An estimation of the impact on net carbon sequestration of forest management including wood products storage

A study prepared for

Options Analysis for the Sinks and Forest Sector Tables

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May, 1999

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Executive Summary

In December 1997, the Parties to the 1992 United Nations Framework Convention on Climate Change adopted a Protocol to the Convention (the Kyoto Protocol) to limit emissions of six greenhouse gases. Canada accepted a target of 6 percent below its 1990 level of emissions.

As part of the Kyoto Protocol, countries are required to report on the net change in carbon storage in forest systems over the period 2008 to 2012. Currently, this change is limited to changes resulting from afforestation, reforestation and deforestation only. However, forest management can also effect carbon storage. This study analyzes the effect forest management has on net carbon sequestration.

As well, the carbon pools that are included in this calculation have yet to be negotiated. This study includes, as separate entities, net carbon storage in litter, soils, wood products and landfills, so that the significance of these pools can be assessed.

Five forest management activities are analyzed using two forests as examples. The five activities are:

1. pre-commercial thinning;
2. commercial thinning for pulp;
3. commercial thinning for pulp and lumber;
4. increasing the rotation length; and
5. increasing the amount of slash used for biofuel.

The two forest examples are:

1. Nova Scotia Red Spruce, site index = 15.4; and
2. Coastal Douglas Fir, site index = 30

As a generalization, the activities that increase rotation length increase biomass in the long-term. In the examples studied, activities 2,3 and 4 result in increased rotation length. Pre-commercial thinning resulted in decreased rotation length in Nova Scotia, but an increase in rotation length in British Columbia.

In the short-term, however, the net biomass is dependent on the timing of the forestry activity. As a result, during the Kyoto target period (2008-2012), only increasing the rotation length sequestered more carbon. There is a cost associated with lost production.

Increasing biofuel use while decreasing slash decreases biomass particularly in the litter and soil pools. This change in biomass is rapid in the short-term and becomes negligible as the forest system reaches a new equilibrium with time. Increasing biofuel avoids more emissions from fossil fuels, but the decrease in emissions does not offset the decrease in biomass in the short-term.

The detailed results are tabulated on the following page.

In conclusion, if Canada is looking at changes in forest management as a method of helping the country reach its Kyoto Protocol commitment, then only activities which increase the rotation length before the target period should be considered.

If Canada is looking for methods of increasing sequestration in the future (for example by 2050), then commercial thinning should be considered. It increases rotation length while increasing productivity.

Nova Scotia, Red Spruce

	Kyoto target period (2008-2012)				2050	
Activity	Biomass emission	Fossil fuel emissions	Total	Cost	Biomass emission	Cost (sequestration only)
	(t CO_2e/ha)	(t CO_2e/ha)	(t CO_2e/ha)	($ / t CO_2e)	(t CO_2e/ha)	($ / t CO_2e)
PCT	6.0	0.0	6.0	not calculated	63.6	not calculated
CT for pulp	3.5	3.5	7.0	not calculated	- 1.7	not calculated
CT for pulp and lumber	2.0	3.2	5.2	not calculated	- 11.0	not calculated
Increasing rotation length (5 years)	- 3.1	-1.1	-4.2	189.68	- 10.9	140.00
Increasing biofuel/slash	3.1	- 2.0	1.1	not calculated	20.5	not calculated

Note: an increase in biomass (i.e. sequestration) is a negative biomass emission.

British Columbia, Douglas Fir

	Kyoto target period (2008-2012)				2050	
Activity	Biomass emission	Fossil fuel emissions	Total	Cost	Biomass emission	Cost (sequestration only)
	(t CO_2e/ha)	(t CO_2e/ha)	(t CO_2e/ha)	($ / t CO_2e)	(t CO_2e/ha)	($ / t CO_2e)
PCT	2.5	0.0	2.5	not calculated	31.6	not calculated
CT for pulp	4.3	2.0	6.3	not calculated	- 79.3	not calculated
CT for pulp and lumber	3.2	1.5	4.7	not calculated	- 86.1	not calculated
Increasing rotation length (5 years)	- 12.0	-6.0	-18.1	101.67	- 41.2	14.80
Increasing biofuel/slash	5.0	- 3.5	1.5	not calculated	33.8	not calculated

Note: an increase in biomass (i.e. sequestration) is a negative biomass emission.

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Preface

In December 1997, the Parties to the 1992 United Nations Framework Convention on Climate Change adopted a Protocol to the Convention (the Kyoto Protocol) to limit emissions of six greenhouse gases. Canada accepted a target of 6 percent below its 1990 level of emissions.

As part of the National Climate Change Process to investigate how to achieve this target the Forest Sector Table and the Sinks Table have undertaken a joint work program to evaluate how forest net carbon sequestration could be increased. This work is one part of each Table's mandate and each Table will prepare an Options Report that includes a discussion of carbon sequestration. The Options Reports are scheduled for completion in the late spring of 1999.

This paper was commissioned by the Forest Sector Table and the Sinks Table as background to assist them in the production of their Options Reports. The Tables welcome comments on this paper or other work that they have commissioned.

The views expressed in this paper are not necessarily those of the Government of Canada, the Tables or the organizations and individuals on the Tables.

Introduction

In March 1999, Woodrising Consulting Inc. was contracted by Natural Resources Canada, Canadian Forestry Service to assess the carbon sequestration and greenhouse gas emission implications of several forestry management activities. These activities include:

- pre-commercial thinning;
- commercial thinning for pulp;
- commercial thinning for pulp and lumber;
- increasing the rotation length; and
- increasing the amount of slash used for biofuel.

A limited number of species-yield examples were to be examined using yield curves provided by various provincial forestry departments. At this time two examples have been analyzed. These include:

1. Nova Scotia Red Spruce, site index = 15.4[1]; and
2. Coastal Douglas Fir, site index = 30[2].

These yield curves are the basis of the modelling procedure. They are first converted from total volume (the inside-bark bole volume including stump and top) to biomass. This step assumes an expansion factor of 1.2 (to account for limbs) and a density of 450 kg (dry)/m^3. The biomass curves are then parameterized using the derivative form of the Chapman-Richards function[3].

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[1] Modelled using the Nova Scotia Softwood Growth and Yield Model (GNY). Data provided by Tim McGrath, Nova Scotia Department of Natural Resources.

[2] Modelled using TIPSY. Data provided by Dave Spittlehouse, British Columbia Department of Forestry.

[3] Cooper C (1982). Carbon storage in managed forests, *Can. J. For. Res.* **13**, 155-166.

Carbon Storage

As part of the Kyoto Protocol, countries are required to report on the net change in carbon storage in forest systems over the period 2008 to 2012. Currently, this change is limited to changes resulting from afforestation, reforestation and deforestation only. However, forest management can also effect carbon storage. This study analyzes the effect forest management has on net carbon sequestration.

As well, the carbon pools that are included in this calculation have yet to be negotiated. This study includes, as separate entities, net carbon storage in litter, soils, wood products and landfills, so that the significance of these pools can be assessed.

Greenhouse Gas Emissions

Changing forest management practices also alters the greenhouse gas emissions from these practices. A discussion of the net greenhouse gas benefits of various forest management alternatives is not complete without including these net emissions.

Modelling Procedure

Stand Level

Forest management activities were analyzed using a modified form of GORCAM[4]. This is a stand-based algorithm that tracks the flow of biomass through the forest, wood products and waste pools. The model uses 10 pools to describe the flow of biomass for the vegetation of interest. These pools are interconnected as shown in Figure 1. A further four pools track the flow of biomass in other vegetation (above ground biomass, roots, above ground and below ground litter). The details of the relationships between these are given in the appendix. Biomass is assumed to be 50% carbon.

Changes in biomass occur as carbon stored in various pools returns to the atmosphere. The carbon stored in the litter and soil is emitted to the atmosphere as carbon dioxide. As well, emissions result from burning of fossil fuels, decaying wood products and wood residues. Finally, the landfill is a source of both carbon dioxide and methane emissions.

The model calculates the biomass and emissions in a step-wise manner (year by year).

Scaling Up to Forest-Level

Biomass

Short-term changes in biomass include the transitional effects as the stand loses or gains biomass as a result of a change in management systems. As such, they are complex and are dependent on when the change in management systems occurs. In this paper, it has been assumed that the change in management system occurs at the earliest possible time (2001).

To scale up from the stand level one must make a few assumptions. The simplest assumption is that the forest has an even age distribution. In this case, the long-term stored biomass is constant. It is the average biomass over a rotation. The long-term net change in biomass is the difference in the average biomass over a rotation.

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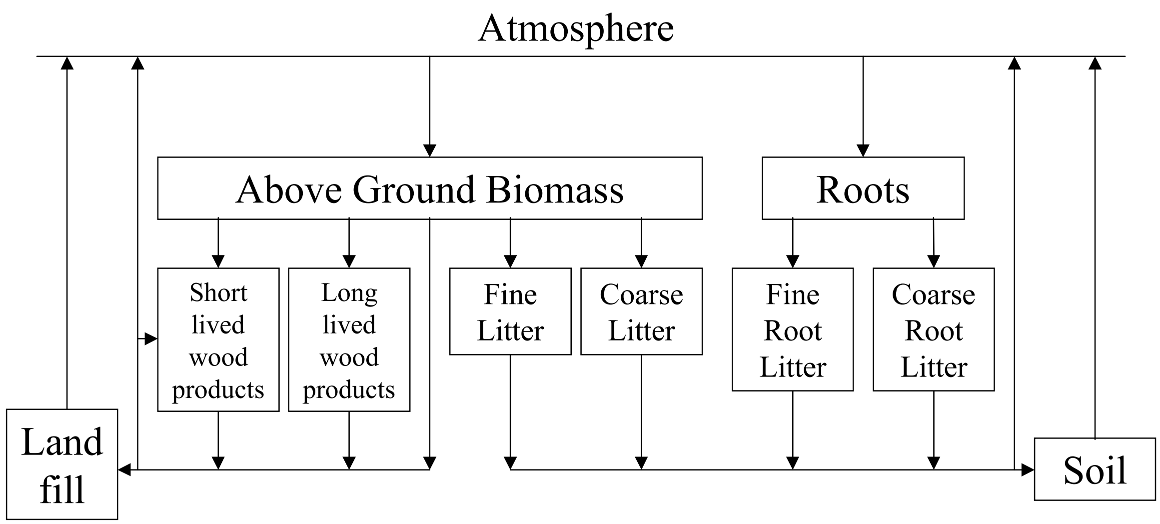
[4] Schlamadinger B and Marland G (1996). The role of forest and bioenergy strategies in the global carbon cycle, *Biomass & Bioenergy* **10**, 5/6, 275-300.

Figure 1: GORCAM flow diagram, forest vegetation



During the transition from one management system to another the net change in biomass is more complicated. A simplifying assumption is that the forest has an even-age distribution. The net biomass is given by the differences in the moving average biomass of the two systems.

Two important outcomes of the even-age assumption must be noted. Firstly, there is no change in biomass during the Kyoto target period for the reference case. Secondly, in calculating net biomass, biomass before the change in systems does not effect the moving average biomass (so it can be set to zero).

Note: at the forest-level, net biomass and net GHG emissions have the units t CO_2e/ha. This refers to total hectares in the forest NOT the number of hectares converted. Formal derivations are given in the appendix.

Greenhouse gas emissions

Greenhouse gases are emitted from a variety of sources in the system. These include:

1. Fossil fuels used (from thinning, harvesting, processing and recycling);
2. Fossil fuels saved (fuel replacement from biofuels);
3. Electricity (processing); and
4. Landfill (methane).

The same assumptions and formulae are used to calculate forest-level net greenhouse gas emissions from changing management schemes.

Example 1 – Nova Scotia

Reference Scenario – Natural Regeneration

Biomass

The reference scenario is naturally regenerating Red Spruce (Site Index 15.4) This stand has a rotation age of 65 years and a mean annual increment (MAI) of 5.22 m^3 per year at maturity. Table 1 lists the average biomass over a rotation in the various pools in this system once equilibrium is achieved. This is equivalent to the forest-level average annual biomass per hectare. There is no change in forest-level biomass with time. The landfill, soil and above ground biomass pools hold 34%, 27% and 19% of the total biomass.

The steady-state stand-level biomass profile over time is shown in Figure 2.

Table 1: Forest-level biomass, Red Spruce, natural regeneration (reference case)

Pool		**Rotation Average Biomass (t/ha)**	
Above Ground Biomass	Trees	106.0	
	Other Vegetation	6.9	
	Total	112.9	112.9
Roots	Trees	24.6	
	Other Vegetation	1.4	
	Total	26.0	26.0
Litter	Above ground	28.4	
	Below ground	27.9	
	Total	56.3	56.3
Soil			159.1
Woodproducts	Short-lived	3.4	
	Long-lived	32.7	
	Total	36.1	36.1
Total (not including landfill)			**390.3**
Landfills			204.4
Total (including landfill)			**594.7**

Greenhouse gas emissions

Stand-level emissions from management of the reference case are shown in Figure 3. The forest-level emissions are the same as the rotation average emissions. They are listed below.

Table 2: Forest-level emissions, Red Spruce, natural regeneration (reference case)

Source	**Rotation Average Emissions (t CO_2e/ha)**
Fossil fuels (processing, waste management)	0.9
Fossil fuels saved (biofuel replacement)	-0.4
Electricity	0.4
Landfills	11.7
Total	**12.6**

Figure 2: Stand-level steady-state biomass, Red Spruce, natural regeneration (reference case)

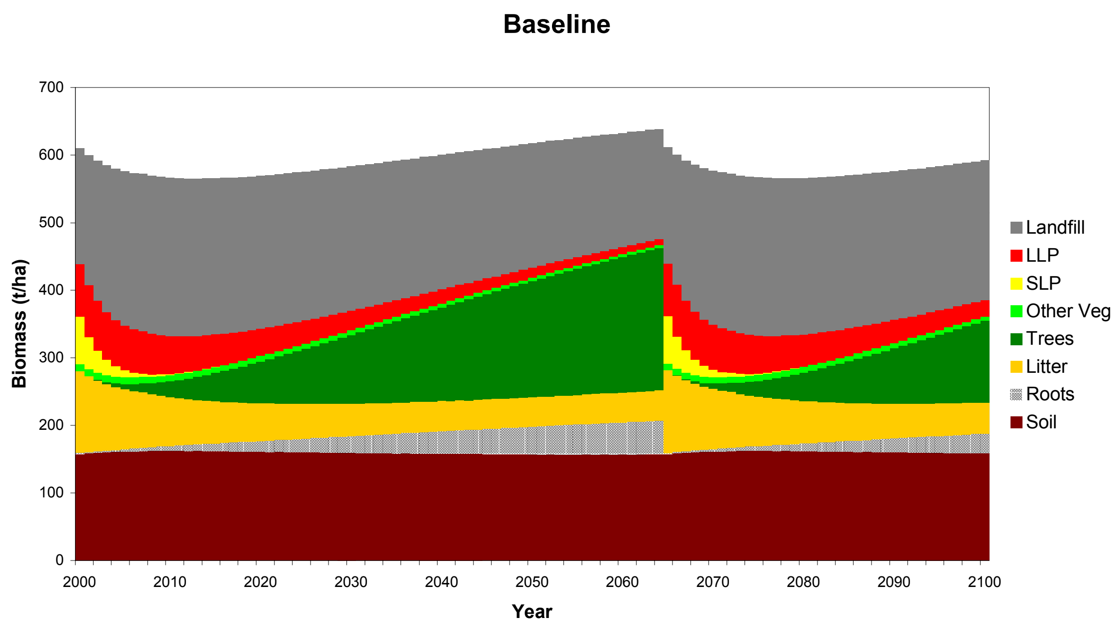
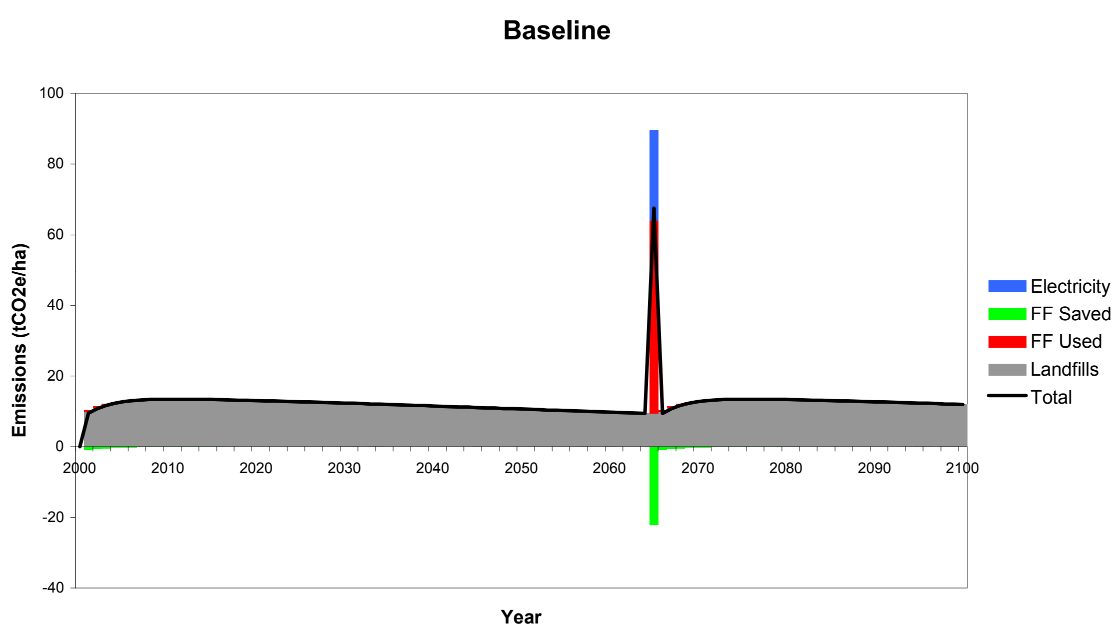


Figure 3: Stand-level, steady-state emissions, Red Spruce, natural regeneration (reference case)



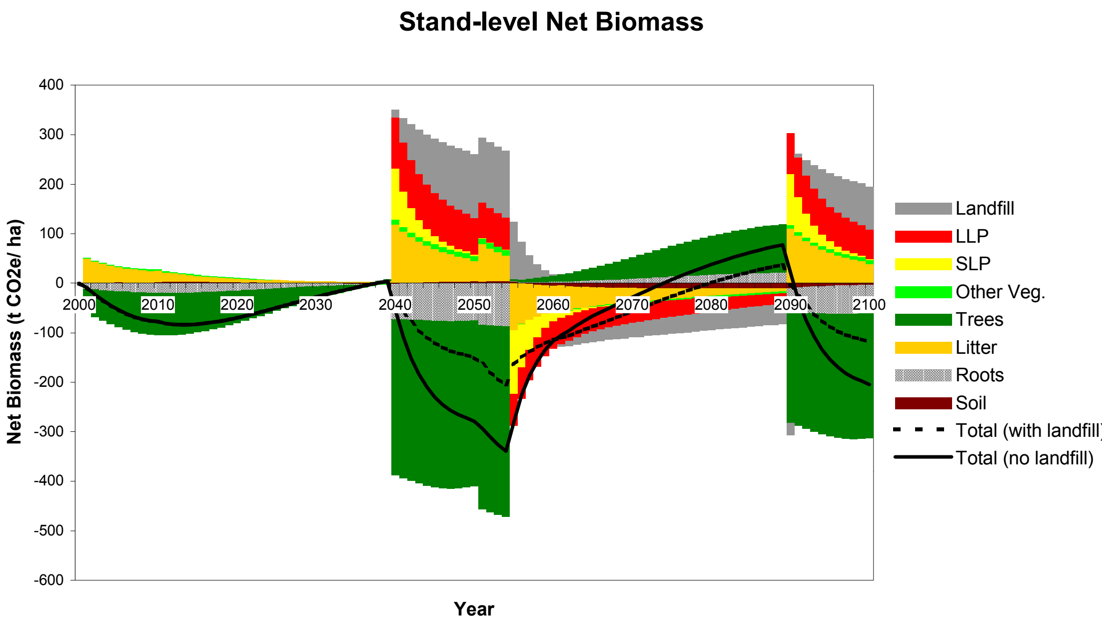
Pre-commercial Thinning

In 2001, at ten years of age, the stand undergoes pre-commercial thinning (PCT) to 2.4 metre spacing. It is assumed that waste is left on-site as litter. This results in increased growth and a shortened rotation length. The harvest takes place after 50 years when MAI reaches 6.22 m^3 per year.

Stand-level net biomass

The net biomass profile for the stand is displayed in Figure 4. The stand is thinned in 2001. There is a loss of biomass in the trees and roots, which is compensated by a smaller gain in biomass in litter and other vegetation. By 2038, the trees are beginning to show a net biomass gain. They are harvested in 2040 whereas the reference stand is not harvested until 2055. During this period there is a net loss of biomass in the new management system. There is a further loss of biomass in 2050 as another pass of thinning occurs. Finally, by 2055, the reference stand is harvested and net biomass increases.

Figure 4: Stand-level net biomass (t CO_2e/ha), Red Spruce, PCT – natural regeneration



Forest-level net biomass

Figure 5 shows the forest-level net biomass as a result of pre-commercial thinning. The forest gradually loses biomass prior to 2040. This is a result of less average biomass in the trees in the PCT stand during this period. Trees in the PCT stand only accumulate more biomass than the naturally regenerating stand after age 45. The large decrease in tree biomass after 2040 occurs because the PCT stands reach maturity and are harvested. After 2054, the natural regenerating stands begin being harvested while some PCT stands are still being harvested. After 2064 only naturally regenerating stands are harvested hence there is an increase in net biomass.

During the Kyoto target period the PCT forest loses 6.0 t CO_2e/ha. There is a large loss in tree and root biomass. Litter, soil and other vegetation pools increase in biomass. Note that there is no change in net biomass in the wood products and landfill pools. During the Kyoto target period there is no change in harvesting.

By 2050, the PCT forest stores 63.6 t CO_2e/ha less than the reference case.

Table 3: Kyoto net biomass (t CO_2e/ha), Red Spruce, PCT- natural regeneration

Year	Trees	Other Veg.	Roots	Litter	Soil	SLP	LLP	Total (no landfill)	Landfill	Total (with landfill)
2007	-7.1	0.2	-1.6	3.9	0.1	0.0	0.0	**-4.6**	0.0	**-4.6**
2012	-13.7	0.4	-3.1	5.5	0.3	0.0	0.0	**-10.6**	0.0	**-10.6**
Kyoto Sequestration	**-6.7**	**0.2**	**-1.5**	**1.6**	**0.2**	**0.0**	**0.0**	**-6.0**	**0.0**	**-6.0**

Net GHG emissions

The PCT has very little effect on net greenhouse gas emissions during the Kyoto target period. Beyond 2040 PCT does generate net emissions due to differences in amount of wood products generated (Figure 6).

Table 4: Net GHG emissions (t CO_2e/ha), Red Spruce, PCT - natural regeneration

Year	FF Used	FF Saved	Electricity	Landfills	Total
2008	0.00	0.00	0.00	0.00	**0.00**
2009	0.00	0.00	0.00	0.00	**0.00**
2010	0.00	0.00	0.00	0.00	**0.00**
2011	0.00	0.00	0.00	0.00	**0.00**
2012	0.00	0.00	0.00	0.00	**0.00**

Figure 5: Forest-level net biomass (t CO_2e/ha), Red Spruce, PCT – natural regeneration

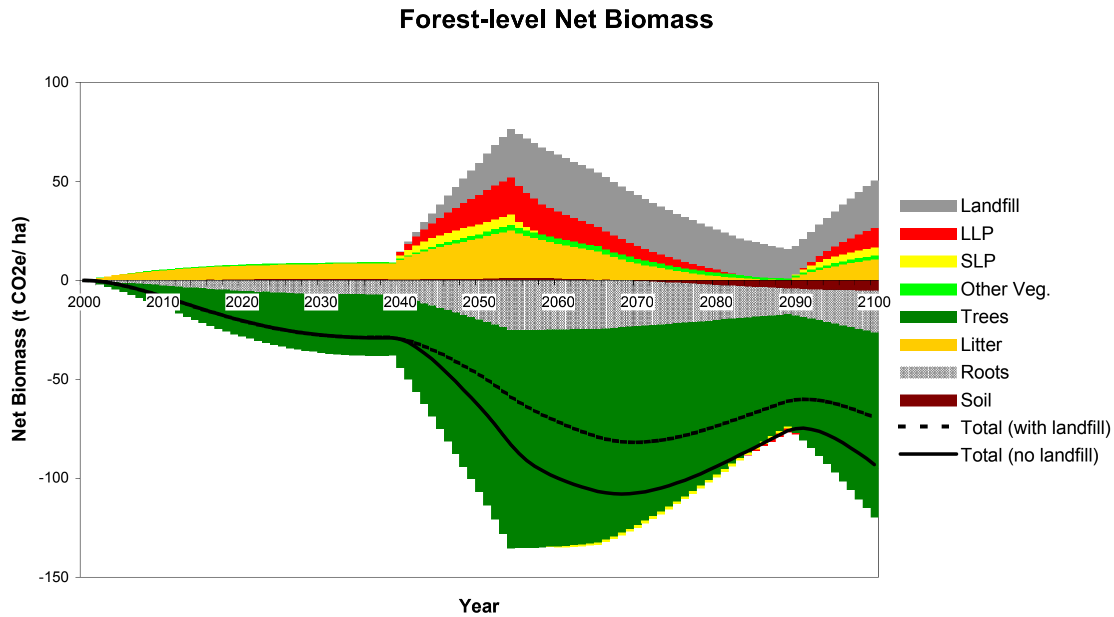
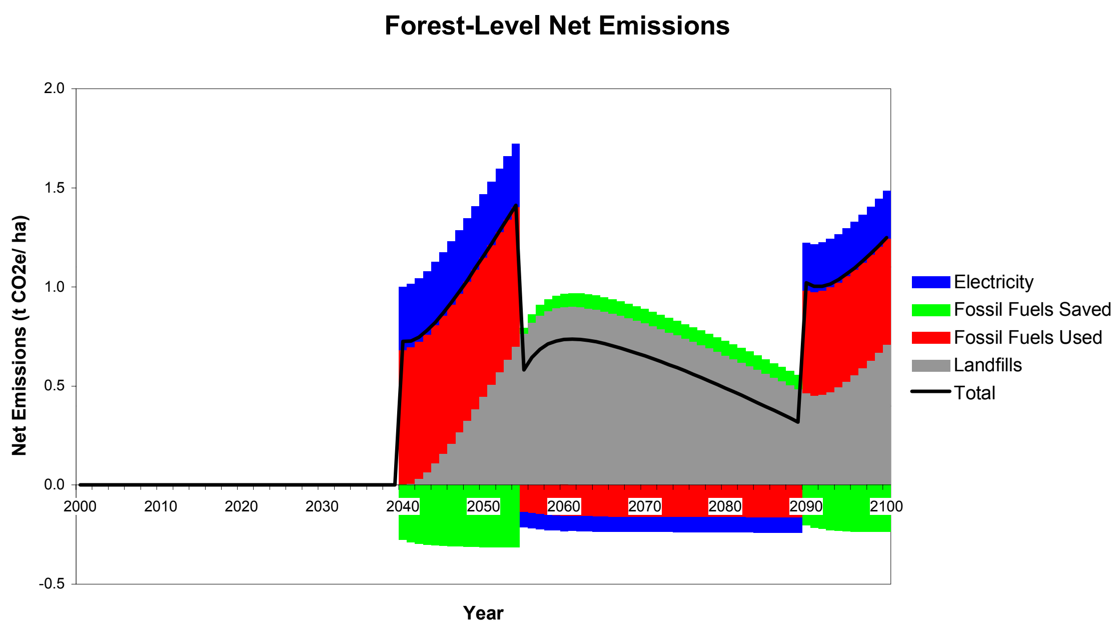


Figure 6: Forest-level net GHG emissions, Red Spruce, PCT – natural regeneration



Commercial Thinning for Pulp

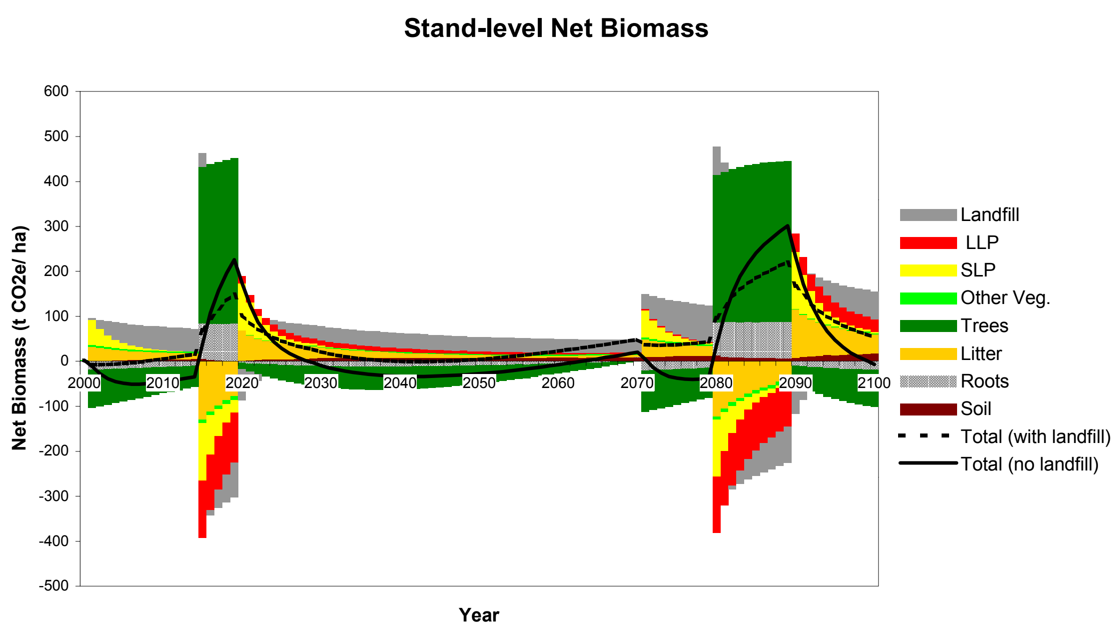
In 2001, at 50 years of age, the stand undergoes commercial thinning (CT). Approximately 27% of the biomass is removed for pulp (66% of harvested material). The stand reaches full harvesting at 70 years of age (MAI = 5.91 m^3/yr).

Stand-level net biomass

Figure 7 displays the stand-level net biomass profile for commercial thinning. In 2001, the stand is thinned. Some of the material becomes short-lived wood product (SLP), and litter, but this is only a portion of the biomass before thinning. As a result, the system has less biomass than the reference case. Commercial thinning increase the rotation length of the stand and in 2015, when the reference case is harvested, there is a net gain in biomass. By 2020, the CT stand is harvested and now there is a net loss of biomass as the reference stand is already growing again.

This pattern repeats again (with slight differences) in 2070.

Figure 7: Stand-level net biomass (t CO_2e/ha), Red Spruce, CT for pulp – natural regeneration



Forest-level net biomass

The net biomass profile for this change in forest management systems is extremely complicated (Figure 8).

Focusing on the net biomass in the trees, CT decreases net biomass until the untreated stands reach maturity. This occurs when they reach age 65, in 2015. At this point, the untreated stands are harvested and the reference case biomass decreases. There is a corresponding increase in net biomass at this time. By 2020, the first of the CT stands reaches harvesting maturity and the net biomass begins decreasing. The entire process repeats itself with further complications after 2065. The ramifications of this process are transferred to the other pools over time.

Like PCT, commercial thinning results in biomass loss during the Kyoto target period. As before, there is loss of biomass from the trees and roots pools. Some of this is recovered through increased storage in litter, other vegetation, soil and wood products. If storage in landfill is included, CT becomes a net sink during the Kyoto period.

By 2050, the CT for pulp forest stores 1.7 t CO_2e/ha more than the reference case.

Table 5: Kyoto net biomass (t CO_2e/ha), Red Spruce, PCT for pulp - natural regeneration

Year	Trees	Other Veg.	Roots	Litter	Soil	SLP	LLP	Total (no landfill)	Landfill	Total (with landfill)
2007	-8.2	0.5	-1.8	2.6	0.2	2.6	0.0	**-4.1**	3.6	**-0.5**
2012	-12.7	0.8	-2.8	3.8	0.5	2.7	0.0	**-7.6**	7.5	**-0.1**
Kyoto Sequestration	**-4.5**	**0.3**	**-1.0**	**1.2**	**0.3**	**0.1**	**0.0**	**-3.5**	**3.9**	**0.4**

Net GHG emissions

There are substantial net GHG emissions from fossil fuels (FF), electricity and landfills during the Kyoto period. This is due to the conversion of harvested material into wood products and an increased amount of wood products circulating. The net GHG emission profile for this example is shown in Figure 9.

Table 6: Net GHG emissions (t CO_2e/ha), Red Spruce, CT for pulp - natural regeneration

Year	FF Used	FF Saved	Electricity	Landfills	Total
2008	0.19	-0.09	0.45	0.11	**0.66**
2009	0.19	-0.09	0.45	0.14	**0.68**
2010	0.19	-0.09	0.45	0.16	**0.71**
2011	0.19	-0.09	0.45	0.19	**0.73**
2012	0.19	-0.09	0.45	0.21	**0.76**

Figure 8: Forest-level net biomass (t CO_2e/ha), Red Spruce, CT for pulp – natural regeneration

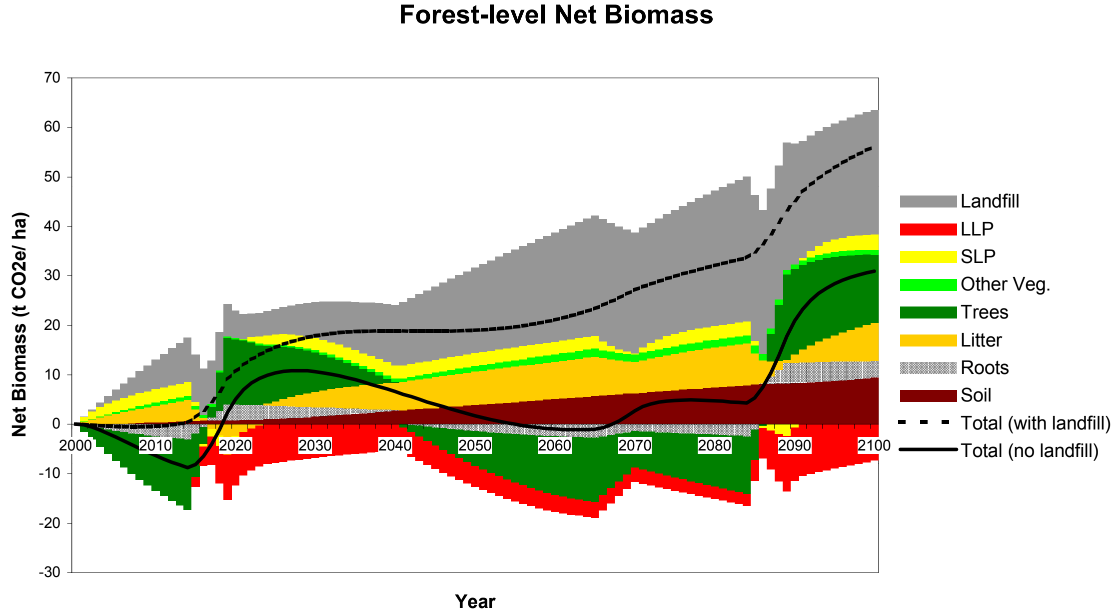
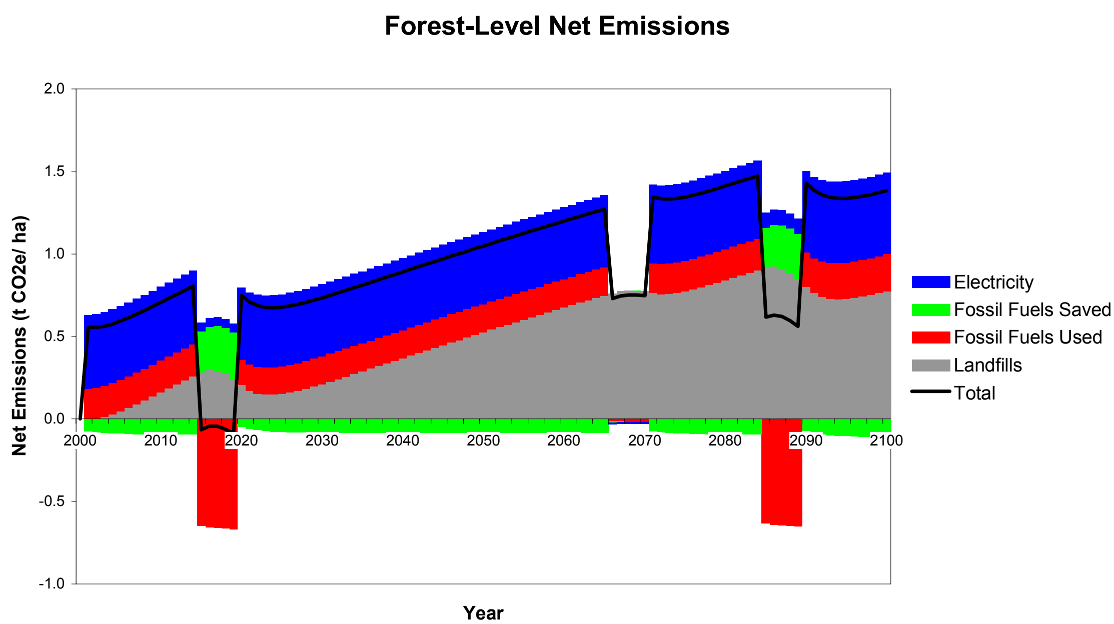


Figure 9: Forest-level net GHG emissions, Red Spruce, CT for pulp - natural regeneration



Commercial Thinning for Pulp and Lumber

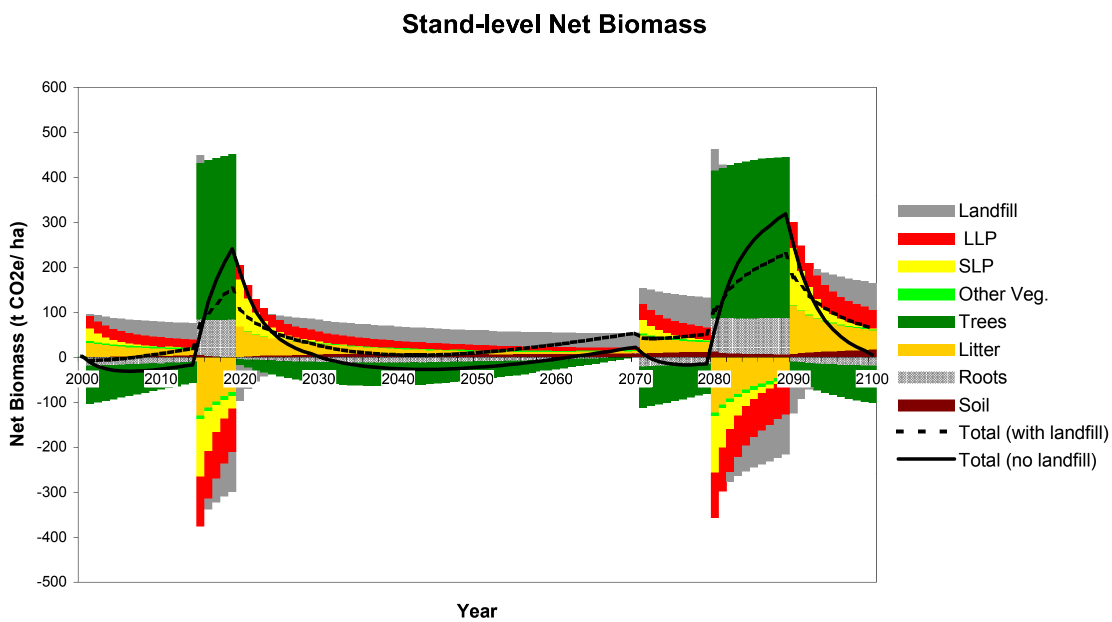
As before, the stand undergoes commercial thinning (CT) in 2001. In this example, the thinning is treated as a full harvest. As a result, 33% of the harvest becomes short-lived and 33% becomes long-lived wood products.

Stand-level net biomass

The stand-level net biomass profile (Figure 10) is nearly identical to the previous example. The difference is that there is a slight bias towards positive net biomass since the long-lived wood products (LLP) decay less rapidly than the short-lived wood products (SLP).

The profile still has the property of net biomass loss in between harvests and a net biomass gain in the years when the reference stand would have been harvested and the CT stand has not reached maturity.

Figure 10: Stand-level net biomass (t CO_2e/ha), Red Spruce, CT for pulp and lumber - natural regeneration



Forest-level net biomass

The general form of the net biomass curve is similar to the previous example. There is a slight increase in net biomass over time as more material ends in the long-lived wood product pool.

During the Kyoto target period commercial thinning for pulp and lumber still loses 2.0 t CO_2e/ha. The wood product pools act as an improved sink as would be expected by an increase in long-lived wood products.

In 2050, the net biomass stored has increased to 11.0 t CO_2e/ha.

Table 7: Kyoto net biomass (t CO_2e/ha), Red Spruce, CT for pulp and lumber - natural regeneration

Year	Trees	Other Veg.	Roots	Litter	Soil	SLP	LLP	Total (no landfill)	Landfill	Total (with landfill)
2007	-8.2	0.5	-1.8	2.6	0.2	1.3	2.7	**-2.7**	2.3	**-0.4**
2012	-12.7	0.8	-2.8	3.8	0.5	1.4	4.3	**-4.7**	4.9	**0.2**
Kyoto Sequestration	**-4.5**	**0.3**	**-1.0**	**1.2**	**0.3**	**0.1**	**1.6**	**-2.0**	**2.6**	**0.6**

Net GHG emissions

There is a slight decrease in net GHG emissions from the previous example. This is a result of less material being recycled; less material being used for biofuel; and less material reaching the landfill since there are more long-lived wood products and less paper.

The net emissions from this example are shown for completeness (Figure 12).

Table 8: Net GHG emissions (t CO_2e/ha), Red Spruce, CT for pulp and lumber - natural regeneration

Year	FF Used	FF Saved	Electricity	Landfills	Total
2008	0.19	-0.08	0.45	0.07	**0.62**
2009	0.19	-0.08	0.45	0.09	**0.64**
2010	0.19	-0.08	0.45	0.10	**0.66**
2011	0.19	-0.08	0.45	0.12	**0.67**
2012	0.19	-0.08	0.45	0.14	**0.69**

Figure 11: Forest-level net biomass (t CO_2e/ha), Red Spruce, CT for pulp and lumber - natural regeneration

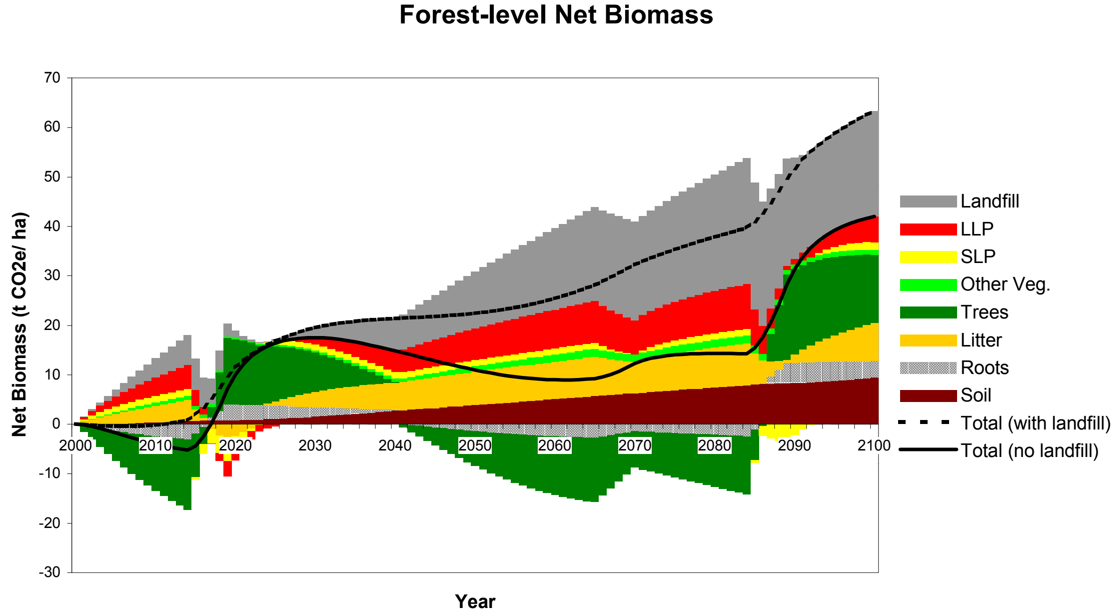
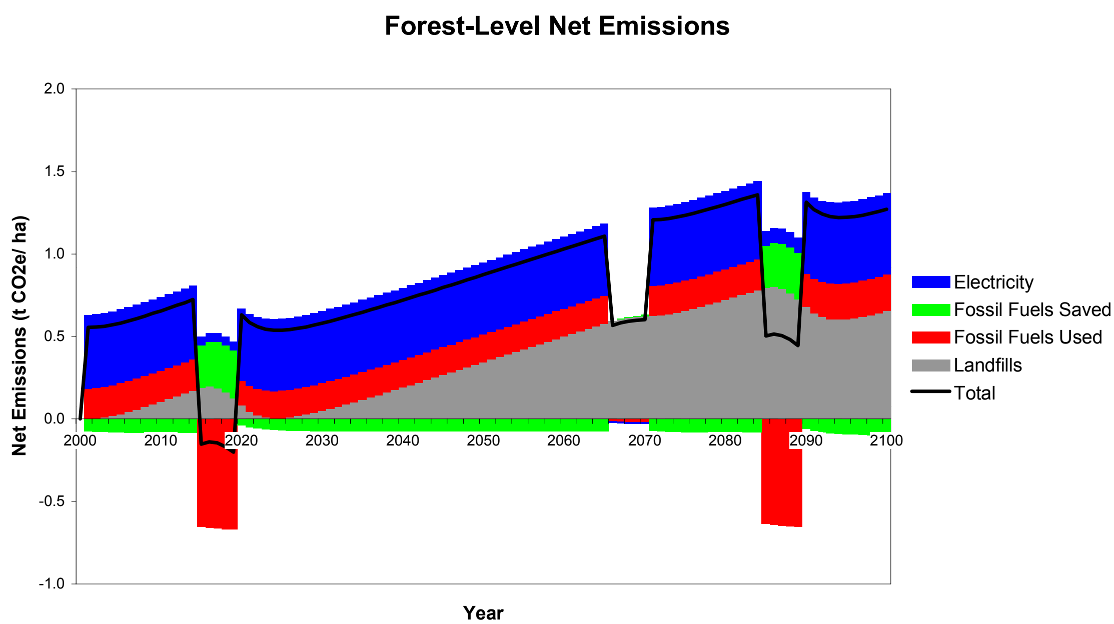


Figure 12: Forest-level net GHG emissions, Red Spruce, CT for pulp and lumber - natural regeneration



Increasing Rotation Length

In an early paper, Cooper (1982)[5] suggested that optimal carbon storage in a managed stand was reduced by harvesting at financial maturity. In this example, the reference stand reaches financial maturity in 2001. The company chooses to harvest the stand 5 years later in 2005. At 70 years, MAI = 5.22 m^3 per year. No other changes in the management regime are included.

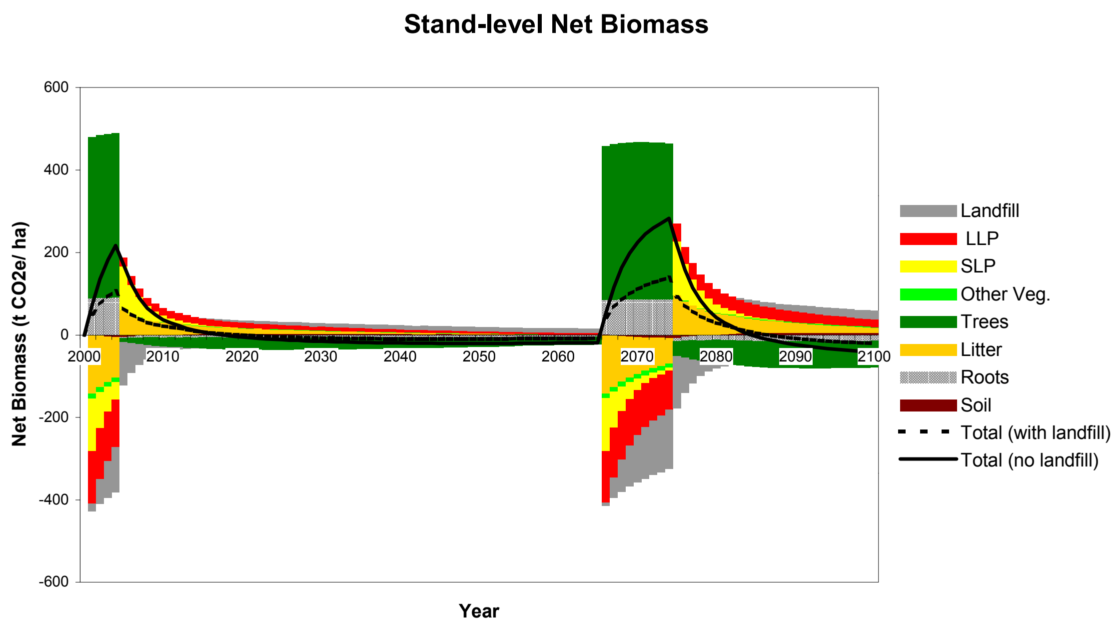
Stand-level net biomass

The stand-level net biomass profile is shown in Figure 13. In 2001, the stand is not harvested, even though it has reached financial maturity. There is a net gain in tree and root biomass, and a corresponding net loss in litter, landfill and short and long-lived wood products (SLP and LLP). Over the next five years, there is a net gain in biomass because there is decay of these litter, landfill, SLP and LLP pools.

In 2005, the stand is harvested. The tree net biomass is slightly negative since in the reference case, the trees would have already started growing again. There is a positive net biomass in litter, SLP and LLP because these pools have not decayed to the same level as in the reference case. In total, the new management system has a net biomass gain.

In 2065, the process repeats itself, except that now there are ten years when the trees in the new management system are standing and the reference system would have been harvested.

Figure 13: Stand-level net biomass (t CO_2e/ha), Red Spruce, Increase rotation length by 5 years



[5] Cooper C (1982). Carbon storage in managed forests, *Can. J. For. Res.* **13**, 155-166.

Forest-level net biomass

Increasing the rotation length results in the net biomass profile shown in Figure 14. There is a net increase in tree and root biomass between 2001 and 2005. During this period, the reference case stands are being harvested while the project case stands continue growing. This increase is offset somewhat by a net decrease in net storage in the wood products and landfill pools. By 2006 there is no more net increase in tree and root biomass as harvesting on the project case stands begins. The disturbance caused by the change in management regimes continues to decrease in net emissions until 2070.

During the Kyoto target period, there is an increase in carbon storage as a result of increasing the rotation length. By this time, the large increase in net biomass in the tree pool is over, but much of this gain has been converted to the wood product pools. The effectiveness of this change in management regime is diminished if storage in landfills is included. This suggests that a larger change in biomass during the Kyoto target period can be achieved by increasing the rotation length even more. By 2050, the forest with a longer rotation length holds 10.9 t CO_2e/ha more than the reference case.

Table 9: Kyoto net biomass (t CO_2e/ha), Red Spruce, Increase rotation length by 5 years

Year	Trees	Other Veg.	Roots	Litter	Soil	SLP	LLP	Total (no landfill)	Landfill	Total (with landfill)
2007	23.7	-0.7	5.4	-5.0	-0.4	-1.4	-6.5	**15.2**	-7.8	**7.4**
2012	22.1	-0.6	5.0	-2.6	-0.4	0.0	-5.1	**18.3**	-9.1	**9.1**
Kyoto Sequestration	**-1.6**	**0.1**	**-0.4**	**2.4**	**0.0**	**1.4**	**1.4**	**3.1**	**-1.3**	**2.7**

Net GHG emissions

Not only does increasing the rotation length increase biomass but it also decreases net GHG emissions. This is due to the delay in material reaching the landfill. Some of the decrease is offset by increased emissions from harvesting and processing.

Figure 15 displays the forest-level net GHG emissions as a result of increasing the rotation length by 5 years.

Table 10: Net GHG emissions (t CO_2e/ha), Red Spruce, Increase rotation length by 5 years

Year	FF Used	FF Saved	Electricity	Landfills	Total
2008	0.03	-0.01	0.02	-0.24	**-0.20**
2009	0.03	-0.01	0.02	-0.26	**-0.22**
2010	0.04	-0.01	0.02	-0.27	**-0.23**
2011	0.04	-0.01	0.02	-0.28	**-0.24**
2012	0.04	-0.01	0.02	-0.28	**-0.24**

Figure 14: Forest-level net biomass (t CO_2e/ha), Red Spruce, Increase rotation length by 5 years

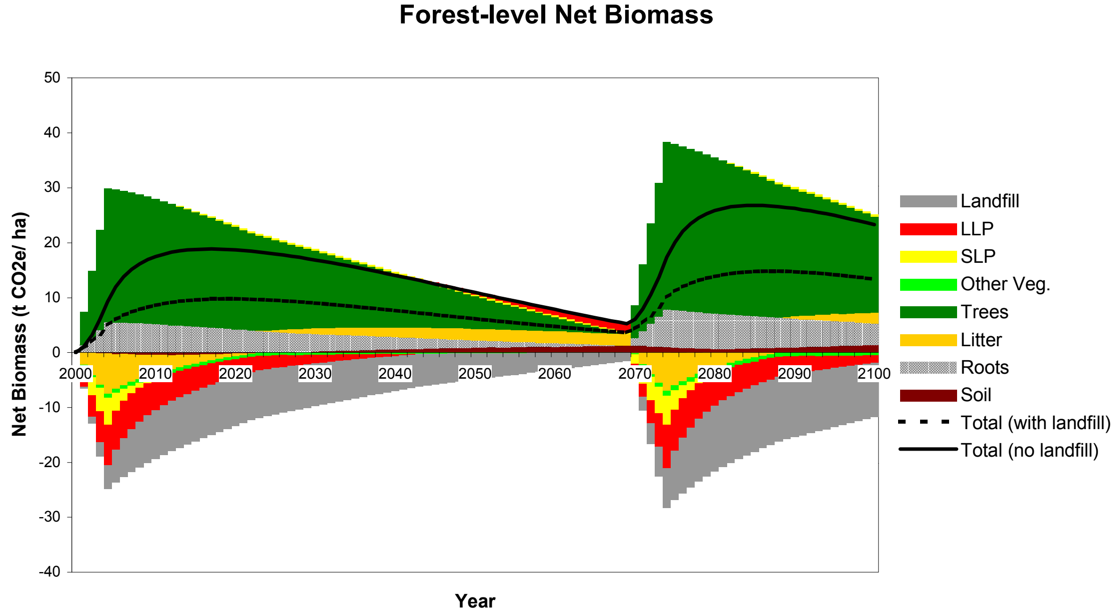
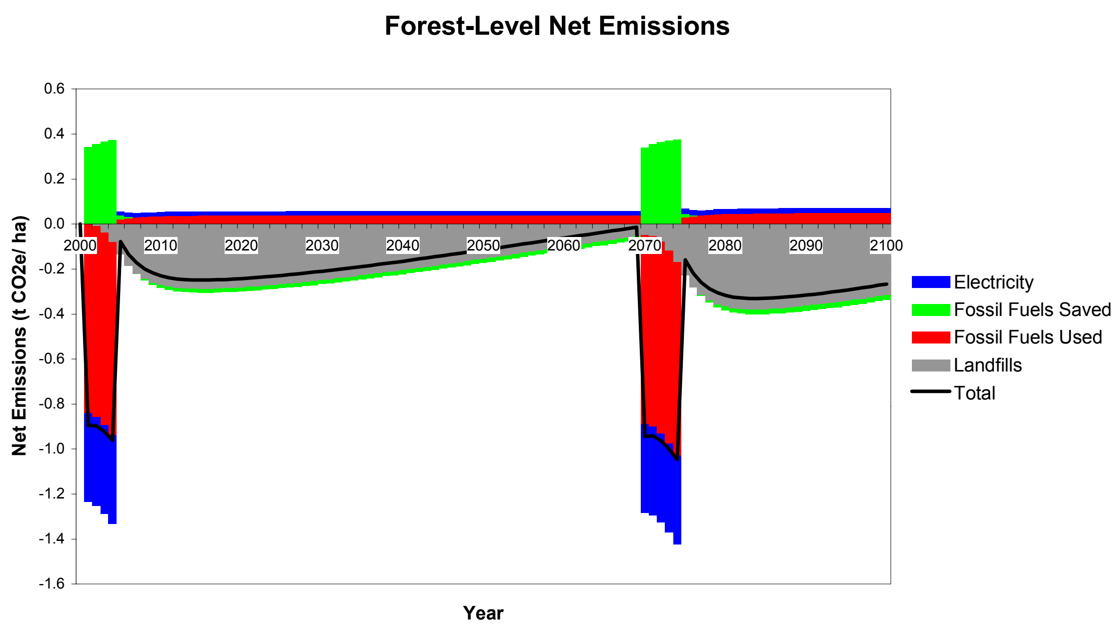


Figure 15: Forest-level net GHG emissions, Red Spruce, Increase rotation length by 5 years



Increasing Biofuel Use

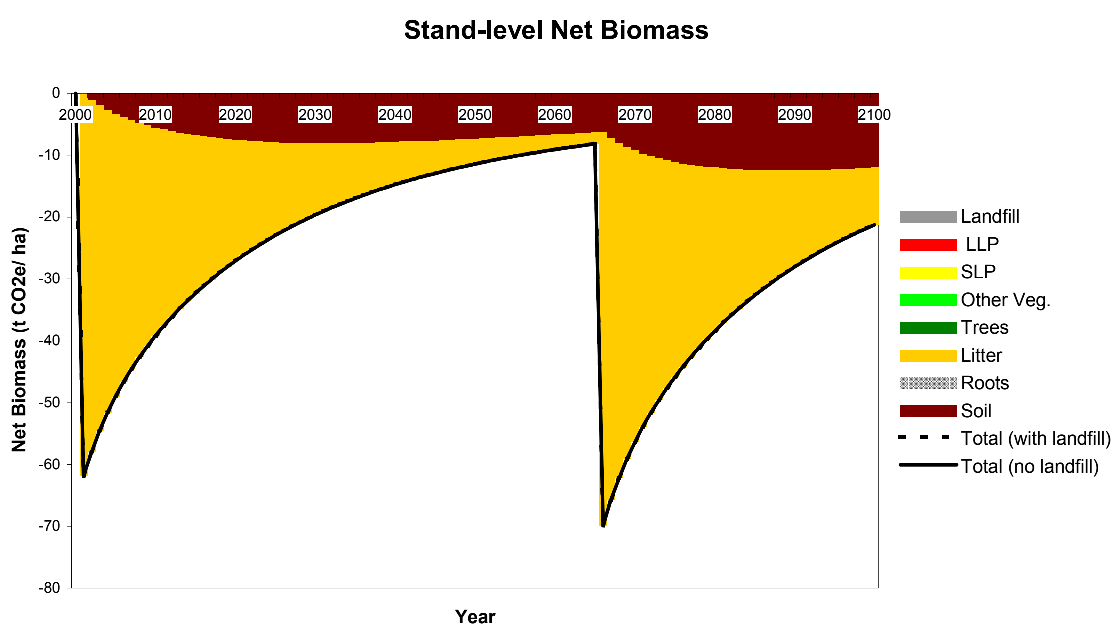
The final example from Nova Scotia examines the effect of increasing biofuel use while decreasing slash. In 2001, a naturally regenerating stand is harvested. Instead of 16% slash left on site, all slash is collected and burnt as biofuel.

Stand-level net biomass

In 2001, the stand is harvested but the slash is used for biofuel instead of left as litter. There is a large net loss of biomass (Figure 16). This decays over time. With less litter there is also a decrease in soil biomass. The net soil biomass loss becomes larger over time because of the dynamics of the litter and soil pools.

The process repeats itself during the next harvest but starts at a negative net biomass. The system stores progressive less biomass until a new equilibrium is reached.

Figure 16: Stand-level net biomass (t CO_2e/ha), Red Spruce, Increase biofuel/slash



Forest-level net biomass

This change in management regime has a simple forest-level net biomass profile (Figure 17). Increasing biofuel while reducing slash reduces litter and soil biomass. The change in biomass is most rapid during the early years. It diminishes in the long-term as a new steady-state is reached.

During the Kyoto target period the change in net biomass is large (but less so if soil is not included).

By 2050, the forest under a no slash management scheme has 20.5 t CO_2e/ha less than the reference case.

Table 11: Kyoto net biomass (t CO_2e/ha), Red Spruce, Increase biofuel/slash

Year	Trees	Other Veg.	Roots	Litter	Soil	SLP	LLP	Total (no landfill)	Landfill	Total (with landfill)
2007	0.0	0.0	0.0	-5.4	-0.3	0.0	0.0	**-5.6**	0.0	**-5.6**
2012	0.0	0.0	0.0	-8.0	-0.7	0.0	0.0	**-8.7**	0.0	**-8.7**
Kyoto Sequestration	**0.0**	**0.0**	**0.0**	**-2.6**	**-0.4**	**0.0**	**0.0**	**-3.1**	**0.0**	**0.0**

Net GHG emissions

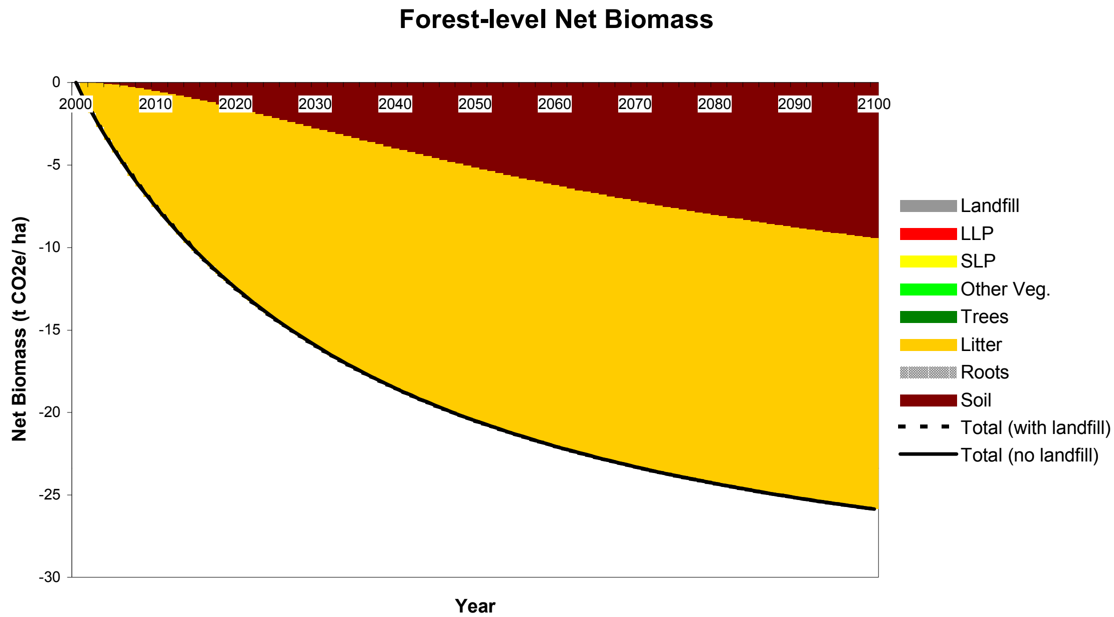
The increase in biofuel saves more fossil fuels. As a result, net GHG emissions decrease. In this example, it was assumed that the biofuels displace natural gas. The amount saved will increase if the biofuels displace a more carbon intensive fuel.

Note that during the Kyoto target period, the fossil fuels saved do not offset the net biomass change. In the long-term, as a new steady-state biomass level is reached, the biofuels will continue to save fossil fuel emissions.

Table 12: Net GHG emissions (t CO_2e/ha), Red Spruce, Increase biofuel/slash

Year	FF Used	FF Saved	Electricity	Landfills	Total
2008	0.0	-0.4	0.0	0.0	**-0.4**
2009	0.0	-0.4	0.0	0.0	**-0.4**
2010	0.0	-0.4	0.0	0.0	**-0.4**
2011	0.0	-0.4	0.0	0.0	**-0.4**
2012	0.0	-0.4	0.0	0.0	**-0.4**

Figure 17: Forest-level net biomass (t CO_2e/ha), Red Spruce, Increase biofuel/slash



Example 2 – British Columbia

Reference Scenario – Natural Regeneration

Biomass

The example from British Columbia is based on coastal Douglas Fir (Site Index 30). The reference case involves natural regeneration without any treatment. The stand reaches financial maturity at 75 years. At this point, MAI is a maximum of 9.80 m^3 / yr. The average biomass over a rotation at equilibrium is listed in Table 13. The soil, above ground biomass and landfill pools store 29.4%, 24.7% and 19.1% of the total biomass respectively.

The steady-state stand-level biomass profile over time is shown in Figure 18.

Table 13: Forest-level biomass, Douglas Fir, natural regeneration (reference case)

Pool		Rotation Average Biomass (t/ha)	
Above Ground Biomass	Trees	165.1	
	Other Vegetation	7.2	
	Total	172.3	172.3
Roots	Trees	38.3	
	Other Vegetation	1.4	
	Total	39.7	39.7
Litter	Above ground	43.7	
	Below ground	43.9	
	Total	87.6	87.6
Soil			204.8
Woodproducts	Short-lived	5.7	
	Long-lived	53.8	
	Total	59.5	59.5
Total (not including landfill)			**563.9**
Landfills			133.5
Total (including landfill)			**697.4**

Greenhouse gas emissions

Stand-level emissions from management of the reference case are shown in Figure 19. The forest-level emissions are the same as the rotation average emissions. They are listed below. Note that they are larger than the Nova Scotia example because more wood product is created over a rotation by this example. The exception is emissions from electricity. This is smaller in British Columbia because of its smaller electrical generation emission intensity (more hydro).

Table 14: Forest-level emissions, Douglas Fir, natural regeneration (reference case)

Source	Rotation Average Emissions (t CO_2e/ha)
Fossil fuels (processing, waste management)	1.4
Fossil fuels saved (biofuel replacement)	-0.6
Electricity	0.1
Landfills	19.4
Total	**20.2**

Figure 18: Stand-level steady-state biomass, Douglas Fir, natural regeneration (reference case)

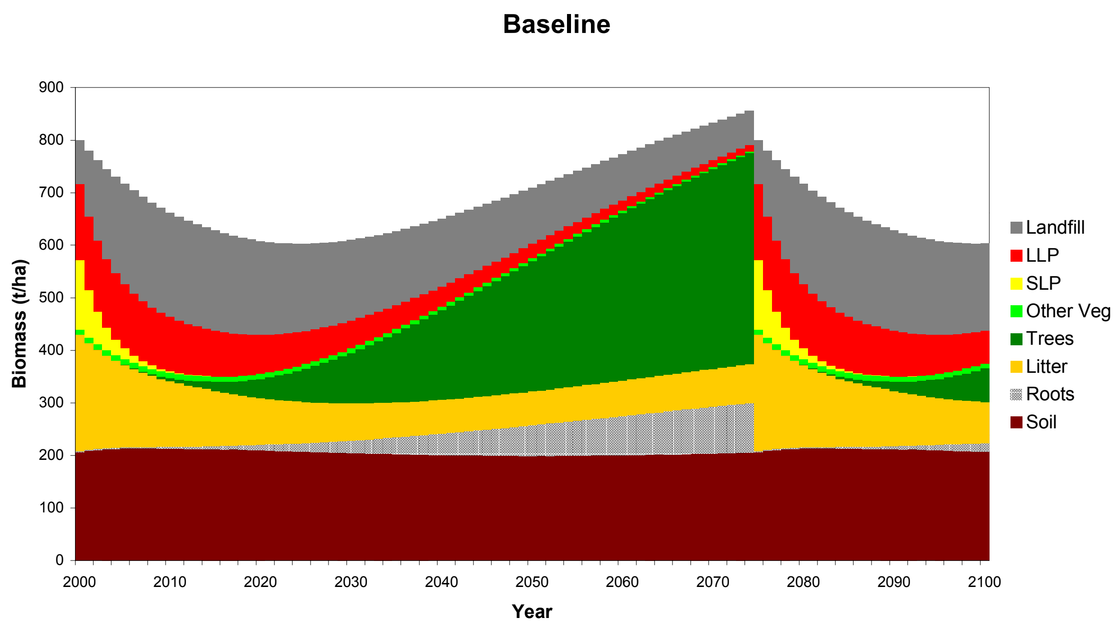
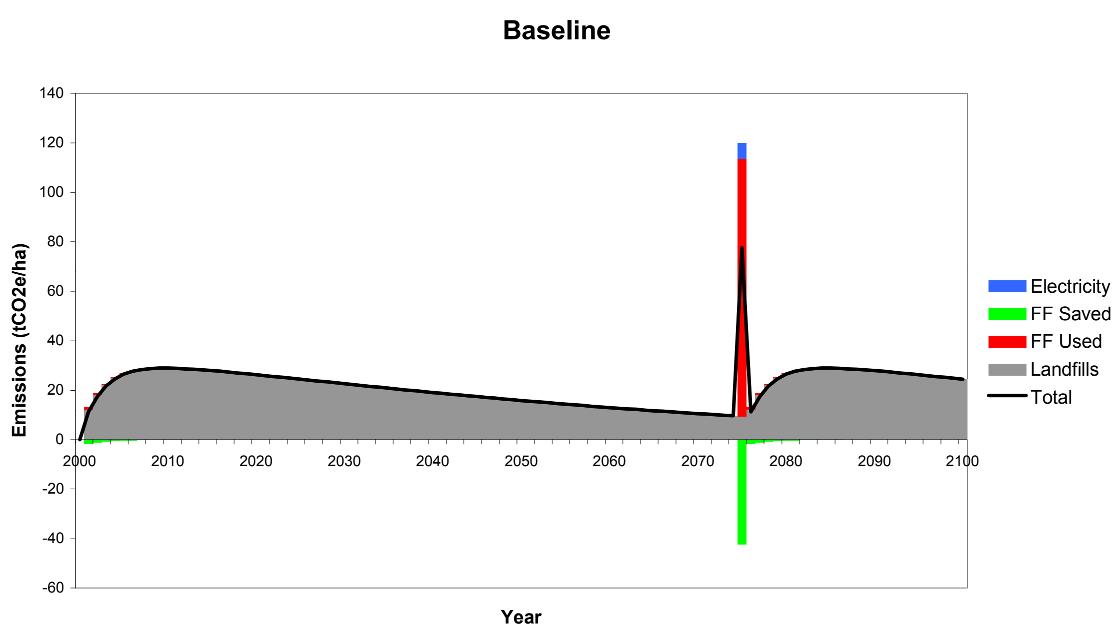


Figure 19: Stand-level, steady-state emissions, Douglas Fir, natural regeneration (reference case)



Pre-commercial Thinning

Dave Spittlehouse provided yield curves for two intensities of pre-commercial thinning (PCT). In both examples, PCT occurs when the trees are ten years old. The moderate PCT decreases the number of trees per hectare from 1,294 to 1,025. After intense PCT, there are 628 trees per hectare. Only the moderate PCT example is presented.

In 2001, at ten years of age, the stand undergoes moderate pre-commercial thinning (PCT). It is assumed that waste is left on-site as litter. Moderate PCT increases the rotation period to 80 years. It also decreases the maximum MAI to 9.69 m^3/yr (down from 9.80 m^3/yr).

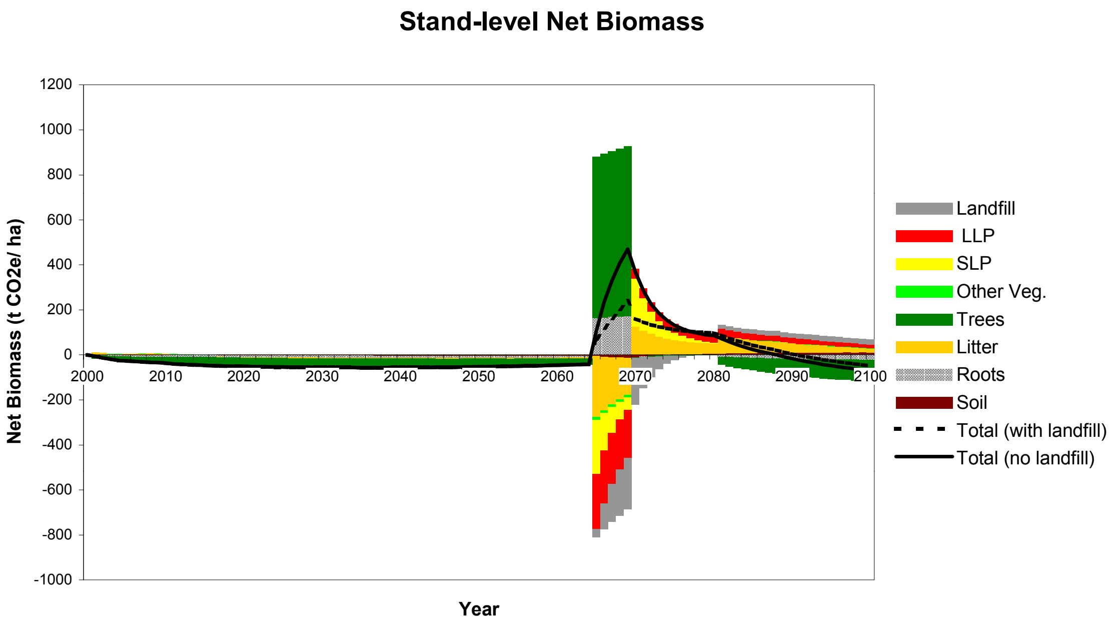
Stand-level net biomass

Figure 20 show the stand-level net biomass profile. In 2001, the stand is ten years old and undergoes pre-commercial thinning. There is a net loss of biomass because the trees always have slightly less biomass than in the baseline scenario. In 2065, the trees in the reference case would have been harvested. There is an increase in net biomass in the trees and roots and a corresponding decrease in net biomass in litter, landfill and short and long-lived wood products pools (SLP and LLP). The decay of these pools cause the system net biomass to increase.

In 2070, the stand is harvested. Now, net biomass in the trees and roots is very small, but there is positive net biomass in the litter, SLP and LLP pools. This decreases with time because of decay.

In 2081, stand undergoes pre-commercial thinning again.

Figure 20: Stand-level net biomass (t CO_2e/ha), Douglas Fir, Moderate PCT – natural regeneration



Forest-level net biomass

Figure 21 shows the forest-level net biomass as a result of moderate pre-commercial thinning. The forest gradually loses biomass prior to 2065. For trees of the same age, the trees in the PCT stand never store more biomass than the naturally regenerating stand. As a result, there is less average biomass in the forest with PCT. The large increase in tree biomass after 2065 occurs because some of the naturally regenerating stands reach maturity and are harvested. After 2070, the PCT stands begin being harvested while some naturally regenerating stands are still being harvested. As a result, the tree biomass decreases. The change in net biomass beyond 2065 is typical of an increase in rotation length. This will be investigated later in the paper.

During the Kyoto target period, the PCT forest loses 2.5 t CO_2e/ha (remember, by definition, the naturally regenerating forest does not lose or gain biomass over time). There is large loss in tree and root biomass. Litter, and other vegetation pools increase in biomass. Note that there is no change in net biomass in the wood products and landfill pools. During the Kyoto target period there is no change in harvesting. By 2050, as a result of PCT the forest stores 31.6 t CO_2e/ha less than the reference case.

Table 15: Kyoto net biomass (t CO_2e/ha), Douglas Fir, PCT - natural regeneration

Year	Trees	Other Veg.	Roots	Litter	Soil	SLP	LLP	Total (no landfill)	Landfill	Total (with landfill)
2007	-2.0	0.0	-0.5	0.5	-0.1	0.0	0.0	**-2.0**	0.0	**-2.0**
2012	-4.2	0.1	-1.0	0.8	-0.2	0.0	0.0	**-4.5**	0.0	**-4.5**
Kyoto Sequestration	**-2.2**	**0.1**	**-0.5**	**0.3**	**-0.1**	**0.0**	**0.0**	**-2.5**	**0.0**	**-2.5**

Net GHG emissions

The PCT has very little effect on net greenhouse gas emissions during the Kyoto target period. Beyond 2065, there are significant net GHG emissions due to differences in the timing and the amount of harvest (Figure 22).

Table 16: Net GHG emissions (t CO_2e/ha), Douglas Fir, Moderate PCT - natural regeneration

Year	FF Used	FF Saved	Electricity	Landfills	Total
2008	0.00	0.00	0.00	0.00	**0.00**
2009	0.00	0.00	0.00	0.00	**0.00**
2010	0.00	0.00	0.00	0.00	**0.00**
2011	0.00	0.00	0.00	0.00	**0.00**
2012	0.00	0.00	0.00	0.00	**0.00**

Figure 21: Forest-level net biomass (t CO_2e/ha), Douglas Fir, Moderate PCT – natural regeneration

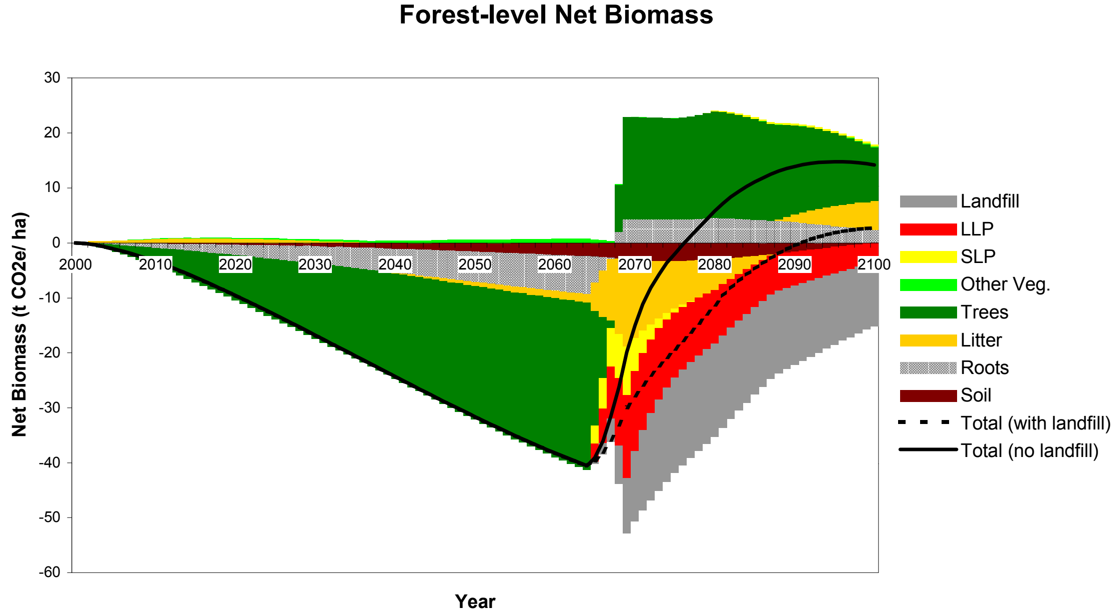
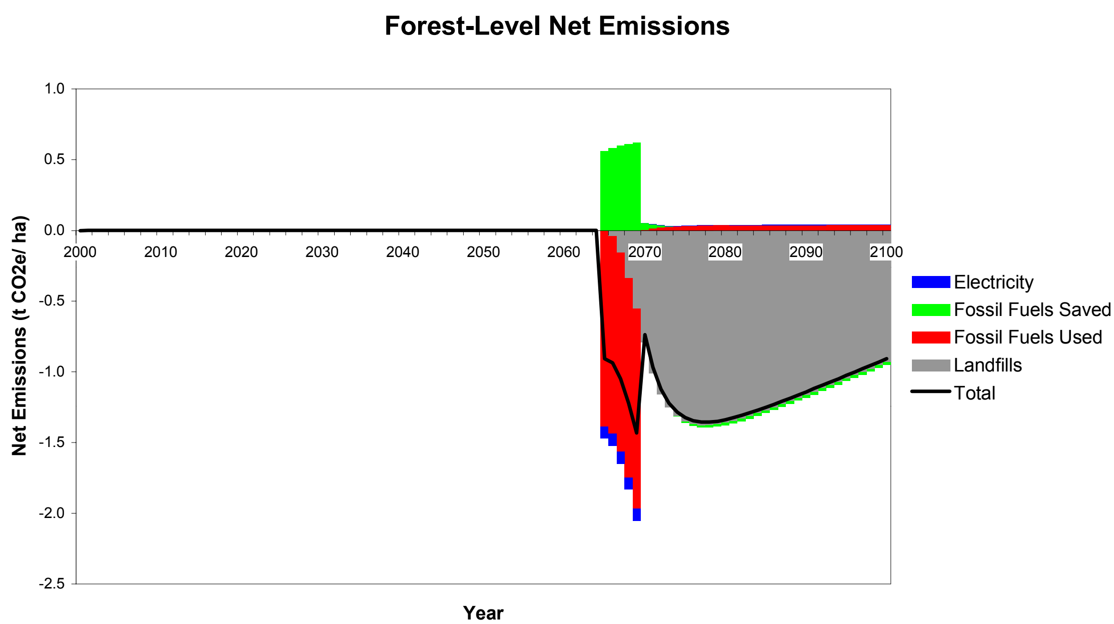


Figure 22: Forest-level net GHG emissions, Douglas Fir, Moderate PCT – natural regeneration



Commercial Thinning for Pulp

In 2001, at 50 years of age, the stand undergoes commercial thinning (CT). Approximately 16% of the biomass is removed for pulp (66% of harvested material). The stand reaches full harvesting age at 85 years of age (MAI = 9.35 m^3/yr).

Stand-level net biomass

This example shows many of the same features as the previous one. The thinning creates a net biomass loss. There is a net biomass gain in some years because of the increase in rotation length (Figure 23).

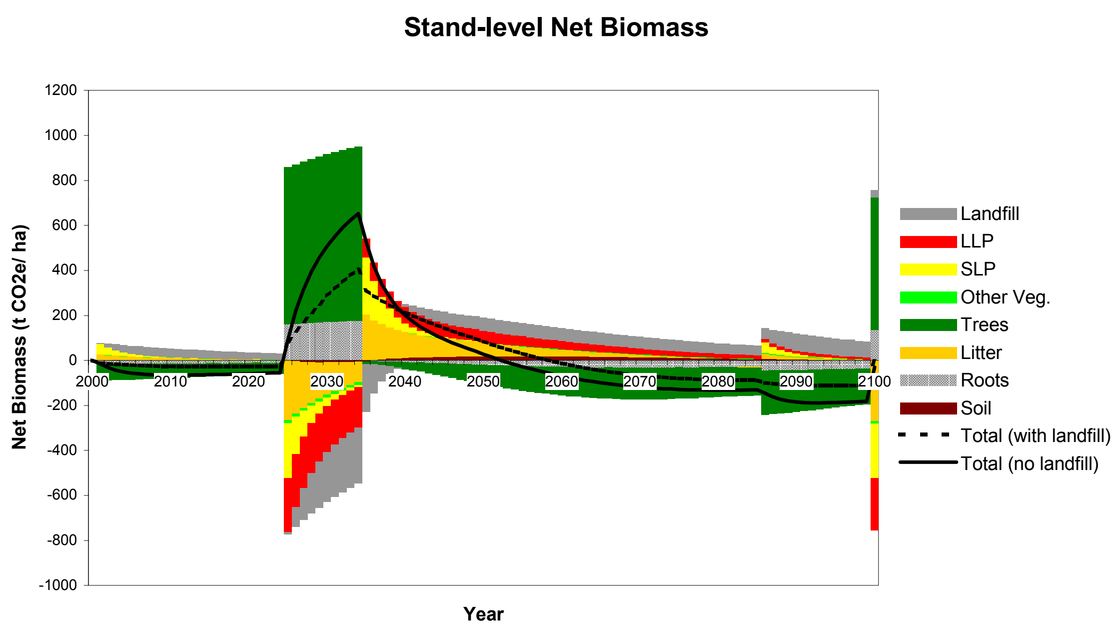
The stand is commercially thinned for pulp in 2001 when it is 50 years old. There is a net loss in tree biomass and a net gain in short-lived product (SLP) biomass. This decays with time so before 2025, the new system has a net biomass loss.

In 2025, the reference stand would have been harvested but the treated stand is left unharvested. As a result there is a large net biomass gain in the trees and roots pools. This is offset somewhat by missing biomass in the litter, landfill, SLP and LLP pools. These pools decay with time some the system progressively gains net biomass.

In 2030, the treated stand is harvested. The previous net biomass gain is transferred to the litter, SLP and LLP pools. These pools decrease with time due to decay. The trees in the reference case would already have started growing by this time. As a result, the total net biomass slowly becomes negative (a loss).

The process repeats itself in 2085.

Figure 23: Stand-level net biomass (t CO_2e/ha), Douglas Fir, CT for pulp – natural regeneration



Forest-level net biomass

The forest-level net biomass profile is displayed in Figure 24. It tells a similar story to the previous example. The system acts a net source of biomass until harvesting occurs. Then, because the CT forest has a longer rotation period, the system gains biomass and becomes a net sink.

During the Kyoto target period CT for pulp forest results in the loss of 4.3 t CO_2e/ha. There is large loss in tree and root biomass while litter and other vegetation pools increase in biomass. Short-lived wood products and landfill are both net stores of biomass.

Approximately 79.3 t CO_2e/ha are stored by the forest system as a result of CT for pulp.

Table 17: Kyoto net biomass (t CO_2e/ha), Douglas Fir, CT for pulp- natural regeneration

Year	Trees	Other Veg.	Roots	Litter	Soil	SLP	LLP	Total (no landfill)	Landfill	Total (with landfill)
2007	-6.6	0.1	-1.5	1.8	0.1	1.9	0.0	**-4.3**	2.6	**-1.7**
2012	-10.9	0.2	-2.5	2.4	0.1	2.0	0.0	**-8.6**	5.1	**-3.5**
Kyoto Sequestration	**-4.3**	**0.1**	**-1.0**	**0.6**	**0.0**	**0.1**	**0.0**	**-4.3**	**2.5**	**-1.8**

Net GHG emissions

During the Kyoto target period some stands are thinned. As a result, there are GHG emissions from harvesting and conversion into wood product. As well, landfill receives more material prior to 2008, so landfill gas emissions also increase. Figure 25 shows the forest-level net GHG emission profile until 2100.

Table 18: Net GHG emissions (t CO_2e/ha), Douglas Fir, Moderate PCT - natural regeneration

Year	FF Used	FF Saved	Electricity	Landfills	Total
2008	0.14	-0.07	0.04	0.20	**0.32**
2009	0.14	-0.07	0.04	0.24	**0.36**
2010	0.14	-0.07	0.04	0.29	**0.40**
2011	0.14	-0.07	0.04	0.33	**0.44**
2012	0.14	-0.07	0.04	0.37	**0.48**

Figure 24: Forest-level net biomass (t CO_2e/ha), Douglas Fir, CT for pulp – natural regeneration

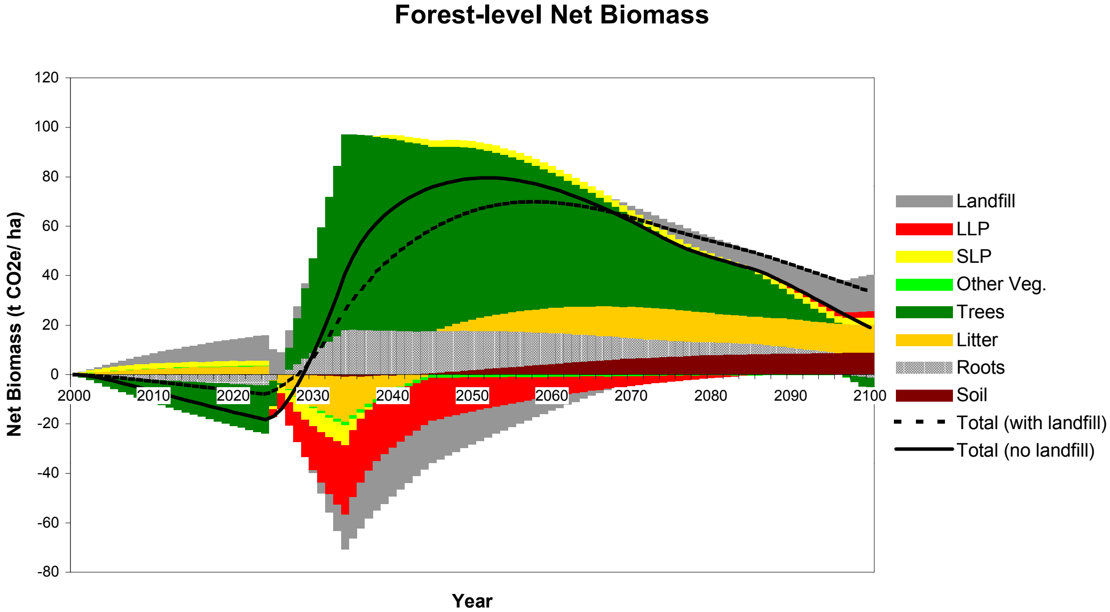
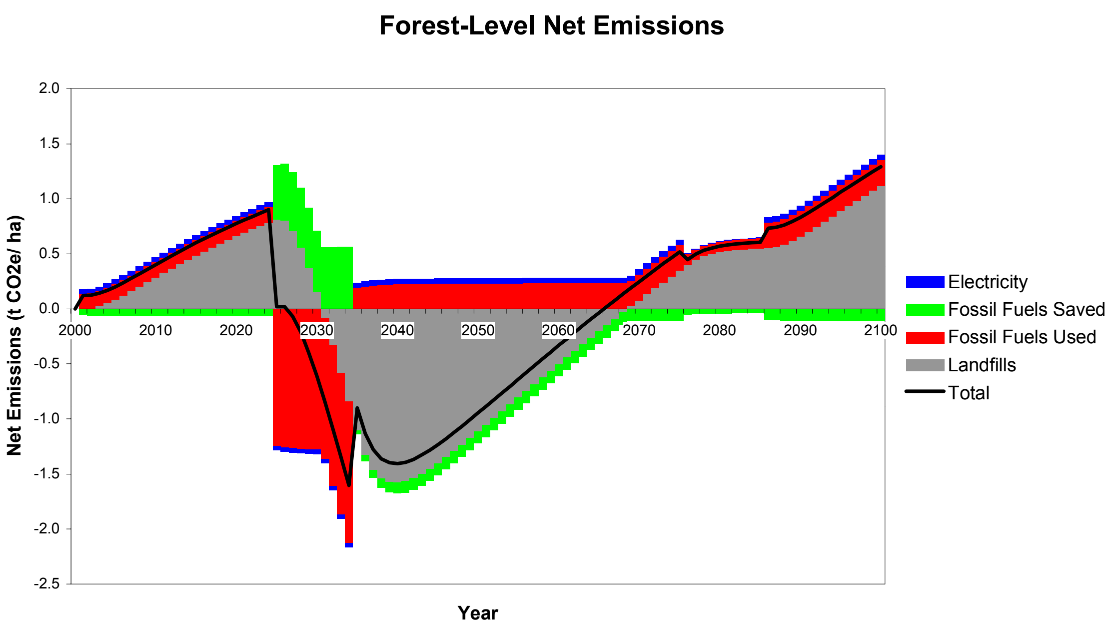


Figure 25: Forest-level net GHG emissions, Douglas Fir, CT for pulp – natural regeneration



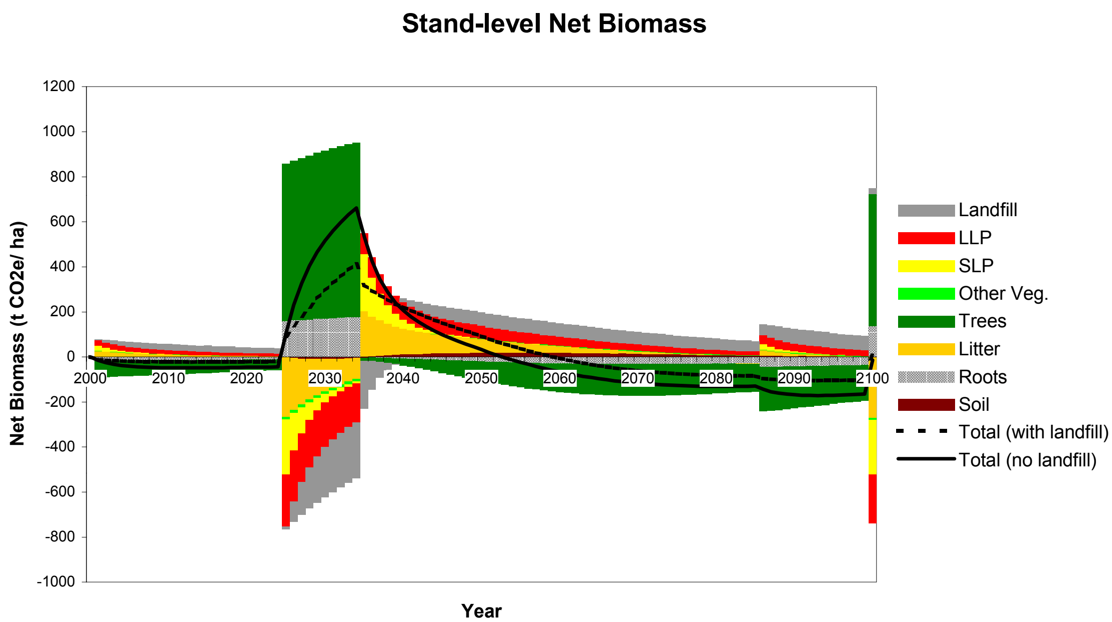
Commercial Thinning for Pulp and Lumber

This example is identical to the previous example except that when the stand is thinned (in 2001, at age 50) the harvested material becomes both short and long-lived wood products. As before, 16% of the stand is harvested but now 33% of the harvested material is converted to pulp and a further 33% to lumber.

Stand-level net biomass

The general form of the stand-level net biomass profile (Figure 26) is similar to the previous example. There is a slight positive bias in net biomass due to the increased decay time of the long-live products over short-lived products.

Figure 26: Stand-level net biomass (t CO_2e/ha), Douglas Fir, CT for pulp and lumber – natural regeneration



Forest-level net biomass

The net biomass profile (Figure 27) is almost identical to the previous example (Figure 24). There is a small difference between 2001 and 2025 due to the change in proportion of short to long-lived wood products.

By increasing the amount of long-lived wood products, the net biomass change during the Kyoto target period decreases. The change in net biomass in all pools is identical to the previous example with the exception of the wood products and landfill pools.

Commercial thinning for pulp and lumber increases net biomass in 2050 to 86.1 t CO_2e/ha.

Table 19: Kyoto net biomass (t CO_2e/ha), Douglas Fir, CT for pulp and lumber - natural regeneration

Year	Trees	Other Veg.	Roots	Litter	Soil	SLP	LLP	Total (no landfill)	Landfill	Total (with landfill)
2007	-6.6	0.1	-1.5	1.8	0.1	0.9	2.0	**-3.2**	1.6	**-1.6**
2012	-10.9	0.2	-2.5	2.4	0.1	1.0	3.2	**-6.4**	3.4	**-3.1**
Kyoto Sequestration	**-4.3**	**0.1**	**-1.0**	**0.6**	**0.0**	**0.1**	**1.2**	**-3.2**	**1.8**	**-1.5**

Net GHG emissions

The net GHG emissions during the Kyoto target period are similar to the previous example. There is no difference in net emissions from fossil fuel used and electricity since the same amount of biomass is harvested. There are differences in net emissions from fossil fuel saved and landfill due to the change in mix of wood products. Short-lived wood products decay more rapidly. Some of the decayed material is used as biofuel and some ends up in landfills. Figure 28 shows the forest-level net GHG emission profile until 2100.

Table 20: Net GHG emissions (t CO_2e/ha), Douglas Fir, Moderate PCT - natural regeneration

Year	FF Used	FF Saved	Electricity	Landfills	Total
2008	0.14	-0.06	0.04	0.13	**0.25**
2009	0.14	-0.06	0.04	0.16	**0.28**
2010	0.14	-0.06	0.04	0.18	**0.30**
2011	0.14	-0.06	0.04	0.21	**0.33**
2012	0.14	-0.06	0.04	0.24	**0.36**

Figure 27: Forest-level net biomass (t CO_2e/ha), Douglas Fir, CT for pulp and lumber – natural regeneration

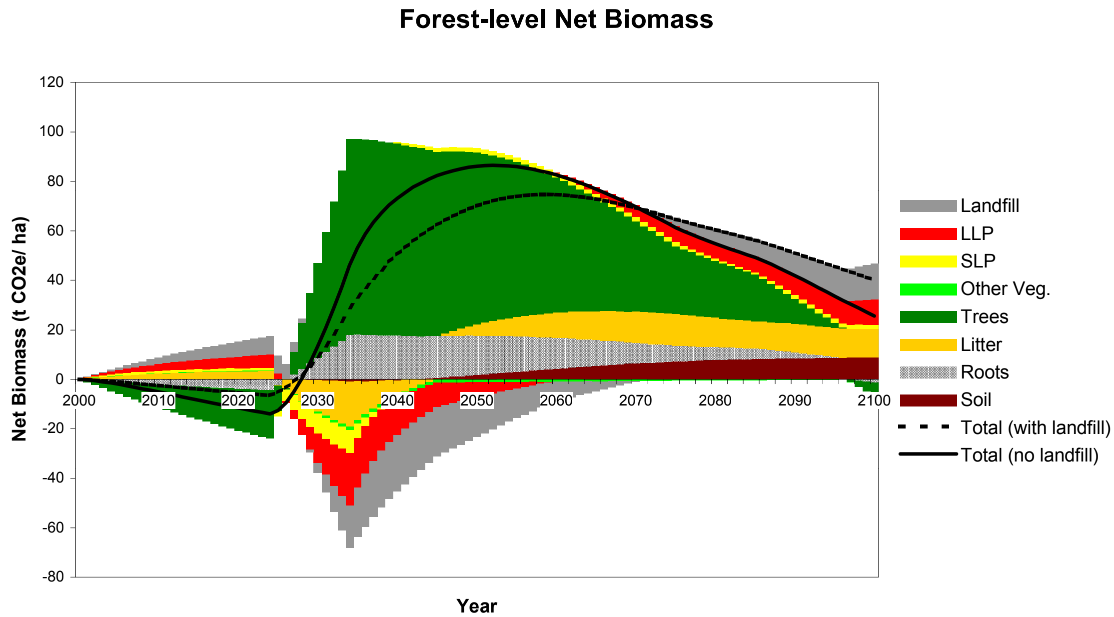
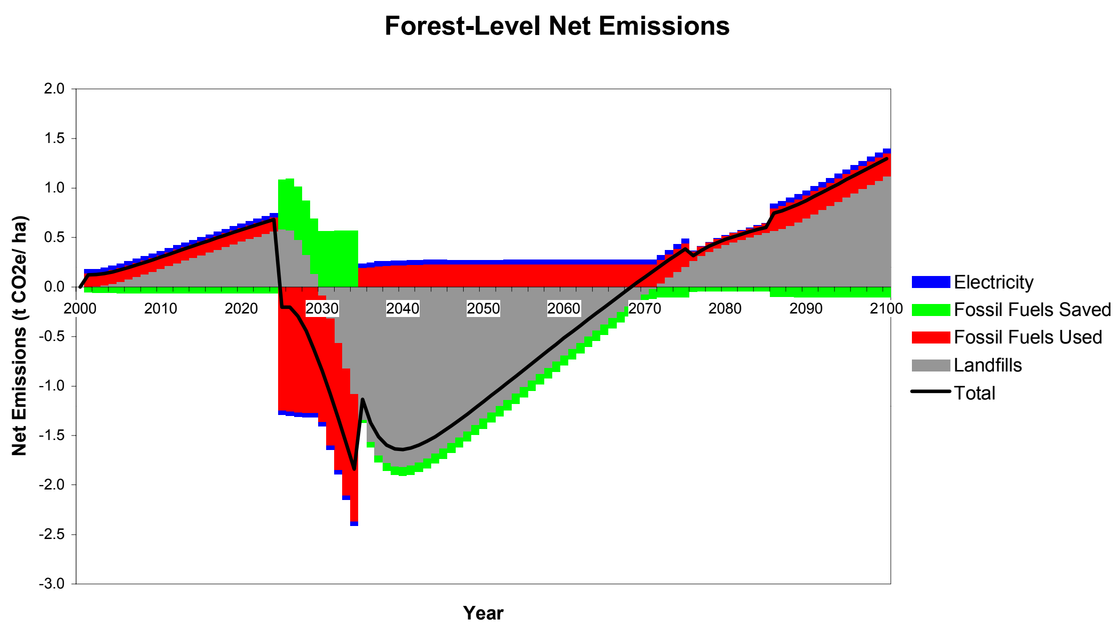


Figure 28: Forest-level net GHG emissions, Douglas Fir, CT for pulp and lumber – natural regeneration



Increasing Rotation Length

The Nova Scotia example of increasing rotation length increased net biomass during the Kyoto target period and beyond. Changing rotation length in other British Columbia examples also had an increase in net biomass. In this example, the reference stand reaches financial maturity in 2001. The company chooses to harvest the stand five years later in 2006. At 80 years, MAI has decreased to 9.78 m^3 per year. No other changes in management regime are included.

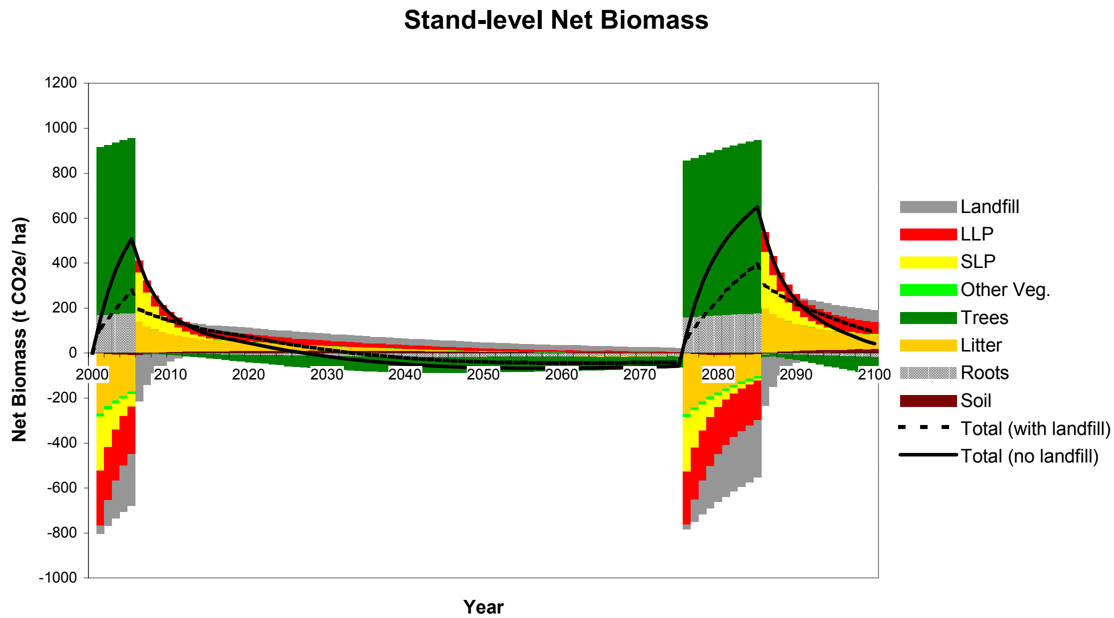
Stand-level net biomass

Figure 29 shows the stand-level net biomass profile as a result of increasing the rotation length by five years. In 2001, the stand is not harvested, even though it has reached financial maturity. There is a net gain in tree and root biomass, and a corresponding net loss in litter, landfill and short and long-lived wood products (SLP and LLP). Over the next five years, there is a net gain in biomass because there is decay of these litter, landfill, SLP and LLP pools.

In 2005, the stand is harvested. The tree net biomass is slightly negative since in the reference case, the trees would have already started growing again. There is a positive net biomass in litter, SLP and LLP because these pools have not decayed to the same level as in the reference case. In total, the new management system has a net biomass gain.

In 2075, the process repeats itself, except that now there are ten years when the trees in the new management system are standing and the reference system would have been harvested.

Figure 29: Stand-level net biomass (t CO_2e/ha), Douglas Fir, Increase rotation length by 5 years



Forest-level net biomass

Figure 30 shows the net biomass profile to 2100 as a result of changing the rotation length by five years. Starting in 2001, there is a sharp increase in net tree and root biomass. This is due to the harvesting of the mature stands in the reference case while they are not harvested in the increased rotation scenario. The difference in harvesting also creates a corresponding decrease of net biomass in the litter, wood products and landfill pools. In 2006, the harvesting of the longer rotation length stands begins. Until 2010 there is little change in net tree and root biomass. From this point to 2080 there is a gradual decrease in net biomass.

The change in net biomass during the Kyoto target period is shown in Table 21. Increasing the rotation length by five years starting in 2001 makes the forest act as a net sink. Similar to the Nova Scotia example, by the Kyoto target period, the large change in net tree and root biomass is over, but the increase has been transferred to the litter, soil, and wood products pools. A larger impact during the Kyoto target period can be achieved by either delaying the change in management systems by five years or lengthening the rotation even more.

By 2050, 41.2 t CO_2e/ha are stored as a result of increasing the rotation length by five years.

Table 21: Kyoto net biomass (t CO_2e/ha), Douglas Fir, Increase rotation length by 5 years

Year	Trees	Other Veg.	Roots	Litter	Soil	SLP	LLP	Total (no landfill)	Landfill	Total (with landfill)
2007	50.8	-0.9	11.6	-10.6	-0.5	-3.8	-13.8	**32.8**	-14.6	**18.2**
2012	50.3	-0.8	11.5	-5.1	-0.2	-0.1	-10.8	**44.8**	-16.9	**27.9**
Kyoto Sequestration	**-0.5**	**0.1**	**-0.1**	**5.5**	**0.3**	**3.7**	**3.0**	**12.0**	**-2.3**	**9.7**

Net GHG emissions

Table 22 and Figure 31 show the net GHG emissions in the Kyoto target period and beyond as a result of increasing the rotation length by five years. During the Kyoto target period the change in management system decreases GHG emissions by over 6.0 t CO_2e/ha. Almost all of this is the result of fewer landfill gas emissions as a result of a delay in wood product production.

Table 22: Net GHG emissions (t CO_2e/ha), Douglas Fir, Increase rotation length by 5 years

Year	FF Used	FF Saved	Electricity	Landfills	Total
2008	0.07	-0.01	0.01	-1.15	**-1.09**
2009	0.07	-0.02	0.01	-1.24	**-1.18**
2010	0.08	-0.02	0.01	-1.30	**-1.24**
2011	0.08	-0.03	0.01	-1.33	**-1.27**
2012	0.08	-0.03	0.01	-1.34	**-1.28**

Figure 30: Forest-level net biomass (t CO_2e/ha), Douglas Fir, Increase rotation length by 5 years

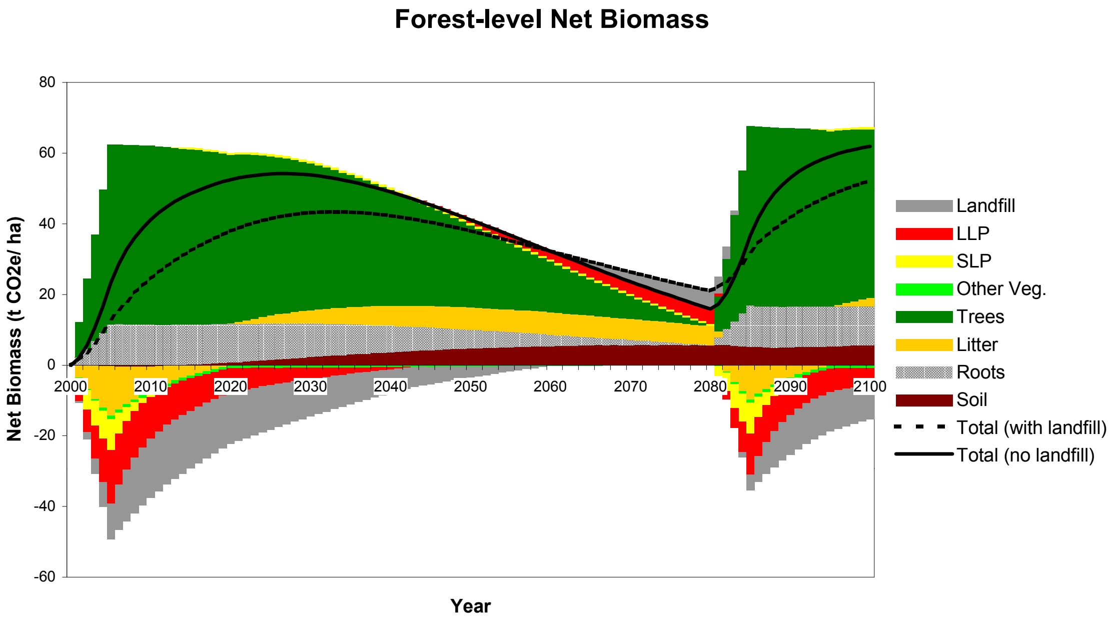
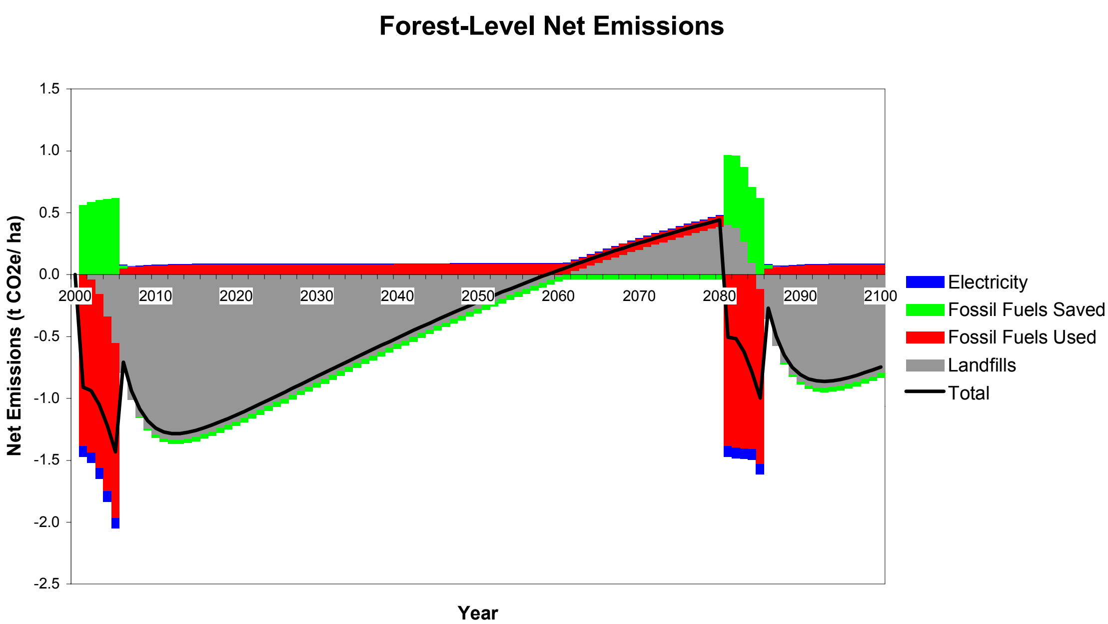


Figure 31: Forest-level net GHG emissions, Douglas Fir, Increase rotation length by 5 years



Increasing Biofuel Use

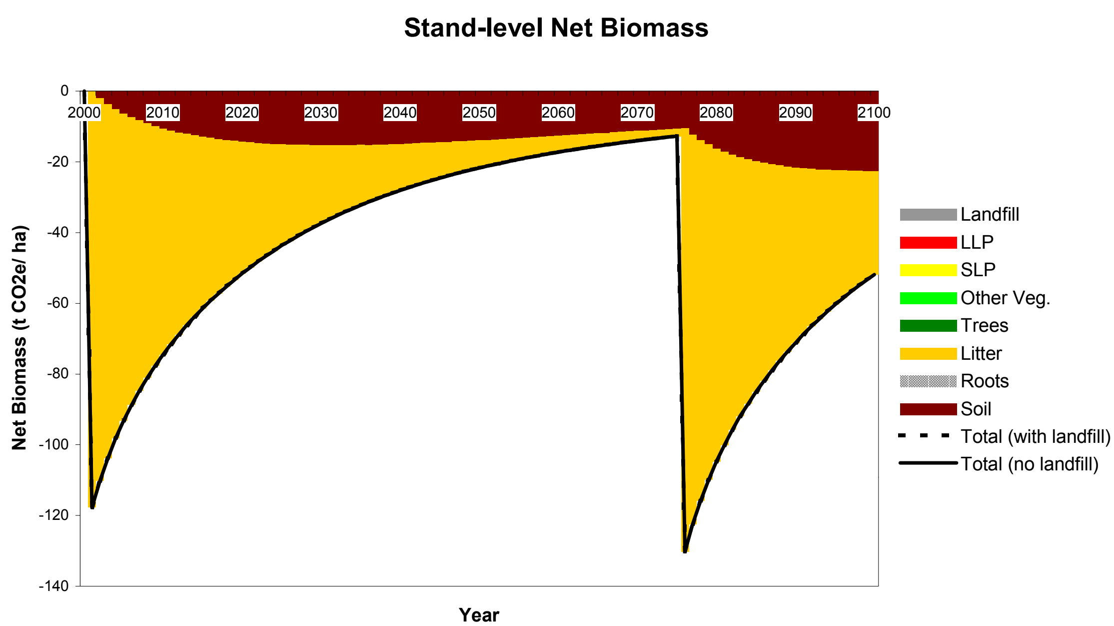
The final example from British Columbia examines the effect of increasing biofuel use while decreasing slash. In the reference case, 16% of the harvest is left as slash and 13% is used for biofuel. Short-lived and long-lived wood products are produced from 33% of the harvest each. The remainder (5%) becomes landfill. Starting with harvests in 2001, all slash is used a biofuel. The other proportions remain the same.

Stand-level net biomass

In 2001, the stand is harvested but the slash is used for biofuel instead of left as litter. There is a large net loss of biomass (Figure 32). This decays over time. With less litter there is also a decrease in soil biomass. The net soil biomass loss becomes larger over time because of the dynamics of the litter and soil pools.

The process repeats itself during the next harvest but starts at a negative net biomass. The system stores progressive less biomass until a new equilibrium is reached.

Figure 32: Stand-level net biomass (t CO_2e/ha), Douglas Fir, Increase biofuel/slash



Net biomass

This change in management regime has a simple forest-level net biomass profile (Figure 33). Similar to the Nova Scotia example, increasing biofuel while reducing slash decreases litter and soil biomass. In the long-term, when the new forest management system has reached equilibrium, the net biomass loss is a constant (~ 42 t CO_2e/ha).

During the Kyoto target period the change in net biomass is large (but less so if soil is not included).

By 2050, net biomass loss has increased to 33.8 t CO_2e/ha by using all slash for biofuel.

Table 23: Kyoto net biomass (t CO_2e/ha), Douglas Fir, Increase biofuel/slash

Year	Trees	Other Veg.	Roots	Litter	Soil	SLP	LLP	Total (no landfill)	Landfill	Total (with landfill)
2007	0.0	0.0	0.0	-8.8	-0.4	0.0	0.0	**-9.3**	0.0	**-9.3**
2012	0.0	0.0	0.0	-13.1	-1.1	0.0	0.0	**-14.3**	0.0	**-14.3**
Kyoto Sequestration	**0.0**	**0.0**	**0.0**	**-4.3**	**-0.7**	**0.0**	**0.0**	**-5.0**	**0.0**	**-5.0**

Net GHG emissions

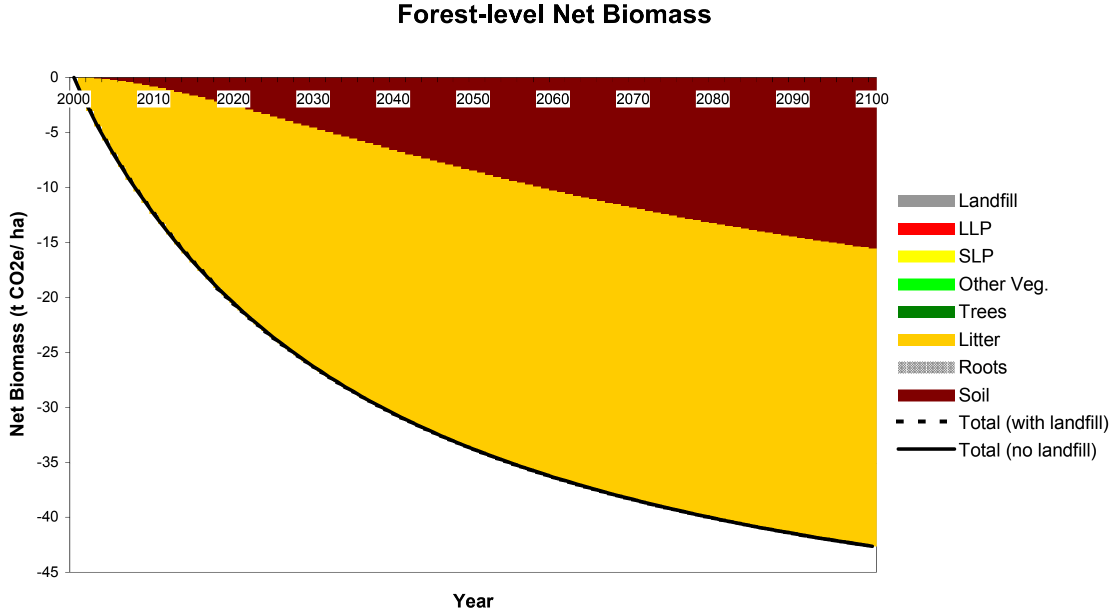
The increase in biofuel saves more fossil fuels. As a result, net GHG emissions decrease. In this example it was assumed that the biofuels displace natural gas. The amount saved will increase if the biofuels displace a more carbon-intensive fuel.

Note that during the Kyoto target period, the fossil fuels saved do not offset the net biomass change. In the long-term, as a new steady-state biomass level is reached there is no change in net biomass, but the biofuels continue to avoid fossil fuel emissions.

Table 24: Net GHG emissions (t CO_2e/ha), Douglas Fir, Increase biofuel/slash

Year	FF Used	FF Saved	Electricity	Landfills	Total
2008	0.00	-0.69	0.00	0.00	**-0.69**
2009	0.00	-0.69	0.00	0.00	**-0.69**
2010	0.00	-0.69	0.00	0.00	**-0.69**
2011	0.00	-0.69	0.00	0.00	**-0.69**
2012	0.00	-0.69	0.00	0.00	**-0.69**

Figure 33: Forest-level net biomass (t CO_2e/ha), Douglas Fir, Increase biofuel/slash



Cost of Implementation

Increasing the rotation length is the only option studied that increases net biomass during the Kyoto target period. As a result, it is the only option for which costs of implementation have been estimated.

Value of Short and Long-lived Wood Products

Increasing the rotation length alters the amount and timing of the production of wood products. The cost of implementation is the loss of revenue and the loss of net present value. To estimate these, the value of short and long-lived wood products must be ascertained. The following table summarizes the sales and production from Canadian operations[6].

Table 25: Production and sales from Canadian operations

			Volumes			Sales (M$)		
	Item	**units**	**1997**	**1996**	**1995**	**1997**	**1996**	**1995**
Short-lived	Wood Pulp	kt	11,197	10,972	11,866	6,642	6,490	11,730
	NewsPrint	kt	11,872	11,121	11,580	8,192	9,457	10,033
	Other Papers and Boards	kt	7,350	6,994	6,636	6,234	5,988	7,633
	Total	**kt**	**30,419**	**29,087**	**30,082**	**21,068**	**21,935**	**29,396**
Long-lived	Lumber	Mbf	27,419	26,691	25,434	14,940	14,172	11,614
	Panels	Msf, 3/8	8,989	7,743	6,334	2,060	1,874	1,829
	Total*	**kt**	**32,695**	**31,426**	**29,530**	**16,685**	**15,795**	**13,061**

** Assumes a density of 450 kg/m^3*

During the same period, operating expenses accounted for 88.4% of total sales. From these data, the average value of each wood product is:

Short-lived wood product = $ 94 / t

Long-lived wood product = $ 57 / t

Note: Net earnings by wood product are also available in the Price Waterhouse report. They were note used because for 1996 and 1997 net earnings from wood pulp and newsprint were negative (i.e. a loss).

[6] Price Waterhouse (1998), The Forestry Industry in Canada, 1997.

Nova Scotia

Increasing rotation length

When the rotation length is increased by five years there are five years of lost production. However, as harvesting progresses, more biomass per hectare is extracted. The cumulative value of the lost production is shown in Figure 34. In 2012, the cumulative lost production is valued at \$ 588 / ha. By 2050, this has decreased to \$ 307 / ha.

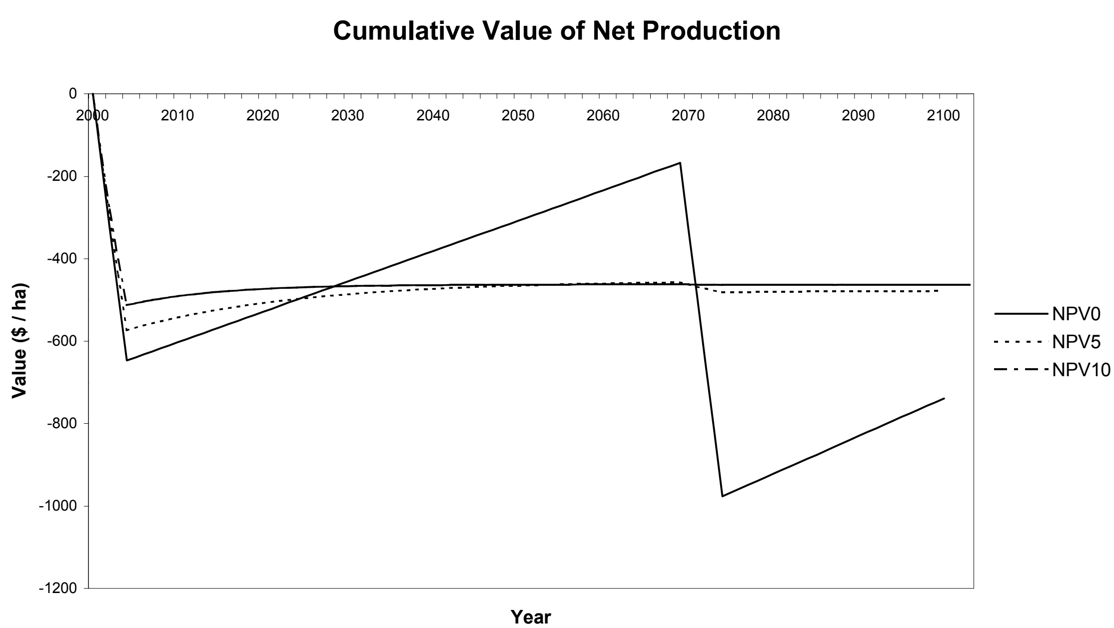
The cost of GHG reductions during the Kyoto target period is displayed in Table 26. By 2050, the cost for sequestration has decreaed to \$ 28.22 / t CO_2e (NPV_5 = \$ 42.66 / t CO_2e, NPV_{10} = \$ 42.47 / t CO_2e). The decrease in cost is caused by a decrease in the cumulative value of lost production not by an increase in the amount of biomass sequestered.

Table 26: Cost of GHG reductions during Kyoto target period, Red Spruce, Increase rotation length

Sequestration (t CO_2e/ha):	3.1		
GHG emissions (t CO_2e/ha):	1.1		
Total (t CO_2e/ha):	**4.2**		
	NPV_0	NPV_5	NPV_{10}
Lost Production (\$/ha)	588	534	486
Sequestration Cost (\$/t CO_2e)	189.68	172.26	156.77
Total Cost (\$/t CO_2e)	140.00	127.14	115.71

NPV_5 refers to the net present value assuming a 5% discount rate.

Figure 34: Cumulative value of net production, Red Spruce, Increase rotation length



British Columbia

Increasing rotation length

Figure 35 shows the value of lost production caused by increasing the rotation length by five years. It is similar in form to the Nova Scotia example. By 2012, lost production totals $ 1,220 / ha. It decreases to $ 610 / ha (NPV_5= $ 930, NPV_{10} = $ 912) by 2050.

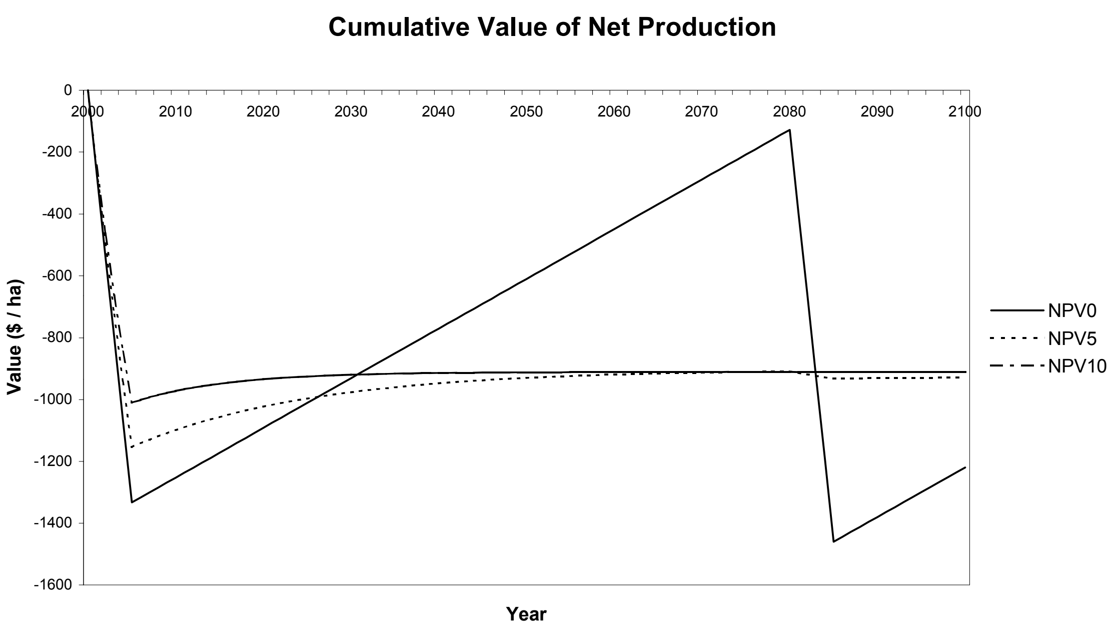
Table 27 shows the cost of sequestration and GHG emission reduction during the Kyoto target period. By 2050, the cost of sequestration is $ 14.80 / t CO_2e (NPV_5 = $ 22.57 / t CO_2e, NPV_{10} = $ 22.14 / t CO_2e).

Table 27: Cost of GHG reductions during Kyoto target period, Douglas Fir, Increase rotation length

Sequestration (t CO_2e/ha):	12.0		
GHG emissions (t CO_2e/ha):	6.0		
Total (t CO_2e/ha):	**18.0**		
	NPV_0	NPV_5	NPV_{10}
Lost Production ($/ha)	1,220	1,081	962
Sequestration Cost ($/t CO_2e)	101.67	90.08	80.17
Total Cost ($/t CO_2e)	67.78	60.06	53.44

NPV_5 refers to the net present value assuming a 5% discount rate.

Figure 35: Cumulative value of net production, Douglas Fir, Increase rotation length



The financial cost to companies in terms of lost production has been assessed. Some of this can be recovered by increasing the amount of material recycled. A recent study by the United States Environmental Protection Agency[7] found that recycling of paper reduces greenhouse gas emissions upstream by ~ 1.5 t CO_2e/t recycled. It also reduces landfill gas emissions by ~ 1.5 t CO_2e/t recycled (these values are dependent on location and type of material recycled).

One must also consider that there is a social cost to lost production as some 250,000 people are employed in the forestry industry.

Conclusion

Generally, the activities that increase rotation length increase biomass in the long-term. In the examples studied, pre-commercial thinning resulted in decreased rotation length in Nova Scotia, but an increase in rotation length in British Columbia. Commercial thinning (independent of harvest use) resulted in increased rotation length. This is similar to Cooper's result[8].

In the short-term, however, the net biomass is dependent on the timing of the forestry activity. As a result, during the Kyoto target period (2008-2012), only increasing the rotation length sequesters more carbon. But there may be an economic and social cost associated with lost production. In this study, no attempt was made to optimize the amount of net biomass sequestered during the Kyoto target period by adjusting the timing of the change in management systems.

Increasing biofuel use while decreasing slash decreases biomass particularly in the litter and soil pools. This change in biomass is rapid in the short-term and becomes negligible as the forest system reaches a new equilibrium. Increasing biofuel use avoids more emissions from fossil fuels, but in the short-term the decrease in emissions does not offset the decrease in biomass.

In conclusion, of the forest management activities considered, only those that increase rotation length before the Kyoto target period (2008-2012) will increase sequestration and help Canada reach its commitment.

[7] United States Environmental Protection Agency (1998), Greenhouse gas emissions from management of selected materials in municipal solid waste, U.S. EPA contract no. 68-W6-0029.

[8] Cooper C (1982). Carbon storage in managed forests, *Can. J. For. Res.* **13**, 155-166.

Appendices

GORCAM – Model Details

GORCAM[9] is a step-wise, spreadsheet-based model that maps the flow of biomass through a stand. This section describes in detail the calculations used to connect each pool.

1. **Trees:** a derivative form of the Chapman-Richard's equation.
2. **Other vegetation:** a linear function of tree biomass to maximum biomass. The vegetation biomass is zero when the tree biomass is a maximum and a maximum when the tree biomass is a minimum.
3. **Tree roots:** an exponential function of tree biomass.
4. **Other vegetation roots:** a constant proportion of other vegetation biomass.
5. **Fine tree litter:** The annual input is a constant proportion of tree biomass. The annual loss is a proportion of the previous annual total. The proportion is such that the pool decays exponentially with a given average lifetime.
6. **Coarse tree litter:** The annual input is a constant proportion of tree biomass. The annual loss is a proportion of the previous annual total. The proportion is such that the pool decays exponentially with a given average lifetime.
7. **Fine tree root litter:** The annual input is a function of tree root biomass. The annual loss is a proportion of the previous annual total. The proportion is such that the pool decays exponentially with a given average lifetime.
8. **Coarse tree root litter:** The annual input is a constant proportion of tree biomass. The annual loss is a proportion of the previous annual total. The proportion is such that the pool decays exponentially with a given average lifetime.
9. **Other vegetation litter**: The annual input is a constant proportion of other vegetation biomass. The annual loss is a proportion of the previous annual total. The proportion is such that the pool decays exponentially with a given average lifetime.
10. **Other vegetation root litter**: The annual input is a constant proportion of other vegetation root biomass. The annual loss is a proportion of the previous annual total. The proportion is such that the pool decays exponentially with a given average lifetime.
11. **Soil:** The annual input is the sum of constant proportions of all litter pools. Each pool has a different constant. The annual loss is a proportion of the previous annual total. The proportion is such that the pool decays exponentially with a given average lifetime.
12. **Short-lived wood products**: The input is a proportion of the harvest during a harvest year.

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[9] Schlamadinger B and Marland G (1996). The role of forest and bioenergy strategies in the global carbon cycle, *Biomass & Bioenergy* **10**, 5/6, 275-300.

Assumptions and Parameters for GORCAM

Expansion factor and density

Yield tables were given as merchantable and total volume, where total volume includes stump and top, but not branches and bark. In this study total volume yield tables were converted to total above ground biomass using a 1.2 expansion factor (Hamburg et al, 1997[10]). As well, a density of 450 kg / m^3 was assumed.

Yield curves

The yield tables were parameterized into a derivative form of the Chapman-Richards equation[11] using a least squares best-fit to the expanded yield tables.

Root biomass relationships

Root biomass was calculated using empirical relationships derived in Kurz et al (1996)[12]. The root biomass is an exponential function of above ground biomass. There are different parameters for a coniferous or deciduous stand.

Litter and Soil

Litter and soil parameters were ascertained by modelling undisturbed stands for 200 years. The parameters were then chosen so that the modelled litter and soil biomass matched measured values given in Siltanen et al (1997)[13]. There are different parameters for coniferous and deciduous stands. Root litter is calculated using an empirical relationship found in Kurz et al (1996)[10].

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[10] Hamburg S, Zamolodchikov D, Korovin G, Nefedjev V, Utkin A, Gulbe J and Gulbe T (1997). Estimating the carbon content of Russian forests; a comparison of phytomass/volume and allometric projections. In: Sathaye J, Makundi W, Goldberg B, Andrasko K and Sanchez A (eds), <u>Proceedings of the International Workshop on Sustainable Forest Management: Monitoring and Verification of Greenhouse Gases</u>, Ernest Orlando Lawrence Berkeley National Laboratory, LBNL-40501.

[11] Cooper C (1982). Carbon storage in managed forests, *Can. J. For. Res.* **13**, 155-166.

[12] Kurz W, Beukema S and Apps M (1996), Estimation of root biomass and dynamics for the carbon budget model of the Canadian forest sector, *Can. J. For. Res.* **26**, 1973-1979.

[13] Siltanen R, Apps M, Zoltai R and Strong W (1997), A soil profile and organic carbon data base for Canadian forest and tundra mineral soils, Canadian Forest Service – Northern Forestry Centre.

Annual foliage litter input	2.9% of tree biomass
Foliage litter average lifetime	3.5 years
Annual woody litter input	0.2% of tree biomass
Woody litter average lifetime	19.2 years
Annual fine root litter input	74% of fine root biomass (from Kurz)
Fine root litter average lifetime	1.0 years (set)
Annual woody root litter input	0.23% of roots (from Kurz)
Woody root litter average lifetime	30.0 years (set)
Input from above-ground decomposition	21%
Input from below-ground decomposition	33%
Soil biomass average lifetime	67.5 years

Typical harvest proportions

A portion of each harvest:

1. remains on site as waste (16%),
2. becomes short-lived wood products (33%),
3. becomes long-lived wood products (33%),
4. is burnt as biofuel (13%); and
5. is landfilled (5%).

These values were taken from a combination of results from Price et al. (1996)[14] and Hatton (1999)[15].

It was assumed that the residue from pre-commercial thinning was left on-site as slash. Sixty-six percent of the material removed during commercial thinning for pulp became short-lived wood product. Commercial thinning for pulp and lumber becomes biofuel, products, landfill and waste using the harvest proportions listed above.

Short-lived, and long-lived wood products

Short-lived wood products average lifetime		2 years (chosen)
Proportion of decay to	biofuel	4%
	compost	0%
	landfill	74%
	recycled	21%
Long-lived wood products average lifetime		30 years (chosen)
Proportion of decay to	biofuel	0%
	compost	0%
	landfill	100%
	recycled	0%

The parameters controlling the waste stream are found in Resource Integration Systems (1996)[16]

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[14] Price D, Mair R, Kurz W and Apps M (1996), Effects of forest management, harvesting and wood processing on ecosystem carbon dynamics: a boreal case study. In: Apps M and Price D (eds), Forest ecosystems, forest management and the global carbon cycle, Springer-Verlag.

[15] Hatton T (1999), Canada's wood residues: a profile of current surplus and regional concentrations. National Climate Change Process, Forest Sector Table (in press).

Landfill

Landfill average lifetimes vary by province as given in Jaques et al. (1997)[17].

Nova Scotia landfill average lifetime	90.9 years
British Columbia landfill average lifetime	41.7 years

Also, it is assumed that 25% of methane emissions from landfill are captured and flared[18].

Emissions from biofuel use

Following IPCC guidelines there are no emissions from biofuel use. Emissions saved by fossil fuel replacement occur from biofuel use. It was assumed that biofuel produces 1.6 GJ / t (Nabuurs, 1996)[19]. It displaces an equivalent amount of energy derived from natural gas[20].

Energy use

Emissions from fossil fuel use during harvesting and processing were estimated using CPPA averages (CPPA, 1998)[21]. They are:

Fossil fuels	0.39 t CO_2e / t WP
Electricity	0.47 MWh / t WP

Indirect emissions from electricity were calculated using provincial emission intensity factors as calculated from Jaques et al (1997)[15] and NRCAN (1997)[22].

Emissions from hand-saw use during pre-commercial thinning are assumed as 0.074 t CO_2e / ha[23].

Finally, there are emissions from the energy consumed by collecting and processing waste for landfilling, biofuel and recycling. The following emissions per tonne of waste are found in Resource Integration Systems (1996)[24].

Landfilling and biofuel	0.013 t CO_2e / t of waste
Recycling	0.012 t CO_2e / t recycled.

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[16] Resource Integration Systems (1996), Perspectives on solid waste management in Canada, Volume I - an assessment of the physical, economic and energy dimensions of solid waste management in Canada. Environment Canada EPS 2/UP/2.

[17] Jaques A, Neizert F and Boileau P (1997), Trends in Canada's greenhouse gas emissions (1990-1995), Environment Canada, En49-5/5-8E.

[18] Mary Ellen Perkins, Environment Canada, personal communication.

[19] Nabuurs G (1996), Significance of wood products in forest sector carbon balances. In: Apps M and Price D (eds), Forest ecosystems, forest management and the global carbon cycle, Springer-Verlag.

[20] Rick Hyndman, University of Alberta, personal communication.

[21] CPPA (1998), CPPA submission to VCR Inc. and IEI/CIPEC Pulp and Paper Industry Report (1997-1998), http://www.vcr-mvr.ca/home_e.cfm.

[22] NRCAN (1997), Canada's energy outlook 1996-2020, Natural Resources Canada, M27-112/1997E.

[23] Martin St-Amour, FERIC, personal communication.

[24] Resource Integration Systems (1996), Perspectives on solid waste management in Canada, Volume I - an assessment of the physical, economic and energy dimensions of solid waste management in Canada. Environment Canada EPS 2/UP/2.

Sensitivity Analysis

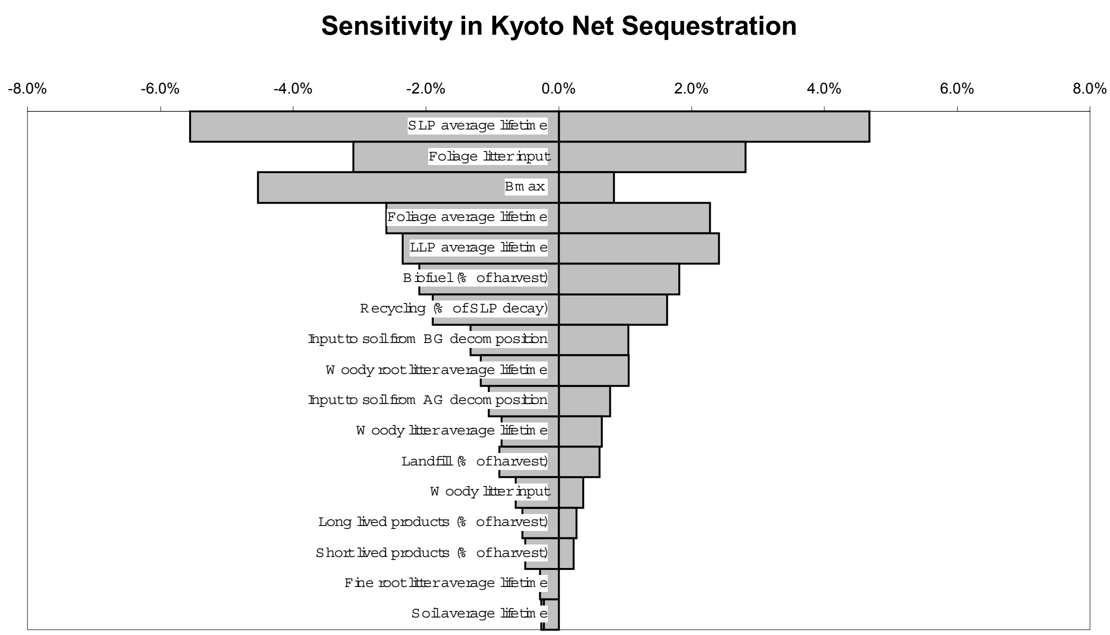
To investigate the sensitivity of the results each parameter is independently varied by ± 10% of its original value. Though this is not exactly the correct procedure (some parameters are interdependent), it does give the reader an idea of the important variables and the precision of the estimates. The variability in modelled Kyoto net sequestration, Kyoto net emissions and 2050 net biomass for the Nova Scotia example of lengthening the rotation length are shown below. Parameters not shown have little or no effect on final estimates.

The Kyoto net sequestration (Figure 36) is most sensitive to wood product average lifetimes, foliage litter parameters and stand growth rate (Bmax). Even though the input parameters were varied by ± 10%, the Kyoto net sequestration estimate varies by less than ± 4% (on average). If the parameters are assumed to be independent (the worse case), then the sensitivity in the Kyoto net sequestration is approximately ± 25%.

The Kyoto net emissions (Figure 37) are very sensitive to landfill related parameters (average lifetime, % of SLP decay, % methane captured). As well, parameters such as SLP and LLP average lifetimes control the amount of material reaching the landfill. Landfill related parameters are not well documented and recent studies from the United States[25] suggest that landfill average lifetimes may be a lot longer than once thought. As a result, variability (independence assumption) may be about ± 50%.

Finally, Figure 38 displays the variability in 2050 net biomass. The most important parameter is related to stand growth (Bmax). The total variability in 2050 net biomass may be about ± 18%.

Figure 36: Sensitivity in Kyoto net sequestration to ± 10% variability in parameters



[25] United States Environmental Protection Agency (1998), Greenhouse gas emissions from management of selected materials in municipal solid waste, U.S. EPA contract no. 68-W6-0029.

Figure 37: Sensitivity in Kyoto net emissions to ± 10% variability in parameters

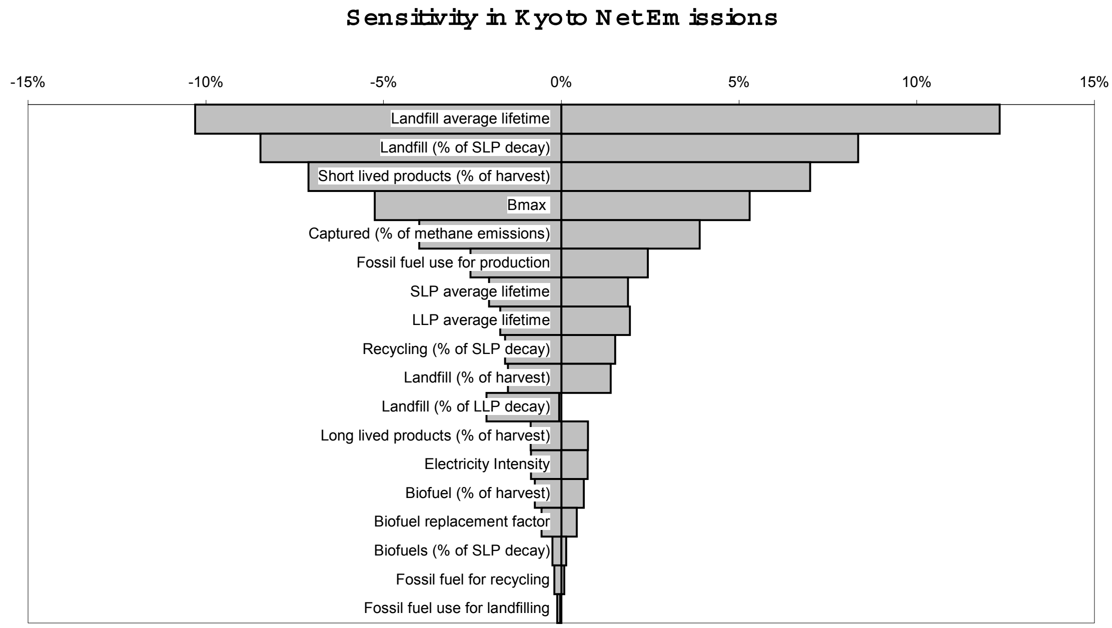
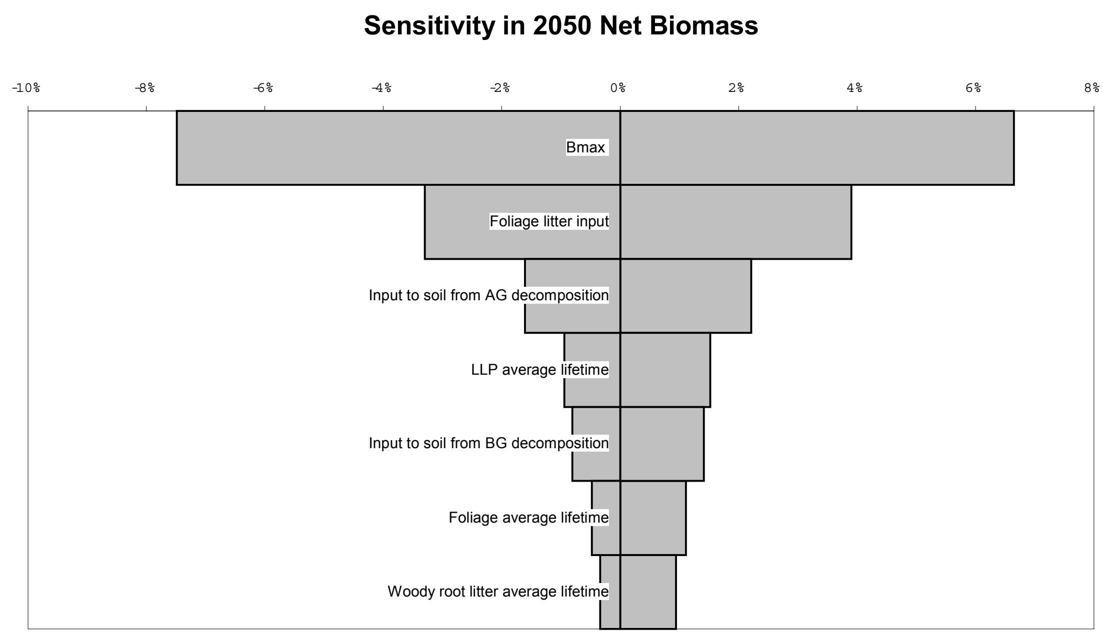
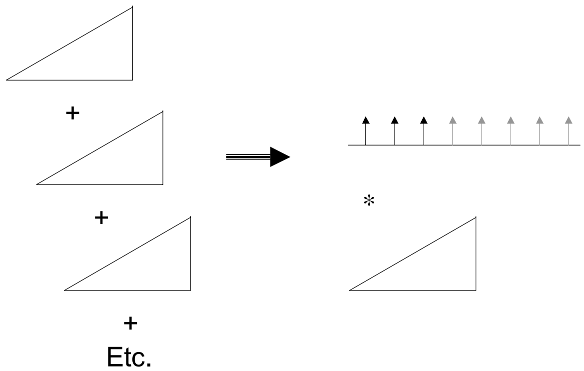


Figure 38: Sensitivity in 2050 net biomass to ± 10% variability in parameters



The Convolution Model

Scaling up from stand to forest-level



The stand has a biomass profile represented schematically by a single triangle at left. In year 0, the stand starts with no trees. As the trees grow, they gain biomass. Finally, the trees are harvested.

Now, in Year 1, a different stand follows the same profile, but delayed by a year. The total biomass in each year is given by the sum of the two profiles.

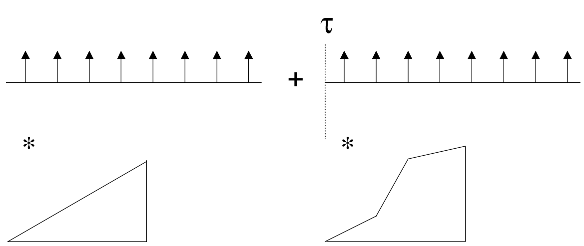
In Year 2, another stand starts the same process only now it is delayed by two years. The total biomass in each year is given by the sum of the three profiles.

This procedure continues into the future.

If the individual stand biomass profiles are the same, then the biomass in every year is given by the mathematical operation *convolution* (represented by the *). The total biomass is calculated by convolving the forcing function (represented by the spikes) with the stand response (the triangle). This forcing function is filtered by the stand response function.

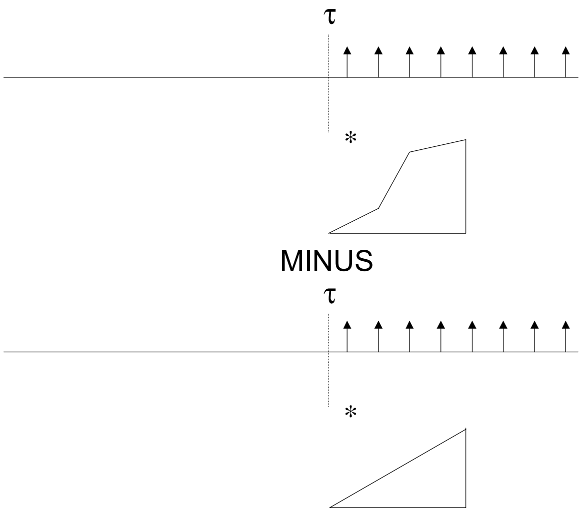
If the forest has an even-age distribution, then the forcing function is a uniform set of spikes. The total biomass at any time is just the sum of biomass at all ages in the stand (since there is a new stand in every year), and the total biomass per hectare is the average biomass in the stand.

Forest-level biomass due to a change in forest management



A change in forest management at time τ causes a change in the stand biomass profile after this time. The total biomass is calculated by summing two separate biomass portions. The first is the convolution of the original stand profile with a forcing function that is spikes before τ and zeroes after. The second portion is the convolution of the new stand profile with a forcing function that is zeroes before τ and spikes after.

Net forest-level biomass



The net forest-level biomass is given by the difference in two portions. The first portion is the convolution of the new stand biomass profile with a forcing function that is zero before τ and spikes afterwards. The first portion is the convolution of the original stand biomass profile with a forcing function that is zero before τ and spikes afterwards.

The portion before τ from the previous diagram cancels with the identical portion in the old management scenario.

If the forest is even-aged, then the average net biomass at any time is given by the moving sum of the difference biomasses over a rotation length divided by the rotation length.

There are two problems that further complicate this simple analysis. Firstly, the project stand profile is not perfectly periodic. It changes slowly with each rotation to account for the transition from one regime to the next. The second is that the two regimes may have different rotation lengths.

The first complication is addressed by allowing the new stand biomass profile to included many rotations (and reducing the number of spikes in the forcing function). The second complication is solved by summing over and normalizing by the rotation length of the reference case. This means that if the new rotation length is smaller that the reference rotation length that extra spikes are added delayed by a rotation length. This is exactly what happens as after the new rotation is completed it adds new stands, but there are stands from the old system still being convereted to the new system.

If the new rotation length is longer than the old one then spikes are removed from the sum. This results in a skip in new stands appearing in the sum.

Biomass Plots

Nova Scotia

Figure 39: Stand-level biomass, Red Spruce, Pre-commercial thinning

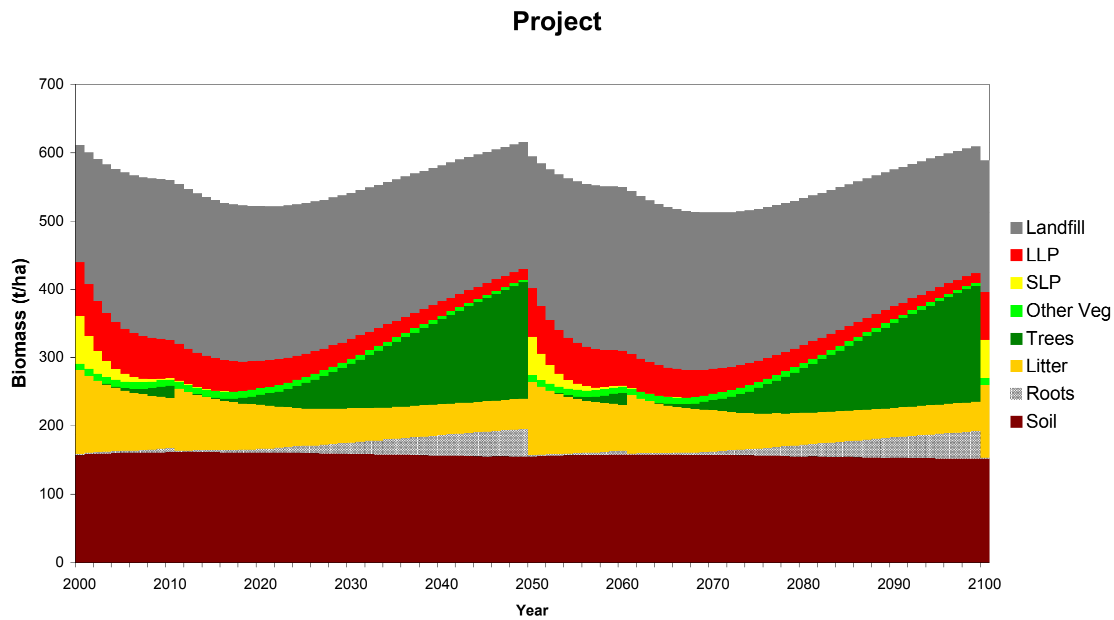


Figure 40: Stand-level biomass, Red Spruce, Commercial thinning for pulp

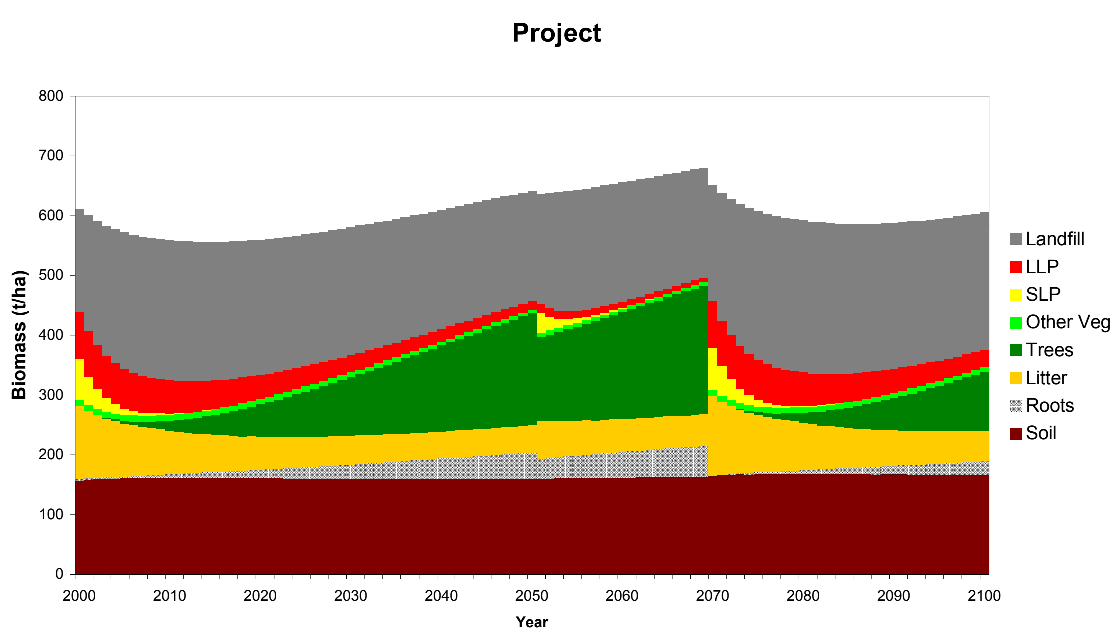


Figure 41: Stand-level biomass, Red Spruce, Commercial thinning for pulp and lumber

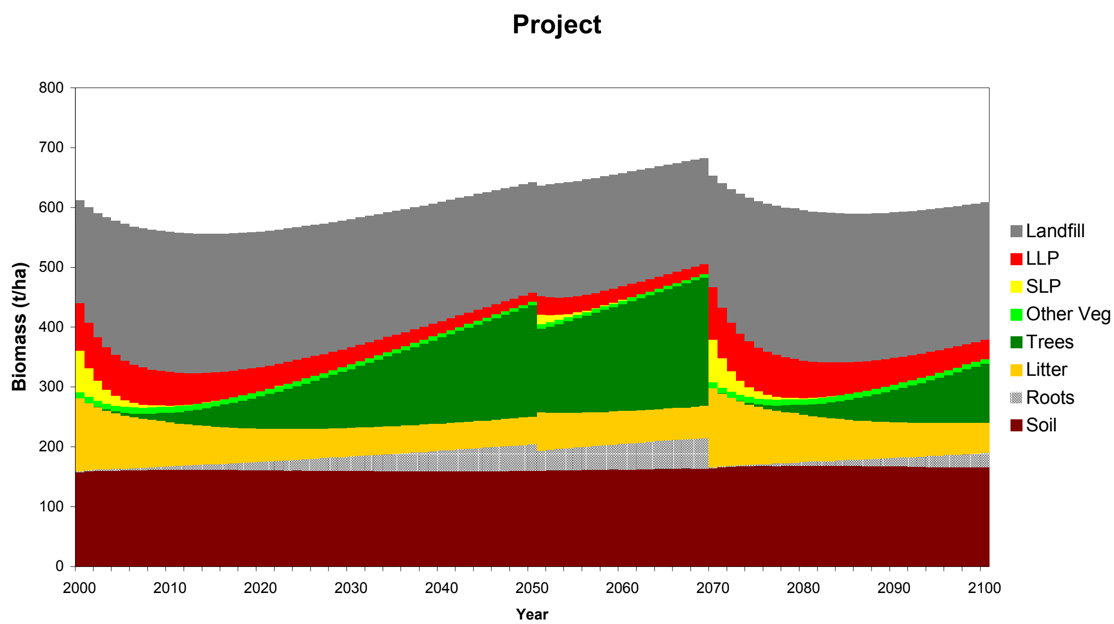


Figure 42: Stand-level biomass, Red Spruce, Increase rotation length by 5 years

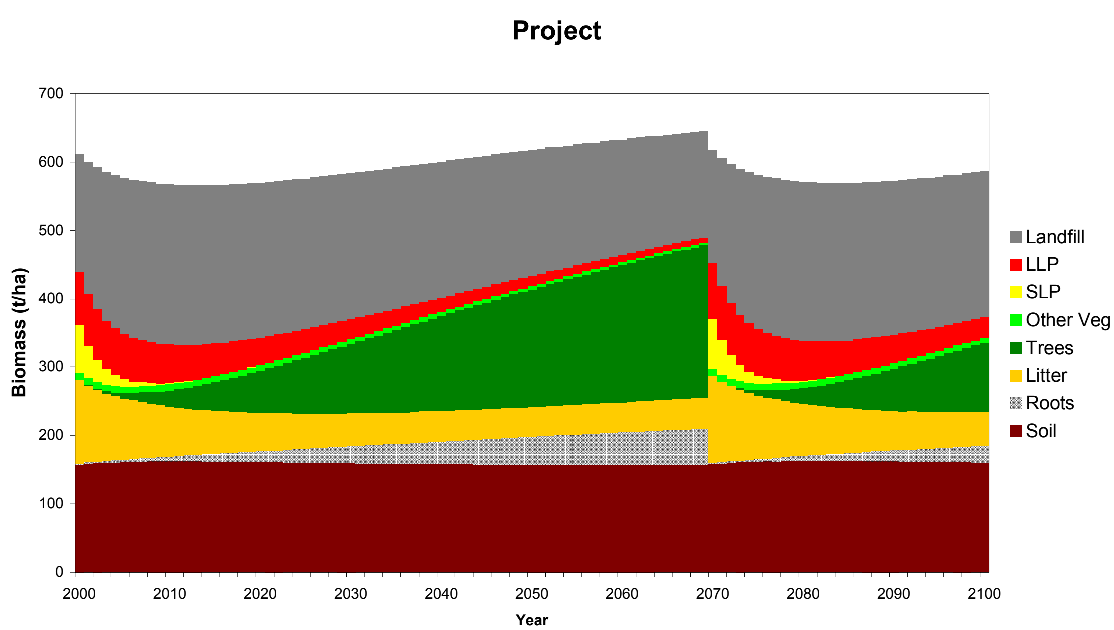
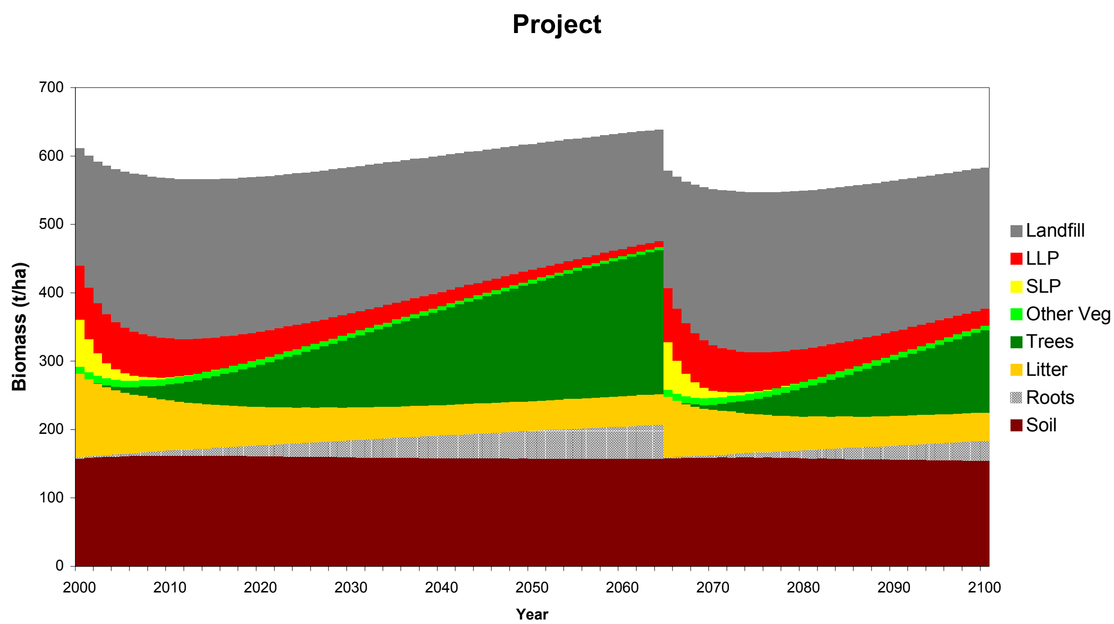


Figure 43: Stand-level biomass, Red Spruce, Increase biofuel/slash



British Columbia

Figure 44: Stand-level biomass, Douglas Fir, Moderate pre-commercial thinning

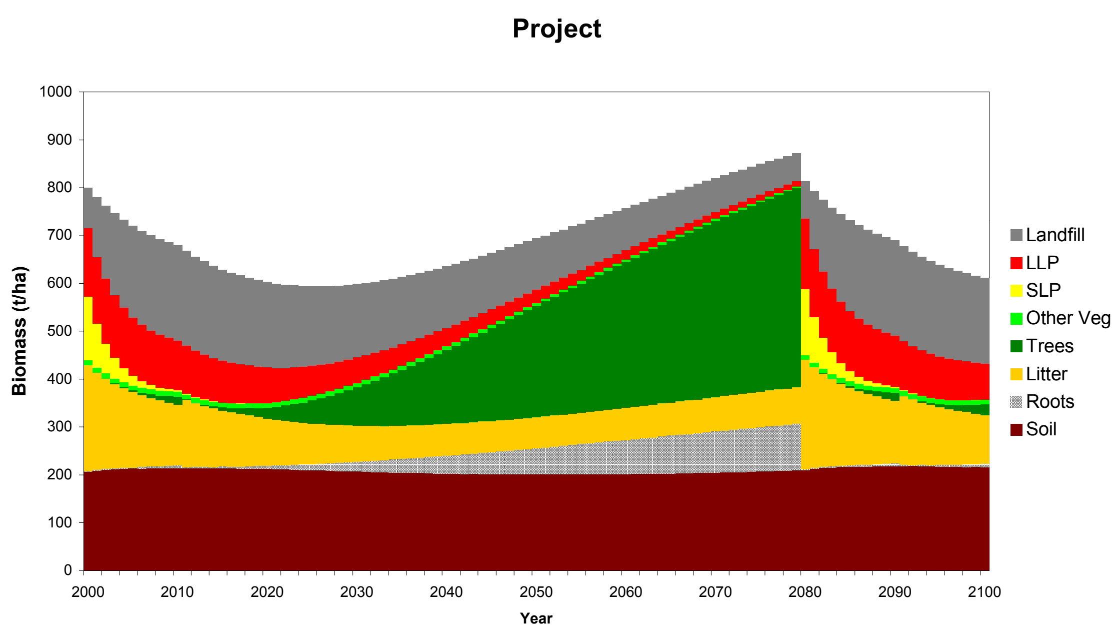


Figure 45: Stand-level biomass, Douglas Fir, Commercial thinning for pulp

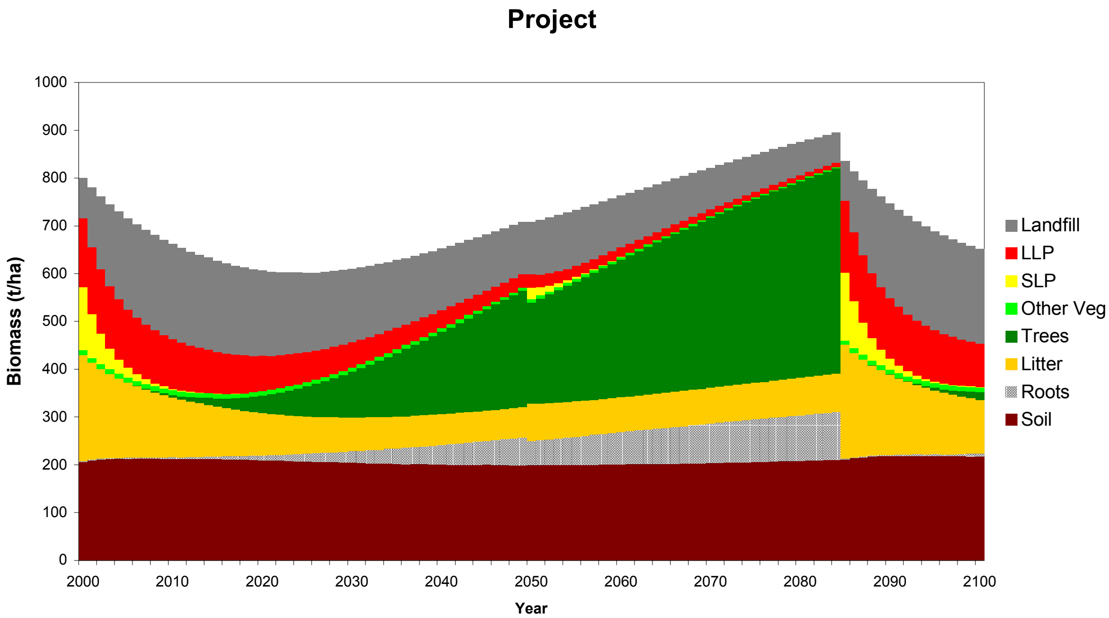


Figure 46: Stand-level biomass, Douglas Fir, Commercial thinning for pulp and lumber

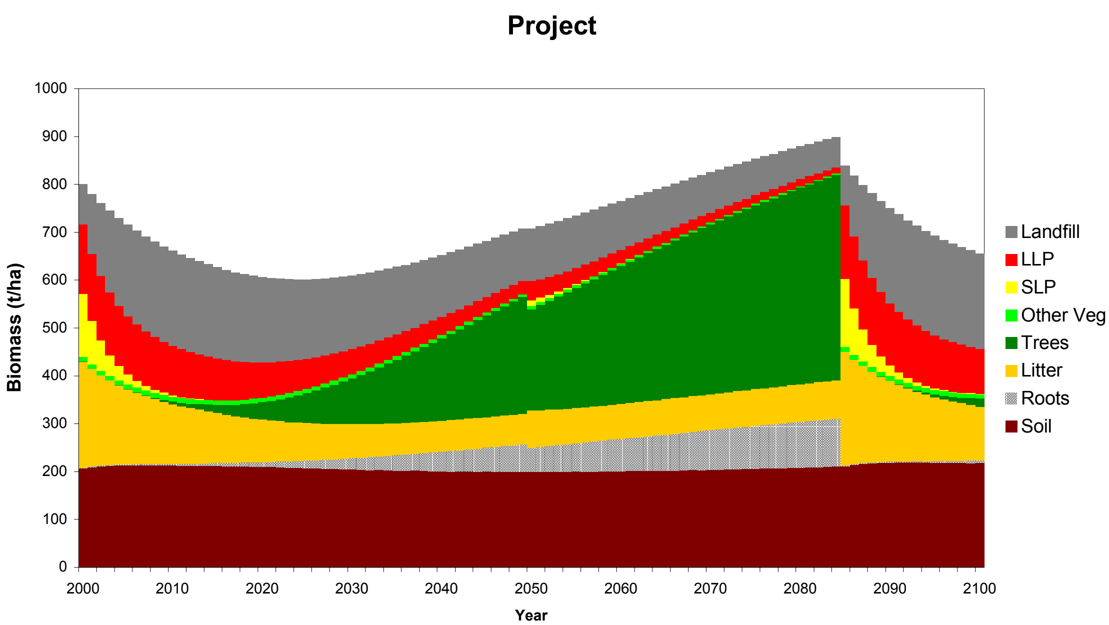


Figure 47: Stand-level biomass, Douglas Fir, Increase rotation length by 5 years

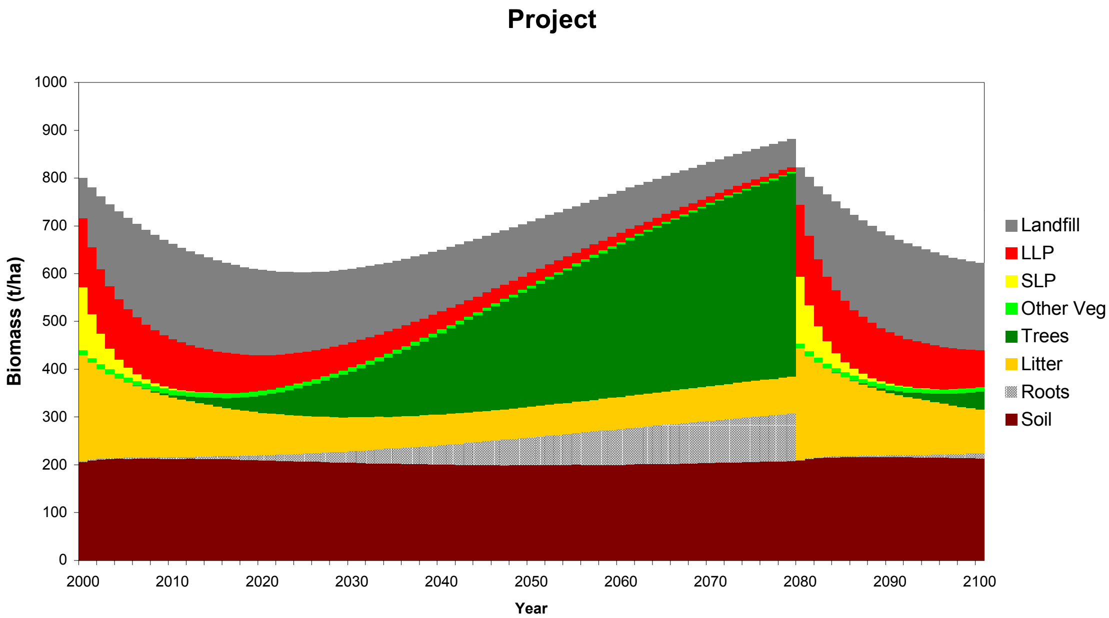


Figure 48: Stand-level biomass, Douglas Fir, Increase biofuel/slash