Economics of Early Intervention to Suppress a Potential Spruce Budworm Outbreak in New Brunswick, Canada

by

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ABSTRACT

Spruce budworm (*Choristoneura fumiferana* Clem.) (SBW) outbreak is the most prominent natural disturbance in eastern Canada. Recently, an early intervention strategy (EIS) has been developed against SBW outbreaks in New Brunswick (NB). In this study, a Spruce Budworm Decision Support System (SBW DSS) was coupled with a Computable General Equilibrium (CGE) model to assess the impacts of forest protection strategies in NB. The results demonstrated that a future SBW outbreak would reduce up to $35.31 billion of NB current value total domestic output. Regarding the efficacy of forest protection strategies, the EIS was predicted to be the most cost-effective and economically efficient. In contrast, if a future SBW outbreak exits, the EIS Fails & Reactive Strategy was anticipated to be more beneficial than the traditional Reactive Strategy. Overall, these results support the continued use of EIS as the most preferred strategy on economic grounds to protect against SBW outbreaks in NB.

Abbreviations: SBW, spruce budworm; GDP, gross domestic production; Btk, *Bacillus thuringiensis Kurstaki*; NB, New Brunswick; EIS, early intervention strategy; SBW DSS, spruce budworm decision support system; GIS, geographic information system; BCA, benefit-cost analysis; CGE, computable general equilibrium; WS, white spruce; RS, red spruce; BS, black spruce; BF, balsam fir; CES, constant elasticity of substitution; CET, constant elasticity of transformation; WTP, willingness to pay; CVM, contingent valuation method; BCR, benefit-cost ratio; NPV, net present value.

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1. INTRODUCTION

1.1 Purpose and background

The Canadian forest sector, as one of the most significant components of the Canadian economy, has contributed 8% to 10% of the manufacturing gross domestic product (GDP) from 2010-2015 (Natural Resources Canada 2015). Approximately CDN$38.30 billion was generated by the forest sector to annual total output in 2014, which accounted for almost 6% of all Canadian exports, worth CDN$30.77 billion (Natural Resources Canada 2015). The forest sector is widely distributed across the whole country, and is a major source of income for 1 out of every 7 Canadian census subdivisions. In 2014, the forest sector accounted for over 185,000 direct jobs (Natural Resource Canada 2015) which are crucial to ensuring their communities' economic sustainability.

Despite the significance of the forest sector to the Canadian economy, it is vulnerable to natural disturbances, which can affect timber supply and cause large scale economic losses. As a predominant natural disturbance, forest pest outbreaks can be a devastating factor that affects the forest sector in Canada (Chang et al. 2012a,b; Hennigar et al. 2013; and Niquidet et al. 2015). Periodic outbreaks of forest pests affect large areas of ecologically and economically important coniferous forests across the whole country. For instance, spruce budworm (*Choristoneura fumiferana* Clem.) (SBW) is the most prominent forest insect to defoliate spruce-fir forests in Atlantic Canada. Historically, SBW outbreaks have impacted millions of hectares of spruce-fir forests every 30-40 years, and outbreaks that generally last about 10-15 years have destroyed hundreds of millions of cubic meters of timber across eastern provinces (Sterner and Davidson 1982; Blais 1983; Royama 1984; MacLean and Ostaff 1989). During the peak of the last SBW outbreak in Canada, mortality losses were estimated at 44 million m^3 of timber volume per year from 1977 to 1981 (Sterner and Davidson 1982).

1.2 Forest protection strategies

To protect against forest pest outbreaks, various forest management/protection strategies have been developed in Canada to reduce timber supply loss and tree mortality caused by forest pest outbreak. These strategies include: (1) conducting reactive foliage protection strategy using biological pesticides (i.e., *Bacillus thuringiensis Kurstaki* (Btk) or tebufenozide) on the infested stands to keep trees alive (MacLean et al. 2002; Hennigar et al. 2013); (2) adopting salvage harvesting to harvest killed trees while they were still usable (Blum and MacLean 1985; Spence and MacLean 2012); (3) re-planning forest management and harvesting schedule to younger stand age (Neilsen et al. 2007; Sainte-Marie et al. 2014); or (4) planting non-susceptible and less vulnerable tree species to minimize forest vulnerability to SBW (Etheridge et al. 2006; Mageroy et al. 2015).

In eastern Canada, past forest protection strategies have used the reactive strategy to spray chemical or biological pesticides on the infested stands after the outbreak has started (Kettela 1995). When pesticide use was not possible due to cost or socio-political concerns, then salvage has been used to harvest killed trees while they were still usable (Etheridge et al. 2006). During the last SBW outbreak in New Brunswick (NB), aggressive aerial spraying of chemical insecticide was used, with over 1.5 million ha of spruce-fir forest sprayed annually from 1970 to 1983 (Miller and Kettela 1975). This protected the provincial forest lands from massive tree mortality, unlike what occurred in Cape Breton, Nova Scotia, where spruce-fir mortality exceeded 85% of the forest (MacLean and Ostaff 1989). However, the cost of aerial application of pesticides is much higher now than in the 1970s-1980s, and it is unlikely that pesticide spraying on that scale can be afforded in the future (personal communication with Dr. David MacLean 2017, University of New Brunswick).

An alternative to a reactive strategy could be an 'early intervention strategy' (EIS) that focuses on altering SBW population dynamics before a full outbreak occurs (Healthy Forest Partnership 2017). The concept of a SBW EIS suggests that identification of low but rising SBW populations in 'hot spots' could be treated with pesticide before defoliation occurs (i.e., much earlier in the SBW outbreak development than in past treatments) and that this could either slow or prevent the progression of the SBW population rise in the treated area. Recent research in Quebec has demonstrated low mating success of female SBW moths when populations are at low levels (Régnière et al. 2012), and the EIS aims to use this feature by detecting low but rising SBW population hot spots and treating these with biological insecticides Btk or tebufenozide (Healthy Forest Partnership 2017).

To assess the impacts of forest protection strategies, the Canadian Forest Service developed the Spruce Budworm Decision Support System (SBW DSS) in the early 1990's to assist forest managers in developing an optimal forest management strategy against SBW outbreaks (MacLean et al. 2000, 2001). Specifically, the SBW DSS uses: (1) mapped forest inventory data to describe the current land base (MacLean et al. 2000); (2) aerial survey to monitor SBW defoliation levels; (3) collected branch-sampled SBW population data (converted to expected defoliation level) and predicted defoliation scenarios to determine stands' vulnerability and SBW outbreak dynamics (MacLean et al. 2000); (4) a stand dynamics model and a regional timber supply model to determine stand and forest-level effects of defoliation and protection (MacLean 1996; Erdle and MacLean 1999); and (5) the ARC/INFO® Geographic Information System (GIS) and Arc Macro Language® (AML) programs to map the vulnerable stands and estimate the potential spruce budworm-caused timber volume losses and associated benefits of a reactive protection strategy.

1.3 An introduction to SBW outbreak impact evaluation

The most recent version of the SBW DSS model, known as Accuair ForPro (McLeod et al. 2012), allows users to examine different reactive SBW control strategies and quantify marginal timber supply benefits of protection in terms of both volume and value per hectare (MacLean et al. 2001). The valuation component of the model is based on benefit-cost analysis (BCA), where protection costs are weighed against timber harvest revenue saved (Slaney et al. 2010, Chang et al. 2012a). This latest development has created an important tool to help policy makers and forest managers make informed decisions regarding SBW protection investments.

In the most recent applied BCA of reactive SBW outbreak control strategies in NB, Chang et al. (2012a) evaluated market and non-market benefits and costs of controlling future SBW outbreak on Crown forest. This study: (1) developed an advanced timber supply model to estimate the potential timber harvest revenue benefits and the costs of pest control efforts in NB; and (2) adopted a recent contingent valuation method analysis (i.e., Chang et al. 2011) to estimate the non-market benefits of forest protection against SBW. A total of six forest protection scenarios, which included two future SBW outbreak patterns (i.e., moderate and severe) and three forest protection levels (i.e., 10%, 20%, and 40% of susceptible Crown forest), were assessed in the BCA. Overall, Chang et al. (2012a) found that the forest pest control program, by protecting 10% of the susceptible Crown forest, had the highest benefit-cost ratio and net present value at 3.24 and $58.7 million, respectively, under the moderate outbreak pattern. Under the severe outbreak pattern, BCA results suggested that the highest benefit-cost ratio of 4.04 occurred when protecting 10% of the susceptible Crown forest, while the highest net present value was projected to be $111 million when protecting 20% of susceptible Crown forest.

Recently, the SBW DSS has been also coupled with a computable general equilibrium (CGE) model to assess economy-wide impacts of conducting reactive SBW control strategies in NB (Chang et al. 2012b). CGE models have become an important tool for policy makers and forest managers to help them better understand the direct (i.e. logging sector) and indirect (i.e. other sectors that interact with the logging sector) impacts of natural disturbances and forest protection scenarios on regional economies (e.g., Patriquin et al. 2007, 2008).

Chang et al. (2012b) adopted a recursive dynamic CGE model to investigate the potential economic impacts of reactive biological pesticide spraying strategies along with salvage and re-planning harvest scheduling in response to possible future SBW outbreak scenarios on Crown forest in NB. A total of sixteen forest protection scenarios were examined: two SBW outbreak severities (moderate vs severe), four SBW control program levels (0%, 10%, 20%, and 40% protection of susceptible forest area), and two pest management strategies (with or without re-planning scheduling and salvage). It was estimated that a total of $3.3 and $4.7 billion (CDN) in present value lost output would result from uncontrolled moderate and severe SBW outbreak scenarios, respectively, without re-planning scheduling and salvage over the 2012-2041 period in NB (Chang et al. 2012b). Total output value loss was projected to decrease by 40%, 56%, and 66% when spraying biological pesticides on 10%, 20%, and 40% of susceptible forest areas, respectively (Chang et al. 2012b). Combining SBW control with re-planning scheduling and salvage strategy was projected to reduce the negative impacts of SBW outbreak by a further 1-18% of output value depending on the level of control implemented.

While Chang et al. (2012a,b) demonstrated that a reactive foliage protection strategy to keep trees alive during SBW outbreaks can have significant positive net present values and substantially mitigate negative economy-wide impacts in NB, there has been no such analysis for EIS. Since the EIS is still in its infancy and its effectiveness is still being investigated, there is an opportunity to use the information that has been gleaned to date to consider the potential outcomes of various scenarios that may be realized. Moreover, since Chang et al. (2012b) used a relatively simple CGE model, there is also a need to develop a more sophisticated state-of-the-art CGE model to re-evaluate the impacts of SBW outbreak and forest protection, especially the EIS, on the regional economy in NB.

1.4 Research objective

The purpose of this study was to: 1) assess the potential timber volume savings associated with implementing a SBW EIS (including both EIS works and fails scenarios) under moderate and severe SBW outbreak scenarios compared to timber volume impacts under more traditional reactive foliage protection strategies; and 2) evaluate costs, benefits, and economy-wide impacts of EIS and reactive forest protection strategies under moderate and severe outbreak scenarios. Overall, it was expected that this research would shed some light on the degree of economic benefits of EIS over the reactive strategy moving forward.

2. METHODS

2.1 Study area

NB is one of three Maritime Provinces in eastern Canada that has 85% of forested land (approximately 6 million hectares) (Erdle and Ward 2008). Approximately 50% of the NB forest land (3.4 million ha) is Crown forest, which is owned by the provincial government and managed by industry. Generally, the NB Crown forest is spread across the province, but much of it lies in large, consolidated blocks in the central, northcentral, and northwest regions (Figure 1). For management purposes, the NB Crown land is divided into 10 Crown Licenses and leased to six forest companies (Erdle and Ward 2008).

The forest sector in NB includes more than 200 company locations and directly employs approximately 10,600 workforce (Government of New Brunswick, Department of Economic Development (NB DED), 2012). Another 3,400 people are indirectly employed by the forest sector, which builds on close to 500 forestry and logging operation locations (2011). Generally, the forest sector directly contributes about 4.4% of annual

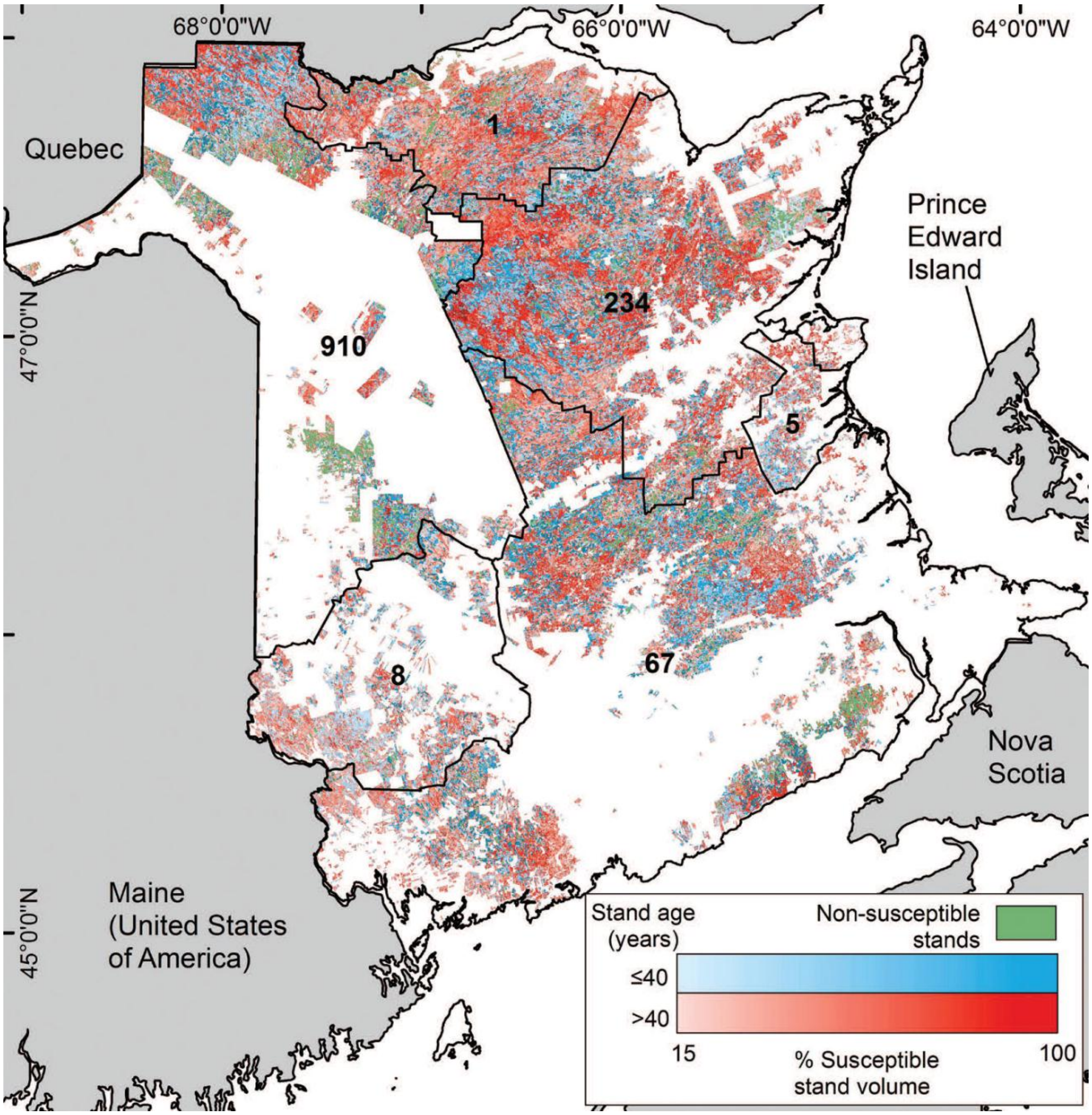

Figure 1. Spruce budworm susceptible Crown forest by percentage of host volume (increasing intensity of red or blue) and stand age (≤40 versus >40 years old in 2012) (Hennigar et al. 2013).

gross domestic production (i.e., C$ 969 million during 2011), and accounts for over 10% of total merchandise exports (i.e., C$ 1.522 billion) (NB-DED, 2012). Moreover, there is a significant indirect impact given the industry's strong linkages with other sectors of the economy such as metal fabrication, transportation and distribution, and professional and technical services (NB-DED, 2012). Overall, NB is identified as the most forest-dependent economy of any province in Canada in percentage terms (Atlantic Provinces Economic Council 2008).

Historically, SBW outbreaks have been the most devastating factor that causes large-scale defoliation and mortality on balsam fir and spruce stands in NB. For instance, approximately 3.5 million and 2.0 million ha of forestlands were moderately-severely defoliated (30-100% of current year foliage) in the peak years of 1975 and 1983 during the 1970s-1980s SBW outbreak in the province (National Forestry Database 2016a). Given that SBW outbreaks in NB have recurred every 30-40 years (Royama et al. 2005), and that a severe SBW outbreak is undergoing in Quebec and beginning in the adjacent areas of northern NB (Healthy Forest Partnership 2018), with the first defoliation detected in NB in 2015, it is widely believed that a new provincial-scale SBW outbreak is beginning.

To protect against a potential SBW outbreak and test the impact of EIS, a SBW EIS research program was underway in New Brunswick from 2014-2018 in a $18 million project (Healthy Forest Partnership 2017). Based on positive results to date, the EIS research trial was continued with $75 million of funding from 2018-2022. This EIS test is in response to detection of increasing SBW populations in northern New Brunswick, with totals of 15,300 ha, 56,800 ha, 150,000 ha, and 200,000 ha of hotspots treated in 2015, 2016, 2017 and 2018, respectively (Healthy Forest Partnership 2018). It is expected that these SBW EIS test results will determine the effectiveness of EIS.

2.2 SBW DSS model

To assess the timber supply impact of potential SBW outbreak scenarios, the Accuair ForPRO system (the most recent SBW DSS) was developed by Dr. Chris Hennigar (NB ERD, 2018). This system consists of three major components: 1) a SBW pre-defined defoliation-damage multiplier file (Erdle and MacLean 1999), which was adopted and modified to forecast SBW defoliation impacts on timber harvest volume; 2) a stand impact matrix (MacLean et al. 2001), which was designed to estimate timber harvest volume reduction based on the defoliation and treatment scenarios; and 3) a timber supply model (Remsoft Inc. 2008), specifically a 2017 model developed by NB Department of Energy and Resource Development (NB ERD) for NB Crown land, which was established to solve the timber supply optimization. Overall, the ForPRO system links these three components to quantify the timber harvest volume benefits of SBW treatments across scenarios during the simulation period.

To simulate SBW impacts in the Accuair ForPRO system, effects of pre-defined 5-year cumulative defoliation levels were calculated and analyzed. To estimate the 5-year periodic cumulative defoliation levels, the current-year defoliation patterns for balsam fir were first adopted from MacLean et al. (2001) with peak year adjustments based on past outbreaks observations (MacLean and Ostaff 1989). Then, these pre-defined current-year balsam fir defoliation patterns were used to estimate the annual L2 population patterns by using the linear relationship between balsam fir defoliation and SBW L2 population (Personal communication with Dr. Chris Hennigar 2017, NB ERD), and eventually these annual L2 population patterns were input into the Accuair ForPRO System to estimate 5-year cumulative individual host defoliation patterns. To better reflect individual host defoliation patterns among different SBW host tree species, defoliation of white spruce (*Picea glauca* (Moench) Voss) (WS), red spruce (*Picea rubens* Sarg.) (RS), and black spruce (*Picea mariana* (Mill.)) (BS) were scaled to 72%, 41%, and 28% that of balsam fir (*Abies balsamea* Mill.) (BF) (Hennigar et al. 2008, 2013). However, these relative differences between BF and other host tree species were assumed to be less significant when BF defoliation was greater than 90% until the SBW defoliation on all host species reach 100% (Personal communication with Dr. Chris Hennigar 2017, NB ERD).

With regards to the pest management strategy, each Licensee was assumed to adopt re-planning harvest scheduling to modify their original planned harvest schedule in response to the potential SBW outbreak since the re-planning harvest scheduling was proven to reduce SBW impacts (Hennigar et al. 2007; Chang et al. 2012b). Additionally, linear programming was used to minimize the SBW impacts on spruce-fir-jack pine (*Pinus banksiana*) harvest and total timber volume harvest (personal communication with Dr. Chris Hennigar 2017, NB ERD) and also to optimally prioritize areas for foliage protection treatments.

2.3 SBW outbreak and control scenarios

To evaluate the impacts of future SBW outbreaks and effectiveness of forest protection strategies, a scenario planning approach (Schoemaker 1995) was used in this study. Overall, a total of eighteen future SBW outbreak and forest protection scenarios (Figure 2) were analyzed in the Accuair ForPRO system across an 80-year study period. These included two future outbreak patterns, one EIS scenario, four Reactive Strategy scenarios, four EIS Fails & Reactive Strategy scenarios, and one no protection scenario.

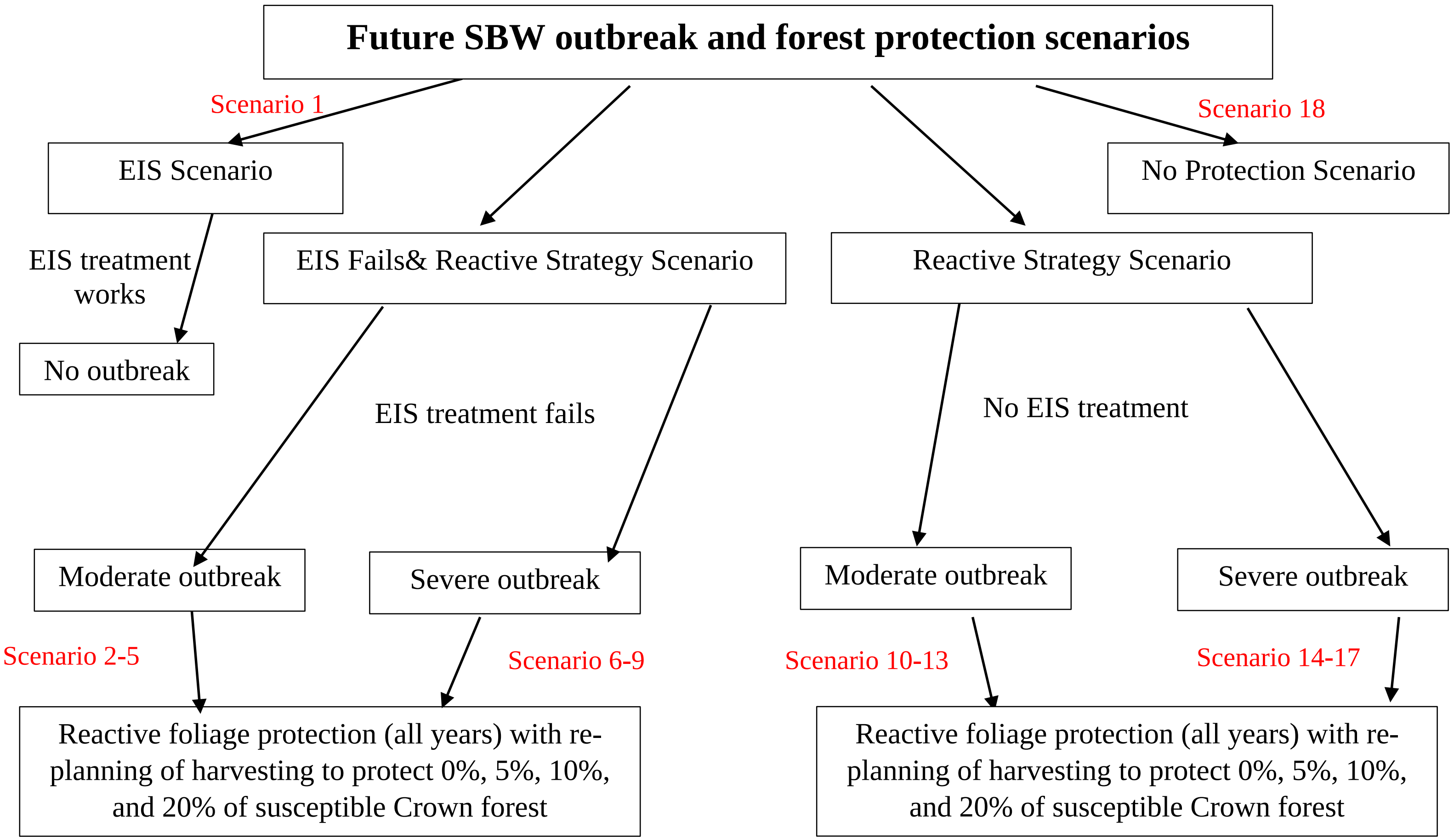

Figure 2. Future SBW outbreak and forest protection scenarios.

Defoliation control scenarios. Nine forest protection strategy scenarios plus one no protection scenario were simulated, including an EIS scenario, four EIS Fails & Reactive Strategy scenarios, and four Reactive Strategy scenarios (Table 1).The no protection scenario assumed that no insecticide treatment was conducted to control a future SBW outbreak, potential timber supply losses were measured as the baseline to compare with nine defoliation control scenarios to determine the marginal timber supply benefits of protection.

The EIS scenario was designed to apply biological insecticide (i.e., Btk or tebufenozide) for all years in SBW hotspots. The insecticide spray treatment varied based on the number of detected overwintering larvae per branch: 1) no protection when ≤ 6 overwintering larvae were detected; 2) applying one Btk application in SBW hotspots when 7-20 overwintering larvae were detected; and 3) applying two Btk applications in SBW hotspots when more than 20 overwintering larvae were detected. The objective of these EIS treatments was to keep SBW population levels low and maintain SBW defoliation below 10%. Additionally, the L2 sample point data (over 1500 points sampled in 2016, Healthy Forest Partnership 2016) was converted to a spatial layer using spatial interpolation (1 ha cells). Then EIS treatments were prioritized based upon the interpolated L2 raster and the percentage of spruce-fir. Overall, higher spray priority value suggested that there was a larger number of overwintering larvae detected and a higher percentage of host species located in those areas.

The Reactive Strategy scenarios assumed that biological insecticides were applied to protect foliage against the full simulated moderate or severe SBW outbreak. Insecticide

Table 1. Defoliation control and treatment scenarios.

Defoliation control scenarios	**EIS**			**EIS Fails & Reactive Strategy[4]**			**Reactive Strategy[4]**		**No Protection**	
Initial treatment[1]	Spray biological insecticides in hotspots			Spray biological insecticides in hotspots (EIS)			Reactive foliage protection in all defoliation years when (BF defoliation > 40%)		N/A	
Effectiveness of initial treatment	EIS works			EIS doesn't work			Reactive strategy works		N/A	
Secondary treatment[2]	N/A			Reactive foliage protection in all years (BF defoliation > 40%) (Reactive strategy)			N/A		N/A	
Outbreak scenario	No outbreak (Low but rising SBW populations)			Moderate		Severe	Moderate	Severe	Moderate	Severe
L2 per branch	0-6	7-20	21-40							
Initial treatment scheme	None	Tebufenozide or *Btk* (1 app)	*Btk* (2 apps)	None	Tebufenozide or *Btk* (1 app)	*Btk* (2 apps)	Spray *Btk* in all years to protect 5%, 10%, or 20%[3] of susceptible area		No treatment	No treatment
Secondary treatment scheme	N/A	N/A	N/A	Spray *Btk* in all years to protect 5%, 10%, or 20%[3] of susceptible area			N/A		N/A	

1. The initial treatment aims to maintain the BF defoliation below 10%.
2. The secondary treatment aims to maintain BF defoliation below 50%.
3. These three protection levels are modified from Hennigar et al. 2013.
4. Re-planning of harvesting with 0% of Crown forest sprayed is also simulated in SBW DSS model to assess the impacts of re-planning of harvesting.

spraying was simulated to protect 5%, 10%, or 20% of susceptible Crown forest area by spraying Btk in all years when balsam fir defoliation exceeds 40%. In addition, the re-planning of harvesting was adopted to combine with insecticide spray treatment to minimize the defoliation-caused impact on NB timber volume harvest. Overall, the objective of the Reactive Strategy was to reduce defoliation to the NB ERD foliage protection target of 50% for balsam fir (personal communication with Dr. Chris Hennigar 2018, NB ERD).

The EIS Fails & Reactive Strategy scenarios assumed that the initial EIS treatments defined above failed to slow or prevent the progression of the SBW population rise, and a moderate or severe SBW outbreak occurred. The moderate or severe outbreak patterns (Table 2) were defined in terms of SBW outbreak severity and duration, which was adopted from a previous SBW impact study in New Brunswick (MacLean et al. 2001). To prevent massive tree mortality, the reactive foliage protection strategy was scheduled to treat the epidemic area with biological insecticides Btk or tebufenozide, in all years when the balsam fir defoliation exceeds 40% (Hennigar et al. 2013). Specifically, this secondary treatment, which was combined with re-planning of harvesting, was anticipated to protect 5%, 10%, or 20% of susceptible Crown forest area. Similar to the Reactive Strategy, the treatment target of the EIS Fails & Reactive Strategy was to reduce the balsam fir defoliation to 50% over entire study period.

EIS SBW hotspot dynamic and treatment schemes. There are strongly divergent ideas about the processes involved in the early stages of a SBW outbreak. One view of SBW outbreak epidemiology suggests that SBW populations are present at low level across a large

Table 2. EIS SBW hotspot dynamic and treatment schemes under the EIS and the EIS Fails & Reactive Strategy scenarios.

Year	EIS scenario / EIS Fails & Reactive Strategy scenario: Initial treatment (EIS)			
	Tebufenozide ('000 Ha)	*Btk* (1 app) ('000 Ha)	*Btk* (2 apps) ('000 Ha)	Total SBW hotspot and EIS treatment area ('000 Ha)
2015	3.30	12.60	0.00	15.90
2016	19.70	32.20	4.90	56.80
2017	52.02	85.04	12.94	150.00
2018	104.05	170.07	25.88	300.00
2019	156.07	255.11	38.82	450.00

Year	EIS works				EIS fails			
	Secondary treatment (Reactive foliage protection)							
	N/A				Treat in all years when BF defoliation > 40%			
	Tebufeno zide ('000 Ha)	Btk (1 app) ('000 Ha)	Btk (2 apps) ('000 Ha)	Total SBW hotspot and EIS treatment area ('000 Ha)	Protect 0% of susceptible area ('000 Ha)	Protect 5% of susceptible area ('000 Ha)	Protect 10% of susceptible area ('000 Ha)	Protect 20% of susceptible area[1] ('000 Ha)
2020	195.09	318.89	48.52	562.5	000.00	142.04	284.09	568.17
2021	195.09	318.89	48.52	562.5	000.00	142.04	284.09	568.17
2022	195.09	318.89	48.52	562.5	000.00	142.04	284.09	568.17
2023	175.58	286.99	43.68	506.25	000.00	142.04	284.09	568.17
2024	149.25	243.94	37.12	430.31	000.00	142.04	284.09	568.17
2025	111.93	182.96	27.84	322.73	000.00	142.04	284.09	568.17
2026	55.97	91.48	13.92	161.37	000.00	***142.04***[2]	***284.09***[2]	***568.17***[2]
2027	0.00	0.00	0.00	0.00	000.00	***142.04***[2]	***284.09***[2]	***568.17***[2]
2028	0.00	0.00	0.00	0.00	000.00	000.00	000.00	000.00
2029	0.00	0.00	0.00	0.00	000.00	000.00	000.00	000.00
2030	0.00	0.00	0.00	0.00	000.00	000.00	000.00	000.00
Total	1,409.86	2,304.44	350.67	4,064.97	000.00 /000.00	852.24 /***1136.32***[2]	1704.54 /***2272.72***[2]	3409.02 /***4545.36***[2]

1. The total SBW susceptible area is estimated at 2,840,860 ha (stand volume > 15% host species) in New Brunswick (Chang et al. 2012b).
2. Two additional years in severe outbreak pattern

geographic area during the endemic period (Sanders 1988). Under favorable conditions (e.g. a decrease in the impact of natural enemies), there will be a generalized increase of SBW population in hotspots, which turns the SBW hotspots into the epicenters to trigger a regional outbreak (Royama 1984, 1992). In general, SBW epidemic behavior can be viewed as a wave spreading across a large geographical area where the hotspots/epicenters are merely the crests of the wave (Régnière and Lysyk 1995). Accordingly, it was assumed that the SBW hotspot dynamic would follow the same pattern as the SBW population dynamic, spreading from existing hotspots to a large geographical area.

To help estimate the probable SBW hotspot dynamic in New Brunswick, the Healthy Forest Partnership established a provincial-level EIS SBW hotspot dynamic pattern for the next decade (personal communication with Dr. David MacLean 2016, University of New Brunswick) using several assumptions: 1) the actual growth rate of SBW hotspot areas was used from 2015 to 2017; 2) the SBW population increases would last 10 years from 2016 to 2026; 3) SBW populations would begin to decrease in northern NB in 2021-2024; 4) there would be less spruce-fir area to treat in southern NB than in northern NB; 5) if EIS treatments would be effective and moth in-flights from QC would cease after 2020, the growth rate and duration of SBW hotspot area would both be less. Overall, as shown in Table 2, the total SBW hotspot area was predicted to increase from 15,900 ha in 2015 to 562,500 ha from 2020-2022, and then decline to 161,370 ha by 2026.

Two EIS SBW hotspot dynamic and treatment schemes (Table 2) were evaluated to help determine the provincial-level timber supply impact of the EIS, for the EIS scenario, and for the EIS Fails & Reactive Strategy scenario. Under the EIS scenario, it was assumed that all increased SBW hotspot areas would be treated; tebufenozide was used on blocks far from residential areas and one application of Btk (Btk-one) would be sprayed on blocks near residential areas (both with L2/branch of 7-20), and two applications of Btk (Btk-two) where L2/branch is >20. The actual size of tebufenozide, Btk-one, and Btk-two would be used to define the proportion of each treatment area to be used from 2017 to 2026 (Table 2).

Under the EIS Fails & Reactive Strategy scenario, it was assumed that the EIS treatments from 2017-2018 are identical to the EIS scenario, but that reactive foliage protection treatments with re-planning of harvesting would begin in 2019 to protect 5%, 10%, or 20% of the susceptible Crown forest area in all years, under the moderate or severe outbreak patterns (Table 2).

2.4 CGE model

To estimate the regional economic impacts of SBW outbreaks and forest protection scenarios on the NB economy, a CGE model was developed. This CGE model, which comprised a series of simultaneous linear and non-linear equations, was similar in structure to that of Ochuodho et al. (2014), Das et al. (2005), Lofgren et al. (2002), and Zhang et al. (2005).

In terms of model specification, the NB economy was defined as a single region that is recursive dynamic and deterministic in nature, with the assumption of a small-open-economy and constant returns to scale technology. The model was calibrated to the regional economy of NB in 2010 using the New Brunswick input-output data from Statistics

Canada’s input-output database (Statistic Canada 2014) - the latest date for which data was available. Following the Canadian System of National Accounts (CSNA) (Statistics Canada 2012), the New Brunswick economy consisted of 32 sectors. For ease of presentation, this study aggregated 12 of the sectors that were thought to be the least impacted from a potential SBW outbreak. Overall, 20 sectors were defined, including: 1) crop and animal sector, 2) forestry and logging sector, 3) fishing, hunting, and trapping, 4) support activities for agriculture and forestry, 5) mining and oil and gas extraction, 6) utilities, 7) construction, 8) manufacturing, 9) wholesale trade, 10) retail trade, 11) transportation and warehousing, 12) information and cultural industries, 13) finance, insurance, real estate, rental and leasing and holding companies, 14) professional, scientific and technical services, 15) administrative and support, waste management and remediation services, 16) educational services, 17) health care and social assistance, 18) arts, entertainment and recreation, 19) accommodation and food services, and 20) other services (except public administration). In addition, we assumed that producers from each sector produce intermediate and primary goods or provide services.

Three primary factors were considered in this study. These included: (1) labor, (2) capital, and (3) stumpage. Several assumptions were made in association with these primary factors. Firstly, it was assumed that labor was mobile and employed across all sectors, and the labor supply was fixed without the effect of interprovincial/international labor movement. Our view of the labor market followed the neoclassical economic theory of labor market. The neoclassical assumption of full employment suggested that labor was only affected by the adjustment on the wage rate (Alavalapati et al. 1996, 1998). As a result, the labor input could be calculated by aggregating wages and salaries, supplementary labor income, and mixed income from input-output table (Statistic Canada 2014).

As the secondary primary factor, capital was assumed to be mobile and used in production across all sectors. Therefore, capital could move from one industry to another freely in the economy, but with a different rental rate (Alavalapati et al. 1998). In this study, the capital input was defined as the summation of taxes on products, taxes on production, subsidies on products, subsidies on production, and gross operating surplus (except stumpage expenditures, as described below) from the 2010 New Brunswick input-output table (Statistic Canada 2014).

Stumpage, as the third primary factor, was defined only for the forestry and logging sector. While stumpage expenditures were included in gross operating surplus in Statistics Canada's input-output table, Statistic Canada does not report separately on this expenditure. Therefore, this study followed Chang et al. (2012b) by using stumpage revenue data from the National Forestry Database (2016b) as the stumpage input in the forestry and logging sector. This value was subtracted from gross operating surplus to appropriately adjust the capital input described above.

With regard to the model structure, simultaneous linear and non-linear equations were used to describe: (1) the behavior of economic agents; (2) market conditions; (3) macroeconomic balances; and (4) growth projections for primary inputs between periods. Overall, these equations were designed to operate recursively for each year over 50 years.

Regarding the behavior of economic agents, producers were assumed to simultaneously maximize their profit and minimize their production cost. To explain the behavior of producers, a constant elasticity of substitution (CES) production technology was assumed. Through the CES function, producers could make their choice between primary factors and thereby could substitute primary factors freely in response to the change of factor prices to produce a most efficient final value-added composite. Once the fraction of primary factors was determined, a Leontief-type technology was adopted to combine value-added composite with a fixed-share of intermediate demands. Specifically, the fixed-share of intermediate demands was assumed since the proportion of intermediate demands was only determined by existing technology rather than producers' decision on primary factors (Ochuodho et al. 2014). Overall, the final output price would be derived from the combined costs of value-added composite and intermediate demands.

A CES Armington function (Armington 1969) was established to explain producers' behavior on selecting intermediate inputs. Specifically, producers were assumed to have choice to purchase intermediate inputs from either domestic or international markets. Since the relative prices of domestic goods and imports (including the rate of tariff) were essential to producers' production cost, the final ratio of imports to domestic goods was determined by producers' cost minimizing decision-making on domestic or foreign goods. Moreover, a constant elasticity of transformation (CET) function was used to distinguish producers' behavior for selling their products. Specifically, to maximize their profit, producers were assumed to have choice to sell their products to the market with the highest returns (where these returns were determined by multiplying the world price to the exchange rate adjusted for any taxes or subsidies).

Overall, the final composite goods, including imported and domestic goods, were assumed to fulfill demands for both intermediate goods and final goods. Specifically, the intermediate goods, which were consumed by producers, were determined by technology and the composition of sectoral production; while the final goods, which were consumed by households, were determined by household income and the composite of aggregate demand.

Households, as the second economic agent, were assumed to maximize their utilities subject to their received income. The received income included: (1) the returns from supplying factors of production (capital, labour, and stumpage); and (2) the domestic government transfers (i.e., unemployment benefits, pensions, and other transfers from their domestic governments). Meanwhile, the supplies of capital and labour were assumed to be fixed within a given time and mobile among all 20 sectors.

Households were assumed to spend a proportion of their total income, and invest/save the remaining. All households were assumed to have identical consumption preferences, with consumption of each commodity affected by prices and incomes. Households make their consumption decisions by maximizing their utility subject to their household budget constraint. A CES utility function was specified to model households' consumption preferences.

Government, as the final economic agent, was assumed to maximize its utility subject to the received tax revenue. The tax revenues were levied on: (1) capital and labour use (i.e., capital and labour tax revenues); (2) income of household (i.e., income tax revenue); (3) consumption of household (i.e., consumption tax revenue); and (4) importing (i.e., tariff revenue). A proportion of tax revenue was transferred from government to households (i.e., unemployment payments, pension, etc.), and the rest was spent on government's expenditure on capital, labour, and other commodities. A Cobb-Douglas utility function (Cobb and Douglas 1928) was specified when the government was maximizing its utility.

Regarding market conditions, it was assumed that market equilibriums were achieved in the CGE model, including: (1) equilibrium in the goods market; and (2) equilibrium in the factor market. Specifically, equilibrium in the goods market consisted of aggregate demand for each commodity (from household and government consumption) equaling aggregate supply from domestic production and imported goods. To achieve equilibrium in the current account, the value of imports were required to equal the summation of the value of exports and the government saving. Since the government saving and exchange rates were defined to be fixed, the change in value of imports would equal that of exports. Regarding the factor market, it was assumed that there was an equilibrium between the factors' demand and their supply. Factor prices on production would simultaneously adjust to ensure the factor demand was equal to the supply. Additionally, an equilibrium was also defined between household saving and investment. Since the household saving rate was assumed to be fixed, household saving would passively adjust until it was equivalent to the investment spending.

To estimate the growth projection of primary inputs over time, it was assumed that, without any SBW outbreaks, the NB economy would operate on the historical, steady-state growth path over the next 50 years (2010-2060). Specifically, the annual growth rate of the labour force was exogenously set at 2% to sustain a 2% annual GDP growth rate. Following Chang et al. (2012b) and Ochuodho and Lantz (2014), the capital stock was endogenously determined through a capital accumulation equation that was influenced by the previous period's capital stock and household total savings (see Appendix 1 for details).

To assess the economic impacts of SBW outbreak and forest protection, the CGE model was designed to re-run annually with the additional exogenously stumpage input changes based on the timber volume harvest results from SBW DSS. To incorporate the SBW DSS output into the CGE model, stumpage was implemented as a primary input in the forestry and logging sector. Timber volume harvest results of each SBW outbreak and forest protection scenario estimated from the SBW DSS were converted to stumpage values. These values were calculated by multiplying the 5-year periodic growth rate of total timber volume harvest from Crown land to the initial stumpage value in 2010 (National Forestry Database 2016b). These stumpage values were adopted to shock the stumpage input in the CGE model. The General Algebraic Modeling System (GAMS) software (Rosenthal 2010) along with the CONOPT 3 solver were used to solve the CGE model.

The economic impact assessment was performed in the CGE model to evaluate the impacts of each SBW outbreak and protection scenario on several major economic variables. These included: (1) total stumpage revenue; (2) value of regional output; and (3) value of provincial trade (i.e., net exports). Additionally, a 4% discount rate was adopted to estimate the present-value of these economic variables.

2.5 Benefit-Cost analysis

A BCA was used in this study to compare market and non-market benefits and costs associated with each SBW defoliation control scenario. Market benefits included the value of timber harvest volume, and market costs included the aerial spraying costs per hectare multiplied by the number of hectares treated. Non-market benefits of each SBW defoliation control scenario were evaluated by aggregating use and non-use values including recreational, wildlife habitat, and other environmental service values as discussed below.

Market benefits, derived from the SBW DSS, were measured by comparing the differences between the per-period (i.e., 5 year) values of timber harvest volume reduction (i.e., all harvest tree species) for each defoliation control scenario compared to the no protection scenario. Specifically, these per-period values of timber harvest volume reduction were calculated by multiplying the wood product harvest volume losses (i.e., pulpwood, sawlogs) with wood product values. To be more specific, wood product values were determined based on: (i) stumpage values (which estimated by using the prices of pulp and sawlog materials on NB private land (NB ERD 2016 Crown model)); (ii) producer surplus in timber and wood products markets (which was assumed to be approximately 20% of the stumpage prices (Chang et al. 2012a)); (iii) a license management fee (i.e., estimated at $\$3/m^3$ (NB ERD 2016 Crown model)); and (iv) a social adjustment cost (i.e., costs of job searching assumed to be approximately 10% of the stumpage prices (from Chang et al. 2012a, based on Van Kooten and Wang 1998)). Overall, the wood product values were estimated at $\$10/m^3$ for pulpwood and $\$27/m^3$ for sawlogs.

Market costs of each SBW defoliation control scenario were calculated by multiplying treatment area per year by spray program costs: 1 application of Btk costs $40/ha; 1 application of tebufenozide costs $40/ha; and 2 applications of Btk cost $80/ha (personal communication with Dr. David MacLean 2018, University of New Brunswick). Average costs for logistical, monitoring, and other costs specific to each strategy were estimated through consultation with experts in the field.

Non-market benefits of each SBW control effort were adopted from the Chang et al. (2011) willingness to pay (WTP) estimation of the public's benefit from controlling future SBW outbreaks in NB. Specifically, Chang et al. (2011) used a contingent valuation method (CVM) analysis to determine that average WTP was $86.19 (CDN 2007) per household per year for 5 years (2007-2011), including timber value, which was considered a market benefit, or $53.87 for the non-market benefit. The associated value for a moderate SBW outbreak was estimated in proportion to the volume lost. All values were assessed in current value (undiscounted) and present value (discounted) terms, with the latter using the market rate of interest (based on a 5-year average of government 10-year bonds) as a discount rate.

Overall, benefit-cost ratio (BCR; present value benefits divided by present value costs) and net present value (NPV; present value benefits minus present value costs) measures were used to compare among forest protection strategies to determine the most preferred strategy on economic grounds. Specifically, the strategy with the highest BCR would be selected if the objective was to maximize protection benefits per unit of control cost – this was a cost-effectiveness measure. The strategy with the highest NPV would be more preferred if the primary goal was to maximize the net returns of SBW control efforts - this was an economic efficiency measure.

3. RESULTS

3.1 SBW DSS results

Projected cumulative timber harvest volume impacts

The projected relative timber volume harvest levels for Crown land in NB from 2012 to 2066 under different SBW outbreak patterns and forest protection scenarios are presented in Figure 3. In the absence of any forest protection, future SBW outbreaks were forecasted to significantly reduce NB timber supply over the next 50 years. The NB timber supply was projected to substantially decline until it reached the nadir during the 2032-2046 period, and then to start to recover. SBW defoliation impact on NB timber supply under a moderate outbreak pattern was expected to be more gradual than a severe outbreak pattern. Specifically, compared to the baseline scenario (i.e., no outbreak scenario), the projected relative timber volume harvest levels (without any forest protection) were estimated to be reduced by 12.92% and 27.04% during the nadir years under moderate and severe outbreak patterns, respectively. Overall, the projected NB timber supply (or harvest level) was expected to be reduced by 27.86 million m^3 and 43.54 million m^3 under moderate and severe outbreak patterns, respectively, over the 50 year period (Table 3).

Regarding the EIS scenario, since it was assumed that a future SBW outbreak would be prevented if the EIS treatment worked, the projected NB timber supply was assumed to be not affected over the next 50 years. Consequently, the projected relative

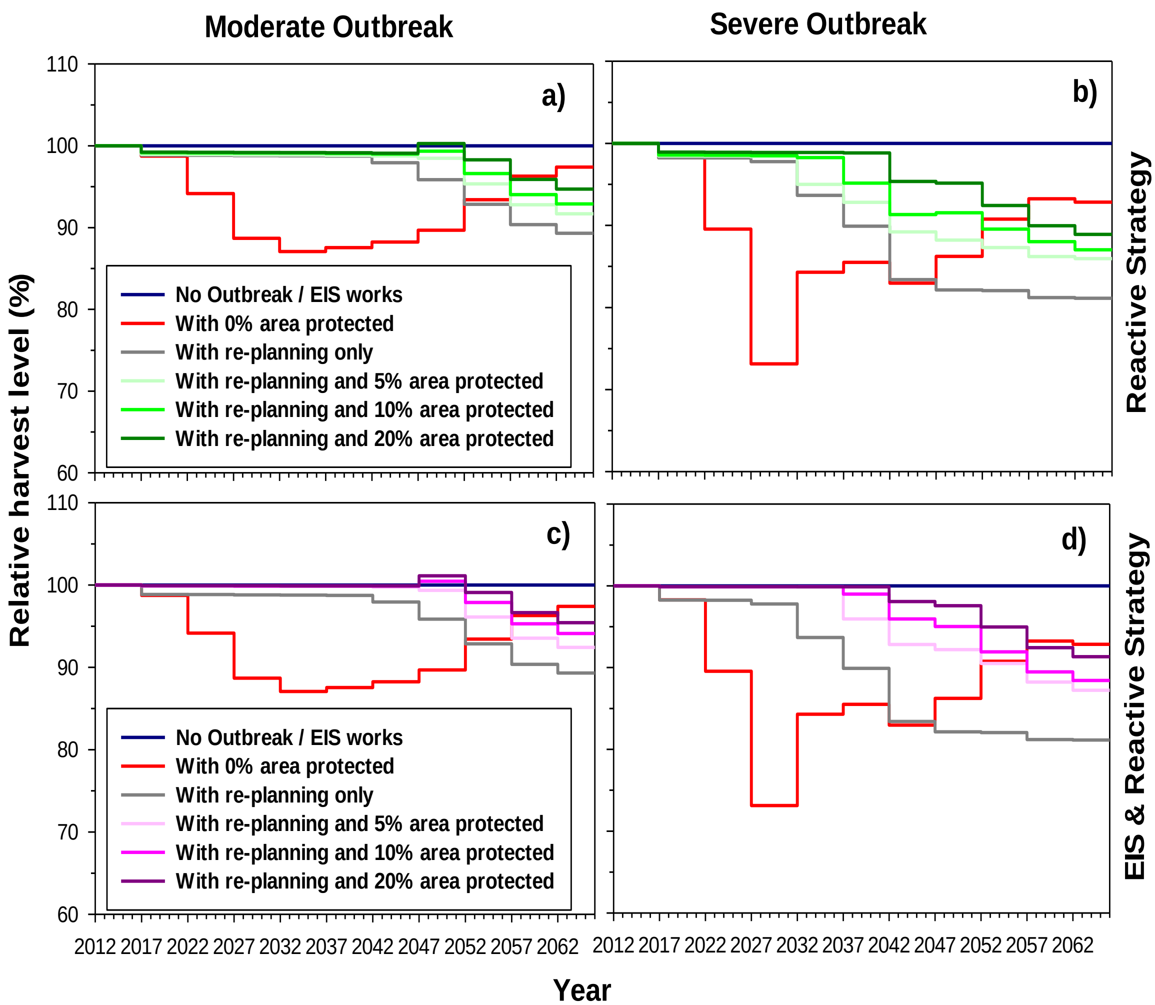

Figure 3. Projected relative total timber volume harvest for all Crown land in New Brunswick from 2012-2066 under each SBW outbreak and protection scenario.

timber volume harvest level under the EIS scenario was expected to remain at the baseline level of 100% (Figure 3). As a result, the 27.86 million m^3 and 43.54 million m^3 of cumulative timber harvest volume losses estimated above were anticipated to be saved by the EIS treatment under moderate and severe outbreak patterns, respectively (Table 3).

The EIS Fails & Reactive Strategy scenarios were also projected to save a significant, but smaller, amount of timber supply loss compared to the EIS scenario (Figure 3c,d). Generally, higher forest protection levels resulted in lower timber supply losses (i.e., higher timber supply savings). For instance, under a moderate outbreak pattern, the cumulative timber harvest volume saving was expected to increase from 20.12 million m^3 to 24.52 million m^3 when area of total susceptible Crown forest that is protected increased from 0% to 20% (Table 3). Under a severe outbreak pattern, the maximum cumulative timber harvest volume saving was projected at 33.19 million m^3 when 20% of total susceptible Crown forest was protected.

Table 3. Summary of timber harvest volume impact from spruce budworm outbreak scenarios (2010-2060).

Impact on:	**Timber harvest volume (Mm^3) by Outbreak and Protection Strategy Scenarios**			
	Moderate outbreak		Severe outbreak	
	Reactive Strategy	EIS Fails & Reactive Strategy	Reactive Strategy	EIS Fails & Reactive Strategy
Cumulative timber volume harvest loss				
With 0% area protected	-27.86		-43.54	
Cumulative timber volume harvest saving				
With re-planning only	12.54		1.20	
With re-planning and 5% area protected	16.90	20.12	13.36	22.85
With re-planning and 10% area protected	19.15	22.67	19.42	27.61
With re-planning and 20% area protected	21.81	24.52	26.71	33.19
With Early Intervention Strategy	27.86		43.54	

Under the Reactive Strategy scenarios, timber supply savings were also found to be substantial, but generally lower than those under the EIS Fails & Reactive Strategy scenarios (Figure 3a,b). Specifically, adopting re-planning of harvesting alone was anticipated to save 12.54 million m^3 of cumulative timber harvest volume loss over the next

50 years (Table 3). By combining reactive foliage protection with re-planning of harvesting, the SBW outbreak impacts on NB timber supply were expected to be even less substantial, and varied with the amount of Crown forest protected (Figure 3c,d). For instance, under a moderate outbreak pattern, reactive foliage protection with re-planning of harvesting was predicted to save 12.54 million m^3 to 21.81 million m^3 of cumulative timber harvest volume losses when spraying 0% to 20% of total susceptible Crown forest, respectively (Table 3). Under a severe outbreak scenario, up to 26.71 million m^3 of NB timber supply loss was estimated to be prevented when 20% of total susceptible Crown forest was sprayed.

3.2 CGE model results

Current value stumpage revenue impacts

Figure 4 presents the projected relative stumpage revenues for Crown land in NB under different SBW outbreak patterns and forest protection scenarios over the 50 year period. Since stumpage revenue values were calculated based on the timber volume harvest results from SBW DSS, the percentage changes in stumpage revenue values were similar to the percentage changes of the NB timber supply under all scenarios considered. Relative stumpage revenues without SBW control dropped the most at 12.92% (moderate outbreak) and 27.04% (severe outbreak). Overall, cumulative current value stumpage revenue losses without forest protection were estimated at $178.49 million and $273.39 million under moderate and severe outbreak patterns, respectively (Table 4).

Under the EIS scenario, stumpage revenue savings were estimated to be substantial since timber supplies were assumed to remain at their baseline levels over the 50 year period

(Figure 4). Specifically, the cumulative current value total stumpage revenue savings were the same as losses without protection: $178.49 million and $273.39 million under moderate and severe outbreaks, respectively (Table 4).

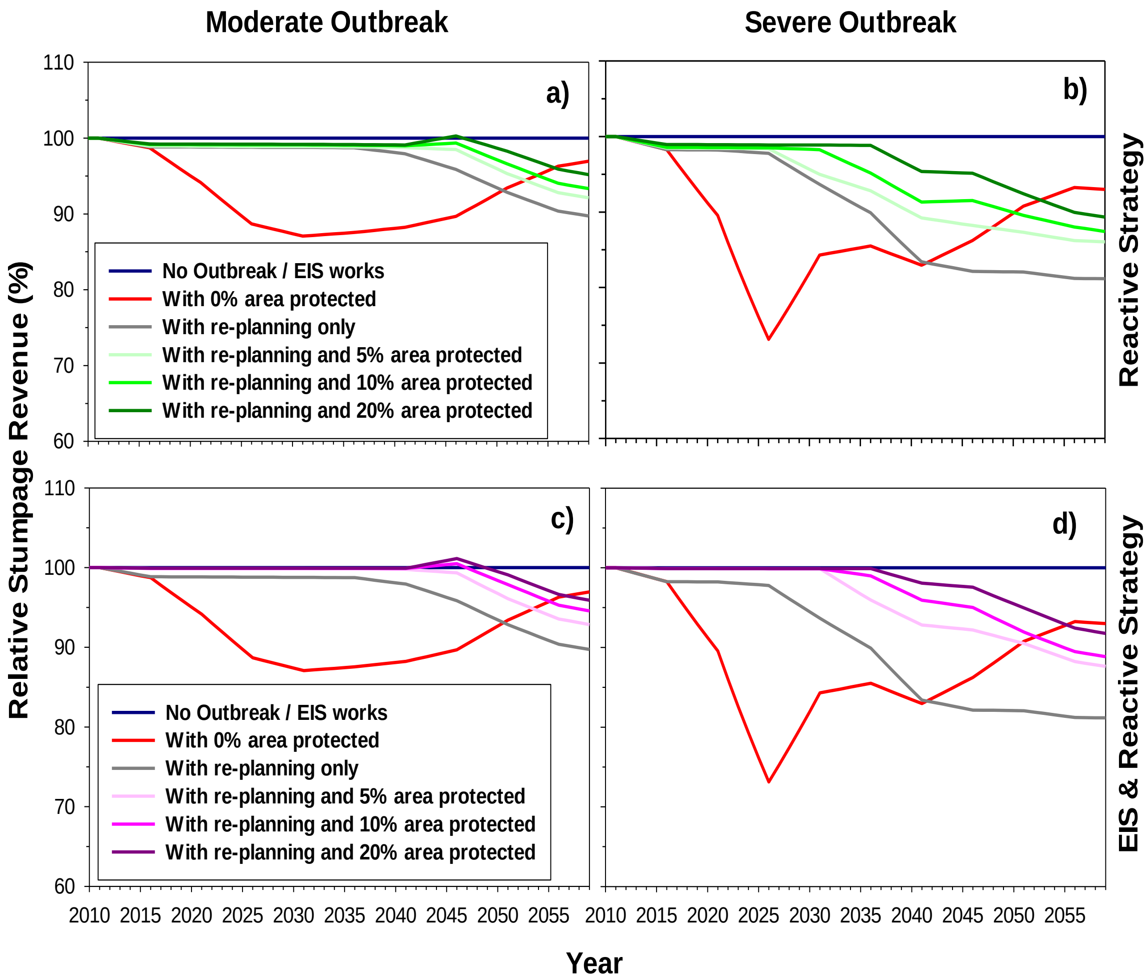

Figure 4. Projected relative stumpage revenue from all Crown land harvest in New Brunswick from 2010-060 under each SBW outbreak and protection scenario.

Under the EIS Fails & Reactive Strategy scenarios, forest protection was estimated to save generally less stumpage revenue compared to the EIS scenario over the 50 year period (Figure 4). However, stumpage revenue savings were projected to increase when protecting larger percentages of susceptible forest area. Specifically, the projected cumulative current value stumpage revenue savings were $100.49-$166.32 million (moderate outbreak), and $38.79-$208.25 million (severe outbreak) when protecting 0-20% of total susceptible Crown forest area, respectively (Table 4).

The Reactive Strategy scenarios were estimated to save generally less stumpage revenue compared to the EIS Fails & Reactive Strategy scenarios over the 50 year period (Figure 4). For instance, the projected cumulative current value stumpage revenue savings were predicted to be $100.49-149.98 million (moderate outbreak) and $38.79-198.01 million (severe outbreak) when protecting 0-20% of total susceptible Crown forest area, respectively (Table 4).

Current value domestic output impacts

Table 4 presents the projected current value domestic output impacts in NB under different SBW outbreak patterns and forest protection scenarios over the 50 year period. The analysis revealed that uncontrolled moderate and severe outbreaks would significantly impact NB's domestic output over the next 50 years. Specifically, compared to the baseline scenario, the cumulative current value domestic output losses were predicted to be $24.63 billion and $35.31 billion without any SBW control under moderate and severe outbreak patterns, respectively.

Under the EIS scenario (assuming EIS treatments worked), the negative impacts of SBW outbreaks on NB domestic output were eliminated over the 50 year period. As such, the cumulative current value total domestic output savings under the EIS scenario were

Table 4. Current value[a] stumpage revenue, output, and net export impacts from spruce budworm outbreak scenarios (2010-2060).

Impacts:	**Outbreak and Protection Scenarios**			
	Moderate outbreak		Severe outbreak	
	Reactive Strategy	EIS Fails & Reactive Strategy	Reactive Strategy	EIS Fails & Reactive Strategy
Stumpage revenue ($million)				
Stumpage revenue loss				
With 0% area protected	-178.49		-273.39	
Stumpage revenue saving				
With re-planning only	100.49		38.79	
With re-planning and 5% area protected	124.11	143.80	114.93	153.72
With re-planning and 10% area protected	136.37	157.00	148.80	198.01
With re-planning and 20% area protected	149.98	166.32	187.65	208.25
With early intervention Strategy	178.49		273.39	
Output ($billion):				
Output loss				
With 0% area protected	-24.63		-35.31	
Output saving				
With re-planning only	21.71		9.58	
With re-planning and 5% area protected	23.14	24.09	18.10	24.14
With re-planning and 10% area protected	23.65	24.49	22.88	31.27
With re-planning and 20% area protected	24.10	24.51	31.24	33.57
With early intervention Strategy	24.63		35.31	
Net Export ($billion):				
Net Export loss				
With 0% area protected	-19.57		-27.79	
Net Export saving				
With re-planning only	17.80		7.75	
With re-planning and 5% area protected	18.80	19.38	14.45	19.09
With re-planning and 10% area protected	19.14	19.47	18.22	25.10
With re-planning and 20% area protected	19.42	19.50	25.04	26.75
With early intervention Strategy	19.57		27.79	

a. Values are presented in current-value Canadian dollar terms.

projected at $24.63 billion (moderate) and $35.31 billion (severe) in NB (Table 4).

The EIS Fails & Reactive Strategy scenarios were found to save relatively less domestic output compared to the EIS scenario over the 50 year period (Table 4). However, output savings were estimated to increase with the level of foliage protection. For instance, the adoption of re-planning of harvesting alone was estimated to save $21.71 billion of cumulative current value domestic output under both outbreak patterns. Cumulative domestic output savings were estimated to be $24.09-$24.51 billion (moderate outbreak) and $24.14-$33.57 billion (severe outbreak) when protecting 5-20% of the susceptible Crown forest, respectively.

The Reactive Strategy scenarios were also found to significantly reduce the impacts of future SBW outbreaks on NB domestic output over the 50 year period, however less so compared to the EIS Fails & Reactive Strategy scenarios (Table 4). For instance, the cumulative current value domestic output savings were projected to be $23.14-$24.10 billion (moderate outbreak) and $18.10-31.24 billion (severe outbreak) when protecting 5-20% of total susceptible Crown forest, respectively.

Current value net export impacts

Projected current value net export impacts in NB under different SBW outbreak patterns and forest protection scenarios, compared to the baseline scenario, were predicted to be $19.57 billion and $27.29 billion if there is an uncontrolled moderate and severe outbreaks, respectively, over the next 50 years. Similar to the impacts on total domestic output, forest protection strategies significantly reduced the SBW defoliation impacts on net exports. For instance, compared to the baseline scenario, the EIS scenario was projected to save entire SBW defoliation-caused net export losses at $19.57 billion and $27.29 billion under both outbreak pattern with the EIS assumption of no future outbreak (Table 4). Moreover, compared to the EIS scenario, the EIS Fails & Reactive Strategy scenarios were projected to be less effective to mitigate the SBW defoliation impacts. Overall, if there is an inevitable future SBW outbreak, which is only delayed by the EIS activities, the EIS Fails & Reactive Strategy scenarios were projected to save up to $19.87 billion and $26.75 billion of current value net export over the next 50 years. Additionally, compared to the EIS and EIS Fails & Reactive Strategy scenarios, the Reactive Strategy scenarios were predicted to save the least current value net export. Up to $21.81 billion and $26.71 billion of current value net export loss was estimated if the Reactive Strategy was employed in NB.

Present value stumpage revenue, domestic output, and net export impacts

Table 5 describes the present value stumpage revenue, domestic output, and net export impacts of future SBW outbreaks and forest protection scenarios on NB economy and forest-based industries over the 2010-2060 period. The impacts of future SBW outbreaks and forest protection on the NB economy generally followed the current values described in the previous section, however, the present values were generally smaller due to the fact that future values were discounted at the market rate of interest. Overall, under the present value analysis, an uncontrolled future SBW outbreak was forecasted to cause $63.61 and $101.19 million of present value stumpage revenue losses under the moderate and severe outbreak patterns, respectively, while these projected present value stumpage revenue losses were forecasted to cause $6.12 billion/$9.63 billion (moderate/severe outbreak) and $4.67 billion/$7.32 billion (moderate/severe outbreak) of domestic output and net export losses, respectively.

Similar to the current value analysis, the present value analysis found that EIS scenario was projected to generally save the highest stumpage revenue, output, and net export losses, followed by the EIS Fails & Reactive Strategy scenarios and the Reactive Strategy scenarios. However, there are some notable exceptions when the present value estimation was adopted. For example, under the current value estimation, the Reactive Strategy scenario to protect 20% of total susceptible Crown forest was predicted to save more domestic output and net export losses than the EIS Fails & Reactive Strategy scenario to protect 5% of total susceptible Crown forest (Table 4). However, since the EIS activities were assumed to only delay the future SBW outbreak by 5 years, the projected SBW defoliation-caused domestic output and net export losses under the EIS Fails & Reactive Strategy scenarios were predicted to be further discounted at the market rate of interest so that the SBW defoliation impacts under the EIS Fails & Reactive Strategy scenarios were less significant comparing to the Reactive Strategy scenarios. As a result, under the present value estimation, the EIS Fails & Reactive Strategy scenario to protect 5% of total susceptible Crown forest was predicted to save more output and net export losses than the Reactive Strategy scenario to protect 20% of total susceptible Crown forest.

Regarding the impacts of future SBW outbreaks and forest protections on NB forest-related sectors, an uncontrolled SBW outbreak was anticipated to cause large scale sectoral output and net export reductions in NB (Table 5). For example, among all sectors,

Table 5. Present value[a] stumpage revenue, output and net export impacts ($million) of spruce budworm outbreak and protection scenarios on Crown Land in New Brunswick (2010-2060).[a]

	Outbreak scenarios and impacts by sector:	No Protection Losses	**Protection Scenario Savings[b]** Reactive Strategy (with re-planning & reactive foliage protection) 0%	5% (1,136)	10% (2,273)	20% (4,546)	Early Intervention Strategy: EIS works (2,040)	EIS Fails & Reactive Strategy 5% (1,622)	10% (2,759)	20% (5,032)
Moderate Outbreak	**Stumpage revenue** ($million)	-63.61	44.49	49.58	52.73	55.53	63.61	57.19	59.72	61.51
	Output ($billion):									
	Forestry and logging	-1,137.09	790.64	882.15	939.26	989.95	1,137.09	1,020.33	1,057.68	1,061.83
	Support activities for A&F[c]	-81.15	52.48	60.32	64.97	69.44	81.15	70.38	73.76	74.09
	Manufacturing	-7,398.01	6,624.32	6,989.64	7,127.82	7,237.06	7,398.01	7,277.23	7,374.61	7,380.56
	Rest of economy	2,493.33	-2,024.59	-2,186.10	-2,265.80	-2,334.43	-2,493.33	-2,364.13	-2,418.81	-2,423.63
	Total	-6,122.93	5,442.85	5,746.01	5,866.25	5,962.02	6,122.93	6,003.82	6,087.24	6,092.85
	Net exports ($million):									
	Forestry and logging	-278.89	174.77	200.93	217.78	233.52	278.89	240.15	251.71	252.96
	Support activities for A&F	-34.94	21.76	25.41	27.53	29.64	34.94	29.79	31.39	31.54
	Manufacturing	-6,543.45	5,860.56	6,183.30	6,305.26	6,401.66	6,543.45	6,437.14	6,523.10	6,528.35
	Rest of economy	2,188.49	-1,790.36	-1,929.61	-1,997.54	-2,055.71	-2,188.49	-2,081.27	-2,127.83	-2,131.89
	Total	-4,668.79	4,266.73	4,480.03	4,553.03	4,609.10	4,668.79	4,625.80	4,678.38	4,680.97
Severe Outbreak	**Stumpage revenue** ($million)	-101.19	39.74	57.16	67.88	80.07	101.19	77.38	84.86	91.50
	Output ($billion):									
	Forestry and logging	-1,807.11	709.46	1,018.19	1,208.84	1,425.36	1,807.11	1,381.21	1,512.96	1,631.83
	Support activities for A&F	-128.27	41.29	65.92	80.39	96.72	128.27	92.67	102.54	112.60
	Manufacturing	-11,563.92	4,609.69	6,990.15	8,396.04	10,469.37	11,563.92	8,783.02	10,505.00	11,122.18
	Rest of economy	3,864.69	-1,396.76	-2,185.22	-2,647.49	-3,295.06	-3,864.69	-2,875.80	-3,374.47	-3,613.79
	Total	-9,634.61	3,963.68	5,889.03	7,037.77	8,696.39	9,634.61	7,381.10	8,746.02	9,252.81
	Net exports ($million):									
	Forestry and logging	-437.66	152.40	227.26	273.33	325.46	437.66	321.49	350.76	383.20
	Support activities for A&F	-55.12	15.90	27.03	33.44	40.63	55.12	38.73	43.06	47.71
	Manufacturing	-10,235.98	4,089.39	6,194.64	7,438.60	9,269.10	10,235.98	7,780.20	9,300.15	9,845.83
	Rest of economy	3,412.06	-1,267.10	-1,958.66	-2,363.30	-2,925.33	-3,412.06	-2,558.25	-2,991.60	-3,199.20
	Total	-7,316.71	2,990.58	4,490.28	5,382.06	6,709.86	7,316.71	5,582.16	6,702.38	7,077.54

a. All values are presented in present value (2011) Canadian dollar terms using a 4% discount rate.
b. Percentages represent percent of area protected, and values in parentheses represent 000's of hectares protected.
c. Agriculture and Forestry.

manufacturing sector, forestry and logging sector, and support activities for agriculture and forestry sector were projected to be the top three most affected sectors by a future SBW outbreak, while a future SBW outbreak was predicted to impact the manufacturing sector the most, followed by the forestry and logging and the support activities for agriculture and forestry sectors. Additionally, under the present value analysis, the impacts of forest protections (i.e., EIS, Reactive Strategy, and EIS Fails & Reactive Strategy) follow the basic same patterns as presented in the current value analysis on mitigating SBW defoliation-caused sectoral output and net export losses except the present value sectoral output and net export savings under the EIS Fails & Reactive Strategy scenario to protect 5% of total susceptible Crown forest was predicted to be higher than the Reactive Strategy scenario to protect 20% of total susceptible Crown forest. However, as described above, this result was expected since the EIS activities under the EIS Fails & Reactive Strategy was assumed to delay the future SBW outbreak by 5 years.

3.3 Benefit-Cost analysis results

Table 6 presents the present value market and non-market benefits, market costs, BCR and NPV results under different SBW outbreak patterns and forest protection scenarios over a 50-year study period. Market benefits, which were based on the 2017 NB Crown SBW DSS model (for timber supply volume savings and market prices), were anticipated to increase significantly when higher forest protection levels were adopted. Under the EIS scenario, the cumulative present value market benefits were projected to be the highest at $161.79 million and $319.33 million under moderate and severe outbreak patterns, respectively. Compared to the EIS scenario, the cumulative present value market benefits under the EIS Fails & Reactive Strategy scenarios were comparatively lower. When moving from 5% to 20% of Crown forest area protected, the present value market benefits were predicted to increase from $143.17 -151.61 million (moderate) to $211.09-250.73 million (severe). The cumulative present value market benefits under the Reactive Strategy scenarios were estimated to be the lowest among all scenarios, at $117.55-130.91 million (moderate) and $147.07-209.84 million (severe) when protecting 5-20% total susceptible forest.

With regard to market costs, cumulative present values also generally increase with more Crown forest protected (Table 6). The EIS Fails & Reactive Strategy scenarios exhibited the highest present value market costs since the total treatment area under these scenarios was the highest (Figure 5c-d). Up to $145.40 million and $175.29 million of cumulative present value market costs were estimated when protecting 20% of total susceptible Crown forest under moderate and severe outbreak patterns, respectively. The Reactive Strategy scenarios, which exhibited comparatively lower cumulative present value costs than the EIS Fails & Reactive Strategy scenarios, ranged from $35.35-$132.94 million (moderate) and $43.26-$163.67 million (severe) when protecting 5-20% of total susceptible Crown forest. The EIS scenario exhibited the least cumulative present value costs at $65.50 million under both outbreak patterns.

For non-market benefits, the public's WTP in NB was estimated to be the highest under the EIS scenario, where NB households were estimated to be willing to pay up to $89.63 million and $98.87 million (present value) over the next 50 years to prevent future moderate and severe outbreaks, respectively (Table 6). However, the public's WTP was

Table 6. Benefits and costs of spruce budworm control programs on Crown land in New Brunswick over the 50 years.

Outbreak scenarios and values	% of susceptible area protected ('000 ha)						
	Reactive foliage protection strategy [a]			Early Intervention Strategy			
	Forest insecticide spraying & re-planning			EIS works	EIS fails & Reactive Strategy		
	5% (1,136)	10% (2,273)	20% (4,546)	(2,040)	5% (1,622)	10% (2,759)	20% (5,032)
Moderate Outbreak							
PV[e] Market Benefit ($million)[c]	117.55	123.94	130.91	161.79	143.17	143.56	151.61
PV Market Costs ($million)[d]	35.35	67.87	132.94	65.50	50.52	82.15	145.40
PV Non-Market Benefits ($million)	4.48	8.96	17.92	89.63	3.83	7.66	15.32
PV BCR[f] of Protection [Market value]($/$)	3.33	1.83	0.98	2.47	2.83	1.75	1.04
PV BCR of Protection [Market & Non-Market values] ($/$)	3.45	1.96	1.12	3.84	2.91	1.84	1.15
NPV[g] of Protection [Market value]($million)	82.20	56.07	-2.03	96.29	92.65	61.41	6.20
NPV of Protection [Market & Non-Market values]($million)	86.68	65.03	15.90	185.92	96.48	69.07	21.53
Severe Outbreak							
PV[e] Market Benefit ($million)[c]	147.07	173.77	209.84	319.33	211.09	228.87	250.73
PV Market Costs ($million)[d]	43.26	83.41	163.67	65.50	58.19	97.22	175.29
PV Non-Market Benefits ($million)	4.94	9.89	19.77	98.87	4.22	8.45	16.90
PV BCR[f] of Protection [Market value]($/$)	3.40	2.08	1.28	4.88	3.63	2.35	1.43
PV BCR of Protection [Market & Non-Market values] ($/$)	3.51	2.20	1.40	6.39	3.70	2.44	1.53
NPV[g] of Protection [Market value]($million)	103.81	90.35	46.17	253.84	152.90	131.65	75.44
NPV of Protection [Market & Non-Market values]($million)	108.75	100.24	65.94	352.71	157.13	140.10	92.34

a. Reactive foliage protection strategy assuming a potential moderate/Severe outbreak starts in 2015. And forest spraying program starts in 2018.
b. The total SBW susceptible area is estimated at 2,840,860 ha in New Brunswick Crown Forest (Chang et al. 2012b).
c. Market benefits are estimated by using the Crown stumpage revenue net of license management fees from the 2017 New Brunswick Crown model.
d. Market costs contains forest insecticide spraying program treatment costs and monitoring costs.
e. PV = present value.
f. BCR = benefit-cost ratio (i.e., BCR of protection = PV benefits / PV costs).
g. NPV = net present value (i.e., NPV of protection = (PV benefits-PV costs) / $(1+ \text{discount rate})^n$).

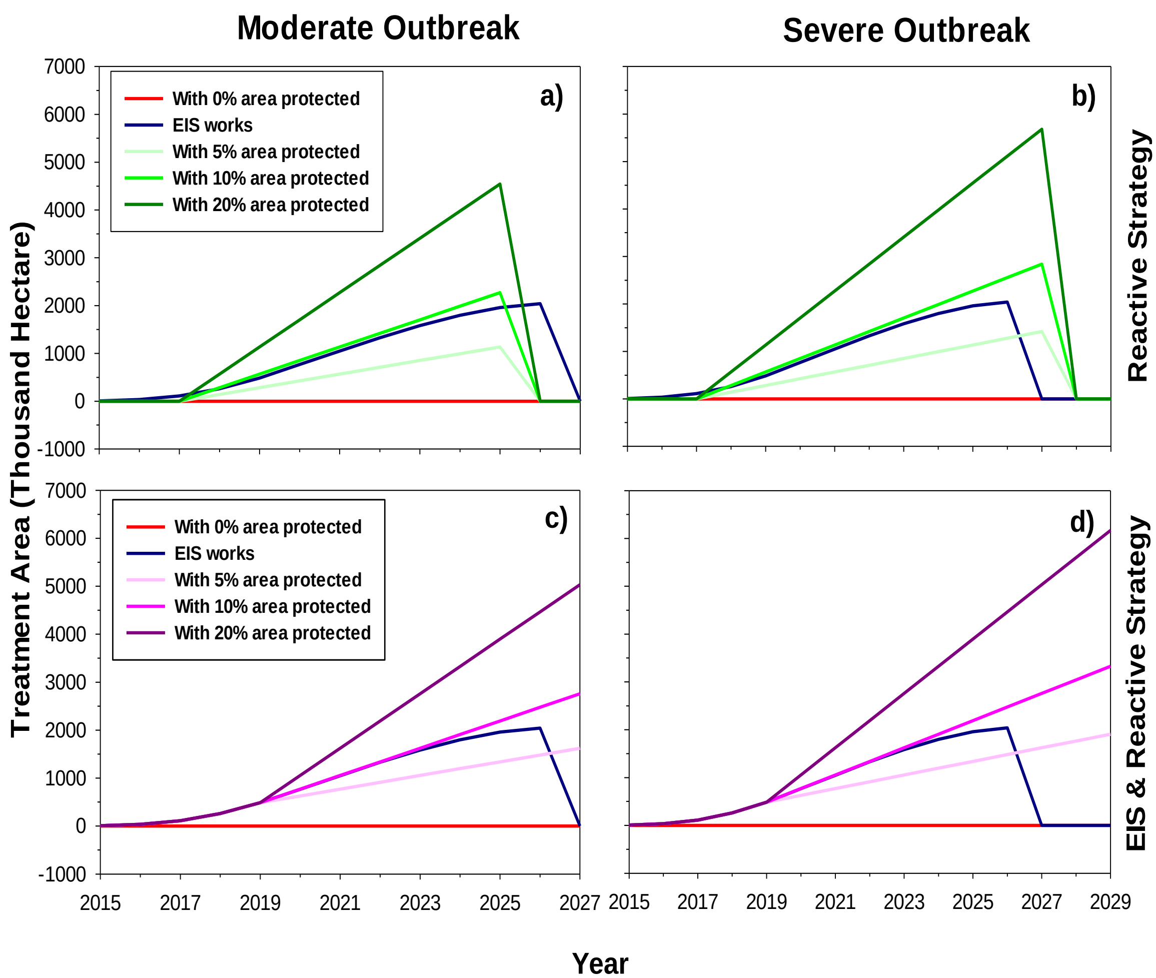

Figure 5. Projected total treatment area for Crown land in New Brunswick under each SBW outbreak and protection scenario.

estimated to be significantly lower if future SBW outbreaks would not be prevented. Under the Reactive Strategy scenarios, the present value non-market benefits ranged from $4.48-$17.92 million (moderate outbreak) and $4.94-19.77 million (severe outbreak) with 5-20% of area protected. Additionally, based on the initial assumption of a 5-year delay on outbreak initiation under the EIS Fails & Reactive Strategy scenarios, the present value non-market benefits were projected to be the lowest at $3.83-15.32 million (moderate outbreak) and $4.22-16.90 million (severe outbreak) when protecting 5-20% of total susceptible Crown forest.

Regarding the efficiency of forest protection scenarios, the NPV analysis indicated that the EIS scenario was the most economically efficient (i.e., highest NPV) forest protection strategy under both market and total (i.e., market and non-market) values (Table 6). The market NPV of the EIS scenario was estimated to be the highest at $96.29 million (moderate outbreak) and $253.84 million (severe outbreak). By including non-market values, the total NPV of the EIS scenario was significantly higher at $185.92 million (moderate outbreak) and $352.71 million (severe outbreak). Compared to the EIS scenario, the EIS Fails & Reactive Strategy scenarios were forecasted to be less efficient. Under a moderate outbreak, the market and total NPV of the EIS Fails & Reactive Strategy scenarios were projected to range from a low of $6.20-21.53 million, respectively (20% Crown forest protected), to a high of $92.56-96.48 million, respectively (5% Crown forest protected). Under a severe outbreak pattern, the market and total NPV of the EIS Fails & Reactive Strategy scenarios were estimated to be the highest at $152.90 million and $157.13 million, respectively, when protecting 5% of total susceptible Crown forest. Additionally, the Reactive Strategy scenarios were forecasted to provide the least efficient forest protection. The market and total NPV of the Reactive Strategy scenarios under a moderate outbreak pattern were estimated to range from $82.20 million and $86.68million, respectively (with 5% of Crown forest protected), to $-2.03 million and $15.90 million, respectively (with 20% of Crown forest protected). These NPV estimates were substantially higher under a severe outbreak pattern, with values of $103.81-65.94 million to $108.75-46.17 million of market and total NPV, respectively, when protecting 5- 20% of total susceptible Crown forest.

With regard to cost-effectiveness considerations, BCR analysis revealed that the EIS was the most cost-effective (i.e., highest BCR) forest protection strategy, with a BCR of 3.84 (moderate outbreak) and 6.39 (severe outbreak) when considering market and non-market values. Findings were mixed, however, when only considering market values, where the EIS scenario had the highest value of 4.88 under a severe outbreak, and the Reactive Strategy scenario with 5% of Crown forest protected had the highest value of 3.33 under a moderate outbreak. Similar to the NPV estimates, higher forest protection levels generally led to lower BCRs. For instance, market BCRs of the Reactive Strategy scenarios were estimated to drop from 3.33 to 0.98 when increasing forest protection levels from 5% to 20% of total susceptible Crown forest, respectively.

4. DISCUSSION and CONCLUSIONS

4.1 Key findings

In this study, an advanced SBW DSS model was coupled with a dynamic CGE model to assess the impacts of future SBW outbreaks and forest protection strategies on NB timber supply and regional economy. Several key findings resulted from this research.

First, the SBW DSS and CGE models results revealed that future moderate or severe outbreaks were projected to have large impacts on the NB timber supply and regional economy. Additionally, sectoral output and net exports among forest-related industries in NB were also expected to be severely affected. These results were consistent with, but relatively higher than, previous economic impact research on SBW outbreaks in NB conducted by Chang et al. (2012b). Since this study utilized more advanced SBW DSS and CGE models (i.e., more refined modelling of the economic structure) and a longer study horizon (i.e., 50 years instead of 30 years), it is reasonable to expect the results presented in this study would be larger and more robust relative to the previous research.

Another key finding in this study was that the forest protection strategies (i.e., EIS, EIS Fails & Reactive Strategy, and Reactive Strategy) significantly mitigated SBW outbreak impacts on the regional economy. The EIS scenario was found to save the most total domestic output and net exports over the 50 year period, because it was assumed to completely prevent a SBW outbreak. This was followed by the EIS Fails & Reactive Strategy and then the Reactive Strategy. All three strategies produced savings generally within one billion dollars of one another (for comparable scenarios), indicating that all are effective in mitigating the impacts of SBW outbreaks on the NB economy.

A third key finding in this study was that, while larger reactive foliage protection levels were consistently associated with larger timber supply, and sectoral/economy-wide savings, they were not always more cost-effective or efficient. BCA and NPV analyses revealed that lower levels of reactive foliage protection (i.e., 5%) were often the most cost effective and efficient due largely to the high rate at which treatment costs increased with the area treated. This finding is consistent with that of previous research by Chang et al. (2012a) except the market costs in our study were comparatively higher than the estimated market costs in Chang et al. (2012a). However, this was expected since the Chang et al.

(2012a) assumed to apply forest protection only in peak defoliation years (i.e., current balsam fir defoliation higher than 70%), whereas we assumed to protect the susceptible Crown forest in all years when current balsam fir defoliation exceeded 40%. Overall, this finding suggested that it is essential for forest policy makers to consider all these economic criteria when making informed forest protection policy decision regarding the desired forest protection strategy in NB.

A fourth key finding in this study was that the implementation of re-planning of harvesting alone under the EIS Fails & Reactive Strategy and Reactive strategy scenarios was forecasted to significantly reduce SBW outbreak impacts on NB gross domestic output and net exports. Combining the re-planning of harvesting with reactive foliage protection led to further substantial output and net export savings. These results were similar to those found in previous research by Chang et al. (2012b), and highlight the importance of both actions in a reactive strategy. However, since this study utilized more advanced SBW DSS and CGE models and a longer study horizon, the domestic output and net export impact results were comparatively larger than the findings presented in Chang et al. (2012b).

A final, and possibly most important, finding was that the EIS scenario was the most cost-effective and efficient forest protection strategies, followed by EIS Fails & Reactive Strategy and then Reactive Strategy scenarios. The EIS finding largely had to do with the significant timber supply and market/non-market savings associated with the assumption that EIS treatments would be effective in preventing a SBW outbreak. This overall finding holds true except in some cases at low levels of reactive foliage protection (i.e., to protect 5% of susceptible Crown forest) implemented under the EIS Fails &

Reactive Strategy and the Reactive Strategy scenarios. Specifically, compared to the EIS Fails & Reactive Strategy and the Reactive Strategy scenarios to protect 5% of total susceptible Crown forest, the EIS scenario was predicted to have the lowest market BCR at 2.47. However, these exceptions were expected since the market cost under the EIS scenario was the highest among these three scenarios. Additionally, as shown in Table 6, the benefits of forest protection largely outweighed the costs associated with EIS scenario even though these costs sometimes were larger than those associated with some other strategy scenarios. However, a notable exception existed when evaluating the efficacy of forest protection under the Reactive Strategy scenario to protect 20% of susceptible Crown forest. Due to the high treatment cost to protect 20% of total susceptible Crown forest, this Reactive Strategy was neither the most cost-effective or economically efficient strategy, and in fact a negative market NPV of protection was estimated at $-2.03 million over the next 50 years.

4.2 Study limitations

While many interesting findings emerged from this research, there were still some unavoidable limitations. First of all, a single regional CGE model was utilized in this study. According to Ochuodho et al. (2014), a multi-regional CGE model would better reflect reality since it would allow for a more detailed accounting of import/export substitution by region of origin and destination. Therefore, it would be interesting to see how the estimates change under a multi-regional model specification. However, this was beyond the scope of the current thesis. It is the intent of the authors to conduct a multi-regional CGE model for more in-depth economic impact analysis in future research.

Another limitation, particularly with regard to the BCA and NPV analysis, is the lack of data on the costs associated with the re-planning of harvesting. More precise estimates may change the cost-effectiveness and efficiency ranking of forest protection strategies. Furthermore, the non-market benefit estimates in this study were taken from Chang et al. (2011) and only included recreation and wildlife values. These values may have changed over time, and other non-market values such as carbon and water quality, which were not valued, may be important to the New Brunswick population. As a result, including updated and more robust non-market values might lead to even greater economic support for forest protection scenarios with high forest protection levels. Future study is needed to provide an updated and full assessment of all non-market values and re-planning of harvesting costs.

4.3 Conclusions

Despite the above limitations, this study has shed important light on potential biophysical and economic consequences of future SBW outbreaks and forest protection strategies in NB. The findings confirmed that an EIS was predicted to best mitigate the negative economic impacts and be the most cost-effective and economically efficient forest protection strategy (assuming that the EIS treatment works). However, if EIS treatment fails and a future SBW outbreak occurs, the EIS Fails & Reactive Strategy would better mitigate the negative economic impacts and provide higher net return than the traditional Reactive Strategy. To sum up, it is justified on economics grounds to continue recent efforts that utilize EIS to control future SBW outbreaks in NB.

BIBLIOGRAPHY

Alavalapati, J., White, W., Jagger, P., and Wellstead, A. 1996. Effect of land use restrictions on the economy of Alberta: a computable general equilibrium analysis. Canadian Journal of Regional Science 19(3): 349-365.

Alavalapati, J., Adamowicz, W., and White, W. 1998. A comparison of economic impact assessment methods: the case of forestry developments in Alberta. Canadian Journal of Forest Research 28(5): 711-719.

Armington, P.S., 1969 A theory of demand for products distinguished by place of production. International Monetary Fund Staff Papers 16 (1): 244-252.

Atlantic Provinces Economic Council. 2003. The New Brunswick forest industry: The potential economic impact of proposals to increase the wood supply. Available from the Atlantic Provinces Economic Council, Halifax, N.S.

BEGAB. 2013. Budworm Eco-Genomics: Applications & Biotechnology (BEGAB). Institut de biologie integrative et des systemes, Universite Laval. Available at http://www.sprucebudworm.ca Accessed July 26, 2013.

Blais, J.R. 1983. Trends in the frequency, extent, and severity of spruce budworm outbreaks in eastern Canada. Canadian Journal of Forest Research 13:539-547.

Blum, B.M., and MacLean, D.A. 1985. Potential silviculture, harvesting and salvage practices in eastern North America. In Recent Advances in Spruce Budworms Research, Proceedings of the CANUSA Spruce Budworms Research Symposium. Canadian Forestry Service, Ottawa, Ont. pp. 264-280.

Carter, N.E., and Lavigne, D.R. 1994. Protection spraying against spruce budworm in New Brunswick 1993. New Brunswick Department of Natural Resources and Energy, Fredericton, NB, Canada.

Chang, W.Y., Lantz, V.A., and MacLean, D.A. 2011. Social benefits of controlling forest insect outbreaks: a contingent valuation analysis in two Canadian provinces. Canadian Journal of Agricultural Economics. 59(3): 383-404.

Chang, W.Y., Lantz, V.A., Hennigar, C.R., and MacLean, D.A. 2012a. Benefit-cost analysis of spruce budworm (*Choristoneura fumiferana* Clem.) control: incorporating market and non-market values. Journal of Environmental Management 93(1): 104-112.

Chang, W.Y., Lantz, V.A., Hennigar, C.R., and MacLean, D.A. 2012b. Economic impacts of forest pests: a case study of spruce budworm outbreaks and control in New Brunswick, Canada. Canadian Journal of Forest Research 42: 490-505.

Cobb, C.W., and Douglas, P.H. 1928. A theory of production. The American Economic Review 18:139-165.

Coulombe Commission (Commission d'etude sur la gestion de la foret publique quebecoise), Chapitre 4: Protection, conservation et gestion multiressource: des axes de changement. Rapport final, Quebec, Canada, pp. 47–92 (2004).

Das, G.G., Alavalapati, J.R.R., Carter, D.R., and Tsigas, M.E. 2005. Regional Impacts of environmental regulations and technical change in the US forestry sector: a multiregional CGE analysis. Forest Policy and Economics 7: 25-38.

Deloitte and Touche Management Consultants. 1992. An assessment of the economic benefits of pest control in forestry. A report prepared for the Forest Pest Management Caucus. Deloitte and Touche Management Consultants, Guelph, Ont.

Erdle, T.A., and MacLean, D.A. 1999. Stand growth model calibration for use in forest pest impact assessment. Forestry Chronicle 75: 141-152.

Erdle, T.A., and Ward, C. 2008. Management alternatives for New Brunswick's public forest: Report of the New Brunswick Task Force on Forest Diversity and Wood Supply: summary. Fredericton, NB, New Brunswick Department of Natural Resources.

Etheridge, D.A., MacLean, D.A., and Wagner, R.G. 2006. Effects of Intensive Forest Management on Stand and Landscape Characteristics in Northern New Brunswick, Canada (1945–2027). Landscape Ecology. 21(4): 509

Fournier, C., Bauce, E., Dupont, A., and Berthiaume, R. 2009. Wood losses and economical threshold of *Btk* aerial spray operation against spruce budworm. Pest Management Science 66(3): 319-324.

Government of New Brunswick. Department of Economic Development. n.d. Rebuilding New Brunswick: New Brunswick Value-added Wood Sector Strategy 2012-2016. Available at http://www2.gnb.ca/content/dam/gnb/Corporate/pdf/EcDevEc/Wood.pdf [Accessed August 20th, 2017].

Hanley, N., and Spash, C.L., 1993. Cost-Benefit Analysis and the Environment. Edward

Elgar Publishing, England.

Healthy Forest Partnership. 2016. Available at http://forestprotectionlimited.maps.arcgis.com/apps/Viewer/index.html?appid=1c6e488b56864964a917b06861382929 [Accessed April 25th, 2016].

Healthy Forest Partnership. 2017. Available at http://www.healthyforestpartnership.ca/en/research/what-where-and-when [Accessed June 12th, 2017].

Healthy Forest Partnership. 2018. Available at http://forestprotectionlimited.maps.arcgis.com/apps/Viewer/index.html?appid=1c6e488b56864964a917b06861382929 [Accessed January 15th, 2018].

Hennigar, C.R., MacLean, D.A., Porter, K.B., and Quiring, D.T. 2007. Optimized harvest planning under alternative foliage protection scenarios to reduce volume losses to spruce budworm. Canadian Journal of Forest Research 37(9): 1755–1769.

Hennigar, C.R., MacLean, D.A., Quiring, D.T., and Kershaw J.A. 2008. Differences in spruce budworm defoliation among balsam fir and white, red, and black spruce. Forest Science 54(2): 158–166.

Hennigar, C.R., Erdle, T.A., Gullison, J.J., and MacLean, D.A. 2013. Re-examining wood supply in light of future spruce budworm outbreaks: A case study in New Brunswick. Forestry Chronicle 89(1): 42-53.

Kettela, E.G. 1995. Insect control in New Brunswick, 1974– 1989. In: Forest insect pests in Canada, J.A. Armstrong and W.G.H. Ives (Editors). Natural Resources Canada, Canadian Forest Service, Ottawa, Ont. pp. 655-665.

Lofgren, H., Harris, R.L., and Robinson, S. 2002. A standard Computable General Equilibrium (CGE) Model in GAMS. Microcomputers in Policy Research 5. IFPRI. Washington, D.C.

MacLean, D.A. 1996. Forest management strategies to reduce spruce budworm damage in the Fundy Model Forest. Forestry Chronicle 72: 399-405

MacLean, D.A., and Ostaff, D.P. 1989. Patterns of balsam fir mortality caused by an uncontrolled spruce budworm outbreak. Canadian Journal of Forest Research 19(9): 1087-1095.

MacLean, D.A., MacKinnon, W.E., Porter, K.B., Beaton, K.P., Cormier, G., and Morehouse, S. 2000. Use of forest inventory and monitoring data in the Spruce Budworm Decision Support System. Computers and Electronics in Agriculture 28: 101-118.

MacLean, D.A., Erdle, T.A., MacKinnon, W.E., Porter, K.B., Beaton, K.P., Cormier, G., Morehouse, S., and Budd, M. 2001. The spruce budworm decision support system: forest protection planning to sustain long-term wood supply. Canadian Journal of Forest Research 31(10): 1742-1757.

MacLean, D.A., Beaton, K.P., Porter, K.B., MacKinnon, W.E., and Budd, M.G. 2002. Potential wood supply losses to spruce budworm in New Brunswick estimated using the spruce budworm decision support system. Forestry Chronicle 78(5): 739-750.

Mageroy, M.H., Parent, G., Germanos, G., Giguere, I., Delvas, N., Maaroufi, H., Bauce, E., Bohlmann, J., and Mackay, J.J. 2015. Expression of the β-glucosidase gene Pgβglu-1 underpins natural resistance of white spruce against spruce budworm.The Plant Journal 81(1): 68-80.

McCay, R.E., and White, W.B. 1973. Economic analysis of the gypsy moth problem in the Northeast: I. Applied to commercial forest stands. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. Research Paper NE-275.

McLean, J.A. 1985. Ambrosia beetles: a multimillion dollar degrade problem of sawlogs in Coastal British Columbia. Forestry Chronicle 62: 295-298.

McLeod, I.M., Lucarotti, C.J., Hennigar, D.A., MacLean, D.A., Holloway, A.G.L., Cormier, G.A., and Davies, D.C. 2012. Advances in aerial application technologies and decision support for integrated pest management. In: Integrated Pest Management and Pest Control Current and Future Tactics. M.L. Larramendy and S. Soloneski, Eds. InTech Open Access Publisher, Rijeka, Croatia. Pp. 651-668.

Miller, C.A. and Kettela, E.G. 1975. Aerial control operations against the spruce budworm in New Brunswick. In: Aerial Control of Forest Insects in Canada, M.L. Prebble (Editor), Department of the Environment, Ottawa, Ont. pp. 94-112.

Milne, G.R. 1986. Economic impact of the spruce budworm outbreak in Newfoundland. Canadian Forest Service, Newfoundland Forestry Center, St. John's, Nfld. Inf. Rep. N-X-237.

National Forestry Database. 2016a. Forest Insects - Quick Facts. Canadian Council of

Forest Ministers. Available at http://www.nfdp.ccfm.org/en/data/insects.php [Accessed January 10th, 2016].

National Forestry Database. 2016b. Statement of Revenues from the sale of timber from Provincial Crown Land. Canadian Council of Forest Ministers. Available at http://www.nfdp.ccfm.org/en/data/revenues.php [Accessed October 2nd. 2016].

Natural Resource Canada. 2015. Overview of Canada's forest industry. Available at http://www.nrcan.gc.ca/forests/industry/overview/13311 [Accessed January 19th, 2016].

Nielsen, A., Totland,O., and Ohlson, M. 2007. The effect of forest management operations on population performance of Vaccinium myrtilus on a landscape-scale. Basic and Applied Ecology 8(3): 231-241.

Niquidet, K., Tang, J., and Peter, B. 2016. Economic analysis of forest insect pests in Canada. The Canadian Entomologist (148): 357-366.

New Brunswick Forest Products Commission and PricewaterhouseCoopers LLP. 2016. New Brunswick Private Woodlot Stumpage Values. Available at http://www2.gnb.ca/content/dam/gnb/Departments/nr-rn/pdf/en/ForestsCrownLands/NBStumpageStudyResults.pdf [Assessed June 16th, 2017].

Ochuodho, T.O., and Lantz, V. 2014. Economic impacts of climate change in the forest sector: a comparison of single-region and multiregional CGE modeling frameworks. Canadian Journal of Forest Research 44(5): 449-464.

Ochuodho, T.O., Lantz, V.A., Lloyd-Smith, P., and Benitez, P. 2014. Regional Economic impacts of climate change and adaptation in Canadian forests: a CGE modeling analysis. Forest Policy and Economics (25):100-112.

Patriquin, M.N., Leake, N.L., White, W.A. 2005. A synthesis of the economic efficiency of beetle-proofing management options. Mountain pine beetle initiative. Canadian Forest Service, Pacific Forestry Centre, Victoria, BC, Canada.

Patriquin, M., Wellstead, A., and White, W. 2007. Beetles, trees, and people: Regional economic impact sensitivity and policy considerations related to the mountain pine beetle infestation in British Columbia, Canada. Forest Policy and Economics 9(8): 938-946.

Patriquin, M., Lantz, V., Stedman, R., and White, W. 2008. Working together: a reciprocal wood flow arrangement to mitigate the economic impacts of natural disturbance. Forestry: 81(2): 227-242.

Régnière, J., and T.J. Lysyk. 1995. Population dynamics of the spruce budworm, *Choristoneura fumiferana*. Pages 95-105 In J.A. Armstrong and W.G.H. Ives, eds. Forest Insect Pests in Canada. Nature Resource Canada, Canadian Forest Service, Ottawa, ON.

Régnière, J., Delisle, J., Pureswaran, D.S., and Trudel, R. 2012. Mate-finding Allee effect in spruce budworm population dynamics. Entomologia Experimentalis et Applicata 146: 112–122.

Remsoft. 2008. Spatial Woodstock 2008.12 user guide. Remsoft Inc., Fredericton, N.B.

Rosenthal, R. 2010. GAMS: a user's guide. GAMS Development Corporation, Washington, D.C.

Royama, T. 1984. Population dynamics of the spruce budworm *Choristoneura fumiferana*. Ecol. Monogr. 54(4): 429-462.

Royama, T. 1992. Analytical Population Dynamics. Chapman & Hall, London. Population and Community Biology Series 10.

Royama, T.O., MacKinnon, W.E., Kettela, E.G., Carter, N.E., and Hartling, L.K. 2005. Analysis of spruce budworm outbreak cycles in New Brunswick, Canada, since 1952. Ecology 86(5):1212-1224.

Sainte-Marie, G.B., Kneeshaw, D. D., MacLean, D. A., and Hennigar, C. R. 2014. Estimating forest vulnerability to the next spruce budworm outbreak: will past silvicultural efforts pay dividends? Canadian Journal of Forest Research 45(3): 314-324.

Sanders, C.J. 1988. Monitoring spruce budworm population density with sex pheromone traps. The Canadian Entomologist. 120:175-183.

Schoemaker, P.J.H. 1995. Scenario planning: a tool for strategic thinking. Sloan Management Review. 36(2): 25-40.

Slaney, G.L., Lantz, V., and MacLean, D.A. 2010. Assessing costs and benefits of pest management on forested landbases in eastern and western Canada. Journal of Forest Economics. 16(1): 19–34.

Spencer, C.E., and MacLean, D.A. 2012. Regeneration and stand development following a spruce budworm outbreak, spruce budworm inspired harvest, and salvage harvest. Canadian Journal of Forest Research 42(10): 1759-1770.

Statistics Canada. 2012. Canadian System of National Accounts (CSNA) 2012-Canada. Available at https://www.statcan.gc.ca/eng/nea/classification/io_ind/cat [accessed 05 August 2017].

Statistics Canada. 2014. Provincial input-output tables, inputs and outputs, summary level, basic price, annual (dollars), CANSIM (database). Available at http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=3810028&& pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid= [Accessed 18th August 2016].

Sterner, T.E., and Davidson, A.G. 1982. Forest insect and disease conditions in Canada 1981. Canadian Forest Service, Ottawa, Ont.

Ochuodho, T.O., and Lantz, V. 2014. Economic impacts of climate change in the forest sector: a comparison of single-region and multiregional CGE modeling frameworks. Canadian Journal of Forest Research 44(5): 449-464.

Van Kooten, G.C., and S. Wang. 1998. Estimating economic costs of nature protection: British Columbia’s forest regulations. Canadian Public Policy 24: 63-71.

Zhang, J., Alavalapati, J.R.R. Shrestha, R.K., and Hodges, A.W. 2005. Economic impacts of closing national forests for commercial timber production in Florida and Liberty County. Journal of Forest Economics 10:207-223.

APPENDIX

Table A1. CGE model variables.

Variables	Description
Production Block	
FAD_{if}	Factor input demand
FAS_{if}	Factor supply
VAD_i	Value-added input demand
IDE_i	Composite intermediate input demand
PVA_i	Value-added input price
PID_i	Intermediate input price
PF_f	Factor price
P_i	Price of composite commodities demand (input)
PD_i	Price of composite domestic production supply (output)
PDD_i	Price of domestic output delivered to home markets
X_i	Domestic sales of composite commodities
XD_i	Domestic production (output)
XDD_i	Domestic output delivered to home markets
Foreign Trade Block	
M_i	Composite import
E_i	Composite export
PM_i	Domestic import price
PE_i	Domestic export price
SAF	Foreign savings
ER	Exchange rate
OBJ	Dummy objective variable

Variables	Description
Household Block	
INC	Household total gross income
SAH	Household savings
CBUD	Household disposable income (budget) after saving
SBUD	Household discretionary (supernumerary budget)
CON_i	Household consumption demand of commodities
SAT	Household savings
INV_i	Household investment demand for commodities
Government Block	
KG	Government capital demand
LG	Government labor demand
CG_i	Public demand for commodities
SAG	Government savings
TAXR	Total tax revenues
TRMT	Total import tariff revenues
TRF	Total government transfer
TRO	Other government transfer
UNEMP	Unemployment level (Philips curve)
CPI	Consumer price index
tc_i	Tax rate on consumer commodities
tk_i	Tax rate on capital use
tl_i	Tax rate on labor use
ty_i	Tax rate on income

*Subscript i is a set that denote sectors of the economy (i.e., 1, 2, 3,…, 23); Subscript f is a set that denotes input factors (i.e., capital, labor, and stumpage).

Table A2. CGE model parameters

Parameters	**Description**
Elasticities of substitution	
σV_i	Substitution in the composite value-added function
σP_i	Substitution between the composite value-added input and the composite intermediate input
σA_i	Armington substitution between imports and domestic commodities
σT_i	CET substitution between domestic and export markets
σY_i	Income elasticities of demand for commodities
Share parameters	
γV_{if}	Share parameter in composite value-added input function
γp_i	Share parameter in total cost (production) function
γA_i	CES share parameter in Armington function
γT_i	CET share parameter in transformation function
Efficiency (shift) parameters	
ØV_i	Shift parameter in the composite value-added input function
ØP_i	Shift parameter in total cost (production) function
ØA_i	Shift parameter in Armington function
ØT_i	Shift parameter in transformation function
Other parameters	
αCG_i	Cobb-Douglas power of commodities bought by government
αKG	Cobb-Douglas power of capital use by government
αLG	Cobb-Douglas power of labor use by government
αI_i	Cobb-Douglas power share parameter for investment goods
trep	Replacement rate
IO_i	Technical coefficients of intermediate input
η	Philips curve parameter
Ψ_i	Budget shares in nested-LES household utility function
μH_i	Household subsistence consumption level
λ_i	Marginal propensity to save
Dynamic Growth Path	
GRW	Initial steady-state labor growth rate
RRR	Real rate of return on capital
$Time_t$	Time period into future from base year 2010
$GrowthTS_t$	Annual stumpage revenue growth rate

*Subscript i is a set that denote sectors of the economy (i.e., 1, 2, 3,…, 23); Subscript f is a set that denotes input factors (i.e., capital, labor, and stumpage); Subscript t is a set that denotes time period in years from base year 2010 (i.e., 1, 2, 3,…, 50).

Table A3. CGE model equations

Equation		**Description**
Production Block		
$FAD_{if} = [VAD_i\,(\gamma V_i)^{\sigma V_i}] / \{ØV_i(PF_f)^{\sigma V_i}[\sum_{f=1}^{3}(\gamma V_i)^{\sigma V_i}\,(PF_f)^{1-\sigma V}]^{\frac{\sigma V_i}{1-\sigma V_i}}\}$ where f denotes labor, capital for all sectors, and stumpage for forestry sector only.	Eq.(A.1)	Factor demand by firm
$VAD_i = \left(\frac{XD_i}{ØP_i}\right)\left(\frac{\gamma p_i}{PVA_i}\right)^{\sigma P_i}[\gamma p_i^{\sigma P_i} PVA_i^{1-\sigma P_i} + (1-\gamma p_i)^{\sigma P_i} PID_i^{1-\sigma P_i}]^{\frac{\sigma P_i}{1-\sigma P_i}}$	Eq.(A.2)	Value-added demand
$PID_i = \left(\frac{XD_i}{ØP_i}\right)\left(\frac{1-\gamma p_i}{PID_i}\right)^{\sigma P_i}[\gamma p_i^{\sigma P_i} PVA_i^{1-\sigma P_i} + (1-\gamma p_i)^{\sigma P_i} PID_i^{1-\sigma P_i}]^{\frac{\sigma P_i}{1-\sigma P_i}}$	Eq.(A.3)	Composite intermediate input
$PD_i XD_i = PVA_i VAD_i + PID_i IDE_i$	Eq.(A.4)	Zero profit condition for the firm
Household Block		
$INC = \sum_{f=1}^{3}(PF_f\,FAS_f) + TRF$	Eq.(A.5)	Household total gross income
$SAH = \lambda_i\,INC$	Eq.(A.6)	Household savings
$CBUD = INC - SAH$	Eq.(A.7)	Household disposable income after tax and savings
$SBUD = CBUD - \sum_{i=1}^{20} P_i\,\mu H_i$	Eq.(A.8)	Household discretionary budget
$(1+tc_i)P_i CON_i = (1+tc_i)P_i\,\mu H_i + \Psi_i[CBUD - \sum_{i=1}^{20}\mu H_i\,(1+tc_i)P_i]$	Eq.(A.9)	Household consumption demand of commodities
$SAT = SH + SG\,CPI + SF\,ER$	Eq.(A.10)	Household total savings
$P_i INV = \alpha I_i SAT$	Eq.(A.11)	Investment demand for commodities
$\left(\frac{\frac{PF_f}{CPI}}{\frac{PF_f^0}{CPI^0}} - 1\right) = \eta\left(\frac{\frac{UNEMP}{FAS_f}}{\frac{UNEMP^0}{FAS_f{}^0}} - 1\right)$ where subscript f denotes labor	Eq.(A.12)	Unemployment level (Philips curve)
$CPI = (\sum_{i-1}^{20} P_i\,CON_t)/(\sum_{i-1}^{20} P_i{}^0\,CON_t{}^0)$	Eq.(A.13)	Consumer price index
Government Block		
$P_i CG_i = \alpha CG_i(TAXR - TRF - SG * CPI)$	Eq.(A.14)	Government demand for commodities
$PF_f KG = \alpha KG(TAXR - TRF - SG * CPI)$ where f denotes capital	Eq.(A.15)	Government capital demand function
$PF_f LG = \alpha LG(TAXR - TRF - SG * CPI)$ where f denotes labor	Eq.(A.16)	Government labor demand function
$TAXR = ty_i INC + \sum_{i=1}^{20}(P_i\,tc_i CON_i + FAD_f tk_i PF_f + FAD_f tl_i PF_f + M_i tm_i PM_i ER)$	Eq.(A.17)	Total tax revenues
$TRF = trep\,PF_f * UNEMP + TROCPI$ where f denotes labor	Eq.(A.18)	Total transfers
$TRMT = \sum_{i=1}^{20} tm_i\,M_i PM_i ER$	Eq.(A.19)	Total tariff revenue

Table A3 (continued).

Equation		Description
Market Clearing Block		
$\sum_{i=1}^{20} FAD_{if} + KG = FAS_f - UNEMP$ where f denotes labor	Eq.(A.20)	Market clearing for labor
$\sum_{i=1}^{20} FAD_{if} + LG = FAS_f$ Where f denotes capital	Eq.(A.21)	Market clearing for capital
$FAD_{if} = FAS_f$ where f denotes stumpage and I denotes forestry and logging sector	Eq.(A.22)	Market clearing for stumpage
$X_i = CON_i + INV_i + CG_i + \sum_{i=1}^{20} IO_i XD_i$	Eq.(A.23)	Market clearing for commodities
$\sum_{i=1}^{20} M_i\, PM_i = \sum_{i=1}^{20} E_i\, PE_i + SAF$	Eq.(A.24)	Trade Balance of payments
Trade Block		
a) Export side		
$XDD_i = (XD_i/\emptyset \mathrm{T}_i)\left(\frac{1-\gamma \mathrm{T}_i}{PDD_i}\right)^{\sigma \mathrm{T}} [\gamma \mathrm{T}_i^{\sigma \mathrm{T}_i} PE_i^{1-\sigma \mathrm{T}_i} + (1-\gamma \mathrm{T}_i)^{\sigma \mathrm{T}_i} PDD_i^{1-\sigma \mathrm{T}_i}]^{\frac{\sigma \mathrm{T}_i}{1-\sigma \mathrm{T}_i}}$	Eq.(A.25)	Domestic supply of domestic output (supply side)
$E_i = (XD_i/\emptyset \mathrm{T}_i)\left(\frac{\gamma \mathrm{T}_i}{PE_i}\right)^{\sigma \mathrm{T}} [\gamma \mathrm{T}_i^{\sigma \mathrm{T}_i} PE_i^{1-\sigma \mathrm{T}_i} + (1-\gamma \mathrm{T}_i)^{\sigma \mathrm{T}_i} PDD_i^{1-\sigma \mathrm{T}_i}]^{\frac{\sigma \mathrm{T}_i}{1-\sigma \mathrm{T}_i}}$	Eq.(A.26)	Export demand for domestic output
$PD_i XD_i = PE_i E_i + PDD_i XDD_i$	Eq.(A.27)	CET zero profit condition (profit maximization)
b) Import side		
$XDD_i = (XD_i/\emptyset \mathrm{A}_i)\left(\frac{1-\gamma \mathrm{A}_i}{PDD_i}\right)^{\sigma \mathrm{A}} [\gamma \mathrm{A}_i^{\sigma \mathrm{A}_i} PM_i^{1-\sigma \mathrm{A}_i} + (1-\gamma \mathrm{A}_i)^{\sigma \mathrm{A}_i} PDD_i^{1-\sigma \mathrm{A}_i}]^{\frac{\sigma \mathrm{A}_i}{1-\sigma \mathrm{A}_i}}$	Eq.(A.28)	Domestic demand for domestically produced goods (demand side)
$M_i = (XD_i/\emptyset \mathrm{A}_i)\left(\frac{\gamma \mathrm{A}_i}{PM_i}\right)^{\sigma \mathrm{A}} [\gamma \mathrm{A}_i^{\sigma \mathrm{A}_i} PM_i^{1-\sigma \mathrm{A}_i} + (1-\gamma \mathrm{A}_i)^{\sigma \mathrm{A}_i} PDD_i^{1-\sigma \mathrm{A}_i}]^{\frac{\sigma \mathrm{A}_i}{1-\sigma \mathrm{A}_i}}$	Eq.(A.29)	Domestic demand for composite imported goods
$PD_i XD_i = PM_i M_i + PDD_i XDD_i$	Eq.(A.30)	Armington CES zero profit condition (cost minimization)
Macroeconomic Closures		
$\overline{FAS_f} = FAS_f^0$	Eq.(A.31)	Exogenously fix factor endowments
$\overline{SAF} = SAF^0$	Eq.(A.32)	Exogenously fix foreign savings
$\overline{SAG} = SAG^0$	Eq.(A.33)	Exogenously fix government savings
$\overline{TRO} = TRO^0$	Eq.(A.34)	Exogenously fix government other transfer
Artificial Objective Function		
$OBJ = 1$	Eq.(A.35)	Dummy objective variable

Table A3 (continued).

Equation		**Description**
Dynamic Growth Path		
$RRR = PF_f^0 FAS_f^0 (\frac{GRW}{SAT^0})$ where f denotes capital factor	Eq.(A.36)	Real rate of return on capital
$GRW_t = (SATRRR)/(PF_f FAS_f)$ where f denotes capital factor input	Eq.(A.37)	Growth path for each time period recursive loop run
$\overline{FAS_f} = (1 + GRW_t)FAS_f$ where f denotes capital factor input	Eq.(A.38)	Exogenously fixing capital growth path dynamic loop
$\overline{FAS_f} = (1 + GSW)FAS_f$ where f denotes labor factor input	Eq.(A.39)	Exogenously fixing labor growth path dynamic loop
$\overline{FAS_f} = (1 + GrowthTS){FAS_f}^0$ where f denotes stumpage in forestry and logging sector	Eq.(A.40)	Exogenously fixing stumpage growth path dynamic loop

*Subscript i is a set that denote sectors of the economy (i.e., 1, 2, 3,…, 23); Subscript f is a set that denotes input factors (i.e., capital, labor, and stumpage); Subscript t is a set that denotes time period in years from base year 2010 (i.e., 1, 2, 3,…, 50).

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Liu, E., Lantz, V.A.*, Hennigar, C.R., and MacLean, D.A. 2018. Economics of early intervention to suppress a potential spruce budworm outbreak in New Brunswick, Canada. Eastern CANUSA Forest Science Conference, October 18-20, Fredericton, New Brunswick, Canada.