softwood supply shortages. In Quebec, the majority of mills are projected to experience moderate (10%-25%) to severe (>25%) softwood shortages, with a number of mills in southern Quebec projected to experience softwood supply failure. Mills in the rest of Canada may see decreases in softwood supply of less than 2% of annual mill capacities.

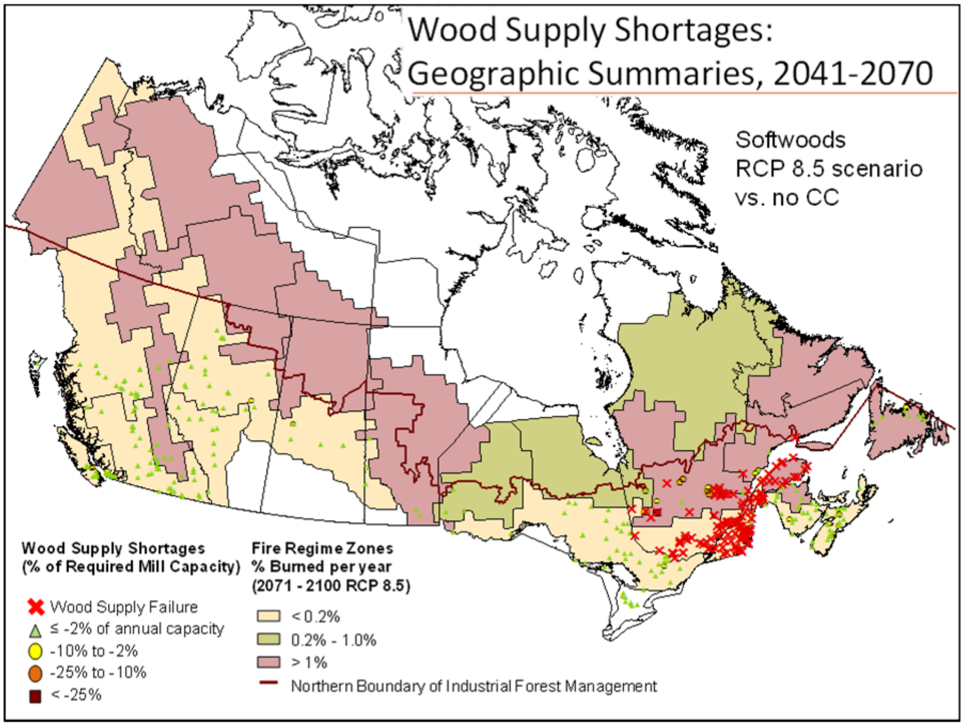


Figure 11. Projected softwood supply shortages at Canadian mills for the 2041-2070 period with 2071-2100 fire regime zones.

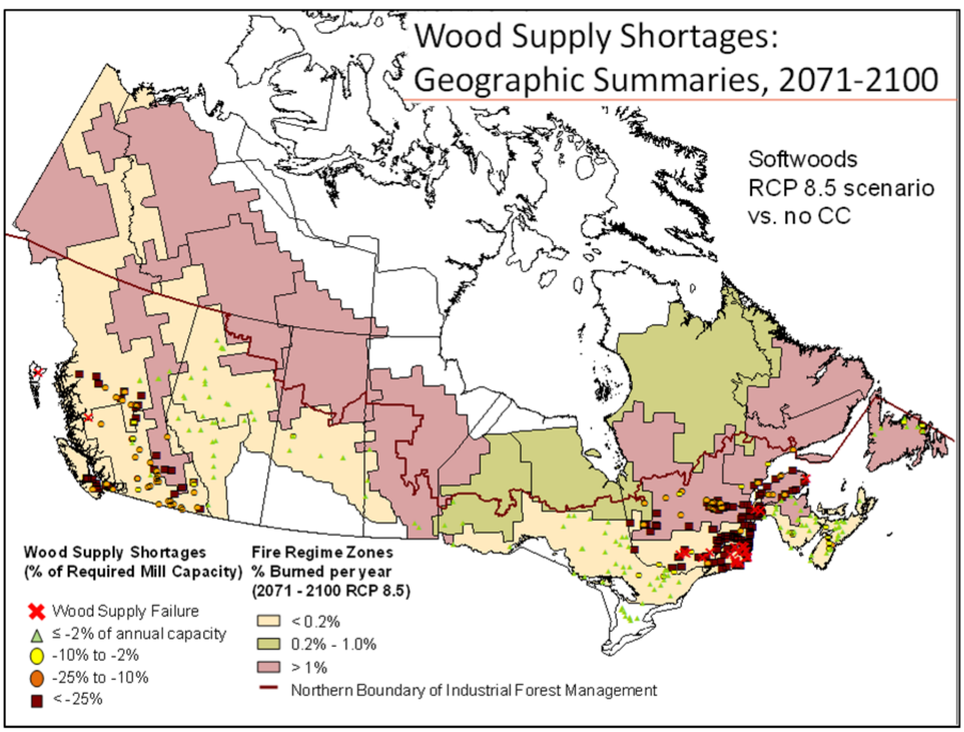


Figure 12. Projected softwood supply shortages at Canadian mills for the 2071-2100 period with 2071-2100 fire regime zones.

Figures 13 and 14 illustrate future hardwood supply shortages and failures. For the 2041 to 2070 period (Figure 13), climate change is projected to have a relatively minor impact on hardwood supply at most mills across the country; however, several mills in eastern Quebec could suffer wood supply failures. From 2071 onward (Figure 14), hardwood supply in British Columbia is projected to be highly variable, with some mills projected to experience minor hardwood supply shortages (<2% of operating capacity) and others experiencing severe shortages (>25% of operating capacity) or hardwood supply failures. Similarly, mills in Quebec and Newfoundland may experience a wide range of hardwood supply impacts toward the end of the current century – with the majority of mills projected to experience moderate to severe shortages (10-25%) or wood supply failures. Mills in the rest of the country are projected to experience relatively minor hardwood supply shortages (< 10%).

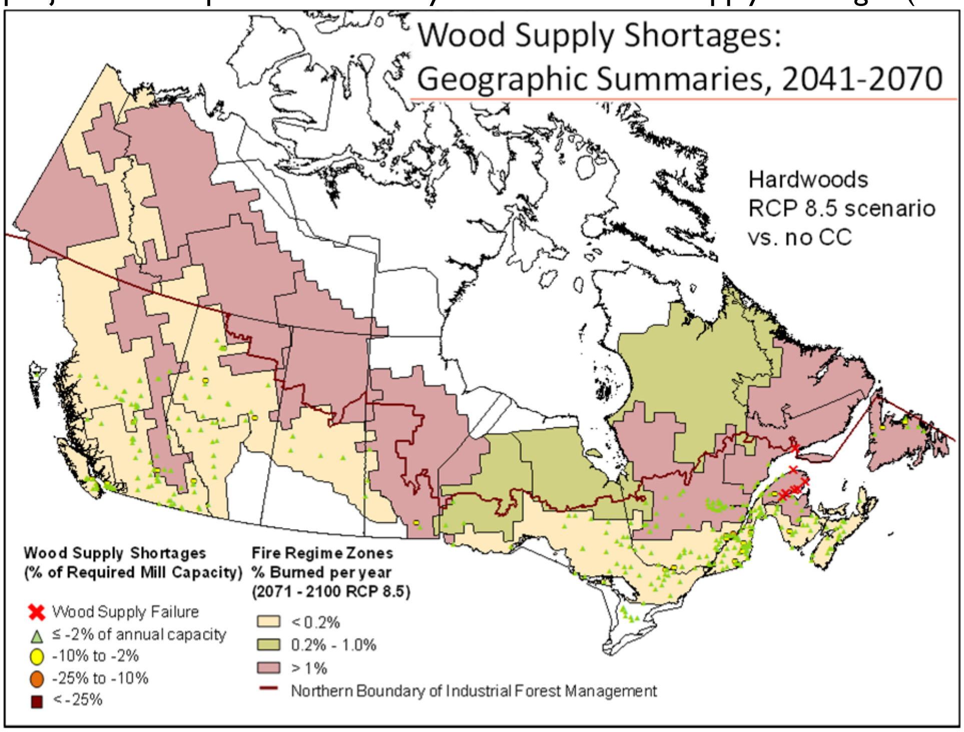


Figure 13. Projected hardwood supply shortages at Canadian mills for the 2041-2070 period with 2071-2100 fire regime zones.

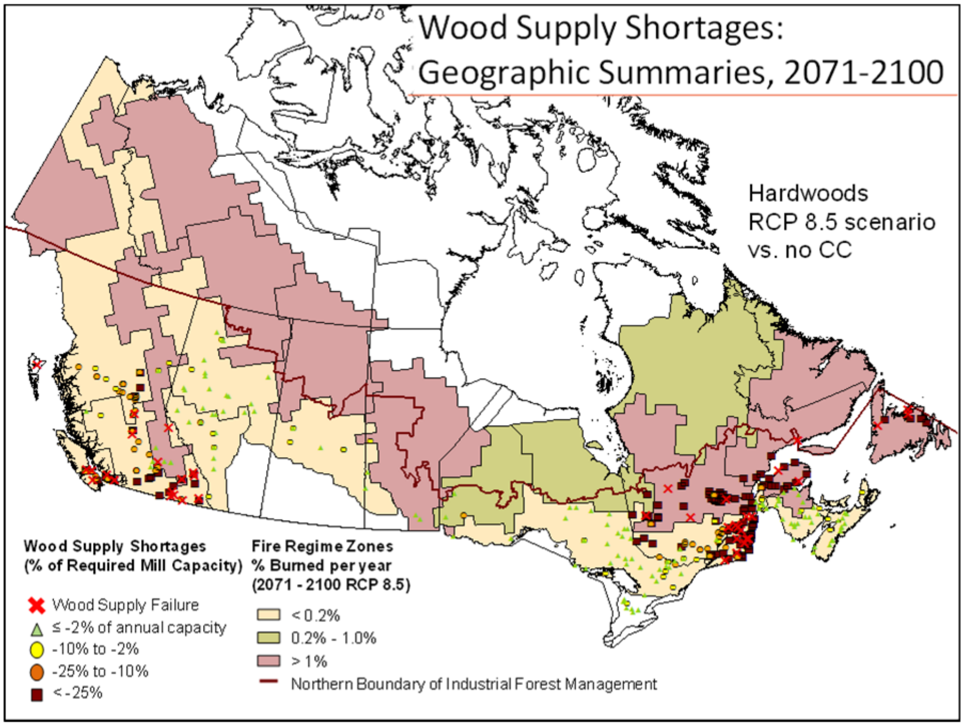


Figure 14. Projected hardwood supply shortages at Canadian mills for the 2071-2100 period with 2071-2100 fire regime zones.

4.0 Discussion and Conclusions

This effort provided estimates of climate change impacts on delivered wood costs and volumes at mills across Canada. By necessity, the analyses undertaken here are very different than those typically carried out on forest management units, which employ high resolution spatial data to identify timber and non-timber values and a sequence of harvest blocks for future harvesting. To our knowledge, this is the first study to incorporate climate change into a spatially explicit, national-scale timber supply analysis (but see also Gauthier et al., 2015 who examined timber supply vulnerability to fire regime changes). As such, it provides a valuable extension to the (mostly non-spatial) Runyon (1990) report, which presented a snapshot of Canadian timber supply roughly 25 years prior to the current assessment.

In section 3.4 of that report, Runyon (1990) provides an outlook for medium-term (i.e., 20-30 years) timber supply in Canada:

"Information on timber supply outlook provided by the provinces indicates that the current levels of softwood harvest can be sustained for the medium term assuming that current management practises and market conditions remain unchanged from current levels. There is also potential for expansion of hardwood harvests."

This statement has largely proven to be true, with harvest levels remaining relatively steady since the 1990s (see Fig. 1) – apart from the sharp decline in timber harvest levels around 2009. As noted previously, this decline was associated with a global financial crisis and a generally declining demand for wood products, which Runyon identified as potential drivers of harvest level variations.

Runyon (1990) also provides an outlook for longer term (i.e., beyond 30 years) timber supply:

"Generally, existing provincial analyses indicate the opportunity for an increased timber supply in the long term. This view, however, is very much conditional on maintaining or expanding the current level of effort in forest regeneration, in improved protection, technological advances in utilization, etc., and on maintaining the currently allocated forest land base for timber production."

This outlook would presumably overlap with some of the analyses provided here, particularly for the 2011-2040 time period; however, few detailed comparisons can be drawn between the two studies. Perhaps most instructive is the fact that climate change was not a prevalent concern at the time of the Runyon report, yet is the main focus of the current effort. Similarly, the ongoing mountain pine beetle outbreak, which was entirely unforeseen in 1990, will have implications for Canadian timber supply for decades to come. The manifestation and timing of these unforeseen drivers (as well as other economic and technological shocks) underline the importance of exercising caution when interpreting timber supply projections – particularly in the long term. Nonetheless, the current study provides a number of insights into potential climate change impacts on timber supply, which are summarized below.

4.1 General Observations (All periods)

A number of general observations are provided here which cover all time periods.

- The results identify two large regions (parts of British Columbia and Quebec) in the country that could experience major wood supply shortages and/or increased wood supply costs as a result of climate change. These two regions are the source of most of the wood production in the country.
- The impacts of climate change on wood supply are likely to be magnified in regions with high concentrations of mills (e.g., southeastern Quebec) where competition for available merchantable biomass is high.
- Mills outside of the highest producing regions (those in Alberta, Saskatchewan, Manitoba, Ontario and Atlantic Canada) are projected to see a moderate impact on their operations as a result of climate change; wood supply costs at these mills are projected to increase slightly. However, although the results of the current CFS-FBM assumptions do not reveal significant impacts for mills in these regions, future alternative scenarios may yield different results.
- It is important to keep in mind that the results from the current simulation study are somewhat optimistic given that, in addition to the maximum harvest base allocated, potentially important wood-supply decreasing disturbances such as drought and insects were not considered at this time.
- Given that the impacts of climate change on forest growth, disturbances, and the availability of local wood supply are at least partly stochastic (i.e. the location and effects of large scale fires through time are impossible to predict with precision or accuracy), the magnitude of the effects of climate change will always remain highly uncertain and difficult to determine with any fine geographic precision.

4.2 Possible Short Term Implications (2011-2040)

- Short-term projections to 2040 indicate that many mills may see some level of wood supply cost increase with the climate change projection used here.
- In British Columbia, a majority of hardwood mills are projected to experience increases in wood supply costs, with some experiencing cost increases in the 10-25% range. More than 50% of softwood mills are projected to see a moderate increase in costs (1-10%).
- While many mills in Quebec may not experience significant cost increases, approximately 20-25% of the mills are projected to experience a moderate increase in wood supply costs (1-10%).
- Only a few mills in the other provinces are projected to have moderate increases in wood supply costs.

4.3 Medium Term Projection (2041-2070)

- In British Columbia, both softwood and hardwood mills are projected to experience continued increases in wood supply costs. While cost increases may be less severe for hardwood mills, there are significant increases projected for softwood mills in comparison to the short-term.
- Many softwood mills in Quebec may experience wood supply shortages, while hardwood mills may see significant increases in supply cost. These projected mid-century softwood shortages reflect the abundance of young forests at the start of the simulation that are not suitable for harvesting until the mid-to-late portion of the century.
- Some mills in the other provinces may experience modest increases in wood supply costs, however the overall proportion of mills experiencing cost increases remains relatively low.

4.4 Long Term Projection (2071-2100)

- Large increases in wood supply cost are projected for both softwood and hardwood mills in British Columbia, with timber shortages likely for select hardwood mills. A majority of softwood mills may face wood supply cost increases greater than 25% and hardwood mills may experience a range of cost increases and/or wood supply shortages.
- Similarly, hardwood mills in Quebec may experience large cost increases and supply shortages. A small portion of softwood mills in Quebec may also face shortages and about 50% are projected to continue to face significant cost increases. The rebound in softwood supply at the end of the century (i.e., compared to the widespread shortages projected for mid-century) reflects the pulse of stands that reach harvestable age by the mid-to-latter part of the current century. Harvest costs remain high however, due to the high density and capacity of mills in this province.
- In contrast to the short and medium term periods, a significant portion of both softwood and hardwood mills in other provinces (greater than 50%) are projected to experience moderate increases in wood supply cost.

4.5 Future Research

Below we identify a number of avenues for future research, ranging from relatively minor additions to the current modelling framework to major extensions.

- Incorporate outputs from multiple climate models and emissions scenarios to address the significant uncertainty in future climate projections (including related impacts on forest growth and disturbance regimes).
- Undertake sensitivity analyses to assess the importance of various model parameters, especially in regions where shortages and cost increases appear most significant.
- Explore the potential of replacing the heuristic harvest allocation algorithms with optimization-based routines. This could help identify the effectiveness of adaptation options to minimize climate change impacts.
- Explore approaches to generate improved growth and yield and forest inventory estimates across the country, both of which are areas of active research.
- Examine the possibility and implications of using mill-based harvest targets, instead of mill capacities, as a means to improve the accuracy of model results.
- Continue efforts to accurately map the harvestable land base across the country, including a better delineation of public and private lands that are available for harvesting.
- Incorporate disturbances other than fire into the model, including insect outbreaks and drought.
- Explore the role of trade across provincial and national (i.e., from the US) boundaries in meeting timber supply targets.
- Incorporate silvicultural impacts (e.g., site preparation, competition control, genetic improvements, etc.) into growth and yield estimates (which currently reflect natural stand development).
- Incorporate a module that tracks carbon fluctuations related to timber supply and reports on related bioeconomic parameters.
- Incorporate successional rules that would reflect expected shifts in species composition in the context of 'natural' regeneration under climate change.
- Explore the potential to incorporate other economic drivers/factors into the modelling framework, including: dynamic mill networks, variable harvest targets through time, trends in global wood supply and demand, technological advances in both wood utilization and forest management and economic analyses of forest management investments.

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Appendix 1

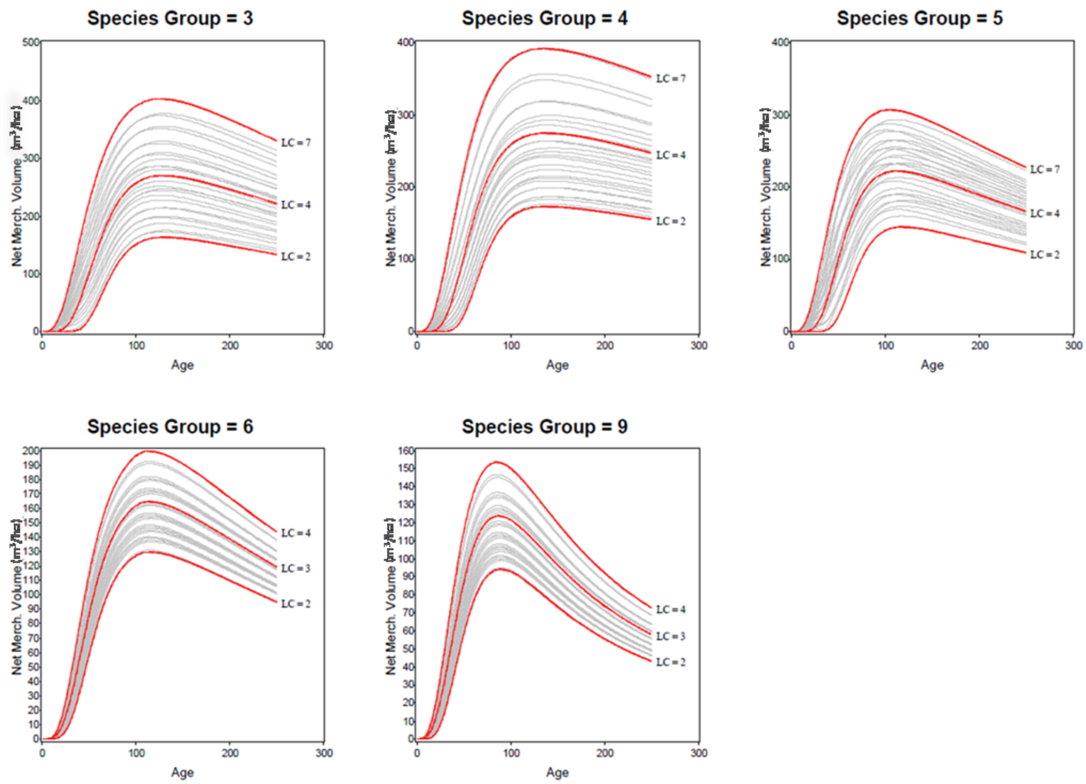
Table 1: Distribution of the world's productive forest land

	Forest Area (1000 ha)	% of World	Productive Forest (1000 ha)	% of World	Population (1000)	Person/ha of Forest land
Africa	674,419	17%	186,027	16%	987,280	1.5
Asia and Pacific	862,710	21%	276,867	24%	4,110,247	4.8
Europe	1,005,001	25%	524,620	46%	731,805	0.7
Latin America (Central and South) and Caribbean	890,782	22%	83,378	7%	467,650	0.5
North America	678,958	17%	97,138	9%	453,543	0.7

Source: FAO, 2013

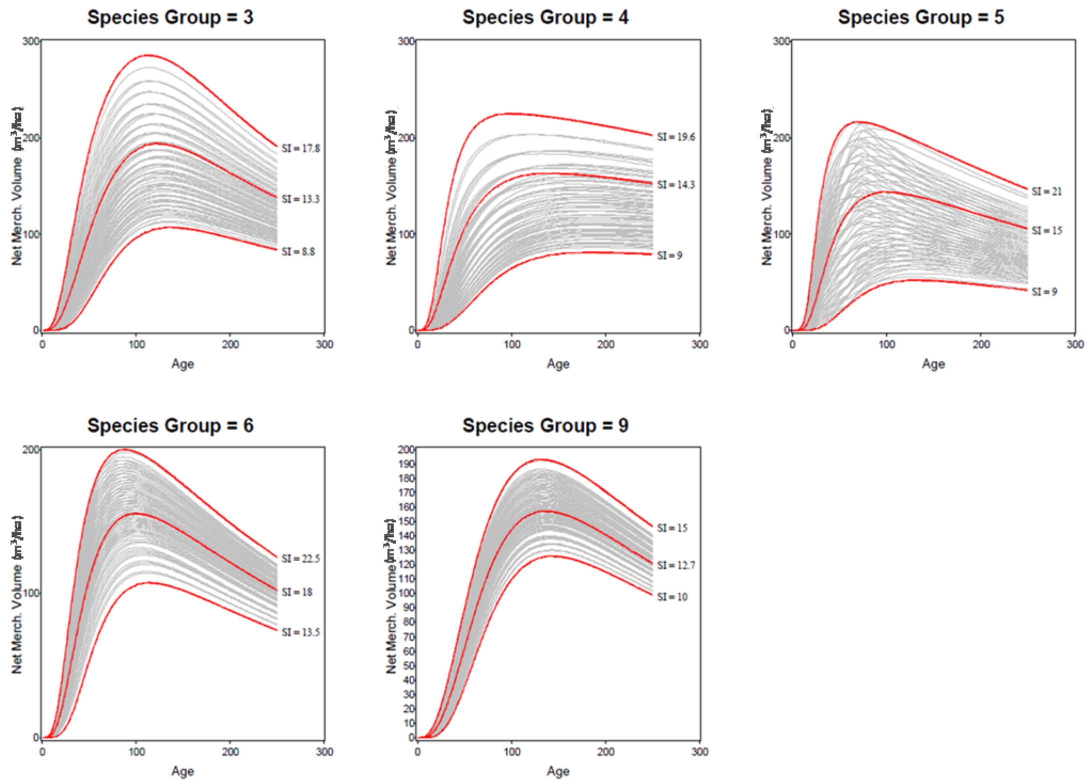
Appendix 2

Figure 1: Nova Scotia (Maritimes) Yield Curves



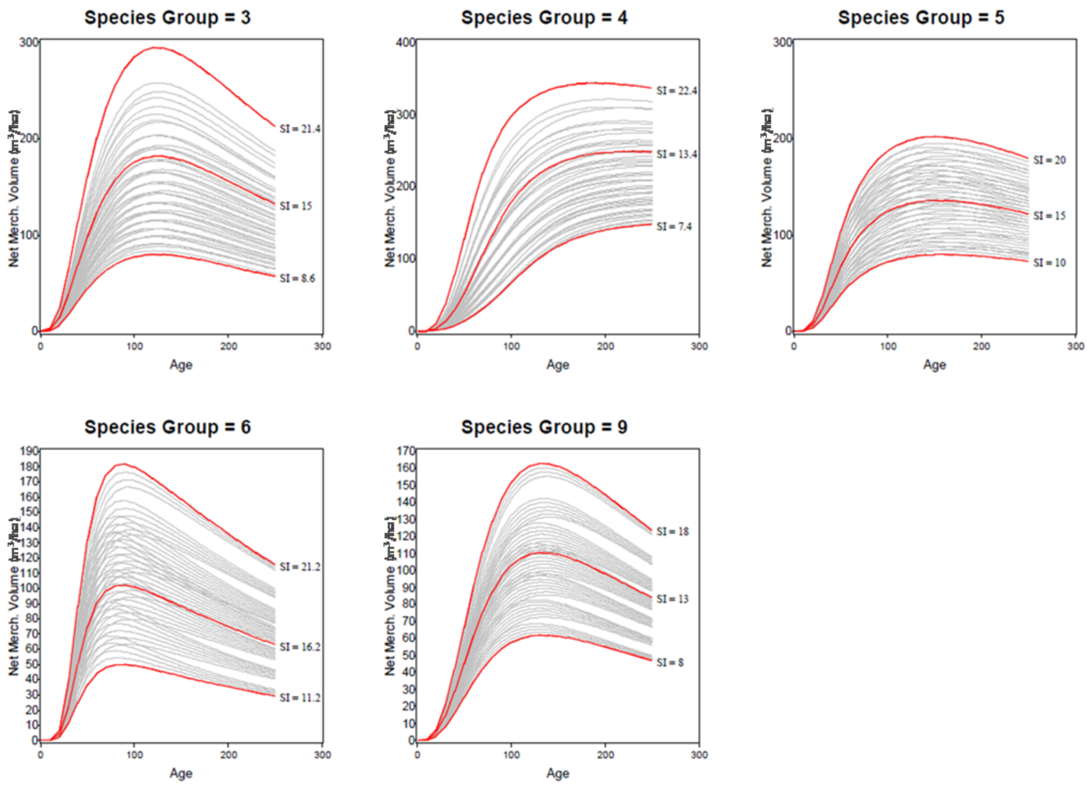
Note: Yield curves based on species groups contained in Table 1 (where present), used for Timber Supply Assessment of Natural Resources Canada's Integrated Assessment for the Maritime Provinces (New Brunswick, Prince Edward Island, Nova Scotia, and Newfoundland). Red lines denote the provincial minimum, mean and maximum curves derived from provincial yield table generator, grey lines indicate results of Ung et al. 2009 aggregated curves, constrained by provincial minimums and maximums. Land Capability Classes are provided for each of the provincially calculated curves.

Figure 2: Quebec Yield Curves



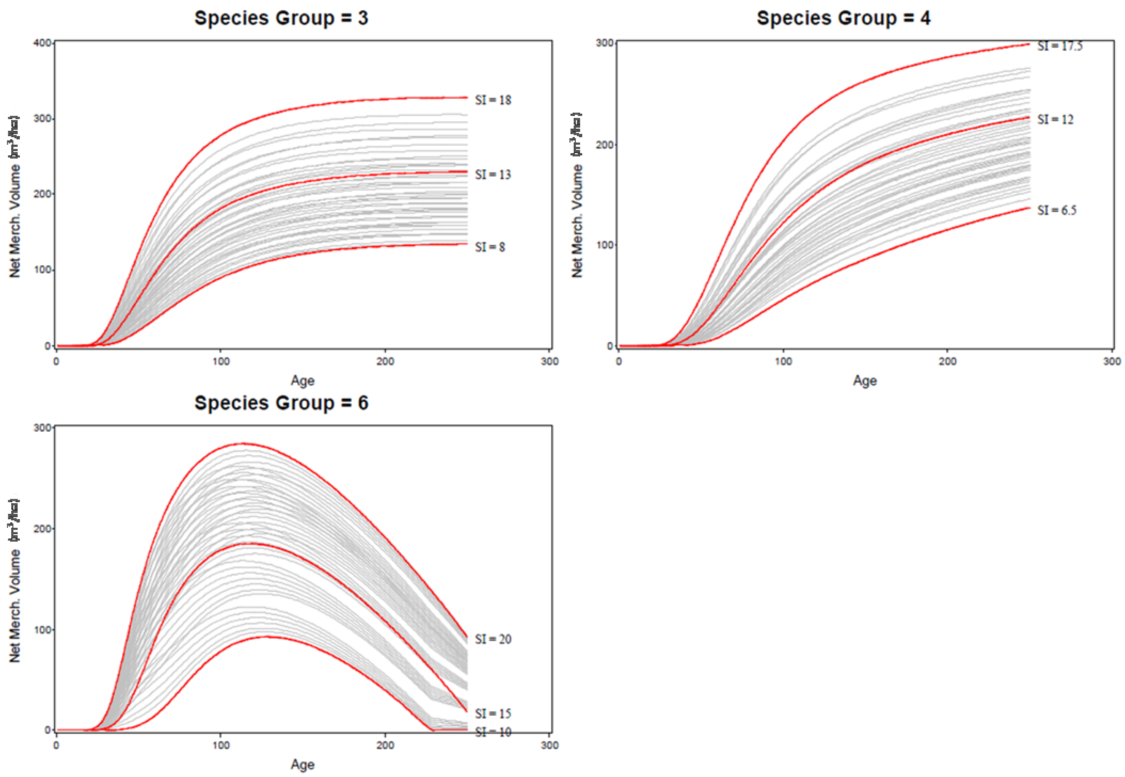
Note: Yield curves based on species groups contained in Table 1 (where present), used for Timber Supply Assessment of Natural Resources Canada's Integrated Assessment for the province of Quebec. Red lines denote the provincial minimum, mean and maximum curves derived from provincial yield table generator, grey lines indicate results of Ung et al. 2009 aggregated curves, constrained by provincial minimums and maximums. Site indices, height (m) at age 50 are provided for each of the provincially calculated curves

Figure 3: Ontario Yield Curves



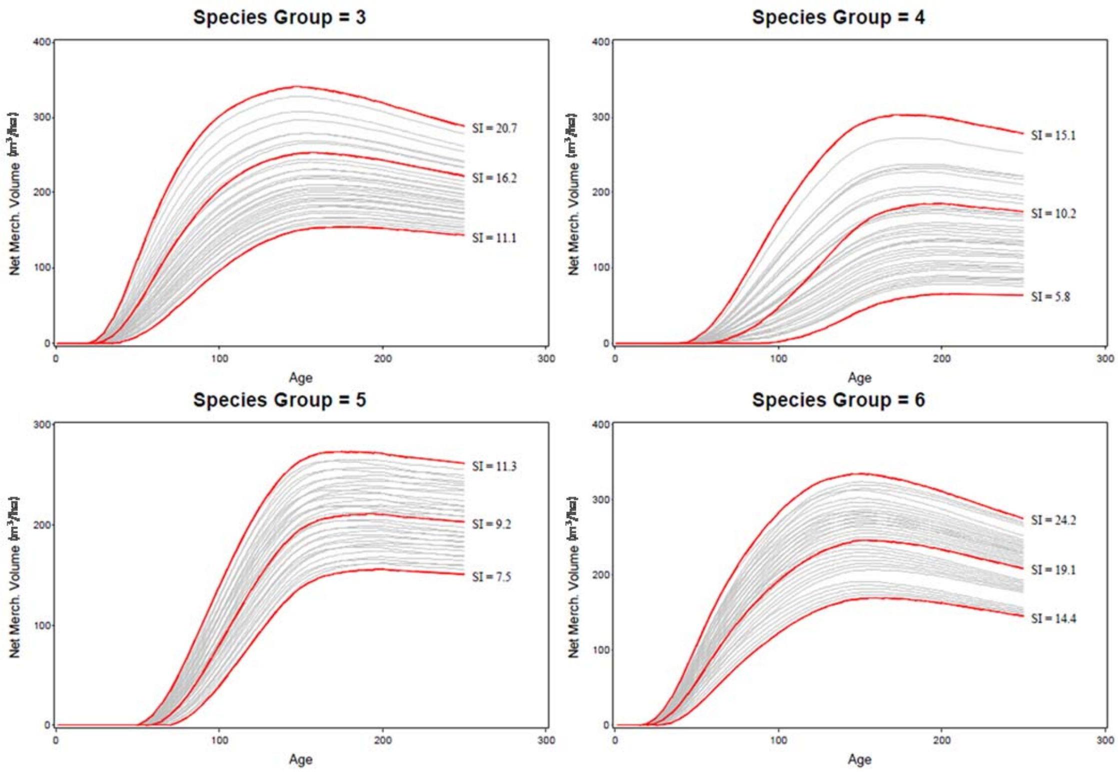
Note: Yield curves based on species groups contained in Table 1 (where present), used for Timber Supply Assessment of Natural Resources Canada's Integrated Assessment for the province of Ontario. Red lines denote the provincial minimum, mean and maximum curves derived from provincial yield table generator, grey lines indicate results of Ung et al. 2009 aggregated curves, constrained by provincial minimums and maximums. Site indices, height (m) at age 50 are provided for each of the provincially calculated curves.

Figure 4: Alberta (Prairie Region) Yield Curves



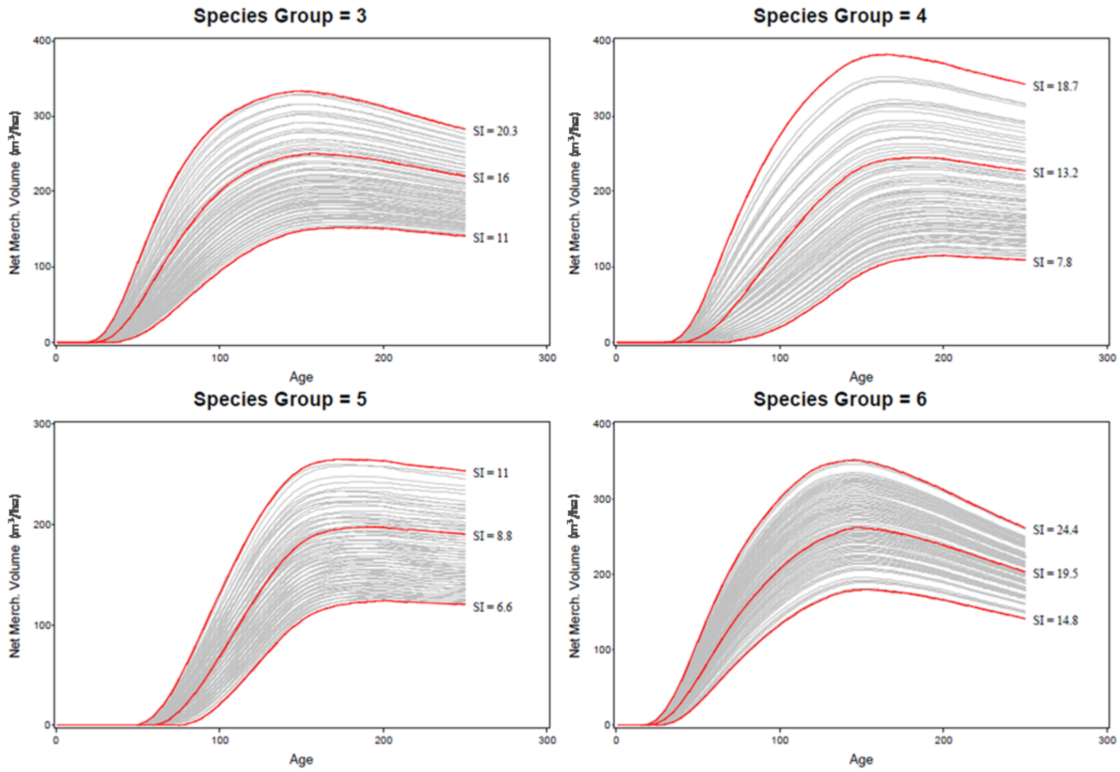
Note: Yield curves based on species groups contained in Table 1 (where present), used for Timber Supply Assessment of Natural Resources Canada's Integrated Assessment for the province of Alberta and by proxy, the Prairies. Red lines denote the provincial minimum, mean and maximum curves derived from provincial yield table generator, grey lines indicate results of Ung et al. 2009 aggregated curves, constrained by provincial minimums and maximums. Site indices, height (m) at age 50 are provided for each of the provincially calculated curves.

Figure 5: British Columbia (Plains Ecozones) Yield Curves



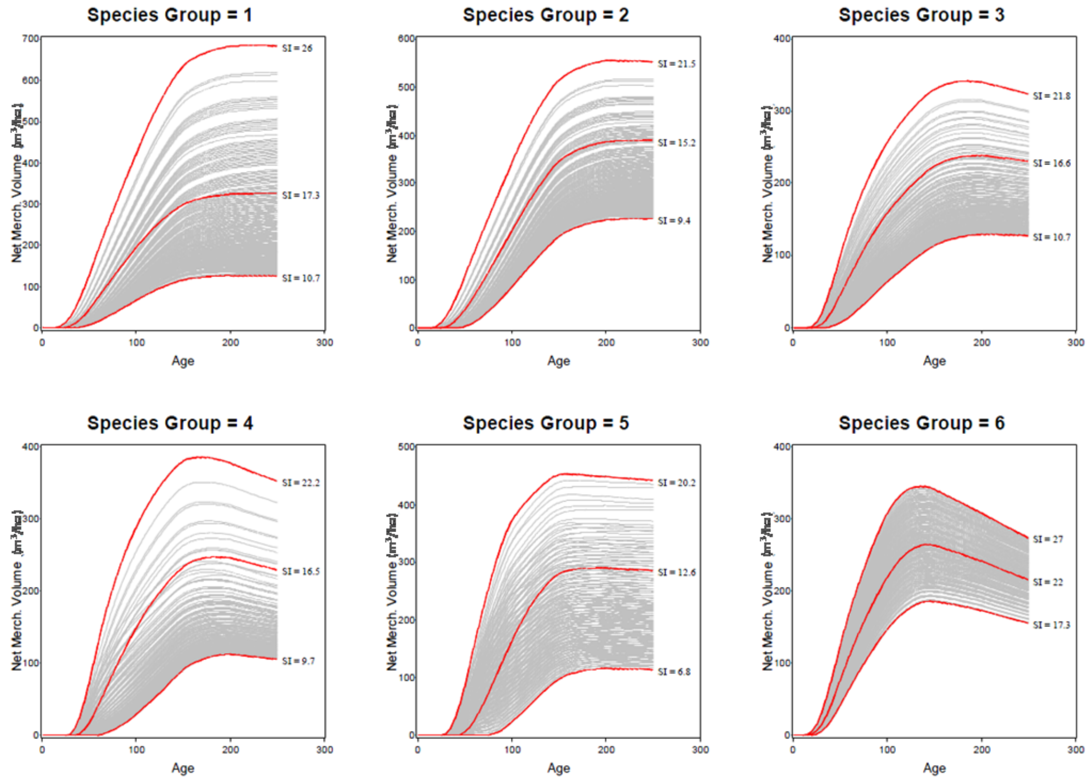
Note: Yield curves based on species groups contained in Table 1 (where present), used for Timber Supply Assessment of Natural Resources Canada's Integrated Assessment for the BC Plains ecozone (Boreal and Taiga Plains) in the province of British Columbia. Red lines denote the provincial minimum, mean and maximum curves derived from provincial yield table generator WinVDYP7 (BCMOF, 2009a,2009b), grey lines indicate results of Ung et al. 2009 aggregated curves, constrained by provincial minimums and maximums. Site indices, height (m) at age 50 are provided for each of the provincially calculated curves.

Figure 6: British Columbia (Boreal Cordillera Ecozone) Yield Curves



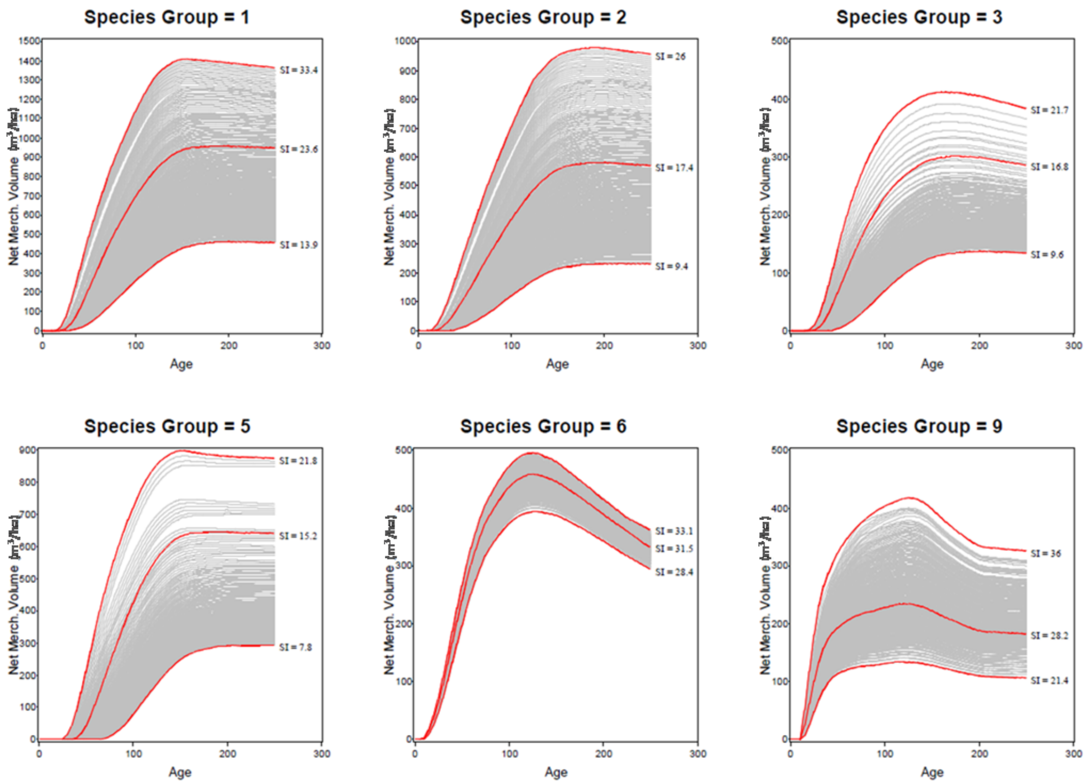
Note: Yield curves based on species groups contained in Table 1 (where present), used for Timber Supply Assessment of Natural Resources Canada's Integrated Assessment for the BC Boreal Cordillera ecozone in the province of British Columbia. Red lines denote the provincial minimum, mean and maximum curves derived from provincial yield table generator WinVDYP7 (BCMOF, 2009a,2009b), grey lines indicate results of Ung et al. 2009 aggregated curves, constrained by provincial minimums and maximums. Site indices, height (m) at age 50 are provided for each of the provincially calculated curves.

Figure 7: British Columbia (Montane Cordillera Ecozone) Yield Curves



Note: Yield curves based on species groups contained in Table 1 (where present), used for Timber Supply Assessment of Natural Resources Canada's Integrated Assessment for the BC Montane Cordillera ecozone in the province of British Columbia. Red lines denote the provincial minimum, mean and maximum curves derived from provincial yield table generator WinVDYP7 (BCMOF, 2009a,2009b), grey lines indicate results of Ung et al. 2009 aggregated curves, constrained by provincial minimums and maximums. Site indices, height (m) at age 50 are provided for each of the provincially calculated curves.

Figure 8: British Columbia (Pacific-Maritime Ecozone) Yield Curves



Note: Yield curves based on species groups contained in Table 1 (where present), used for Timber Supply Assessment of Natural Resources Canada's Integrated Assessment for the BC Pacific-Maritime ecozone in the province of British Columbia. Red lines denote the provincial minimum, mean and maximum curves derived from provincial yield table generator WinVDYP7 (BCMOF, 2009a,2009b), grey lines indicate results of Ung et al. 2009 aggregated curves, constrained by provincial minimums and maximums. Site indices, height (m) at age 50 are provided for each of the provincially calculated curves.