ASSESSING THE LONG-TERM IMPACTS OF HIGH MOOSE DENSITIES ON GROS MORNE NATIONAL PARK

by

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ABSTRACT

Moose (*Alces alces*) browsing in Gros Morne National Park (GMNP) has caused substantial damage to its current balsam fir (*Abies balsamea*)-dominated forest. In this study estimates of stocking rates, stand yield and carbon stocks were generated from a regeneration-survey focused on sites suppressed by moose browsing. Scenario analysis (i) assessed moose browsing and domestic harvest impacts on forest regeneration and development; (ii) carbon storage within the forest ecosystem; and (iii) quantified effectiveness of forest restoration strategies, such as moose population control and reforestation. Regeneration survey indicates that high moose browsing has resulted in a significant portion of regenerating areas to fall within the “not sufficiently regenerated” category (NSR). Scenario analysis shows continued heavy moose browsing levels will lower growth and yield expectations within the park and slowly transition balsam fir-dominated stand types to spruce. Optimizing carbon stocks within the park can increase forest ecosystem carbon stocks over baseline levels in GMNP.

DEDICATION

To my wife Julie and daughter Anne

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1 General Introduction

1.1 Introduction

Gros Morne National Park (GMNP) is a World Heritage Site located on the west coast of Newfoundland. Situated on the Gulf of St. Lawrence at 1,805 km^2, it is the second largest national park in Atlantic Canada. Its 992 km^2 balsam fir-dominated forest plays a critical role in preserving local biodiversity, providing a wide range of habitats for plants and animals alike, but currently suffers significant moose (*Alces alces* L.) browsing damage. In a recent management plan, Gros Morne National Park (GMNP) identified the gradual decline in forest ecosystem as the single largest threat to ecosystem health within the park (Gros Morne National Park, 2009). This decline in forest ecosystems has been partially attributed to hyperabundant moose populations that have drastically reduced forest regeneration success within the park (Zhu et al., 2010; Parks Canada, 2016). Many studies on moose within GMNP have not produced an accurate measure of regeneration success; instead studies that try to quantify moose impacts on regeneration relied on estimates, expert opinions, and/or rates from outside the park boundaries, where moose densities are lower (Zhu et al., 2010; McLaren et al., 2009). To help park managers develop management strategies for slowing the gradual decline in forest health and restoring integrity to forest ecosystems, it is essential to quantify regeneration success rates and forest developmental patterns.

High moose densities are undeniably a factor impacting forest regeneration within GMNP, and understanding the dynamics that influence the amount of regeneration is critical to describing moose impacts on the GMNP forested ecosystem. Disturbances within the park are classified as either one of two categories, natural or man-made. Insect and wind have been identified as two major natural disturbances that impact the forests within GMNP (Meades and Moores, 1994; Engelmark, 1999). The GMNP forest has a long history of insect outbreak events with at least one major spruce budworm (*Choristoneura fumiferana*) or hemlock looper (*Lambdina fiscellaria*) outbreak occurring in each of the past four decades (McLaren et al., 2009). The GMNP forest inventory chronicles many reoccurring wind disturbance events ranging in size from a few hectares up to over 70 ha in size over the entire forest landscape. The agreement that first established GMNP in 1973 also established forest harvesting rights to the communities that border the park, which has allowed park residents (for two generations) to extract wood for personal use, such as for building homes and boats, and heating homes (McCarthy, 2000; Parks Canada, 2005). Small-scale domestic harvesting activity occurs within 12 designated cutting blocks and has created small isolated clear-cuts within domestic harvest blocks that have resulted in a mosaicked landscape of different forest successional pathways and favorable habitat for moose (Connor et al., 2000). Insect, wind and domestic harvesting disturbances have influenced the amount of the GMNP forested areas that enters a regenerative state that, in turn, is impacted by moose browsing. Understanding how each disturbance impacts forest development is critical to accessing long-term sustainability of the GMNP forest ecosystem.

National parks, like GMNP, is an integral part in Canada's plan for combating climate change by providing a healthy ecosystem that can act to capture and store carbon (Parks Canada, 2018). Recent increases in disturbances levels within Canada's forest has suggested that our national forested ecosystem has moved from sink to source of carbon (Metsaranta et al., 2010; Kurz et al., 2008). Active forest management can influence the state of carbon on the land base to increase carbon storage and offset disturbance impacts on carbon (Hennigar and Maclean, 2010; Lee et al., 2002). Given the history of natural and man-made disturbance patterns within GMNP, the impact of moose on forest regeneration concerns about the status of the carbon budget within GMNP have been raised.

By understanding and quantifying how moose is affecting forest regeneration and development within GMNP and integrating that knowledge within scenario modeling of moose browsing and domestic harvesting, this thesis advances the understanding of hyperabundant moose impact on the GMNP forest ecosystem. That information can then be used to determine the status of the carbon budget within GMNP and provide management scenarios to maintain or improve carbon storage within the park.

1.2 Objectives

1) Advance understanding of regeneration success following hyperabundant moose browsing in Gros Morne National Park by:

    a. developing GMNP-specific transitions from stocking rates for tree species within recently disturbed stands suppressed by moose browsing; and

    b. using temporary sample plot data (TSP) to develop GMNP-specific yield curves for each of the ecoregions within the park.

2) Using state-of-the-art forest-estate modeling and the latest regeneration stocking levels and forest inventory to explore impacts of moose browsing and domestic harvesting levels within GMNP, to assess:

    a. moose browsing and domestic harvest impacts on park-forest development through a range of disturbance levels; and
    b. forest restoration strategies by implementing programs of moose population control and reforestation.
3) Incorporating carbon yields into a forest-estate model to evaluate the changes in ecosystem carbon pools by evaluating:
    a. the impact on carbon due to the domestic harvesting program within GMNP; and
    b. the impact of heavy and light moose browsing on park carbon stores.

1.3 Thesis Structure

This thesis is presented in an article format following UNB graduate thesis guidelines. The body of the thesis contains three distinct papers (Chapters 2–4) with each successive chapter building on the results of the previous chapter, with a general discussion of results in Chapter 5. **Chapter 2** uses the results of a regeneration survey to develop forest transition rules that describe the impact of moose browsing and the resulting suppression on forest regeneration and used GMNP specific sample plot data to describe growth and yield patterns with the park boundaries. **Chapter 3** uses a forest-estate scenario modeling to explore impacts of moose browsing levels and domestic harvesting within GMNP. The model uses forest regeneration and growth and yield information created in Chapter 2. Scenario analysis is subsequently used to conduct model sensitivity analysis in describing the impacts of each moose browsing and domestic harvesting scenario to describe risk to the forested ecosystem. A sensitivity analysis is also performed on the use of planting as a tool to offset the impact of moose browsing and domestic harvesting, as an option to improve forest health. **Chapter 4** integrates carbon curves developed with the aid of the Carbon Budget Model of the Canadian Forest Service (CBM-CFS3) and the forest-estate model created in Chapter 3 to quantify impacts on carbon storage between high and low moose browsing and domestic harvesting levels within GMNP. It also presents an alternative forest management scenario for GMNP, with a focus on optimizing carbon storage within the park. **Chapter 5** summaries conclusions from Chapters 2–4 and suggests potential management strategies that may help GMNP managers improve forest ecosystem health within the park.

I am senior author on all manuscripts, and for his role in project inception, sampling design, and discussion, Dr. Xinbiao Zhu, Dr. Fan Rui Meng, and Dr. Charles Bourque are included as co-author on all manuscripts. The field study component in this Thesis is conducted in cooperation with GMNP field staff, summer students, and representatives from the Canadian Forest Service.

1.4 References

Connor, K. J., Ballard, W. B., Dilworth, T., Mahoney, S., and Anions, D. (2000). Changes in structure of a boreal forest community following intense herbivory by moose. Alces, 36: 111–132.

Engelmark, O. (1999). Boreal forest disturbances. In L. Walker, Ecosystems of the World, vol. 16. Ecosystems of Disturbed Ground (pp. 161–186). Amsterdam, The Netherlands: Elsevier Science.

Gros Morne National Park. (2009). Gros Morne National Park of Canada Management Plan. Rocky Harbour, NL: Library and Archives Canada Cataloguing in Publication.

Hennigar, C. R., and MacLean, D. A. (2010). Spruce budworm and management effects on forest and wood product carbon for an intensively managed forest. Canadian Journal of Forest Research, 40(9), 1736–1750.

Kurz, W. A., Stinson, G., Rampley, G. J., Dymond, C. C., and Neilson, E. T. (2008). Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. Proceedings of the National Academy of Sciences, 105(5), 1551–1555.

Lee, J., Morrison, I. K., Leblanc, J. D., Dumas, M. T., and Cameron, D. A. (2002). Carbon sequestration in trees and regrowth vegetation as affected by clearcut and partial cut harvesting in a second-growth boreal mixedwood. Forest Ecology and Management, 169(1–2), 83–101.

McLaren, B. E., Roberts, B. A., Djan-Chekar, N., and Lewis, K. P. (2004). Effects of overabundant moose on Newfoundland landscape. Alces, 40:45–59.

McLaren, M. E., Taylor, S., and Luke, S. H. (2009). How moose select forested habitat in Gros Morne National Park. Alces, 45: 125–135.

Meades, W., and Moores, L. (1994). Forest site classification manual: a field guide to the Damman forest types of Newfoundland. Second edition. Western Newfoundland Model Forest, Inc; Department of Forestry and Agriculture; Natural Resources Canada Canadian Forest Service, Forest Resources Development Agreement FRDA Rep. 003.

Metsaranta, J. M., Kurz, W. A., Neilson, E. T., and Stinson, G. (2010). Implications of future disturbance regimes on the carbon balance of Canada's managed forest (2010–2100). Tellus B: Chemical and Physical Meteorology, 62(5), 719–728.

Parks Canada. (2005). Park backgrounder: Gros Morne National Park of Canada. Retrieved from In Special places: Eco-lessons from the national parks in Atlantic Canada. Parks Canada: www.pc.gc.ca/apprendre-learn/prof/sub/eco/itm5/fi-lr1/gros-morne_e.asp

Parks Canada. (2016). Retrieved from National Parks: http://www.pc.gc.ca/eng/progs/np-pn/sf-fh/index.aspx

Parks Canada. (2018). Climate Change and protected areas. Retrieved from Parks Canada - Science and conservation: https://www.pc.gc.ca/en/nature/science/climat-climate

Zhu, X., Bourque, C. P., Taylor, S., Cox, R., and Wentzell, C. (2010). Predicting the effects of woodcutting and moose browsing on forest development in Gros Morne National Park, Newfoundland, Canada. The Forestry Chronicle, 86:178–192

2 Moose Browsing Impacts on Forest Regeneration and Yield Development within Gros Morne National Park

2.1 Abstract

Moose (*Alces alces*) browsing in Gros Morne National Park (GMNP), western Newfoundland, has caused substantial damage to its forests [mainly dominated by balsam fir (*Abies balsamea*)], which in advanced stage of damage has led to their ongoing conversion to grassland and shrub barrens. Scenario analysis of browsing impacts on forest development using a forest-estate model requires key information about forest regeneration and yield. This study aims to (1) measure stocking rates through intensive regeneration survey for tree species within recently disturbed stands, and (2) develop GMNP-specific yield curves using temporary sample plot data (TSP) from GMNP and the provincial permanent sample plots (PSPs) in the region. Regeneration surveys indicate that high moose browsing has resulted in a significant portion of regenerating areas to fall within the “not sufficiently regenerated” category (NSR). The amount of balsam fir within the park will decrease and slowly transition to spruce-dominated stands. High levels of moose browsing in GMNP has lowered growth and yield expectations relative to areas of lower moose browsing levels.

Keywords: balsam fir, browsing, moose population density, spruce, stocking, transition rules, growth and yield.

2.2 Introduction

The balsam fir-dominated forests of Gros Morne National Park (GMNP) currently suffers significant moose (*Alces alces L.*) browsing damage that has led to their ongoing conversion from healthy forests to grassland and shrub barrens (Gosse et al., 2011; Zhu et al., 2010). Gros Morne's unique dual mandate to manage the ecological assets of the park, while supporting domestic harvest programs within its boundaries has exacerbated the moose browsing situation. The domestic harvest program dates to the creation of the park and has permitted residents to extract wood fibre for personal use, such as providing building supplies and for heating homes (McCarthy 2000; Parks Canada, 2005). These small domestic cuts have created a pattern of small isolated clear-cuts that provide both food and shelter for moose and unintendedly promote moose population growth (Connor et al., 2000). Under such circumstances, maintaining and restoring ecological integrity in parks is a significant philosophical shift in park management for many park managers (Sy et al., 2009). Moose were first introduced to the island-portion of Newfoundland and Labrador in 1878, with a second release in 1904 (Pimlott 1953). Low predation rates within the province created an ideal situation for the moose population to successfully spread across the entire province, including GMNP by the late 1940's (Murie 1934; Pimlott 1953; Pimlott 1959; Caines and Deichmann 1989; McLaren et al., 2009; Furgeuson and Messier 1996). The termination of hunting within GMNP, coinciding with the park designation in 1974 and coupled with high forest-regeneration levels following regional outbreaks of defoliation (McCarthy and Weetman 2007), led to a rapid expansion of the moose population within the park during the 1980's and 1990's (Janes 1976; Taylor 1991). During that time, the moose population increased from 270 individuals in 1972, to well over 7,000 individuals in 1998, making it one of the highest moose densities anywhere (McLaren et al., 2004). This high moose population is believed to be at the habitat carrying capacity (Mawhinney and Mahoney 1994) and has over time severely impacted the parks ecosystem integrity and forest regeneration (Gosse et al., 2011; Zhu et al., 2010). More recently, moose population numbers have been declining (Thompson 2007), especially after implementing an annual hunting season in 2011, however these declines were realized mostly in the highlands of the park. Park official estimate that there are 3,000 individuals still present in the productive forest lowlands of the park. The moose population numbers still pose a significant challenge for GMNP managers in protecting forest-ecosystem functioning within the park.

Large herbivories have been shown to impact landscape-level processes, including changing the regeneration success of forested species (Mathisen et al., 2017). The impact can ultimately influence species abundance and direct species change at the landscape level (Milligan and Koricheva, 2013). Moose browsing has been shown to change forest species composition, successional pathways, and even influence ecosystem productivity (Jeffries et al., 1979; McNaughton 1979; Hobbs et al., 1991; Paster et al., 1997). In GMNP, moose have consumed nearly all their preferred browse species, including Canada yew (*Taxus canadensis* Marsh), mountain maple (*Acer spicatum* Lam.), mountain ash (*Sorbus Americana* Marsh), northern wild raisin (*Viburnum cassinoides* L.), and have recently progressed to target balsam fir [*Abies balsamea* (L.) Mill]; Connor et al., 2000; Humber et al., 2009). Repeated heavy browsing on balsam fir seedlings has greatly reduced balsam fir regeneration levels, leading to a proliferation of shrubs and herbs and suppression of balsam fir regeneration (Gosse et al., 2011). About 37–45% of balsam fir was expected to be replaced by low-density black spruce and grassland in the next century (Zhu et al., 2010). In Cape Breton Highlands National Park, managers have concluded that due to hyperabundance of moose, forested ecosystems will not recover without intervention by lowering moose densities and reforestation efforts (Smith et al., 2015).

Trees damaged by browsing can respond in several ways (Kalen 2006). Studies have shown that after browsing some tree species respond with increasing growth, but for most species the regrowth after browsing tend to be quite low especially in conifer species, like balsam fir (Persson et al., 2007). Increased moose densities and the resulting increase in browsing has been shown to negatively impact tree height growth (Bergeron et al., 2011). Within stands, tree heights can be quite variable under heavy browsing, with average heights lower that stands with light browsing, which can lead to an overall impact of decreasing biomass and yield estimates for the entire stand (Mathisen et al., 2017).

Growth and yield estimates have long been used as a tool in forest management to provide estimates of present and future values (like volume or basal area or tree count and age) over the development of a stand (Curtis 1972; Weiskittel et al., 2011). Abundant sample plot data enables empirical yield estimates to generate forest measure predictions well into the future (Yaussy 1999), and any use of growth and yields estimates used in forest management must account for any losses within forest stands (Curtis 1972). These empirical yield estimates are built on average stand stocking levels typically found when sampling forest stands in the field and can then be applied to any stand that has the same species and growing conditions (Weiskittel et al., 2011). The province of Newfoundland and Labrador generates empirical yield estimates using its network of permanent and temporary sample plot data (PSP and TSP, respectively) and regression analysis to generate growth and yield curves (Robert Sutton, DNR personal communication, 2016). However, forest stand observations made by GMNP staff suggest that the forests within the park are not producing volume growth at the same rate, or at the same level as stands with low moose browsing levels found on the adjacent, provincially-managed forest lands.

Gros Morne National Park managers have concerns that heavy moose browsing within the park will negatively impact balsam fir regeneration and restrict forest stand development and lead park managers to actively manage moose populations by implementing an annual moose hunting program. This concern is supported by many recent studies within the park (e.g., Connor et al., 2000; Humber et al., 2009), highlighting long-term planning in the park had relied on estimates of regeneration success and yield information that was not localized to GMNP forest ecosystems (Zhu et al., 2010). The aim of this study is to (1) measure stocking rates for tree species within recently disturbed stands, and (2) using TSP data to develop GMNP-specific yield curves for each of the ecoregions within the park. We expect that with improved regeneration stocking levels and stand yield information we can produce a more accurate representation of the GMNP forest ecosystem, enabling improved forest management planning.

2.3 Methods

2.3.1 Study Area

Gros Morne National Park (1,805 km²) is a UNESCO World Heritage Site, located on the western coast of Newfoundland and Labrador (49°41′22″N 57°44′17″W). Climate is controlled by prevailing southwesterly winds that blow onshore from the Gulf of St. Lawrence and result in cool summers (July mean of 15°C) and mild winters (mean of -7.5°C), with average rainfall of 1397 mm and snowfall of 328 cm (Humber et al, 2009; Zhu et al, 2010). Its land base is composed of three ecoregions (Northern, Western and Land Range Barrens) and stretches from coastal lowlands to high alpine plateaus, from which the park gets its name. The coastal lowlands are dominated by bogs and shrub forestland, while the alpine plateau is sparsely covered by forest heath and shrub barrens, with small forested areas in sheltered valleys. The productive stands are found to grow on the transitional slopes between the coastal plains and alpine plateau. Fifty-five percent of the park is covered by forest comprising of primarily balsam fir and white birch (*Betula papyrifera*), with lesser amounts of black spruce (*Picea mariana*), white spruce (*P. glauca*), yellow birch (*B. alleghaniensis*), red maple (*Acer rubrum*), trembling aspen (*Populus tremuloides*), white Pine (*Pinus strobus*), and eastern Larch (*Larix laricina*).

Fire, insects, wind, and fungi are major stand-replacing-disturbance vectors in the Boreal Forest. However, fire has a limited history in western Newfoundland due to its humid maritime climate (Meades and Moores 1994; Engelmark 1999). Recurring insect outbreaks have become the primary natural stand-replacing mechanisms in western

Newfoundland (Bergeron and Leduc, 1998; Bouchard et al., 2005), with insect outbreaks of spruce budworm (*Choristoneura fumiferana*) in 1977 and hemlock looper (*Lambdina fiscellaria*) in 1969, 1988, and 1996, affecting large forested areas in the region (McLaren et al., 2009). The GMNP forest inventory has shown disturbance patterns characterized by recurring small-scale disturbances punctuated by the occasional large and severe windstorm, with blowdown patches averaging 7.4 ha, and ranging up to 70.8 ha. The park is home to 700 species of flowering plants and 400 species of bryophytes, 239 species of birds, and 14 species of mammals (Government of Canada, 2010).

2.3.2 Forest regeneration survey for forest transition rules

A forest regeneration survey was first conducted within the park in 2005 on 46 randomly stratified disturbance sites evenly distributed between the Northern Peninsula and Western Newfoundland Ecoregions (23 sites per ecoregion) following the Newfoundland and Labrador Regeneration Assessment Procedures and Alberta Forest Disturbance Survey Protocol (DNR 1993; Alberta 2003; Fig. 2-1). Since that time, GMNP has implemented a moose hunting program. A remeasurement survey was made from June–August in 2016 on randomly selected 16 of 46 initial sites (Table 2-1). The resurvey occurred five years after the start of the yearly moose hunt within GMNP, with the intention of capturing the impacts of moose reduction caused by the hunting program.

For each regenerating area a disturbance type was assigned based on the initiation event and recorded as insect, wind, harvesting, or combination of two or more of these causes. The previous forest type was assigned using historical forest inventory information that included pre-disturbance seedlings and saplings counts. Circular plots (10 m^2) across the entire regenerating area was established at regular intervals along pre-defined survey lines on a 25×25, 40×40, or 60×60 m grid depending on the size of the area. The first plot of each site was established at 12.5 m from the disturbed area’s edge, with sample lines running parallel to the longest axis of the disturbance (Fig. 2-1).

In each sample plot location measures, adopted from the Alberta Regeneration Survey Manual (Alberta 2003), were collected that included species, health status, height class, and assigned non-stocking codes (Table 2-2). Each stem recorded in the plot was assigned a health status, desirable or undesirable, as defined based on the Newfoundland and Labrador Regeneration Assessment Procedures (DNR 1993). The plot is considered stocked if it contains at least one desirable seedling in it (Ritchie 2020) A desirable tree/seedling was defined as a native tree species, alive and in good health, undamaged, and have a well-defined stem with no more than two stems originating from its base. An undesirable tree/seedling was defined as a native tree species, alive, but possesses one or more undesirable characteristics, including galls, dwarf mistletoe, lean, chlorosis, poor vigour, browse damage, and/or multiple stems originating from its base (> 2). Height codes were assigned to each stem measured from 1 of 4 classes, class 1 (1–30 cm), class 2 (31–200 cm), class 3 (201–400 cm), or class 4 (> 401 cm). If browsing damage was observed, the height of damage on the stem was recorded, as well as an estimation of distance and direction of the nearest healthy tree that could serve as a suitable seed source to foster future forest growth. If a plot was encountered that contained no regeneration, a non-stocking code (DNR 1993) was assigned that ranged from 0–6, where: 0-No cause, suitable for regeneration, 1-Stockable road/trail, 2-Rock outcrop or soil barren, 3-Residual stand, 4-Wet patch, 5-Bog or scrub, and 6-Non-stockable road/trail.

2.3.3 Forest growth and yield curves

Yield curves were generated by applying the Newfoundland and Labrador Provincial Growth and Yield Tool (NLGY) on a combination of 605 TSPs of GMNP and nearby provincial PSPs and TSPs of similar forest communities (2,203 plots, in total), given the lower number of park TSPs for some forest communities. Provincial PSP data was selected from the same ecoregions encounter within the park and adjacent to park boundaries. The plot data used for yield projection were stratified by site class (i.e., good, medium, and poor), and species or species grouping (i.e., white birch dominant, mixedwood with softwood leading, mixedwood with hardwood leading, balsam fir dominant, and spruce dominant forest communities), and ecoregion (northern *vs.* western).

2.3.4 Data analysis

Using survey data, stocking levels were calculated for each plot and then summarized by forest community for each disturbed area for the two forested ecoregions within GMNP (e.g., the western and northern Peninsular ecoregions). When compiling regeneration survey data any stem that was classified as undesirable was excluding from stocking calculations even though some of these stems could potentially recover and reach maturity (Bergeron et al., 2011). Comparisons were first made between regeneration stocking data collected in both 2005 and more recent 2016 survey to assess impacts of moose hunting on regeneration within the park. We specifically compared stocking levels within each or the four recorded height classes, level of undesirable stems, and total stocking levels for each ecoregion. Comparisons were then made between the 2016 stocking levels and the provincial standard, exploring relative differences between the two assessments.

Using GMNP sample datasets, forest growth and yield information was generated and compared to existing provincial yield curves to assess the impacts of moose browsing on forest yields. Relative difference in total volume by site class and ecoregion was examined.

2.4 Results and Discussion

Total average stocking rate from the 2016 survey is 56% across all 16 plots and height classes, which is slightly lower than the 61% stocking rate found in the 2005 survey (Table 2-3). Stocking levels in the Northern ecoregion ranging from 20–61% in 2016, but in 2005 had a range of 44–75% across all areas. Stocking levels in the Western ecoregion ranged from 32–75% in 2016, slightly lower than the 56–78% range surveyed in 2005. The 2016 survey found a slight 3% decrease in the amount of desirable regeneration across all plots from the 37% level found in 2005 (Table 2-4). This decrease is associate with a 3% increase in the amount of undesirable regeneration over the same time period. Total tree density also slightly decreased from the 2005 to 2016 survey (12,860 *vs.*10,436 stems ha^{-1}; Table 2-5). We anticipated a slightly lower stocking rate in 2016, as a result of the ongoing moose browsing found within the park

(Gosse et al., 2009; Humber et al., 2009; Connor et al., 2000), since before the initial survey of 2005, until the moose hunt lowered their numbers.

Average stocking levels increased for the 31–200 cm height class from 26% in 2005 to 45% in 2016 (Table 2-3). Only small increases of 2% and 1% were observed in the 201–400 cm and 400+ cm height class, respectively, between the two surveys. The 0–30 cm height class was the only one that witnessed a decrease in stocking level. The 45% stocking level in the 31–200 cm height class in the 2016 survey was expected, given the stocking rate in 2005 for the 0–30 cm class was 46% and the time elapse between the two surveys had allowed the trees to grow. Knowing that heavy moose browsing tends to suppress tree height growth (Bergeron et al., 2011), our results suggest that the reduction in moose population gained through the park’s moose hunting program may have lessen moose browsing pressure and enabled smaller trees to grow. Unfortunately, since the survey was conducted five years after the moose hunt, this remains speculative and will only be confirmed with a future survey.

The transition roles generated from the 2016 regeneration surveys are shown in Table 2-6. There were 33% and 45% of the surveyed areas in the western and northern ecoregions fell into a category of “not sufficiently regenerated” (NSR) compared with 10% in the provincial forests outside of the park. Balsam fir and white birch stocking levels ranged from 21–28% and 24–26%, respectively, for both ecoregions, followed by black spruce and white spruce (7–13%), and lesser amounts of eastern larch and red maple (~1%).

Studies have shown high browsing pressures by moose negatively impacted forest regeneration and volume growth (McInnes et al., 1993; Kalen 2006). Modelled stocking level of balsam fir within the heavily browsed areas of GMNP is approximately a third of stocking levels observed under the light moose browsing scenario in areas adjacent to the park and represents nearly four times more total NSR-area. A previous study found that about 40–60% stocking level in a young stand is required for the stand to be fully stocked when mature (Bergeron et al., 2011). We found balsam fir stocking levels (25%) declined significantly when compared to provincial forests (60%), while spruce stocking levels increased (Table 2-6). This observed change is consistent with previous studies in Norway and Finland, which have shown tree species changes can arise at the landscape level because of acute herbivory by moose (Mathisen et al., 2017; Milligan and Koricheva 2013).

The results of the regression analysis used to generate yield curve using GMNP sample plot data can be found in Table 2-7. High variance of wood volume of sample plots within strata and site class lead to relatively high standard error and low r-squared values of these regressions, but they were consistent with the standard of the provincial yield curve generation (Robert Sutton, DNR personal communication, 2016). Yield curves generated from GMNP sample plot data were consistently lower in the same ecoregion classification and site, when compared to provincial yield curves where moose is actively managed (Fig. 2-3). This difference is highlighted when comparing the peak yield volume estimate on good sites between GMNP and provincial yield curves within the northern and western ecoregions (Table 2-8). This is in agreement with an another study in GMNP that concluded that lower volume estimates can be directly attributed to moose browsing, owing to the fact that other natural disturbances (e.g., insect outbreaks) are typically applied evenly in forests both inside and outside of the park in western Newfoundland (Meades and Moores, 1994). Studies that have found high browsing pressures by moose negatively impacted forest regeneration and volume growth (McInnes et al., 1993; Kalen 2006), is consistent with our own findings.

2.5 Concluding remarks

Our field survey has found that high moose browsing levels within GMNP has resulted in a significant portion of regenerating areas to fall within the not sufficiently regenerated (NSR) category. Although the amount of land area successfully regenerating is still high enough to develop into fully stocked stands, moose browsing dramatically alter the landscape through changes in species composition in GMNP. At the current state of moose browsing in the park, and without intervention to lower their densities, the amount of balsam fir will be drastically reduced and be replaced by spruce. Balsam fir-dominated stands will continue to be replaced even at lower regeneration rates and eventually the balsam fir and spruce-dominated stands will slowly transition to purely spruce-dominated stands. High levels of moose browsing in GMNP has lower growth and volume expectations when compared to areas outside the park that have moose population controls in place.

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2.7 References

Alberta Sustainable Resource Development, Forest Management Branch (2003). Alberta Regeneration Survey Manual. doi:10.5962/bhl.title.134795

Bergeron, Y., and Leduc, A. (1998). Relationships between change in fire frequency and mortality due to spruce budworm outbreaks in the southern Canadian boreal forest. Journal of Vegetation Science, 9(4), 492–500. doi:10.2307/3237264

Bergeron, D. H., Pekins, P. J., Jones, H. F., and Leak, W. B. (2011). Moose browsing and forest regeneration: a case study in northern New Hampshire. Alces, 47, 39–51.

Bouchard, M., Kneeshaw, D., and Bergeron, Y. (2005). Mortality and stand renewal patterns following the last spruce budworm outbreak in mixed forests of western Quebec. Forest Ecology and Management, 204(2–3), 297–313. doi:10.1016/j.foreco.2004.09.017

Caines, P., and Deichmann, H. (1989). Resource Description and Analysis; Gros Morne National Park. Rocky Harbour, NL: Environ. Canada, Unpublished Report.

Connor, K. J., Ballard, W. B., Dilworth, T., Mahoney, S., and Anions, D. (2000). Changes in structure of a boreal forest community following intense herbivory by moose. Alces, 111–132.

Curtis, R. O. (1972). Yield tables past and present. Journal of Forestry, 70(1), 28–32.

Department of Natural Resources. (1993). Newfoundland and Labrador Regeneration Assessment Procedures. Unpublished Report.

Engelmark, O. (1999). Boreal forest disturbances. In L. Walker, Ecosystems of the World, vol. 16. Ecosystems of Disturbed Ground (pp. 161–186). Amsterdam, The Netherlands: Elsevier Science.

Furgeuson, S. H., and Messier, F. (1996). Can human predation of moose cause population cycles? Alces, 32, 149–161.

Government of Canada. 2000. Canada National Parks Act. (C.32) No. 14-01. Ottawa.

Gosse, J., Hermanutz, L., McLaren, B., and Knight, T. (2011). Degradation of Boreal Forest by Non-native Herbivores in Newfoundland's National Parks: Recommendations for Ecosystem Restoration. Natural Areas Journal, 31(4),331–339. doi:10.3375/043.031.0403

Hobbs, N. T., Schimel, D. S., Owensby, C. E., and Ojima, D. S. (1991). Fire and grazing in the tallgrass prairie: contingent effects on nitrogen budget. Ecology, 72(4), 1374–1382. doi:10.2307/1941109

Humber, J. (2009). Non-native plant invasions of boreal forest gaps: implications for stand regeneration in a protected area shaped by hyperabundant herbivores. M.S. thesis, Department of Biology, Memorial University of Newfoundland, St. John’s.

Janes, G. (1976). Moose and Caribou census of Gros Morne Nat. Park. Rocky Harbour: Parks Canada.

Jeffries, R. L., Jensen, A., and Abraham, K. F. (1979). Vegetational development and the effect of geese on vegetation at La Perouse Bay, Manitoba, Canada. Canadian Journal of Botany, 57(13), 1439–1450. doi:10.1139/b79-178

Kalen, C. (2006). Deer Browsing and Impact on Forest Development. Journal of Sustainable Forestry, 53–64. doi:10.1300/j091v21n02_04

Mathisen, K.M., Milner, J.M., Skarpe, C. (2017). Moose-tree interactions: rebrowsing is common across tree species. BMC Ecology, 17(1) ,12. doi:10.1186/s12898-017-0122-3

Mawhinney, K., and Mahoney, S. P. (1994). Aerial moose census of management units 5, 6 and 7 in Western Newfoundland Model Forest, 1993 and 1994. Corner Brook, NL: Western Newfoundland Model Forest.

McCarthy, C. (2000). Gros Morne Domestic Timber Harvest Information Newsletter.

McCarthy, J.W. and Weetman. (2007). Stand structure and the development of an insect-mediated boreal forest landscape. Forest Ecology and Management. 241(1-p3), 101–114. doi:10.1016/j.foreco.2006.12.030

McInnes, P. F., Naiman, R. J., Pastor, J., and Cohen, Y. (1992). Effects of moose browsing on vegetation and litter of the boreal forest, Isle Royale, Michigan, USA. Ecology, 73(6), 2059–2075.

McLaren, B. E., Roberts, B. A., Djan-Chekar, N., and Lewis, K. P. (2004). Effects of overabundant moose on Newfoundland landscape. Alces, 40, 45–59.

McLaren, M. E., Taylor, S., and Luke, S. H. (2009). How moose select forested habitat in Gros Morne National Park. Alces, 45, 125–135.

McNaughton, S. J. (1979). Grassland-herbivore dynamics. In A. R. Sinclaire, and M. Norton-Griffins, Serengeti: dynamics of an ecosystem. (pp. 46–81). Chicago, Illinois: University of Chicago Press.

Meades, W., and Moores, L. (1994). Forest site classification manual: a field guide to the Damman forest types of Newfoundland. Second edition. Western

Newfoundland Model Forest, Inc; Department of Forestry and Agriculture; Natural Resources Canada Canadian Forest Service, Forest Resources Development Agreement FRDA Rep. 003.

Milligan, H.T and Koricheva, J. (2013). Effects of tree species richness and composition on moose winter browsing and foraging selectivity: an experimental study. Journal of Animal Ecology, 82(4), 739–748. doi:10.1111/1365-2656.12049

Murie, A. (1934). The moose of Isle Royale. Anne Arbor, Michigan: Museum of Zoology, University of Michigan, Miscellaneous Publications No. 25.

Parks Canada. (2005). Park backgrounder: Gros Morne National Park of Canada. Retrieved from In Special places: Eco-lessons from the national parks in Atlantic Canada. Parks Canada: www.pc.gc.ca/apprendre-learn/prof/sub/eco/itm5/fi-lr1/gros-morne_e.asp

Paster, J., Moen, R. A., and Cohen, Y. (1997). Spatial heterogeneities, carrying capacity, and feedbacks in animal landscape interactions. Journal of Mammalogy, 78(4), 1040–1052. doi:10.2307/1383047

Pimlott, D. H. (1953). Newfoundland Moose. Trans. N. A. Wild. Conf, 18: 563–581.

Pimlott, D. H. (1959). Reproduction and productivity of Newfoundland Moose. Journal of Wildlife Management, 23(4), 381–401. doi:10.2307/3796486

Smith, R., Smith, M., Clifford, P., and Bellemore, C. (2015). Hyperabundant Moose Management Plan for North Mountain, Cape Breton Highlands National Park. Ingonish Beach, NS: Parks Canada Agency.

Taylor, E. (1991). Gros Morne National Park Aerial Moose Survey. Rocky Harbour: Parks Canada.

Sy, K., Keenleyside, K., Adare, B., Reader, B., Deering, P. (2009). Protecting native biodiversity from high-impact invasive species through the protected areas of Parks Canada. Biodiversity, 10(2-3),51–55. doi:10.1080/14888386.2009.9712843

Thompson, R. (2007). Gros Morne National Park Aerial moose survey. Rocky Harbour, NL: Parks Canada.

Weiskittel, A. R., Hann, D. W., Kershaw Jr, J. A., and Vanclay, J. K. (2011). Forest growth and yield modeling. John Wiley and Sons.

Yaussy, D. A. (2000). Comparison of an empirical forest growth and yield simulator and a forest gap simulator using actual 30-year growth from two even-aged forests in Kentucky. Forest Ecology and Management, 126(3), 385–398.

Zhu, X., Bourque, C. P., Taylor, S., Cox, R., and Wentzell, C. (2010). Predicting the effects of woodcutting and moose browsing on forest development in Gros Morne National Park, Newfoundland, Canada. The Forestry Chronicle, 86(2), 178–192. doi:10.5558/tfc86178-2

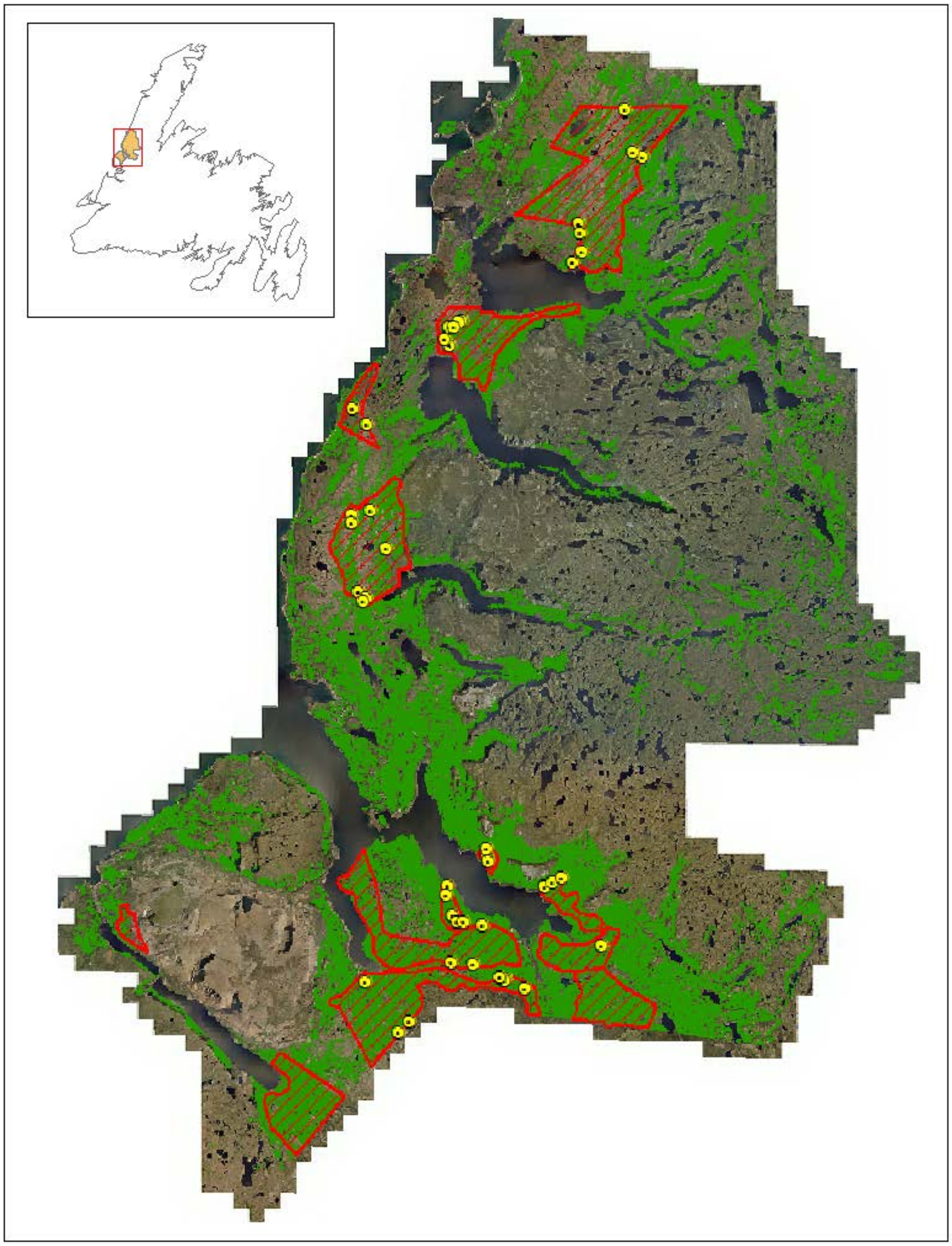


Figure 2-1. Locations of GMNP domestic harvest blocks (red), displaying their positions within the productive forest zone within the park. Regeneration-survey plots are displayed as yellow dots.

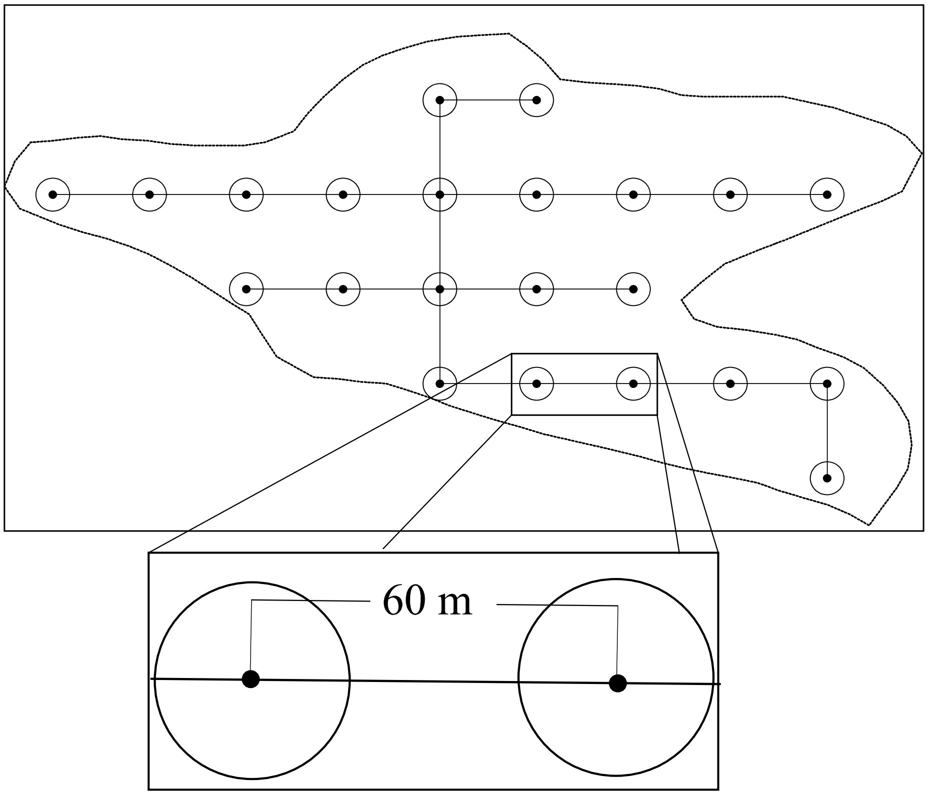
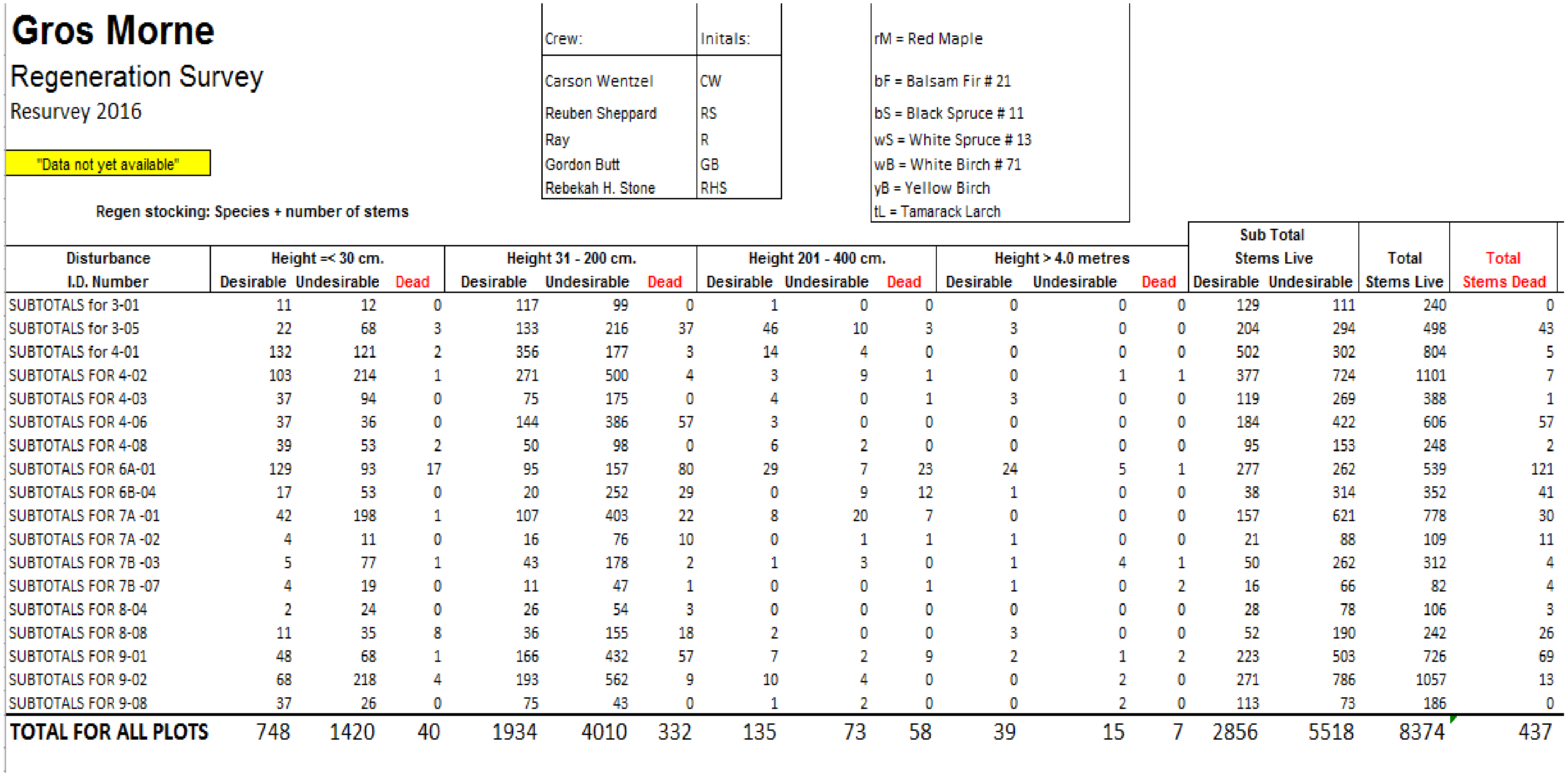


Figure 2-2. Sample disturbance areas displaying regeneration plots that were established for systematically sampling in the entire disturbed area.

Table 2-1 Sample plot measures in regeneration survey indicating the ecoregion it is found in, the disturbance type that created the regenerating area, approximate year of disturbance, age of the regenerating stands, the number of plots measured in each disturbed area and the total area of the regenerating area.

Plot	Grid size	Ecoregion	Disturbance Event	Disturbance year	No. of Sub Plots	Area (ha)
301	25 X 25	W	Cutting	1999	14	0.88
305	25 X 25	W	Cutting/Insect	2000	60	3.75
401	25 X 25	W	Cutting	1984	65	4.06
402	25 X 25	W	Wind/Cutting	1994	96	6
403	25 X 25	W	Insect	1987	56	3.5
406	40 X 40	W	Insect	1996	25	4
408	40 X 40	W	Insect	1987	34	5.44
6a01	25 X 25	W	Cutting	1987	50	3.13
6b04	60 X 60	W	Cutting/Insect	1987	46	16.56
7a01	25 X 25	N	Cutting	1995	62	3.88
7a02	25 X 25	N	Cutting/Insect	1987	112	7
7b03	60 X 60	N	Insect	1987	32	11.52
7b07	60 X 60	N	Insect	1987	14	5.04
804	40 X 40	N	Insect	1991	13	2.08
901	25 X 25	N	Cutting/Insect	1977	91	5.69
902	25 X 25	N	Insect	1977	74	4.63

Table 2-2 Sample plot measures in regeneration survey capturing species, stem condition, height class and count of dead stems.



Gros Morne

Regeneration Survey

Resurvey 2016

"Data not yet available"

Crew:	Initals:
Carson Wentzel	CW
Reuben Sheppard	RS
Ray	R
Gordon Butt	GB
Rebekah H. Stone	RHS

rM = Red Maple

bF = Balsam Fir # 21

bS = Black Spruce # 11

wS = White Spruce # 13

wB = White Birch # 71

yB = Yellow Birch

tL = Tamarack Larch

Regen stocking: Species + number of stems

Disturbance I.D. Number	Height =< 30 cm.			Height 31 - 200 cm.			Height 201 - 400 cm.			Height > 4.0 metres			Sub Total Stems Live		Total	Total
	Desirable	Undesirable	Dead	Desirable	Undesirable	Dead	Desirable	Undesirable	Dead	Desirable	Undesirable	Dead	Desirable	Undesirable	Stems Live	Stems Dead
SUBTOTALS for 3-01	11	12	0	117	99	0	1	0	0	0	0	0	129	111	240	0
SUBTOTALS for 3-05	22	68	3	133	216	37	46	10	3	3	0	0	204	294	498	43
SUBTOTALS for 4-01	132	121	2	356	177	3	14	4	0	0	0	0	502	302	804	5
SUBTOTALS FOR 4-02	103	214	1	271	500	4	3	9	1	0	1	1	377	724	1101	7
SUBTOTALS FOR 4-03	37	94	0	75	175	0	4	0	1	3	0	0	119	269	388	1
SUBTOTALS FOR 4-06	37	36	0	144	386	57	3	0	0	0	0	0	184	422	606	57
SUBTOTALS FOR 4-08	39	53	2	50	98	0	6	2	0	0	0	0	95	153	248	2
SUBTOTALS FOR 6A-01	129	93	17	95	157	80	29	7	23	24	5	1	277	262	539	121
SUBTOTALS FOR 6B-04	17	53	0	20	252	29	0	9	12	1	0	0	38	314	352	41
SUBTOTALS FOR 7A -01	42	198	1	107	403	22	8	20	7	0	0	0	157	621	778	30
SUBTOTALS FOR 7A -02	4	11	0	16	76	10	0	1	1	1	0	0	21	88	109	11
SUBTOTALS FOR 7B -03	5	77	1	43	178	2	1	3	0	1	4	1	50	262	312	4
SUBTOTALS FOR 7B -07	4	19	0	11	47	1	0	0	1	1	0	2	16	66	82	4
SUBTOTALS FOR 8-04	2	24	0	26	54	3	0	0	0	0	0	0	28	78	106	3
SUBTOTALS FOR 8-08	11	35	8	36	155	18	2	0	0	3	0	0	52	190	242	26
SUBTOTALS FOR 9-01	48	68	1	166	432	57	7	2	9	2	1	2	223	503	726	69
SUBTOTALS FOR 9-02	68	218	4	193	562	9	10	4	0	0	2	0	271	786	1057	13
SUBTOTALS FOR 9-08	37	26	0	75	43	0	1	2	0	0	2	0	113	73	186	0
TOTAL FOR ALL PLOTS	748	1420	40	1934	4010	332	135	73	58	39	15	7	2856	5518	8374	437

Table 2-3 Average stocking levels of commercially desirable (balsam fir, black spruce, white spruce, white birch, yellow birch, eastern larch, red maple) seedlings in height classes < 30 cm, 31–200 cm, 201–400 cm, and > 400 cm.

		< 30 cm		31 – 200 cm		201 – 400 cm		> 4.0 m		Total Stocking	
Plot	Ecoregion	2005	2016	2005	2016	2005	2016	2005	2016	2005	2016
3-01		67%	27%	3%	52%	0%	3%	0%	0%	61%	58%
3-05	W	50%	17%	31%	52%	3%	6%	3%	2%	63%	60%
4-01	W	50%	41%	31%	64%	6%	8%	4%	0%	67%	75%
4-02	W	59%	29%	14%	54%	1%	1%	0%	0%	63%	63%
4-03	W	37%	21%	24%	46%	3%	3%	0%	2%	56%	59%
4-06	W	58%	33%	27%	59%	7%	6%	2%	0%	78%	70%
4-08	W	41%	34%	34%	49%	0%	3%	0%	0%	59%	68%
6A-01	W	50%	48%	30%	39%	13%	16%	2%	17%	70%	75%
6B-04	W	36%	12%	46%	25%	0%	2%	3%	2%	64%	32%
7A-01	N	59%	19%	12%	35%	0%	3%	0%	0%	66%	46%
7A-02	N	26%	4%	7%	17%	0%	0%	0%	1%	44%	20%
7B-03	N	43%	7%	41%	38%	0%	2%	0%	2%	62%	42%
7B-07	N	35%	13%	26%	30%	0%	0%	0%	4%	45%	43%
8-04	N	58%	5%	33%	65%	0%	0%	0%	0%	75%	60%
9-01	N	28%	16%	22%	48%	2%	5%	1%	1%	50%	59%
9-02	N	38%	19%	34%	49%	2%	7%	1%	0%	57%	61%
Total		46%	22%	26%	45%	2%	4%	1%	2%	61%	56%

Table 2-4 Comparison between the 2005 and 2016 regeneration surveys displaying stocking level comparisons for desirable and undesirable seedlings in the northern and western ecoregion for all native tree species found within GMNP.

Species (Region)	2005		2016	
	Desirable	Undesirable	Desirable	Undesirable
bF(North)	16%	45%	15%	39%
bP(North)	2%	0%	4%	1%
rM(North)	0%	0%	0%	0%
tL(North)	1%	0%	0%	0%
wB(North)	16%	18%	6%	32%
wS(North)	1%	0%	1%	0%
bF(West)	22%	49%	26%	36%
bP(West)	1%	0%	3%	2%
rM(West)	0%	0%	0%	0%
tL(West)	0%	0%	0%	0%
wB(West)	11%	13%	8%	22%
wS(West)	2%	0%	1%	0%
Total	37%	63%	34%	66%

bF = balsam fir; bS = black spruce; rM = red maple; tL = eastern Larch; wB = white birch; wS = white spruce

Table 2-5 Stem density comparison between the 2005 and 2016 regeneration surveys.

Plot	2005 (Stems ha^{-1})	2016 (Stems ha^{-1})
301	13857	17143
305	9683	8300
401	15031	12369
402	13521	11469
403	6482	6929
406	22520	24240
408	5324	7294
6a01	21240	10780
6b04	11043	7652
7a01	19758	12548
7a02	4563	2232
7b03	11625	9750
7b07	5786	5857
804	21923	8154
901	10912	7978
902	12486	14284
Total	12860	10436

Table 2-6 GMNP-specific transition rules derived from 2005 and 2016 regeneration-survey data, displaying the percentage of species expected to regenerate following stand succession in a heavy browsing. The provincial transition rules due to the long-term moose population control in the provincial forest were used by the light moose browsing scenario which is assumed to be achieved by GMNP through its recently launched moose population control program.

Source	Ecoregions	Regenerating Species (%)
GMNP	Northern	bF(21), bS(3), tL(1), wB(26), wS(4), NSR(45)
	Western	bF(28), bS(3),rM(1), wB(24), wS(10), NSR(33)
Province	Both	bF(60), bFsP(10), MSW(15), MHW(3), wB(2), NSR(10)

Table 2-7 The model formula results from a regression analysis conducted to generate curves from GMNP sample temporary sample plot data using the Newfoundland and Labrador Provincial Growth and Yield Tool yield.

Strata	Model Formula	B1	B2	B3	B4	B5	B6	B7	B8	B9	R²	Std Error
wB	Y = (B1) * (X1 - B0)^B2 * EXP(B3 * (X1 - B0))[1]	20	0.16	1.99	-0.03	--	--	--	--	--	0.12	50.02
MHW	Y = (B1 +B4*X2) * (X1 - B0)^B2 * EXP(B3 * (X1 - B0))[2]	20	1.26	1.37	-0.02	0.37	--	--	--	--	0.12	72.76
MSW	Y = (B1) * (X1 - B0)^B2 * EXP(B3 * (X1 - B0))[3]	20	4.23	1.05	-0.01	--	--	--	--	--	0.12	49.11
bF	Y = (B1 + B4 * X2 + B5 * X3 + B6 * X4 + B7 * X5 + B8 * X6 + B9 *X7) * (X1 - B0)^B2 * EXP(B3 * (X1 - B0))[4]	20	0.91	1.76	-0.03	-0.02	0.08	-0.23	-0.40	-0.03	0.33	61.46
bFsP	Y = (B1 + B4* X2 + B5 * X3 + B6 * X4 + B7 *X5) * (X1 - B0)^B2 * EXP(B3 * (X1 - B0))[5]	20	6.91	1.05	-0.01	-0.71	-0.53	-2.22	-3.52	--	0.31	54.74
sP	Y = (B1 + B4 * X2 + B5 * X3 + B6 * X4) * (X1 - B0)^B2 * EXP(B3 * (X1 - B0))[6]	20	4.26	1.05	-0.01	-0.12	0.28	-1.70	--	--	0.22	43.96

[1] *Y=t_mervol,X1=plot age*

[2] *Y=s_mervol,X1=plot age,X2=dm_er1*

[3] *Where: Y=t_mervol,X1=plot age*

[4] *Where: Y=t_mervol,X1=plotage,X2=dm_er1,X3=dm_er2,X4=dm_sc1,X5=dm_sc2,X6=dm_cc1,X7=dm_cc2*

[5] *Where: Y=t_mervol,X1=plotage,X2=dm_er1,X3=dm_er2,X4=dm_sc1,X5=dm_sc2*

[6] *Where: Y=h_mervol,X1=plotage,X2=dm_er1,X3=dm_er2,X4=dm_sc1*

Table 2-8 Peak yield volume comparisons on Good Sites between GMNP and Provincial yield curves within the Norther and Western ecoregions

Species (Region)	Peak Volume (m^3 ha^{-1})	
	GMNP	Province
wB (North and West)	124.98	142.59
MSW (North and West)	165.36	207.47
MHW (North and West)	148.2	190.98
bF (West)	204.39	213.67
bF (North)	185.35	207.46
bFsP (West)	166.53	165.67
bFsP (North)	109.73	138.16
sP (West)	127.6	165.54

bF = balsam fir; sP = Spruce; bFsP = fir spruce; wB = white birch; MSW = mixedwood with softwood leading; MHW = mixedwood with hardwood leading;

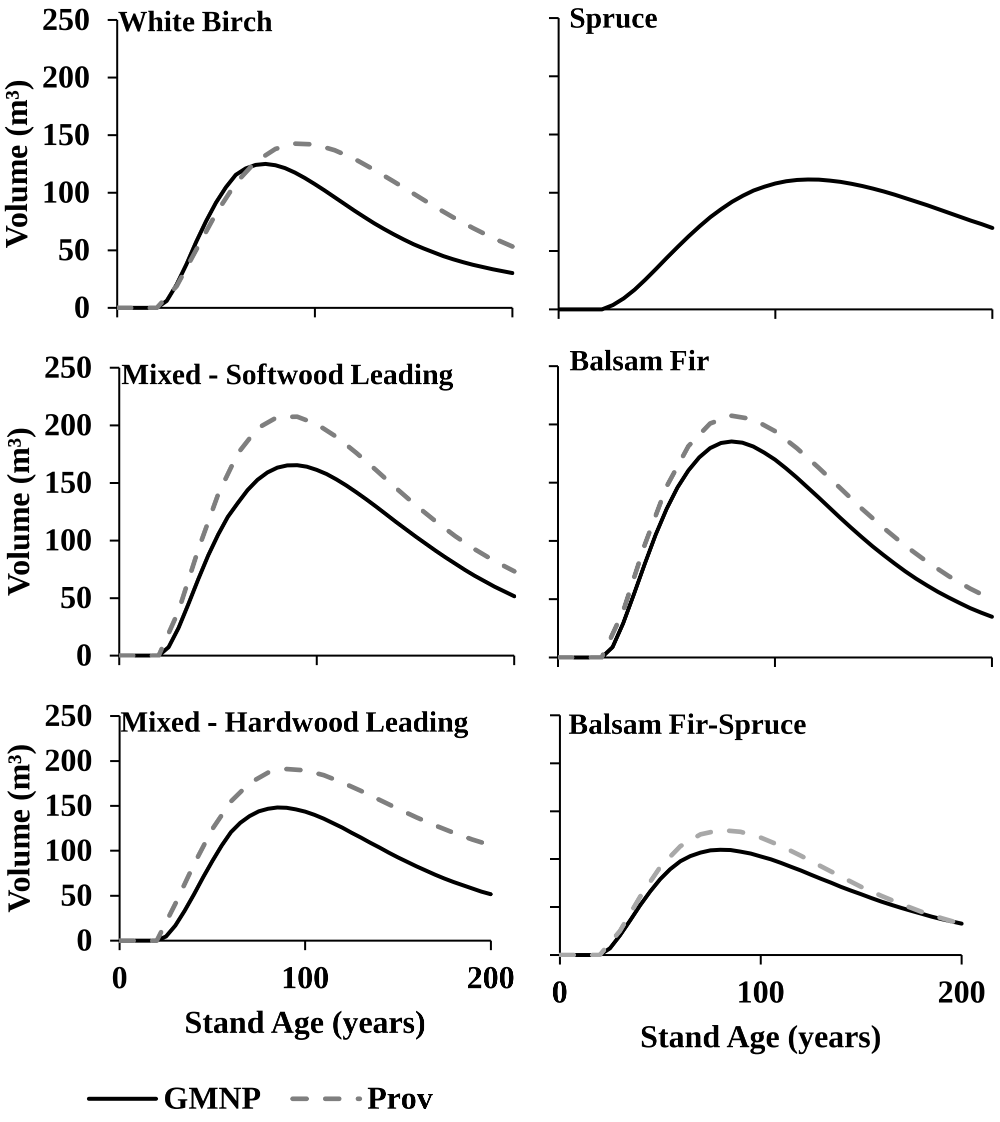


Figure 2-3. Comparison of strata-based GMNP yield curves on good sites vs. existing provincial yield curves on good sites. GMNP-based yield curves were generated from a combination of GMNP TSP and Provincial PSP and TSP data for ecoregions overlapping with park boundaries

3 Intensive Moose Browsing and Small-Scale Domestic Woodcutting Impacts on Forest Successional Trajectories in Gros Morne National Park, Canada

Submitted to Forestry Chronicle for publication

3.1 Abstract

Moose (*Alces alces*) browsing in Gros Morne National Park (GMNP), western Newfoundland, has caused substantial damage to its current balsam fir (*Abies balsamea*)-dominated forest, which has led portions to convert to grassland and shrub barrens. In a similar study that investigated moose browsing impacts on forest dynamics in the park, model inputs of regeneration rates and forest growth were derived entirely from expert judgement and provincial standards. Here, the estimates of stocking rates and stand yield curves were generated directly from regeneration-survey and plot data in stands disturbed and subsequently suppressed by moose browsing. Scenario analysis focus here on: (i) assessing moose browsing and domestic harvest impacts on forest regeneration and development; and (ii) quantifying effectiveness of forest restoration strategies, such as moose population control and reforestation. Results indicated that under heavy moose browsing scenarios, total growing stock of balsam fir will be reduced by 38%, compared with 1% under light browsing. The geographic extent of spruce forests (*Picea mariana* and *P. glauca*) increased by 32% under the heavy moose browsing scenario, relative to that realized by light browsing. Collectively, annual allowable cut (AAC) in the park's 12 domestic timber harvest blocks, representing 19,400 ha of productive forests , across a 100-year planning horizon remained at 120,979 m^3 in the lightly browsed areas, about 21% higher than the AAC estimated for heavily browsed areas. These results suggest that the extent of moose browsing has significant impact on forest productivity throughout the park. Planting in heavily browsed areas would reforest 97% of 7,194 ha of disturbed area, or account for about a 22% increase in total growing stock and increase sustainable harvest levels from 95,351

to 122,194 m^3 in the heavily browsed areas. Tree planting could provide an important first step in the successful restoration of forest health in GMNP.

3.2 Introduction

Gros Morne National Park (GMNP) is located on the western coast of the island of Newfoundland. Its 992 km^2 balsam fir-dominated forest plays a critical role in preserving local biodiversity, providing a wide range of habitats for plants and animals alike, but currently suffers significant moose (*Alces alces* L.) browsing damage. Gros Morne National Park is a unique national park with to manage the ecological assets of the park, while supporting domestic harvest programs for residents within the park boundaries. The domestic timber harvest program was developed based on the 1973 park establishment agreement, which has allowed park residents (for two generations) to extract wood for personal use, such as for building homes and boats, and heating homes (McCarthy, 2000; Parks Canada, 2005). Small-scale domestic harvesting activity occurs within 12 designated cutting blocks and has created small isolated clear-cuts within domestic harvest blocks that have resulted in a mosaicked landscape of different forest successional pathways and favourable habitat for moose. The mosaic of forests throughout the park provides moose food and shelter, and perhaps unintentionally promotes the unconstrained growth of the area’s moose population (Connor et al., 2000). Under such circumstances, maintaining and restoring ecological integrity within the context of heavy moose browsing levels in parks is a significant philosophical shift in park management for many park managers (Sy et al., 2009).

Moose were first introduced to the island-portion of Newfoundland and Labrador in 1878, and again in 1904 (Pimlott, 1953). Since then, the moose population has swollen to cover the entire island-portion of the province, including Gros Morne and the northern Peninsula by the late 1940's (Caines and Deichmann, 1989). Moose populations have been shown to increase rapidly, especially in the absence of hunting and limited natural predation (Murie, 1934; Pimlott, 1953). The extinction of the Newfoundland wolf (*Canis lupus*) in the early part of the 20th century (Pimlott, 1959; Furgeuson and Messier, 1996) and reductions in black bear (*Ursus americana*) populations created a situation in GMNP, where moose population growth was practically unconstrained from predation (McLaren et al., 2009). Low predation rates and termination of hunting in 1974, together with high forest-regeneration levels following regional outbreaks of spruce budworm defoliation (McCarthy and Weetman, 2007), led to a rapid expansion of the moose population during the 1980’s and 1990's (Janes, 1976; Taylor, 1991). The moose population increased from approximately 270 individuals in 1971, to well over 7,000 individuals in 1998, making it one of the highest moose densities anywhere (McLaren et al., 2004). This hyperabundant population was believed at the time to have reached the park’s maximum habitat carrying capacity (Mawhinney and Mahoney, 1994). In general, the increase of browsing damage by moose in the past several decades has severely affected park ecosystem integrity and forest regeneration (Gosse et al., 2011; Zhu et al., 2010). Moose populations began to slowly decline in the early 2000s, particularly in the park highlands (Thompson, 2007) but intense browsing continued to limit forest regeneration. Park managers implemented an annual hunt, beginning in 2011, to reduce the population to more sustainable levels. As of 2019, there are approximately 2,160 individuals mostly in the lowland, productive forests of the park. Maintaining moose population numbers remain a significant challenge for GMNP managers in their mission to safeguard forest ecosystem functioning and services throughout the park.

Moose browsing can alter species composition of forest communities, successional pathways, nutrient cycling, and ecosystem productivity (Jeffries et al., 1979; McNaughton, 1979; Hobbs et al., 1991; Paster et al., 1997). Large herbivores have been shown to change landscape-level processes by altering the regeneration success of forested species (Mathisen et al., 2017), which, in turn, can alter species abundance and steer species changes at the landscape level (Milligan and Koricheva, 2013). In GMNP, moose have consumed nearly all their preferred browse species, including Canada yew (*Taxus canadensis* Marsh), mountain maple (*Acer spicatum* Lam.), mountain ash (*Sorbus Americana* Marsh), northern wild raisin (*Viburnum cassinoides* L.), and have progressed to target balsam fir [*Abies balsamea* (L.) Mill; Connor et al., 2000; Humber et al., 2009]. Repeated heavy browsing on balsam fir seedlings has greatly reduced balsam fir regeneration levels, leading to a proliferation of non-palatable shrubs and herbs and a subsequent increase in balsam fir regeneration suppression (Gosse et al., 2011). Without intervention, about 37–45% of balsam fir is expected to be replaced by low-density black spruce and grasses in the next century (Zhu et al., 2010). At high browsing levels, where the density of balsam fir in the understorey are low and seed sources have been severely degraded, supplemental planting is seen as the only option to restore natural forest ecosystems (Gosse et al., 2011). In Cape Breton Highlands National Park, managers have concluded that due to hyperabundance of moose, forested ecosystems will not recover without intervention to lower moose population densities and implement reforestation efforts (Smith et al., 2015). Trees damaged by browsing can respond in several ways (Kalen, 2006). Increased moose densities and the resulting increase in browsing has been shown to negatively impact tree height growth (Bergeron et al., 2011). Within stands, tree heights can be quite variable under heavy browsing, with an overall impact of decreasing biomass in affected stands (Mathisen et al., 2017). Forests within the park are currently not producing volume growth at the same rate or at the same level as stands with low moose-browsing levels. This observation was communicated to be an important limitation of a prior study by Zhu et al. (2010).

Developing appropriate management strategies for forests, like those in GMNP, requires accurate prediction of periodic variations in forest age-class distribution, species composition, and stocking levels over the long term. Forest models have the benefit of being able to generate multiple realistic, and even hypothetical, scenarios to allow comparison between different management strategies (Pretzch, 2008). Due to complexities in forest-ecosystem responses to variable moose browsing, simply performing an analysis on existing datasets may not lead to a decisive resolution of the problem. Linear programming (LP) techniques in forest modeling have been widely used to simulate forest-development responses to activities that may have an impact on forest development, allowing managers to assess consequences of different management strategies in land-use planning (Gustafson and Crow, 1996; Cieszewski et al., 2004).

Forest management models require accurate representations of forest ecosystems by first describing the forest of interest, often by stratifying the forest by forest community type and age class (Remsoft, 2016). The forest model describes how the forest develops over time based on different indicators, such as merchantable volume, carbon, and stock and habitat suitability for wildlife (Gustafson and Crow, 1996; Vanclay, 2002; Tomppo et al., 2008; Shifley, 2017).

The accuracy of forest management models is governed by the accuracy of inputs being used to describe and predict the forest dynamics in response to different management prescriptions (Shifley et al., 2017). In previous studies, yield curves and forest transition rules were developed based on data from adjacent provincial forests due to lack of forest inventory survey and sampling plots within the park (Zhu et al., 2010). In provincial forests, moose browse was much less intense compared with the national park due to hunting regulations and available silvicultural treatments to enhance regeneration levels on disturbed sites (Robert Sutton, DNR personal communication, 2016). Researchers were aware of the problem that provincial yield curves and transition rules could possibly diminish credible accounting of impact of heavy moose browsing on forest regeneration success within the national park. In the past few years, intensive field sampling surveys were conducted in order to create GMNP-specific yield curves and transition rules. Based on the implementation of a state-of-the-art forest-estate model, the objective of this study was to conduct a scenario analysis using the latest forest inventory and field survey data to assess (i) moose browsing and domestic harvest impacts on park-forest development, and (ii) forest restoration strategies by implementing programs of moose population control and reforestation.

3.3 Methods

3.3.1 Study Area

Gros Morne National Park (1,805 km²) is a UNESCO World Heritage Site, located on the western coast of the island of Newfoundland (49°41′22″N 57°44′17″W). The park provides a wide range of habitats for over 700 species of flowering plants and 400 species of bryophytes, 239 species of birds, and 14 species of mammals (Government of Canada, 2010). The land base stretches from coastal lowland dominated by bogs and shrub forestland to the alpine plateau, sparsely covered by forest heath and shrub barrens, with small forest patches in sheltered valleys. Productive forest stands are found on the transitional slopes between the coastal plains and alpine plateau and represents 55% of the park's land base. The forest is comprised of primarily balsam fir and white birch (*Betula papyrifera*), with lesser amounts of black spruce (*Picea mariana*), white spruce (*P. glauca*), yellow birch (*B. alleghaniensis*), red maple (*Acer rubrum*), trembling aspen (*Populus tremuloides*), white pine (*Pinus strobus*), and eastern larch (*Larix laricina*). Regional climate is controlled by prevailing southwesterly winds that blow onshore from the Gulf of St. Lawrence resulting in cool summers (July mean temperature of 15°C) and mild winters (-7.5°C), with 1,200–1,450 mm of rain (Humber et al., 2009) and 328 cm of snow (Zhu et al., 2010).

Fire has a limited control on forest development in western Newfoundland, due to the region's humid maritime climate (Meades and Moores, 1994; Engelmark, 1999). Recurring insect outbreaks have been the primary natural stand-replacing mechanism in this region. For example, a spruce budworm (*Choristoneura fumiferana*) outbreak in 1977 and hemlock looper (*Lambdina fiscellaria*) in 1969, 1988, and 1996, affected large tracks of forests in the region (Bergeron and Leduc, 1998; Bouchard et al., 2005; McLaren et al., 2009). As evident in the forest inventory, wind is also an ever-present natural disturbance in GMNP. Wind driven disturbances have created a landscape with small stand-level openings driven by recurring small-scale wind events, and occasional large blowdown patch sizes averaging 7.4 ha and ranging up to 70.8 ha created by severe windstorms.

The park's domestic harvesting program involves 12 harvest blocks, 19,400 ha of productive forests in total, approximately 25% of the park's land base (Fig. 3-1). Past harvesting rates (1993–2015) within the park are quite variable with an average historical harvest level of approximately of 313 m^3 $year^{-1}$. In an effort to reduce moose, park managers initiated a moose hunting program in 2011 which has continued each year to the present and has expanded from a small pilot area in 2011 to include almost the entire park and has resulted in nearly 4,100 moose taken from inside the park in that time period.

3.3.2 Forest management modeling

Forest management models examine how varying processes affect a forested landbase by utilizing linear programming to project the long-term spatial consequences of different management strategies (Gunn,2009; Gustafson & Crow, 1996). Remsoft Woodstock^{TM} is the standard for forest estate modeling for many jurisdictions throughout the world that can use inputs derived from real datasets ranging from forest regeneration, growth dynamics, productivity, forest inventory, management practices, and management objectives (Hennigar, 2009; Zhu et al., 2010).

Remsoft's Woodstock^{TM} was used to evaluate the combined effects of moose and domestic harvesting and to optimize management strategies with a focus on restoring forest integrity within the park. Woodstock^{TM} is a standard forest-modeling tool used by forest industry and government agencies for long term forest management planning and wood supply analysis across Atlantic Canada. The key model inputs (i.e., transition rules, yield curves, and description of the forested land base derived from datasets ranging from forest regeneration surveys, growth and yield information, GIS forest inventory) along with forest management actions and disturbances determine forest-development dynamics.

3.3.3 Transition ruleset

To build forest transition rulesets for the model, we classified regeneration plots into forest community types according to GIS-based forest inventory and pre-disturbance seedling and sapling counts. Stocking levels were calculated for each plot and then summarized by forest community types, corresponding with western and northern peninsula ecoregions.

Regeneration surveys were conducted in the disturbed areas of productive forests during June–August 2016 (Fig. 3-1), following the Newfoundland and Labrador Regeneration Assessment Procedures and Alberta Regeneration Survey Manual (NL DNR, 1993). Stocking rate, tree height, and damage of dominant stems were measured to assess regeneration and browsing damage among the different tree-age classes in the park. Presence or absence of native tree species (e.g., white spruce, black spruce, balsam fir, white birch, yellow birch, red maple, white pine, eastern larch, or trembling aspen) was also recorded. At each plot location, a visual survey for moose damage on individual stems was conducted. If moose damage was observed, the height of damage on affected stems was recorded, as well as an estimate of distance and direction of the nearest healthy tree that could serve as a good seed source to foster future forest growth.

3.3.4 Forest growth and yield curves

Yield curves were generated by applying the Newfoundland and Labrador Provincial Growth and Yield Tool (NLGY) on a combination of 605 TSPs located within the park and nearby provincial PSPs and TSPs (2,203 plots, in all) of similar forest communities, given the lower number of park TSPs for some forest communities. The plot data used for yield projection were stratified by site class (i.e., high-good, medium, and poor), and by species or species grouping (i.e., white birch dominant, mixedwood with softwood leading, mixedwood with hardwood leading, balsam fir dominant, and spruce dominant forest communities) and ecoregion (northern and western).

3.3.5 Forest inventory

Accurate forest inventory information is the foundation for developing landscape-level forest management plans, forest monitoring, and environmental-policy development. In the spring of 2016, GMNP concluded a photointerpretation of aerial imagery acquired in 2010. The GMNP land base inventory based on this imagery was transferred into vector polygons with similar characteristics for both forested and non-forested areas. The forest polygons contained detailed information about tree species composition, age, tree height, site, crown closure, etc. This information was subsequently used to further stratify the forest landscape into dominant, forest species developmental types. Non-forest areas in GMNP included areas unsuitable for tree growth. These include bogs, barrens, pooled surface water, right of ways for roads and transmission lines, as well as agricultural lands. Forest inventory interpretations were vetted against GMNP's own TSPs to ensure accuracy of specific forest traits, like forest development and productivity, and successional trends. The interpretation was further enhanced to account for areas recently affected by widespread defoliation by insects, blowdown, and domestic harvesting.

3.3.6 Modeling scenarios

Six scenarios were formulated to assess forest development in GMNP, including two realistic scenarios and four hypothetical scenarios representative of heavy to light moose browsing, sustainability of wood supply, and recovery of forest ecosystem through moose population control and tree planting over a 100-year planning horizon (see Table 3-1).

Scenario one assumed no harvesting and a light amount of moose browsing concomitant with the current provincial moose population of two animals per km^2. This density is comparable to that of surrounding forests adjacent to the park (McLaren et al., 2004), where hunting of moose is permitted by law (Mawhinney and Mahoney 1994). Scenario two assumed high moose browsing, with no domestic harvesting. Scenarios three and four explored the impacts of various moose browsing pressures, with the addition of domestic harvesting set at a maximum sustainable level for each scenario. This hypothetical maximum annual allowable cut provides park managers with guidance of sustainable limits for equitable harvesting levels, while still allowing for effective ecosystem functioning and a target-level constraint that should not be exceeded without risking ecosystem decline. Maximum sustainable harvest levels are often controlled by past management practices, which can be used to determine if ecosystem functioning has been negatively affected by overharvesting. Impacts of tree planting on the recovery of forest integrity were evaluated by scenarios five and six. Scenario five assumed light moose browsing coupled with domestic harvesting and planting, whereas scenario six assumed heavy moose browsing, some domestic harvesting, and planting.

3.3.7 Data analysis

Forest ecosystem integrity was evaluated by tracking the total growing stock, age class structure, changes in forest communities, and the amount of non-regenerating forest stands over time. Impacts of moose browsing, domestic harvesting, and tree planting were assessed by comparing changes in relative abundance of ecosystem indicators.

3.4 Results and Discussion

The transition rules based on the regeneration surveys are shown in Table 3-2. Based on survey results, there were 33 and 45% of the surveyed areas in the western and northern ecoregions that fell into a category of “not sufficiently regenerated” (NSR) compared with 10% in the provincial forests outside of the park (Table 3-2). Balsam fir and white birch stocking levels ranged from 21–28% and 24–26%, respectively, for both ecoregions, followed by black spruce and white spruce (7–13%), and lesser amounts of eastern larch and red maple (1%).

Modelled stocking level of balsam fir under heavy moose browsing is approximately a third of stocking levels observed under the light moose browsing scenario in areas adjacent to the park and represents nearly four times more total NSR-area. Based on a previous study, about 40–60% stocking level in a young stand is required for the stand to be fully stocked when mature (Bergeron et al., 2011). We found balsam fir stocking levels (25%) declined significantly when compared to provincial forests (60%), while spruce stocking levels increased (Table 3-2). This observed change is consistent with previous studies, which have shown tree species changes can arise at the landscape level because of acute herbivory by moose (Mathisen et al., 2017; Milligan and Koricheva, 2013).

Our results indicate that the scenarios with light moose browsing consistently provided more tree volume through higher levels of total growing stock, leading to higher sustainable harvest levels, when compared against scenarios with heavy moose browsing (Fig. 3-2). These differences can be attributed to lower maximum volume estimates from the volume yield curves specific to the GMNP land base, when compared to the yield curves adopted from a nearby provincial forest, where moose populations are actively managed (Fig. 3-3). This difference is evident in many instances where expected forest yields on good sites in heavily browsed areas can compare to volume estimates achieved on medium sites under light browsing. This is consistent with another study of GMNP that concluded that lower volume estimates can be directly attributed to moose browsing, owing to the fact that other natural disturbances (e.g., insect outbreaks) are typically applied evenly in forests both inside and outside of the park in western Newfoundland (Meades and Moores, 1994). A study in Sweden (Kalen, 2006) found that high browsing pressures by moose negatively impacted forest regeneration and volume growth, consistent with our own findings. Greater volume growth associated with light moose browsing led to elevated sustainable harvest levels (Fig. 3-3).

The levels of browsing and woodcutting impacts are also reflected in the relative changes in species composition and distribution throughout the park between lightly and heavily browsed areas. Results display balsam fir-dominated areas increased with light browsing and decreased with heavy browsing. Likewise, areas with balsam fir-spruce forests decreased under light browsing, compared to heavy browsing (Fig. 3-4 and 3-6). Spruce-dominated stands tended to increase for both heavy and light moose browsing, with an expanded distribution and occurrence of spruce under heavy-browsing conditions (Fig. 3-4 and 3-6). Net results from heavy browsing is a general reduction in balsam fir, accompanied by a significant increase in spruce-dominated stands. This is consistent with findings of a field study conducted in GMNP, which found large-scale changes in forest composition driven by suppression of balsam fir regeneration by moose and other non-native herbivores, including red squirrels (*Tamiasciurus hudsonicus*) and snowshoe hares (*Lepus americanus*; Gosse et al., 2011).

Browsing impacts on balsam fir were also observed in other national parks in eastern Canada. For example, a study in Isle Royale National Park revealed significant reduction in fir-dominated stands, due to browsing by moose (Snyder and Janke, 1976). Severe browsing damage caused by white tail deer on Anticosti Island has led to a prediction of complete balsam fir removal over the long term (Potvin et al., 2003). Low regeneration rates in balsam fir-dominated forests due to moose browsing has been acknowledged for Cape Breton Highlands National Park (Smith et al., 2015).

Age-class distributions can be used to evaluate forest ecosystem sustainability and increasing age-class distributions, including old-age stands, can improve wildlife conservation efforts by providing favourable habitat for all types of wildlife (Thompson and Curran, 1995; Zhu et al., 2010; Didion and Fortin, 2007). In this study, old-growth forest was estimated to increase in the northern ecoregion, but decrease in the western ecoregion for both light and heavy moose browsing (Fig. 3-7). It is observed that more harvesting activities occur in the western ecoregion than in the northern ecoregion, which could account for differences in old forest occurrence (Fig. 3-5 to 3-7). Another consideration for the increase of old forests in the northern ecoregion is a higher percentage of less palatable spruce stocking compared to the western ecoregion, leading to lower impact by moose (Fig. 3-4, 3-6, and 3-7). The difference between balsam fir and spruce is not believed to impact old forest amounts, since both species follow very similar developmental patterns (Farrar, 1998). The increased regeneration success of spruce, when compared to balsam fir, has allowed more spruce-dominated stands to reach old age (Fig. 3-4, 3-6, and 3-7).

Planting was suggested as a tool to park managers as a means to improve regeneration success within the park and to combat the lower regeneration success rates caused by heavy moose browsing (Humber, 2009; Goose et al., 2011). In this model, the action of planting balsam fir to maintain species balance in GMNP was initially explored and abandoned with the consideration that any investment in planting within the park with a species that is palatable to moose would not be a sound investment, until such time that the hyperabundant moose population is controlled. Instead, the planting action of the model used spruce to target areas that were designated as NSR, based on the success of planting spruce by the forest industry due to poor natural regeneration of spruce. The simulated results of the planting improved TGS, harvest levels, helped balance age-class structures in heavily browsed areas and effectively reduced NSR-areas within the park, while having nominal impact in lightly browsed areas (Fig. 3-5 to 3-8). Planting spruce increased harvest and TGS levels in both scenarios; in heavily browsed areas, planting produced greater amounts in both measures (Fig. 3-5). This counterintuitive result was directly related to heavily browsed areas having more NSR-areas available for planting, when compared to lightly browsed areas. Increased planting in heavily browsed areas produced greater TGS levels than in the lightly browsed areas at the landscape level by the end of the planning horizon (volume = 2,952 *vs.* 934,883 m^3, respectively). Higher TGS levels tended to enable higher maximum harvest levels of 138,511 m^3 in the heavy browse scenario, compared to 122,194 m^3 in the light browse scenario (Fig. 3-5).

Planting can help establish forest cover but at high moose densities, planting spruce as the only feasible option, can speed up the process of stand conversion to spruce-dominated stands. It will remain as a significant challenge for park managers to keep current species balance, plantation area sizes, and associated costs with planting. In heavily browsed areas, assuming a planting cost of \$580 ha^{-1} (Robert Sutton, DNR personal communication, 2016), it would require \$941,340 for each 5-year period to treat 1,625 ha. By provincial and industrial forestry standards, planted area sizes attended to here are mostly small. However, for parks this would prove to be costly, especially when coupled with road inaccessibility to most of the forest, which would increase the price of planting. Indeed, Cape Breton Highlands National Park managers investigated a similar option of planting disturbed areas, even establishing small-scale plantations, but concluded that landscape-level planting would be largely prohibitive (Smith et al., 2015).

Species distribution patterns under scenarios of heavy and light browsing, combined with planting, did not vary much beyond the results found with the scenarios without planting. The only difference between scenarios was in the rate of stand conversion to occur. Heavy browsing and planting resulted in more spruce-dominated sites across the forested landscape, nearly doubling that simulated for light moose browsing. Under light moose browsing, requirement of planting was generally less, resulting in more total balsam fir- and balsam fir and spruce-dominated stands resident on the land base (Fig. 3-4 and 3-6).

3.5 Concluding remarks

Our field survey found that high moose browsing levels within GMNP resulted in a significant portion of regenerating areas to fall within the “not sufficiently regenerated” (NSR) category. However, the stocking level of the regenerating forested area is still at a level high enough to develop into fully stocked stands. The impact of moose browsing in GMNP has lowered growth and volume expectations, when compared to areas outside the park that have moose population controls in place. At heavy moose browsing levels and no control on population densities the amount of balsam fir will be drastically reduced and eventually replaced by spruce. Balsam fir-dominated stands will continue to be replaced even at lower regeneration rates. However, balsam fir and spruce-dominated stands will slowly evolve to purely spruce-dominated stands. Our modeling results indicate that tree planting can be an effective tool in improving regeneration success. However, planting non-palatable spruce may help accelerate the landscape-level conversion from balsam fir dominance. This is particularly a problem for park managers trying to maintain current species distribution. Our results emphasize the importance of reducing moose densities in the park as a necessary first step to return the park's forest to its natural balsam fir-dominated state.

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3.7 References

Bergeron, Y., and Leduc, A. (1998). Relationships between change in fire frequency and mortality due to spruce budworm outbreaks in the southern Canadian boreal forest. Journal of Vegetation Science, 9(4), 492–500. doi:10.2307/3237264

Bergeron, D. H., Pekins, P. J., Jones, H. F., and Leak, W. B. (2011). Moose browsing and forest regeneration: a case study in northern New Hampshire. Alces, 47, 39–51.

Bergerud, A., Manuel, F., Whalen, H. (1968). The harvest reduction of a moose population in Newfoundland. The Journal of Wildlife Management 32, 722–728.

Caines, P., and Deichmann, H. (1989). Resource Description and Analysis; Gros Morne National Park. Rocky Harbour, NL: Environment Canada, Unpublished Report.

Cieszewski, C., Zasada, M., Borders, B., Lowe, R., Zawadzki, J., Clutter, M., and Daniels, R. (2004). Spatially explicit sustainability analysis of long-term fiber supply in Georgia, USA. Forest Ecology and Management, 187(2-3), 349–359.

Connor, K. J., Ballard, W. B., Dilworth, T., Mahoney, S., and Anions, D. (2000). Changes in structure of a boreal forest community following intense herbivory by moose. Alces, 111–132.

Didion, M., and Fortin, M.-J. (2007). Forest age structure as indicator of boreal forest sustainability under alternative management and fire regimes: a landscape level sensitivity analysis. Ecolological Modeling, 200(1-2), 45–58.

Department of Natural Resources. (1993). Newfoundland and Labrador Regeneration Assessment Procedures. Unpublished Report.

Engelmark, O. (1999). Boreal forest disturbances. In L. Walker, Ecosystems of the World, vol. 16. Ecosystems of Disturbed Ground (pp. 161–186). Amsterdam, The Netherlands: Elsevier Science.

Farrar, J.L. (1995). Trees in Canada. Nat. Res. Can., Can. For. Serv. And Fitshenr and Whiteside, Ottawa.

Furgeuson, S. H., and Messier, F. (1996). Can human predation of moose cause population cycles? Alces, 32:149–161.

Government of Canada. 2000. Canada National Parks Act. (C.32) No. 14-01. Ottawa.

Garet, J., Raulier, F., Pothier, D., and Cumming, S. (2012). Forest age class structures as indicators of sustainability in boreal forest: Are we measuring them correctly? Ecological Indicators, 202–210.

Gosse, J., Hermanutz, L., McLaren, B., and Knight, T. (2011). Degradation of Boreal Forest by Non-native Herbivores in Newfoundland's National Parks: Recommendations for Ecosystem Restoration. Natural Areas Journal, 31(4),331–339. doi:10.3375/043.031.0403

Gros Morne National Park. (2009). Gros Morne National Park of Canada Management Plan. Rocky Harbour, NL: Library and Archives Canada Cataloguing in Publication.

Gunn, E. (2009). Some perspectives on strategic forest management models and the forest products supply chain. INFOR: Information Systems and Operational Research, 47(3), 261-272. doi:10.3138/infor.47.3.261

Gustafson, E. J., and Crow, T. R. (1996). Simulating the effects of alternative forest management strategies on landscape structure. J. Env. Manage., 46: 77–94.

Hennigar, C. R. (2012). Modeling the influence of forest management and spruce budworm epidemics on timber supply and carbon sequestration. Library and Archives Canada= Bibliothèque et Archives Canada.

Hobbs, N. T., Schimel, D. S., Owensby, C. E., and Ojima, D. S. (1991). Fire and grazing in the tallgrass prairie: contingent effects on nitrogen budget. Ecology, 72(4), 1374–1382. doi:10.2307/1941109

Humber, J. (2009). Non-native plant invasions of boreal forest gaps: implications for stand regeneration in a protected area shaped by hyperabundant herbivores. M.S. thesis, Department of Biology, Memorial University of Newfoundland, St. John’s.

Janes, G. (1976). Moose and Caribou census of Gros Morne Nat. Park. Rocky Harbour: Parks Canada.

Jeffries, R. L., Jensen, A., and Abraham, K. F. (1979). Vegetational development and the effect of geese on vegetation at La Perouse Bay, Manitoba, Canada. Canadian Journal of Botany, 57(13), 1439–1450. doi:10.1139/b79-178

Kalen, C. (2006). Deer Browsing and Impact on Forest Development. Journal of Sustainable Forestry, 53–64. doi:10.1300/j091v21n02_04

MacLean, D. A. (2015). Impacts of insect outbreaks on tree mortality, productivity, and stand development. The Canadian Entomologist, 148(S1), S138–S159.

Martin, J.-L., and Baltzinger, C. (2002). Interaction among deer browsing, hunting, and tree regeneration. Canadian Journal of Forest Research, 32(7), 1254–1264.

Mathisen, K.M., Milner, J.M., Skarpe, C. (2017). Moose-tree interactions: rebrowsing is common across tree species. BMC Ecology, 17(1) ,12. doi:10.1186/s12898-017-0122-3

Mawhinney, K., and Mahoney, S. P. (1994). Aerial moose census of management units 5, 6 and 7 in Western Newfoundland Model Forest, 1993 and 1994. Corner Brook, NL: Western Newfoundland Model Forest.

McCarthy, C. (2000). Gros Morne Domestic Timber Harvest Information Newsletter.

McCarthy, J.W. and Weetman. (2007). Stand structure and the development of an insect-mediated boreal forest landscape. Forest Ecology and Management. 241(1-p3), 101–114. doi:10.1016/j.foreco.2006.12.030

McLaren, B. E., Roberts, B. A., Djan-Chekar, N., and Lewis, K. P. (2004). Effects of overabundant moose on Newfoundland landscape. Alces, 40, 45–59.

McLaren, M. E., Taylor, S., and Luke, S. H. (2009). How moose select forested habitat in Gros Morne National Park. Alces, 45, 125–135.

Mcleod, I., Lucarotti, C., Chris, H., Maclean, D., Holloway, G., Cormier, G., and Davies, D. (2012). Advances in Aerial Application Technologies and Decision Support for Integrated Pest Management, Dr. Sonia Soloneski (Ed.). InTech, DOI: 10.5772/32708.

McNaughton, S. J. (1979). Grassland-herbivore dynamics. In A. R. Sinclaire, and M. Norton-Griffins, Serengeti: dynamics of an ecosystem. (pp. 46–81). Chicago, Illinois: University of Chicago Press.

Meades, W., and Moores, L. (1994). Forest site classification manual: a field guide to the Damman forest types of Newfoundland. Second edition. Western Newfoundland Model Forest, Inc; Department of Forestry and Agriculture;

Natural Resources Canada Canadian Forest Service, Forest Resources Development Agreement FRDA Rep. 003.

Milligan, H.T and Koricheva, J. (2013). Effects of tree species richness and composition on moose winter browsing and foraging selectivity: an experimental study. Journal of Animal Ecology, 82(4), 739–748. doi:10.1111/1365-2656.12049

Murie, A. (1934). The moose of Isle Royale. Anne Arbor, Michigan: Museum of Zoology, University of Michigan, Miscellaneous Publications No. 25.

Parks Canada. (2005). Park backgrounder: Gros Morne National Park of Canada. Retrieved from In Special places: Eco-lessons from the national parks in Atlantic Canada. Parks Canada: www.pc.gc.ca/apprendre-learn/prof/sub/eco/itm5/fi-lr1/gros-morne_e.asp

Paster, J., Moen, R. A., and Cohen, Y. (1997). Spatial heterogeneities, carrying capacity, and feedbacks in animal landscape interactions. Journal of Mammalogy, 78(4), 1040–1052. doi:10.2307/1383047

Pimlott, D. H. (1953). Newfoundland Moose. Trans. N. A. Wild. Conf, 18: 563–581.

Pimlott, D. H. (1959). Reproduction and productivity of Newfoundland Moose. Journal of Wildlife Management, 23(4), 381–401. doi:10.2307/3796486

Potvin, F., Beaupre, P., and Laprise, Gaetan. (2003). The eradication of balsam fir by white-tailed deer on Anticosti Island, Quebec: A 150-year process. Ecoscience, 487–495.

Pretzch, H., Grote, R., Reineking, B., Rotzer, T., and Seifert, S. (2008). Models for forest Ecosystem Management: A European Perspective. Annals of Botany, 101:1065–1087.

Rae, L., Whitaker, D., and Warkentin, I. (2014). Multiscale impacts of forest degration through browsing by hyperabundant moose (*Alces alces*) on songbird assemblages. Diversity and Distributions, 20:382–395.

Remsoft. (2016). Spatial Woodstock user guide. Fredericton, NB: Remsoft Inc.

Shifley, S.R., Hong, S.H., Lischke, H., Wang, W.J., Wenchi, J., Gustafson, E.J., Thompson, J.R., Thompson, F.R.III, William, D.D., Yang, J. (2017). The past and future of modeling forest dynamics: from growth and yield curves to forest landscape models. Landscape Ecology, 32(7), 1307–1325.

Smith, R., Smith, M., Clifford, P., and Bellemore, C. (2015). Hyperabundant Moose Management Plan for North Mountain, Cape Breton Highlands National Park. Ingonish Beach, NS: Parks Canada Agency.

Snyder, J. D., and Janke, R. A. (1976). Impact of Moose Browsing on Boreal-type Forests of Isle Royale National Park. The American Midland Naturalist, Vol. 95, No. 1, 79–92.

Solarik, K. A., Volney, W., Lieffers, V., Spence, J., and Hamann, A. (2012). Factors affecting white spruce and aspen survival after partial harvest. Journal of Applied Ecology, 145–154.

Taylor, E. (1991). Gros Morne National Park Aerial Moose Survey. Rocky Harbour: Parks Canada.

Sy, K., Keenleyside, K., Adare, B., Reader, B., Deering, P. (2009). Protecting native biodiversity from high-impact invasive species through the protected areas of Parks Canada. Biodiversity, 10(2-3), 51–55.

Thompson, I.D., and Curran W.J. (1995). Habitat suitability for marten of second growth balsam fir forests in Newfoundland. Canadian Journal of Zoology, 73(11), 2059–2064.

Thompson, R. (2007). Gros Morne National Park Aerial moose survey. Rocky Harbour, NL: Parks Canada.

Tomppo, E., Olsson, H., Stahl, G., Nilsson, M., Hagner, O., and Katila, M. (2008). Combining national forest inventory field plots and remove sensing data for forest databases. Remote Sensing of Environment, 1982–1999.

Vanclay, J. (2002). Forest Growth and Yield Modeling. In El-Shaarawi, A., Piegorsch, W. Encyclopaedia of Environmetrics (pp. 811–812). NY: Wiley.

Zhu, X., Bourque, C. P., Taylor, S., Cox, R., and Wentzell, C. (2010). Predicting the effects of woodcutting and moose browsing on forest development in Gros Morne National Park, Newfoundland, Canada. The Forestry Chronicle, 86(2), 178–192. doi:10.5558/tfc86178-2

Table 3-1. Six scenarios used to assess moose browsing and domestic harvest impacts on forest regeneration and development: as well as forest restoration strategies by implementing programs of moose population control and reforestation. Detail descriptions refer to main text.

Scenario	Scenario name	Ruleset[1]	Browsing[2]	Harvesting[3]	Harvest Level[4]
1	Light Browsing	Province	Light	No	--
2	Heavy Browsing	GMNP	Heavy	No	--
3	Light Browsing and Harvest	Province	Light	Yes	Max. AAC
4	Heavy Browsing and Harvest	GMNP	Heavy	Yes	Max. AAC
5	Light Browsingand Harvest and Planting	Province	Light	Yes	Max. AAC
6	Heavy Browsing and Harvest and Planting	GMNP	Heavy	Yes	Max. AAC

[1] *Source of yield and transition modeling information*

[2] *Level of moose browsing*

[3] *Harvesting permitted*

[4] *Annual Allowable Cut* - *Maximum even flow sustainable harvest level*

Table 3-2. GMNP-specific transition rules derived from 2005 and 2016 regeneration-survey data, displaying the percentage of species expected to regenerate following stand succession in a heavy browsing scenario. The provincial transition rules due to the long-term moose population control in the provincial forest outside GMNP were used by the light moose browsing scenario which is assumed to be achieved by GMNP through its recently launched moose population control program.

Source	Ecoregions	Regenerating Species (%)
GMNP	Northern	bF(21), bS(3), tL(1), wB(26), wS(4), NSR(45)
	Western	bF(28), bS(3),rM(1), wB(24), wS(10), NSR(33)
Province	Both	bF(60), bFsP(10), MSW(15), MHW(3), wB(2), NSR(10)

bF = balsam fir; bS = black spruce; bFsP = fir spruce; rM = red maple; tL = eastern larch; wB = white birch; wS = white spruce; MSW = mixedwood with softwood leading; MHW = mixedwood with hardwood leading; NSR = "not sufficiently regenerated"

Table 3-3. Contribution of bF, SP, and wB to the total harvest level (m^3) for the western and the northern ecoregions under scenarios 3–6 that explored the impacts of light and heavy moose browsing pressures, with the addition of maximum sustainable level for the domestic harvest program (scenarios 3 and 4) and tree planting strategies (scenarios 5 and 6) in GMNP.

Species (Region)	Scenario 3	Scenario 4	Scenario 5	Scenario 6
bF(West)	1,312,542 (79%)	896,916 (76%)	1,344,416 (79%)	721,106 (71%)
sP(West)	310,100 (69%)	406,129 (62%)	341,311 (77%)	1,162,448 (78%)
wB(West)	147,576 (74%)	187,845 (76%)	141,292 (75%)	135,093 (73%)
sP(North)	140,780 (31%)	153,166 (38%)	100,493 (23%)	331,387 (22%)
bF(North)	353,407 (21%)	285,599 (24%)	357,381 (21%)	292,050 (29%)
wB(North)	51,517 (26%)	60,065 (24%)	47,580 (25%)	51,202 (27%)

bF = balsam fir; SP = spruce; wB = white birch;

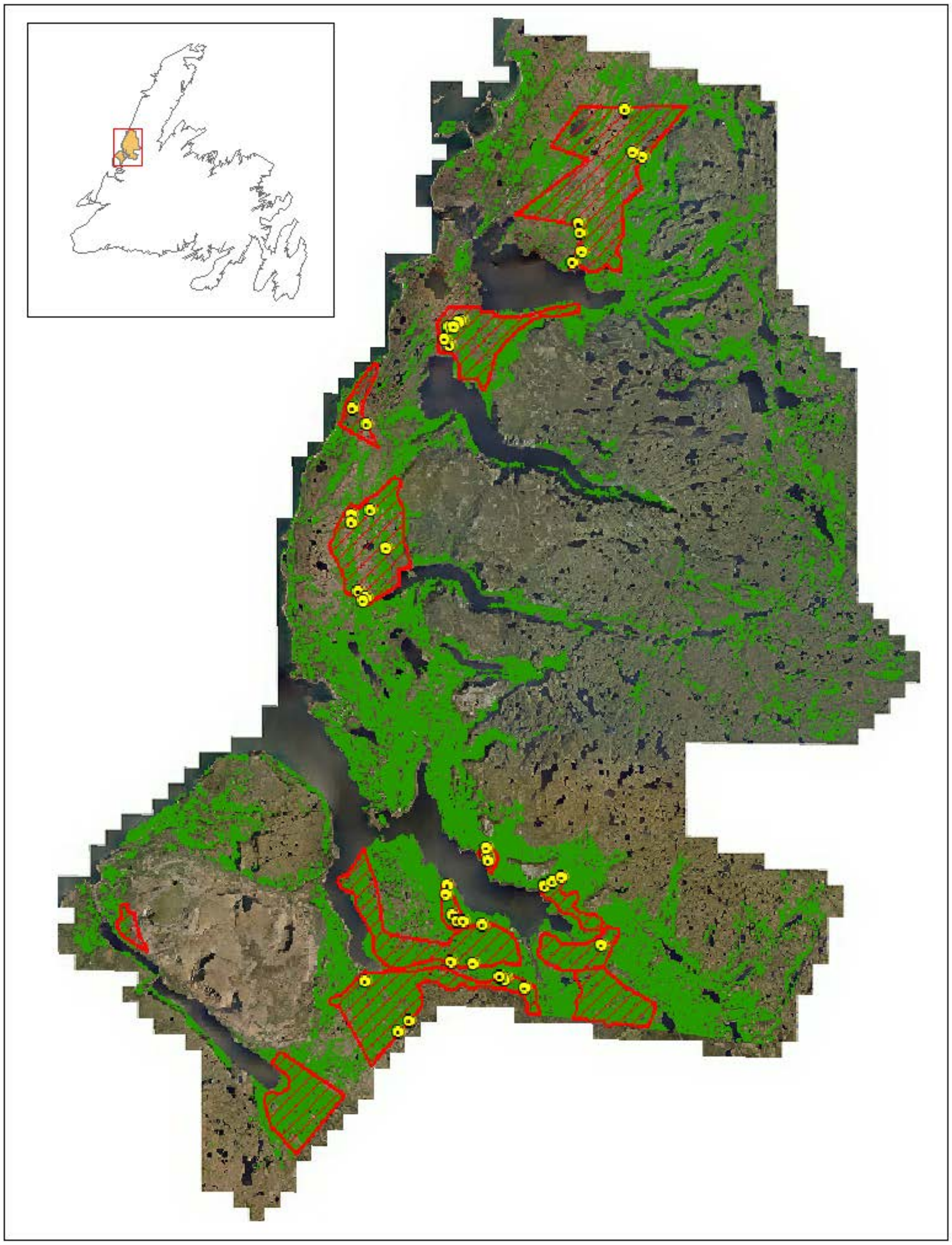

Figure 3-1. Locations of GMNP domestic harvest blocks (red), displaying their positions within the productive forest zone within the park. Regeneration-survey plots are displayed as yellow dots.

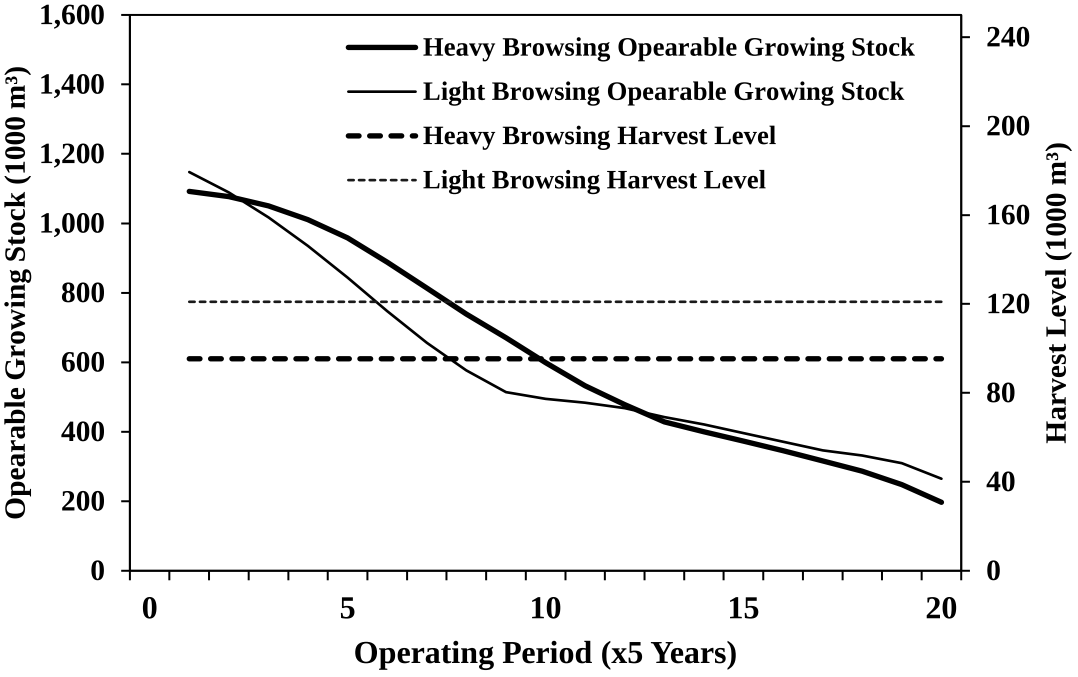

Figure 3-2 Total operable growing stock and maximum sustainable harvest level under scenarios three and four explored the impacts of light and heavy moose browsing pressures, with the addition of domestic harvesting set at a maximum sustainable level for each scenario.

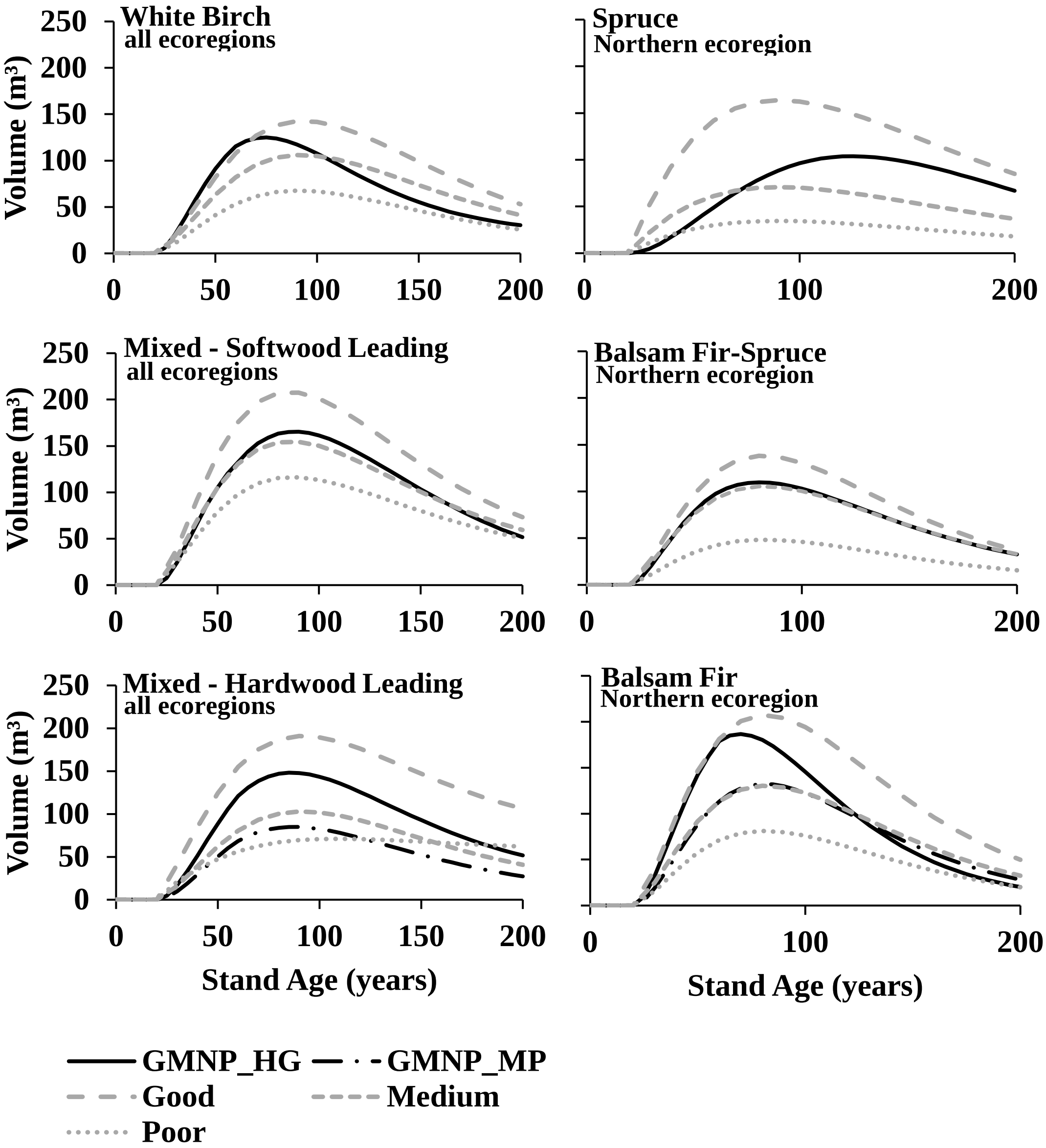

Figure 3-3. Comparison of strata-based GMNP yield curves on good (HG) sites and medium to poor (MP) sites versus existing provincial yield curves on good, medium and poor sites. GMNP-based yield curves were generated from a combination of GMNP TSP and Provincial PSP and TSP data for ecoregions intersecting with park boundaries.

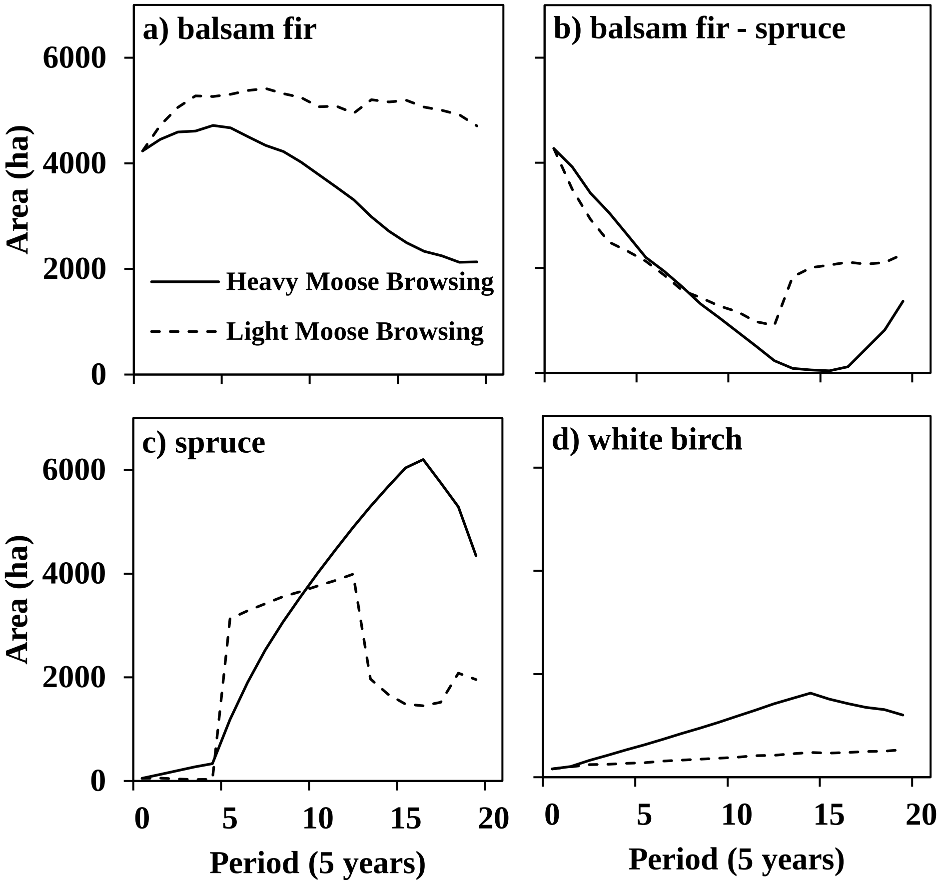

Figure 3-4. Area of balsam fir, balsam fir-spruce, spruce and white birch forests under scenarios three and four explored the impacts of light and heavy moose browsing pressures, with the addition of domestic harvesting set at a maximum sustainable level for each scenario.

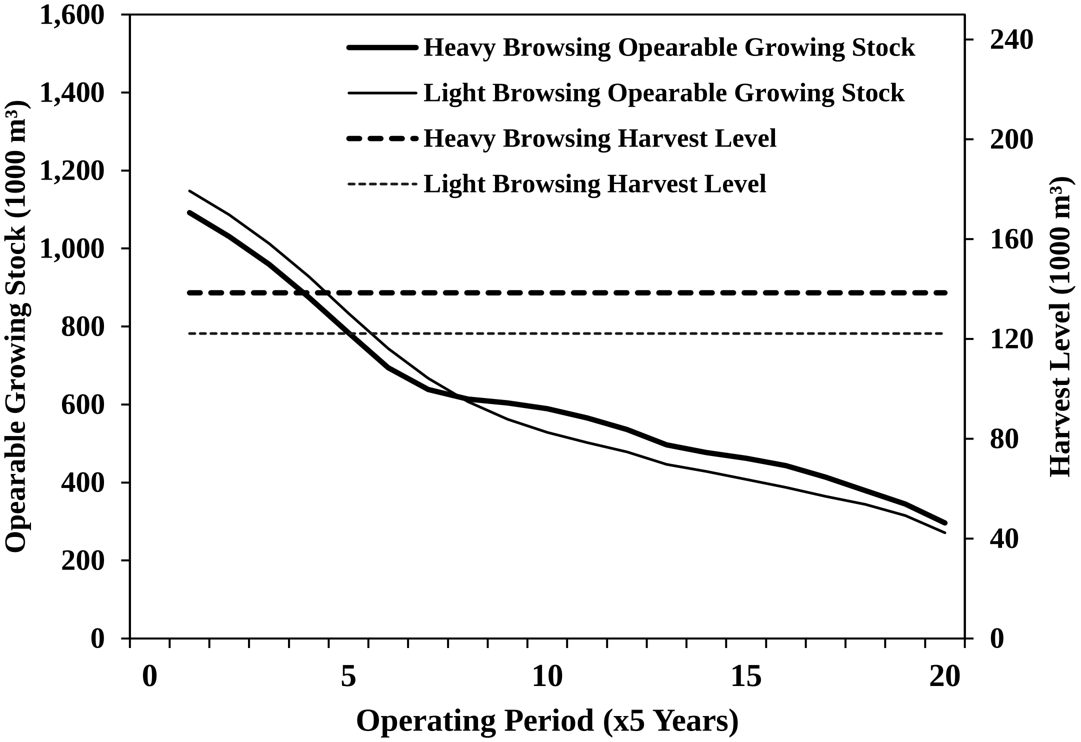

Figure 3-5. Total operable growing stock compared to maximum sustainable harvest level under scenarios five and six to evaluate recovery of forest integrity through tree planting to improve forest regeneration over the long term. Scenario five assumed light moose browsing coupled with domestic harvesting and planting, whereas scenario six assumed heavy moose browsing, domestic harvesting, and tree planting.

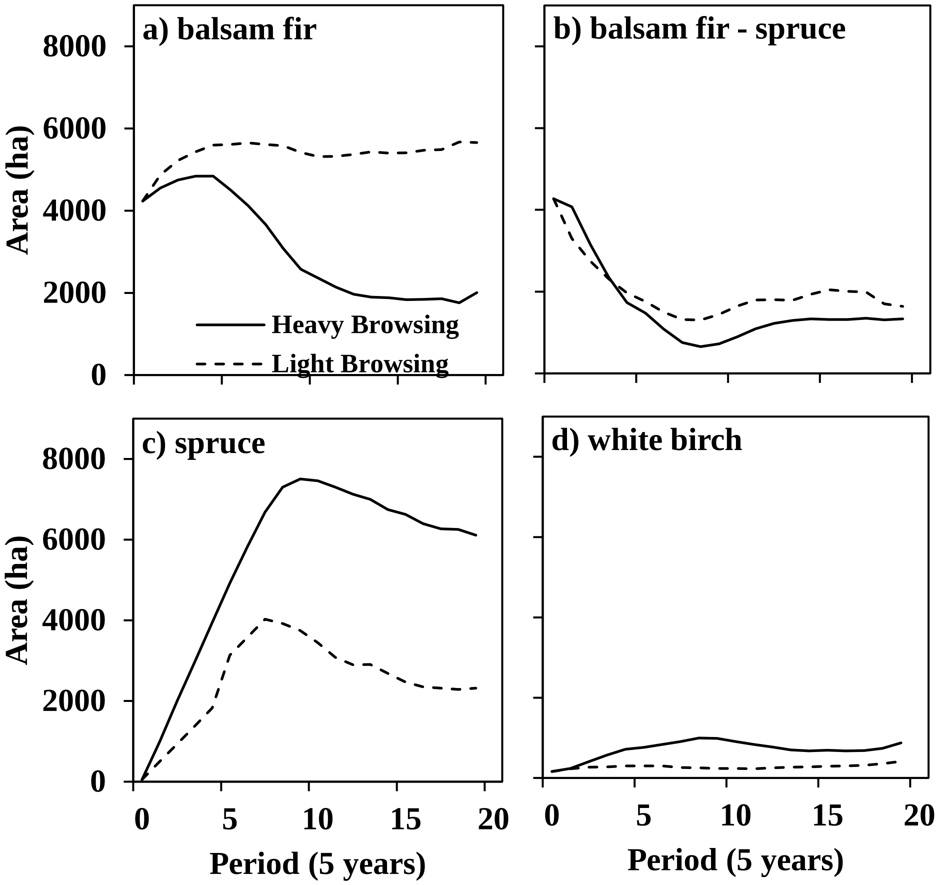

Figure 3-6. Area of balsam fir, balsam fir-spruce, spruce and white birch forests under scenarios five and to evaluate recovery of forest integrity through tree planting to improve forest regeneration over the long term. Scenario five assumed light moose browsing coupled with domestic harvesting and planting, whereas scenario six assumed heavy moose browsing, domestic harvesting, and tree planting.

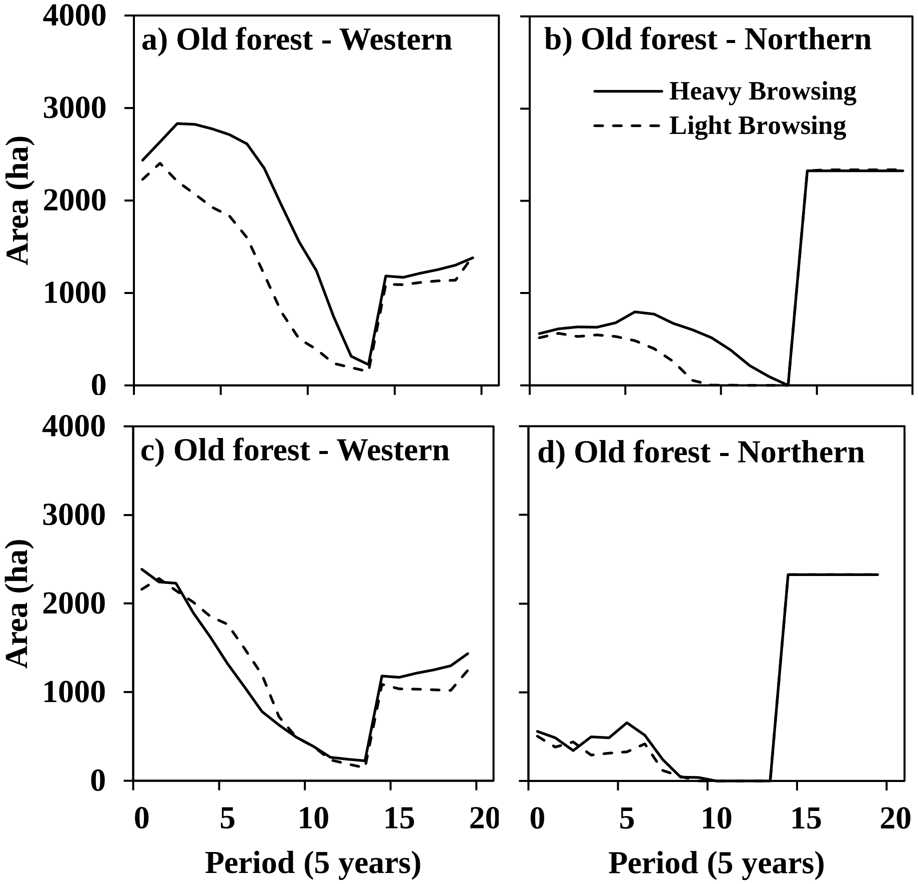

Figure 3-7. Subfigures (a) and (b) represent the area of old-age forests within the northern and western ecoregions under scenarios three and four exploring the impacts of light and heavy moose browsing pressures, with the addition of domestic harvesting set at a maximum sustainable level for each scenario. Subfigures (c) and (d) give the area of old-age forests within the two ecoregions under scenarios 5 and 6 for similar conditions with the addition of tree planting.

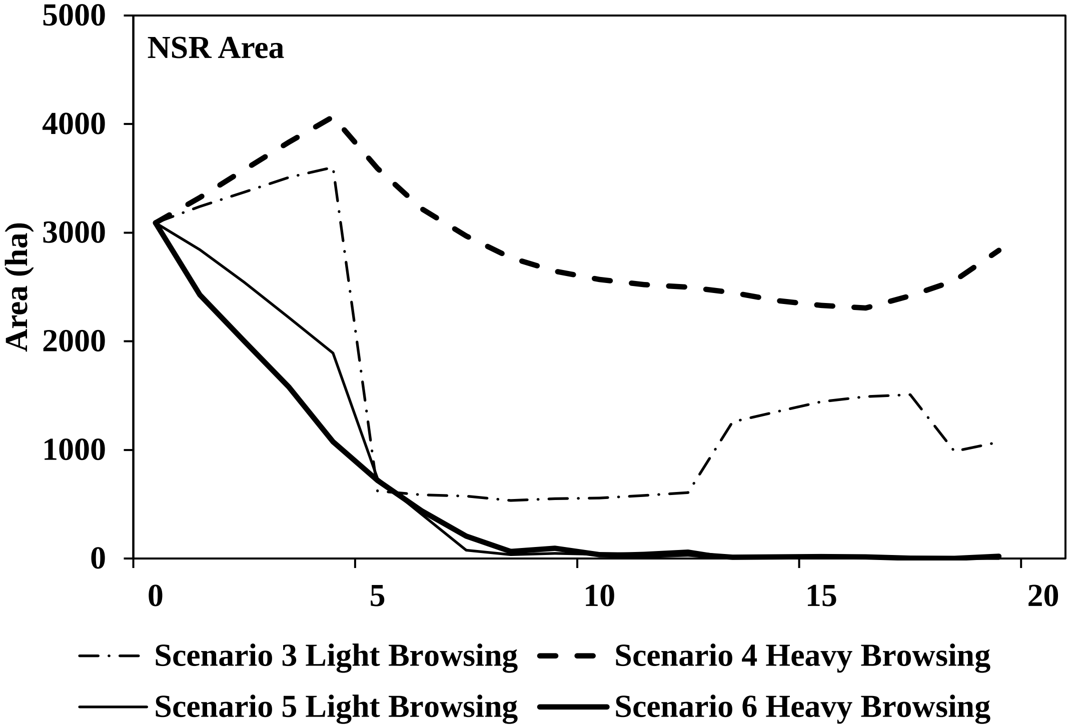

Figure 3-8. “Not sufficiently regenerated” (NSR) area under scenarios 3 and 4 exploring the impacts of light and heavy moose browsing pressures, with the addition of domestic harvesting set at a maximum sustainable level for each scenario, and scenarios 5 and 6 for similar conditions with the addition of planting spruce.

4 Impacts of Moose Browsing and Domestic Harvesting on Carbon Dynamics within Gros Morne National Park, Canada

4.1 Abstract

Forested ecosystems within Canada store significant amounts of carbon and contribute greatly to the global changes in the carbon cycle. These forested ecosystems are often impacted by disturbances, whether natural or manmade, that can determine if a forested ecosystem is a net source or sink for carbon. Gros Morne National Park (GMNP), located in western Newfoundland, is mandated to provide domestic harvesting opportunities for the communities that fall within its boundaries which impacts the forest ecosystem. The GMNP forest ecosystem also suffered significant browsing damage from hyperabundant moose (*Alces alces*) populations within the park. In this study we evaluated changes in carbon levels under different forest management scenarios by exploring (1) the impacts of domestic harvesting and planting on the carbon pools in the forested ecosystem of Gros Morne National Park, and (2) explored carbon pool differences between heavy and light moose browsing using GMNP and the standard provincial models. Results have shown that by reducing the amount of forested areas by harvesting or reducing forest yield expectations by moose browsing, carbon levels are reduced. Using planting as a forest management tool can mitigate degradation of forest integrity due to harvesting and hyperabundant moose browsing. Optimizing carbon storage within the park can increase forest ecosystem carbon stocks by 12% over the baseline and increase domestic harvesting by 28,541 m^3 above historical levels. This result suggests that using carbon as the management objective for the park, then it is possible to meet key objectives of the park, including maintaining a healthy forest ecosystem, providing domestic harvest opportunities, while helping to mitigate climate change.

4.2 Introduction

Forested ecosystems within Canada store significant amounts of carbon and contribute greatly to the global changes in the carbon cycle (Kurz and Apps, 1995). This carbon stored in forest biomass, dead organic material, and soils contributes to the exchange of carbon between the forest and the atmosphere (Kurz, et al., 2009 and 2013). Forest stands are dynamic by nature; they develop and eventually experience succession and are continually in a state of change in terms of structure and carbon. These ever-changing forests are often impacted by disturbances, both natural and manmade. These disturbances often determine if a forest ecosystem is to be a source or a sink for carbon (Kurz and Apps, 1999). Recent studies have suggested that Canadian forests have experienced recent increases in fire and insect disturbances and, therefore, has moved from a carbon sink to a source (Metsaranta et al., 2010; Kurz et al., 2008). Changes to forest structure through active forest management, however, could potentially increase carbon storage to offset disturbance levels by preventing tree loss and mortality to improving regeneration and tree growth (Lee et al., 2002; Hennigar and Maclean, 2010). There are many uncertainties surrounding which forest management activities and their timings are applied across a land base to produce acceptable carbon stock levels (Jandl et al., 2007). Estimating and understanding the implications on carbon considering this uncertainty of alternative forest management decisions and of natural disturbances is critical to any ecosystem manager.

Moose (*Alces alces* L.) have been shown to impact large landscape-level processes (Jeffries et al., 1979; McNaughton, 1979; Hobbs et al., 1991; Paster et al., 1997; Milligan and Koricheva, 2013; Mathisen et al., 2017) and the moose browsing impact on

GMNP is documented in Chapter 3 of this work. In summary, moose have nearly consumed all preferred browse species and have since move to target balsam fir (*Abies balsamea* (L.) Mill; Connor et al., 2000; Humber et al., 2009). Studies by Zhu et al. (2010), and as indicated in Chapter 3 of this work, have shown forests within the park are not producing volume growth at the same rate or at the same level as adjacent stands with low moose-browsing levels. The differences between GMNP forests with heavy moose browsing and the adjacent light moose browsed areas of the provincial forests is not well understood and has led to uncertainties as to our understanding of carbon storage dynamics in GMNP.

Carbon can be measured in forests in several ways using several different methods ranging from tree-level biomass equations (Lambert's equations) to ecosystem models like the Carbon Budget Model of the Canadian Forest Service (CBM-CFS3), henceforth referred to as CBM (Lambert and Raulier, 2005; Kurz et al., 2013). The CBM is core to the Canadian forest carbon monitoring system and the tool central to this study (Moroni et al., 2010). The CBM measures carbon at the landscape level from a forest inventory and then calculates any changes in carbon resulting from land use change, including increasing carbon storage from tree growth and decreasing carbon from mortality, disturbance, and harvesting (Kurz et al., 2009 and 2013).

Forest-estate models have long been used to evaluate the long-term spatial impacts of alternative forest management decisions (Gustafson and Crow, 1996; Vanclay, 2002; Tomppo et al., 2008; Shifley, 2017). Remsoft' s Spatial Woodstock (henceforth referred to as Woodstock) is a forest-estate modeling software that utilizes linear optimization techniques to find solutions to complex forest management problems (Remsoft, 2016) and is the standard forest-modeling software for the province of Newfoundland and Labrador (Robert Sutton, DNR personal communication, 2016). In this study we incorporate carbon yields generated using the CBM into Woodstock to evaluate the changes in carbon under different management scenarios. We explored (1) the impacts of domestic harvesting and planting on the carbon pools within the forested ecosystem of Gros Morne National Park, and (2) carbon pool differences between heavy and light moose browsing using GMNP and the standard provincial models.

4.3 Methods

4.3.1 Study Area

Gros Morne National Park (1,805 km²) is a UNESCO World Heritage Site, located on the western coast of Newfoundland and Labrador (49°41′22″N 57°44′17″W). Climate is controlled by prevailing southwesterly winds that blow onshore from the Gulf of St. Lawrence and result in cool summers (July mean of 15°C) and mild winters (mean of -7.5°C), with an average rainfall of 1397 mm and snowfall of 328 cm (Humber et al., 2009; Zhu et al., 2010). Its land base is sectioned into three ecoregions (Northern, Western and Land Range Barrens), which stretches from coastal lowland to high alpine plateaus, from which the park gets its name. The coastal lowland is dominated by bogs and shrub forestland, while the alpine plateau is sparsely covered by forest heath and shrub barrens, with small forested areas in sheltered valleys. The productive stands are found to grow on the transitional slopes between the coastal plains and alpine plateau. Fifty-five percent of the park is covered by forest comprising of primarily balsam fir and white birch (*Betula papyrifera*), with smaller amounts of black spruce (*Picea mariana*), white spruce (*P. glauca*), yellow birch (*B. alleghaniensis*), red maple (*Acer rubrum*), trembling aspen (*Populus tremuloides*), white Pine (*Pinus strobus*), and eastern Larch (*Larix laricina*). Fire, insects, wind, and fungi are major stand-replacing-disturbance vectors in the Boreal Forest. However, fire has a limited history in western Newfoundland due to its humid maritime climate (Meades and Moores 1994; Engelmark 1999). Recurring insect outbreaks have become the primary natural stand-replacing events in western Newfoundland (Bergeron and Leduc, 1998; Bouchard et al., 2005), with insect outbreaks of spruce budworm (*Choristoneura fumiferana*) in 1977 and hemlock looper (*Lambdina fiscellaria*) in 1969, 1988, and 1996, affecting large forested areas in the region (McLaren et al., 2009). The GMNP forest inventory has shown disturbance patterns characterized by recurring small-scale disturbances punctuated by the occasional large and severe windstorm, with blowdown patches averaging 7.4 ha, and ranging up to 70.8 ha. The park is home to 700 species of flowering plants and 400 species of bryophytes, 239 species of birds, and 14 species of mammals (Government of Canada, 2010).

For the purposes of this study only the forested area of the park was assessed for carbon stocks (Fig. 4-1). Non-forested areas, such as organic soils, waterbodies, barrens peatland, hardwood and software shrub areas are not eligible for forest management activities and/or do not have volume yield curves associated with them; subsequently carbon will not vary across different management scenarios. Forest management activities are permitted to occur within GMNP boundaries, but only within 10 special domestic harvesting blocks (outlined in red Fig. 4-1); therefore, any impact from domestic harvesting will be naturally restricted to these zones.

4.3.2 Forest management modeling

The Remsoft's Woodstock^{TM} was used to evaluate carbon changes across varying management scenarios. Woodstock^{TM} is a standard forest-modeling tool used by forest industry and government agencies for long-term forest management planning and wood supply analysis across Atlantic Canada. In this study, a model was built based on the latest NL provincial wood supply model (Table 4-1) and adopted to the GMNP area using the park's recent forest inventory, regeneration rules (transitions), and yield data (Table 4-2 and 4-3). The latter two model sections were built to capture the impacts of hyperabundant moose browsing impacts found within GMNP boundaries. The reader is referred to Chapters 2 and 3 for specific details outlining the establishment of GMNP-specific sections of the model.

4.3.3 Carbon curve development

The CBM-CFS3 was used to convert the strata-based GMNP and provincial yield curves into carbon curves (tonne ha^{-1}) for the Woodstock model to estimate carbon storage in different carbon pools (Natural Resources, 2013), including (1) living biomass – merchantable and sub-merchantable stemwood, foliage, coarse and fine roots, stumps, bark, and branches, and (2) dead organic matter (DOM) – above and belowground pools for very fast, fast, medium, and slow DOM, and DOM pools for snags and branches. Strata-based carbon curves were then used as model inputs in Woodstock allowing optimization in forest carbon management (Table 4-4 to 4-6).

4.3.4 Modeling scenarios

The modeling exercises evaluated in the effects of forest management strategies on carbon storage in GMNP (Table 4-8) included:

(1) A baseline scenario S_C1 preformed a forest inventory projection by removing all disturbance events, excluding the impacts of moose throughout the planning horizon.

(2) Scenario S_C2 addressed domestic harvest within GMNP (Fig. 4-1). The harvest volume target was determined based on historical minimum and maximum levels for each of individual domestic harvesting blocks and an overriding even-flow harvesting constraint applied to the entire harvested area throughout the planning horizon (Table 4-7).

(3) Scenario S_C3 permitted planting within GMNP to help restore forest regeneration to offset the impact of moose browsing, domestic harvesting, and natural disturbance. Planting was assumed to occur across the entire land base with an even-flow planting constraint to ensure the same areas were planted across the model time horizon.

(4) Scenario S_C4 maximized the amount of carbon stocks in GMNP forested areas. This scenario allows all management actions (planting and harvesting) to occur with no restriction on volume targets in order to reach that maximum amount of carbon on the land base. Domestic harvesting was as usual limited to the designated harvest blocks.

(5) Scenario S_C5 maximumed harvesting in the designed harvest blocks without limits on the target volume or harvest area.

(6) The two final scenarios S_C7 and S_C8 provided comparisons of carbon stocks between the standard provincial model and the GMNP-adopted model; scenario S_C7 used a simple forest inventory projection. Scenario S_C8 used an objective function that maximize the sustainable harvest for both models.

4.3.5 Data Analysis

The model simulations were evaluated by tracking total growing stock (TGS), forest species composition, age-class structure, and carbon stocks for the entire ecosystem, biomass, and DOM. Impacts of management scenarios and moose browsing impacts were assessed by comparing the differences between each scenario.

4.4 Results

Scenarios S_C1 to S_C5 explored the varying forest management strategies on carbon storage using GMNP-specific carbon curves created from its strata-based volume yields. The projected TGS decreased by 19% (902,430 m^3) for domestic harvesting scenarios S_C2 and 4% (166,806 m^3) for maximizing harvest scenario S_C5 , in contrast to 31% (1,263,804 m^3) increase for the planting scenario S_C3, and 6% (43,188 m^3) increase for scenario S_C4 (Fig. 4-2).

The age-class structure for scenarios 1–5 at periods 5, 10 and 20 is presented in Fig. 4-3. At the end of the planning horizon (i.e., period 20 or 100 yrs) the domestic harvesting scenario S_C2 showed an increase in regenerating stands (ages 1–20), 11% greater than baseline levels, but a decrease in semi-mature (age 41–60), mature (61–80), and overmature stands (ages 81+) by 5, 7, and 4%, respectively. Young stands (ages 21–40) remained unchanged when compared to baseline levels. Planting (scenario

S_C3) did not change regeneration levels at the end of the planning horizon, when compared to baseline levels, but did show a nominal increase in 1% in young stands, 2% in semi-mature stands, a 7% increase in overmature stands, and a 1% decrease in mature stands. Maximizing carbon (S_C4) resulted in a 14% increase in regenerating stands, with no change in young stands. Semi-mature and mature stands decreased by 1% and 5%, while overmature stands increased by 2% over baseline levels. Maximizing harvest levels (S_C5) resulted in a 18% increase in regenerating stands and a 3% increase in young stands. Semi-mature, mature, and overmature decreased by 1, 6, and 5%, respectively, when compared to baseline levels.

The distribution of forest community types in the domestic harvesting scenario S_C2 decreased BS (4%) and SP (5%) , while increasing mixed hardwood (1%), fir-spruce (4%), and NSR(5%) above baseline (Fig. 4-4). Mixed softwood (MSW) and white birch (WB) stands remained at baseline levels. Planting scenario S_C3 resulted in increases in SP stratum types by 9% over the baseline, while maintaining BF, MHW, MSW, WB, and BFSP levels at baseline levels. Scenario S_C3decreased the amount of NSR to 1% across the total land base, a reduction of 8% when compared to the baseline scenario (Fig. 4-5). Maximizing carbon scenario S_C4 increased MHW (2%), MSW (3%), WB (1%), and BFSP (3%) forest communities over baseline levels, with 2, 2, and 3% decrease in BF, SP, and NSR, respectively. Scenario S_C5 resulted in a 6% decrease in BF and 8% decrease in NSR, but an increase of MHW (1%), MSW (1%), WB (2%), BFSP (4%), and SP (7%).

The historical block level scenario S_C2 produced sustainable maximum harvest levels of 95,351 m^3 (Fig. 4-6). Maximizing carbon (scenario S_C5) on the land base produced a sustainable harvest level of 31,673 m^3, while maximizing sustainable harvest levels which generated a harvest level of 152,324 m^3.

The amount of planting that occurred in each scenario was constrained to be equal throughout the entire planning horizon (even flow) and resulted in 886 ha of planting in scenario S_C3, 1517 ha in scenario S_C4, and 1,575 ha i planting in scenario S_C5 during each period (Fig. 4-7).

Biomass carbon experienced resulted in decreases for all scenarios except for one by the end of the planning horizon (Fig. 4-8). Domestic harvesting (S_C2) reduced biomass pools to 80% (575,180 tonne) of baseline levels (S_C1). Maximizing carbon (S_C4) lowered DOM stocks by 52,489 tonne (2%), and maximizing harvest levels (S_C5) reduced biomass carbon by 2% (52,489 tonne). Planting (S_C3) increased biomass carbon by 10% (286,770 tonne), when compared against baseline levels.

Historical domestic harvesting (S_C2) experienced a decline in biomass carbon of 3% (288,295 tonne) and 1% (126,351 tonne; Fig. 4-9). All other scenarios, maximizing planting (S_C3), maximizing harvest scenario (S_C5) and maximizing carbon storage scenario (S_C4) increased carbon by 7% (604,206 tonne), 16% (1,386,263 tonne), and 11% (1,008,175 tonne) over the planning time horizon.

Ecosystem carbon declined in domestic harvesting scenario S_C2 by 6% (863,475 tonne), while planting (S_C3), maximizing carbon (S_C4), and maximizing harvesting (S_C5) generated increases in ecosystem pools of 8% (890,976 tonne), 12% (1,333,774 tonne), and 6% (615,904 tonne) over baseline levels (Fig. 4-10).

The inventory projection in scenario S_C7 resulted in higher TGS in period one based on provincial yield curves, when compared to GMNP-based yields (1,092,027 *vs.*

1,147,700 m^3, respectively; Fig. 4-12). TGS estimated with GMNP model eventually surpassed estimates from the provincial standard model for the same area at period 4 and remained greater until period 13, where provincial curves overtook GMNP curves and remained greater until the end of the planning horizon. The maximum sustainable harvest scenario S_C8 also had initially higher estimates of TGS in period 1, when compared to provincial estimates (1,092,027 *vs.* 1,147,700 m^3; Fig. 4-12). GMNP estimates surpassed provincial levels at period 3 and remained greater until period 12, when provincial estimates exceeded GMNP estimates and remained higher through to the end of the planning horizon. The TGS for both GMNP and provincial carbon models in scenario S_C8 decreased steady across the planning horizon and resulted in a level that was significantly lower than that achieved with scenario S_C7 at period 20; i.e., 902,217 m^3 lower with the GMNP model and 924,296 m^3 lower with the provincial model (Fig. 4-13). In scenario S_C8, GMNP maximum sustainable harvest level was found to be 95,351 m^3 in scenarios S_C8, while the maximum sustainable harvest for the provincial model was 120,979 m^3 (Fig. 4-13).

The inventory projection in scenario S_C7 resulted in an increase in DOM carbon across both GMNP and provincial models (Fig. 4-14) by the end of the planning horizon. GMNP and provincial carbon models estimated DOM-carbon content to be 1,712,994 and 1,740,445 tonne, respectively at period 1. However, the provincial model estimate of DOM was 301,347 tonne greater than GMNP estimates (2,347,319 *vs.* 2,045,972 tonne) by the end of the planning horizon. The provincial model for scenario S_C8 also resulted in higher estimates of DOM, when compared against GMNP-model results through the entire planning horizon (Fig. 4-14). At period 20, the provincial model estimated the forest ecosystem to contain 2,385,899 tonne of DOM carbon, whereas the GMNP model estimated 1,759,394 tonne of DOM carbon.

Biomass carbon in both scenarios S_C7 and S_C8 for both GMNP and provincial models experienced a net decline across the planning horizon (Fig. 4-15). Using inventory projections, GMNP biomass carbon resulted in a 47,731 tonne decline from a period 1 level of 750,796 tonne; the provincial model resulted in a 53,136 tonne decline from a period 1 level of 561,265 tonne. Estimates of the maximum sustainable harvest in scenario S_C8 resulted in a decline of 547,477 tonne of biomass-based carbon in the GMNP model, while the provincial model estimated a loss of 327,952 tonne by the end of the planning horizon.

Ecosystem carbon increased in both GMNP and provincial models during the inventory projection for scenario S_C7 (Fig. 4-16). The model resulted in a 285,447 tonne increase in total ecosystem carbon, while the provincial model estimated a 660,009 tonne increase in carbon by the end of the planning horizon. The provincial model, however, estimated 212,683 tonne more carbon than the GMNP model, i.e., 2,961,720 *vs.* 2,749,037 tonne. The GMNP model, with a maximum sustainable harvest objective found in scenario S_C8, resulted in a decline of 451,469 tonne of ecosystem carbon across the planning horizon and ended the scenario run with a total of 1,888,501 tonne of total ecosystem carbon. The provincial model gave an increase of 275,079 tonne of total ecosystem carbon during the same time frame and resulted in 2,574,102 tonne of total ecosystem carbon at the end of the planning horizon; this represents 685,601 tonne more ecosystem carbon than the total generated with the GMNP model.

4.5 Discussion

This study found by decreasing TGS through harvesting, disturbance, or moose browsing the total forest ecosystem carbon stock estimated was lowered for the GMNP forested ecosystem (Fig. 4-8 to 4-10 and 4-13 to 4-16). The reduction in carbon stocks by lowering inventory volumes has been observed in other studies when carbon curves are built on merchantable forest yield information that emphasize the fact that forest yields have a direct impact on all carbon pools (Luckai et al., 2012; Remsoft, 2016; Natural Resources Canada, 2013). This relationship between volume and carbon was also highlighted in a study by Neilson et al. (2008) that displayed a reduction in total ecosystem carbon, when harvest levels were doubled for a particular area. Still another study by Hennigar and Maclean (2010) found that total carbon was reduced following a reduction in volume after insect disturbance.

Forest ecosystems has also been shown to increase carbon storage through silviculture treatments (Neilson et al., 2008). In this study, all planting scenarios (i.e., scenarios S_C3 to S_C5) resulted in an increase of forest ecosystem carbon stocks between 6–12% (Fig. 4-8 to 4-10). Surprisingly, scenario S_C5 increased ecosystem carbon by 6%, while maintaining a much greater harvest level than held historically. This increase may be related to the following factors: (1) plantations increased TGS by 4% (166,806 m^3) over baseline levels, and by association greater amounts of carbon are available on the land base (Luckai et al., 2012); and/or (2) plantations have increased across the forested land base, which tend to serve as large carbon sinks (Fig. 4-3; Jandl et al., 2007).

Our results indicate that maximizing carbon storage within GMNP can be achieved while still meeting or improving timber volume and forested ecosystem integrity. The ability to meet forest management objectives and still improve carbon storage aligns with the study of Neilson et al. (2008) that found that it is possible to both actively manage a forested land base and provide opportunities to enhance carbon storage. Maximizing carbon in GMNP produced a 12% increase in carbon storage over the baseline levels, while still providing a sustainable even-flow harvest level of 31,673 m^3 throughout the entire planning horizon (Figs. 4-6 and 4-10). When this harvest level is compared against the actual domestic harvest rates recorded in the park from 1993-2015 we see that the sustainable even-flow harvest level represents an increase of 28,541 m^3 over the amount actually harvested and suggests that maximizing carbon storage will provide ongoing domestic harvesting opportunities that do not adversely impact forest sustainability.

Maximizing carbon within GMNP improved the percentage of nearly all forest strata types, including MHW, MSW, WB, BFSP, and SP. Balsam fir strata types and non-regenerating sites (NSR) are the only forest types that resulted in a decrease because of maximizing carbon objective (Figs. 4-4 and 4-5). Our study indicates that the decrease in BF was a consequence of poor regeneration success of BF following moose browsing, while the decrease in NSR levels can be attributed to the regeneration success of forest due to planting and increases in other plant species that moose find less palatable (Zhu et al., 2010). Improvements in hardwood types and mixedwood types, would be achieved by an optimization model that increases carbon stocks simply because hardwoods store more carbon than softwoods (Neilson et al., 2008), and as such the increase in these forest types improves the percentage distribution and total percentage cover of forest strata types within GMNP.

4.6 Concluding remarks

Our model runs indicate that using historical disturbance levels of harvesting carbon stores within GMNP forested ecosystem will decrease, shifting GMNP carbon status to a net source. Planting as a management strategy can replace the loss of forest cover and mitigate degradation of forest integrity due to hyper-excessive browsing and transition of the park to a net carbon sink. When carbon is set as a management objective, it is possible to meet the key management objectives of the park, including maintaining a healthy forest ecosystem, providing opportunities for harvesting and carbon sequestration.

4.7 References

Connor, K. J., Ballard, W. B., Dilworth, T., Mahoney, S., and Anions, D. (2000). Changes in structure of a boreal forest community following intense herbivory by moose. Alces, 111–132.

Gustafson, E. J., and Crow, T. R. (1996). Simulating the effects of alternative forest management strategies on landscape structure. Journal of Environmental Management, 46, 77–94. doi:10.1006/jema.1996.0008

Hennigar, C. R., and MacLean, D. A. (2010). Spruce budworm and management effects on forest and wood product carbon for an intensively managed forest, Canada. Canadian Journal of Forest Research, 40(9), 1736-1750. Doi: 10.1139/x10-104

Hobbs, N. T., Schimel, D. S., Owensby, C. E., and Ojima, D. S. (1991). Fire and grazing in the tallgrass prairie: contingent effects on nitrogen budget. Ecology, 72(4), 1374–1382. doi:10.2307/1941109

Humber, J. (2009). Non-native plant invasions of boreal forest gaps: implications for stand regeneration in a protected area shaped by hyperabundant herbivores. M.S. thesis, Department of Biology, Memorial University of Newfoundland, St. John’s.

Jandl, R., Vesterdal, L., Olsson, M., Bens, O., Badeck, F., and Rock, J. (2007). Carbon sequestration and forest management. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 2(17), 1–16

Jeffries, R. L., Jensen, A., and Abraham, K. F. (1979). Vegetational development and the effect of geese on vegetation at La Perouse Bay, Manitoba, Canada. Canadian Journal of Botany, 57: 1439–1450. doi:10.1139/b79-178

Kurz, W. A., and Apps, M. J. (1995). An analysis of future carbon budgets of Canadian boreal forests. In Boreal Forests and Global Change (pp. 321–331). Springer, Dordrecht. doi: 10.1007/978-94-017-0942-2_32

Kurz, W. A., and Apps, M. J. (1999). A 70-year retrospective analysis of carbon fluxes in the Canadian forest sector. Ecological applications, 9(2), 526–547. doi:10.1890/1051-0761(1999)009[0526:ayraoc]2.0.co;2

Kurz, W. A., Shaw, C. H., Boisvenue, C., Stinson, G., Metsaranta, J., Leckie, D., and Neilson, E. T. (2013). Carbon in Canada’s boreal forest—a synthesis. Environmental Reviews, 21(4), 260–292. doi: 10.1139/er-2013-0041

Kurz, W. A., Dymond, C. C., White, T. M., Stinson, G., Shaw, C. H., Rampley, G. J., and Metsaranta, J. (2009). CBM-CFS3: a model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecological modeling, 220(4), 480–504. doi: 10.1016/j.ecolmodel.2008.10.018

Kurz, W. A., Stinson, G., Rampley, G. J., Dymond, C. C., and Neilson, E. T. (2008). Risk of natural disturbances makes future contribution of Canada's forests to the global carbon cycle highly uncertain. Proceedings of the National Academy of Sciences, 105(5), 1551–1555. doi:10.1073/pnas.0708133105

Lambert, M. C., Ung, C. H., and Raulier, F. (2005). Canadian national tree aboveground biomass equations. Canadian Journal of Forest Research, 35(8), 1996–2018. doi:10.1139/x05-112

Lee, J., Morrison, I. K., Leblanc, J. D., Dumas, M. T., and Cameron, D. A. (2002). Carbon sequestration in trees and regrowth vegetation as affected by clearcut and partial cut harvesting in a second-growth boreal mixedwood. Forest Ecology and Management, 169(1–2), 83–101. doi:10.1016/s0378-1127(02)00300-6

Luckai, N., Larocque, G. R., Archambault, L., Paré, D., Boutin, R., and Groot, A. (2012). Using the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) to examine the impact of harvest and fire on carbon dynamics in selected forest types of the Canadian Boreal shield. The Forestry Chronicle, 88(4), 426–438. doi:10.5558/tfc2012-079

Mathisen, K.M., Milner, J.M., Skarpe, C. (2017). Moose-tree interactions: rebrowsing is common across tree species. BMC Ecology, 17(1) ,12. doi:10.1186/s12898-017-0122-3

McNaughton, S. J. (1979). Grassland-herbivore dynamics. In A. R. Sinclaire, and M. Norton-Griffins, Serengeti: dynamics of an ecosystem. (pp. 46–81). Chicago, Illinois: University of Chicago Press.

Metsaranta, J. M., Kurz, W. A., Neilson, E. T., and Stinson, G. (2010). Implications of future disturbance regimes on the carbon balance of Canada's managed forest (2010–2100). Tellus B: Chemical and Physical Meteorology, 62(5), 719–728. doi: 10.1111/j.1600-0889.2010.00487.x

Milligan, H.T and Koricheva, J. (2013). Effects of tree species richness and composition on moose winter browsing and foraging selectivity: an experimental study. Journal of Animal Ecology, 82: 739–748. doi:10.1111/1365-2656.12049

Moroni, M. T., Shaw, C. H., and Otahal, P. (2010). Forest carbon stocks in Newfoundland boreal forests of harvest and natural disturbance origin I: field study. Canadian journal of forest research, 40(11), 2135–2145. doi:10.1139/x10-154

Natural Resources Canada. (2013). Instructions for using the Carbon Curve Project Creator Plug-in. Northern Forestry Centre: Natural Resources Canada.

Neilson, E. T., MacLean, D. A., Meng, F. R., Hennigar, C. R., and Arp, P. A. (2008). Optimal on-and off-site forest carbon sequestration under existing timber supply constraints in northern New Brunswick. Canadian Journal of Forest Research, 38(11), 2784–2796. doi:10.1139/X08-120

Paster, J., Moen, R. A., and Cohen, Y. (1997). Spatial heterogeneities, carrying capacity, and feedbacks in animal landscape interactions. Journal of Mammalogy, 78:1040–1052. doi:10.2307/1383047

Remsoft. (2016). Spatial Woodstock user guide. Fredericton, NB: Remsoft Inc.

Shifley, S.R., Hong, S.H., Lischke, H., Wang, W.J., Wenchi, J., Gustafson, E.J., Thompson, J.R., Thompson, F.R.III, William, D.D., Yang, J. (2017). The past and future of modeling forest dynamics: from growth and yield curves to forest landscape models. Landscape Ecology, 32(7), 1307–1325. doi:10.1007/s10980-017-0540-9

Smith, R., Smith, M., Clifford, P., and Bellemore, C. (2015). Hyperabundant Moose Management Plan for North Mountain, Cape Breton Highlands National Park. Ingonish Beach, NS: Parks Canada Agency.

Tomppo, E., Olsson, H., Stahl, G., Nilsson, M., Hagner, O., and Katila, M. (2008). Combining national forest inventory field plots and remove sensing data for forest databases. Remote Sensing of Environment, 1982–1999. doi:10.1016/j.rse.2007.03.032

Vanclay, J. (2002). Forest Growth and Yield Modeling. In El-Shaarawi, A., Piegorsch, W. Enclyclopaedia of Environmetrics (pp. 811–812). NY: Wiley. doi:10.1002/9780470057339.vaf011

Zhu, X., Bourque, C. P., Taylor, S., Cox, R., and Wentzell, C. (2010). Predicting the effects of woodcutting and moose browsing on forest development in Gros Morne National Park, Newfoundland, Canada. The Forestry Chronicle, 86(2), 178–192. doi:10.5558/tfc86178-2

Table 4-1 Wood supply model parameters adapted from the provincial wood supply base model

Model Parameters	Value Ranges
Planning horizon	160 years
Harvest Flow Constraints	Even-flow Harvest
Management Objective	Maximum Harvest Level
Minimum Harvest Age	> 25 years old
Planning time Step	5 years per period
Natural succession Ages	120 years as determined by sample plots
NSR regeneration lag	25years

Table 4-2. GMNP specific transition rules derived from 2005 and 2016 regeneration-survey data, displaying the percentage of species expected to regenerate following stand succession in a heavy browsing. The provincial transition rules due to the long-term moose population control in the provincial forest were used by the light moose browsing scenario which is assumed to be achieved by GMNP through its recently launched moose population control program

Source	Ecoregions	Regenerating Species (%)
GMNP	Northern	bF(21), bS(3), tL(1), wB(26), wS(4), NSR(45)
	Western	bF(28), bS(3),rM(1), wB(24), wS(10), NSR(33)
Province	Both	bF(60), bFsP(10), MSW(15), MHW(3), wB(2), NSR(10)

bF = balsam fir; bS = black spruce; bFsP = fir spruce; rM = red maple; tL = eastern larch; wB = white birch; wS = white spruce; MSW = mixedwood with softwood leading; MHW = mixedwood with hardwood leading; NSR = "not sufficiently regenerated"

Table 4-3. Gros Morne National Park strata based ($m^3 ha^{-1}$) represented by combinations of stratum, ecoregion and site class yield curves. GMNP-based yield curves were generated from a combination of GMNP-TSP data for ecoregions intersecting with park boundaries.

Strata	Ecoregion	Site	Age (Years)																		
			20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
MHW	NW	G	5	17	52	89	121	139	147	148	144	136	126	115	104	93	83	74	65	58	52
	NW	MP	3	10	29	50	69	79	84	85	82	78	72	66	59	53	46	41	36	31	27
wB	NW	All	3	10	30	52	71	83	90	92	90	87	81	75	68	62	55	49	44	39	34
MSW	NW	All	7	24	66	105	132	153	163	165	161	153	142	129	116	103	91	80	69	60	52
bF	W	G	10	32	89	140	177	197	204	201	190	175	157	139	122	105	91	78	66	57	49
	W	MP	8	26	72	114	143	160	166	164	155	143	129	114	100	86	74	63	53	45	37
	N	G	9	29	81	127	160	180	185	181	170	154	137	120	103	88	74	62	51	42	35
	N	MP	8	26	71	113	142	161	169	167	159	146	131	116	100	86	73	61	51	42	35
bFsP	W	G	8	26	71	112	141	159	167	165	156	144	130	115	101	87	74	63	53	45	37
	W	MP	5	17	49	79	103	113	116	112	105	95	85	75	64	55	47	39	33	27	23
	N	G	28	49	82	103	117	126	130	130	127	122	117	111	105	99	93	87	81	76	71
	N	MP	4	12	36	62	84	97	104	105	103	97	90	83	74	66	59	51	45	39	33
sP	W	All	3	10	31	55	77	96	110	120	125	128	127	124	119	113	106	98	90	82	74
	N	All	4	9	25	44	63	79	92	102	108	111	111	109	106	101	95	89	83	76	70

bF = balsam fir; sP = Spruce; bFsP = fir spruce; wB = white birch;

MSW = mixedwood with softwood leading; MHW = mixedwood with hardwood leading

N = Northern Ecoregion; W = Western Ecoregion; NW = Northern and Western Ecoregion

G = Good Site; MP = Medium and Poor Sites; All = All Sites

Table 4-4. GMNP strata base carbon biomass yield curves (tonne ha^{-1}) represented by combinations of stratum, ecoregion and site class.

Strata	Ecoregion	Site	Age (Years)										
			10	20	30	40	50	60	70	80	90	100	110
wB	NW	All	1.6	7.7	19.6	36.7	52.7	64.5	72.3	76.6	78.6	78.7	77.5
MHW	NW	G	1.7	8.8	23.8	46.4	69.0	86.6	98.1	103.7	105.6	104.7	101.9
		MP	1.6	7.8	20.0	37.3	54.9	68.3	77.4	82.7	85.4	86.0	85.0
MSW	NW	All	2.2	11.2	28.8	54.5	78.0	93.9	104.4	111.0	113.7	113.1	110.4
bF	N	G	2.4	12.6	29.8	52.5	70.8	83.6	91.4	95.0	95.0	92.6	88.6
		MP	2.6	12.9	30.0	50.0	66.7	78.4	85.8	89.8	90.5	89.0	85.7
	W	G	2.3	12.7	30.5	54.7	74.3	88.1	96.4	100.3	100.7	98.5	94.6
		MP	2.5	12.7	29.9	50.2	67.0	78.7	85.8	89.2	89.6	87.9	84.7
bFsP	N	G	6.6	22.4	40.9	57.4	66.8	72.6	76.3	78.2	78.7	78.2	77.0
		M	2.5	11.1	24.2	38.7	50.3	59.7	66.0	69.3	70.6	70.4	69.0
		P	2.9	11.9	25.0	38.9	49.9	58.2	63.8	67.1	68.6	68.6	67.5
	W	G	2.6	12.8	29.9	49.9	66.4	78.0	85.4	89.2	89.8	88.3	85.1
		MP	2.4	11.6	26.5	43.1	56.5	66.3	72.0	74.0	73.7	71.9	69.1
sP	N	All	2.7	10.4	21.5	33.4	43.1	51.6	58.8	64.4	68.6	71.4	73.0
	W	All	2.2	9.8	21.6	35.2	47.0	56.8	64.6	70.6	74.8	77.4	78.8

bF = balsam fir; sP = Spruce; bFsP = fir spruce; wB = white birch;

MSW = mixedwood with softwood leading; MHW = mixedwood with hardwood leading

N = Northern Ecoregion; W = Western Ecoregion; NW = Northern and Western Ecoregion

G = Good Site; MP = Medium and Poor Sites; All = All Sites

Table 4-5. GMNP strata base carbon DOM yield curves (tonne ha^{-1}) represented by combinations of stratum, ecoregion and site class.

Strata	Ecoregion	Site	Age (Years)										
			10	20	30	40	50	60	70	80	90	100	110
wB	NW	All	244	226	221	223	232	241	250	258	266	273	279
MHW	NW	G	336	314	308	314	326	339	352	364	374	384	393
		MP	291	273	269	274	285	296	307	318	327	336	344
MSW	NW	All	358	336	330	337	349	362	374	386	397	406	416
bF	L	All	163	148	142	141	141	143	144	145	147	149	152
	N	G	177	160	153	152	152	153	154	155	157	160	163
		MP	172	155	149	147	148	148	150	151	152	154	158
	W	G	186	167	160	158	158	158	159	161	162	165	168
		MP	170	154	148	147	147	148	149	150	152	154	157
bFsP	L	G	165	151	146	146	146	147	148	149	150	151	154
		MP	154	142	137	137	138	139	140	141	142	144	146
	N	G	163	150	146	146	146	146	147	148	148	149	151
		M	143	130	125	125	126	127	129	130	132	133	135
		P	141	129	124	124	125	126	128	129	130	132	134
	W	G	171	154	148	147	147	148	149	150	152	154	157
		MP	147	134	129	129	130	131	133	135	136	139	141
sP	N	All	145	131	125	123	123	124	125	126	127	129	130
	W	All	153	138	131	129	129	129	130	132	133	135	136

bF = balsam fir; sP = Spruce; bFsP = fir spruce; wB = white birch;

MSW = mixedwood with softwood leading; MHW = mixedwood with hardwood leading

N = Northern Ecoregion; W = Western Ecoregion; NW = Northern and Western Ecoregion

G = Good Site; MP = Medium and Poor Sites; All = All Sites

Table 4-6. GMNP strata base carbon total ecosystem yield curves (tonne ha^{-1}) represented by combinations of stratum, ecoregion and site class

Strata	Ecoregion	Site	Age (Years)										
			10	20	30	40	50	60	70	80	90	100	110
wB	NW	All	245	234	240	260	284	305	322	335	345	351	357
MHW	NW	G	337	323	332	361	395	425	450	468	480	489	495
		MP	292	281	289	311	340	364	385	401	413	422	429
MSW	NW	All	360	347	359	392	427	456	479	497	510	520	526
bF	N	G	180	173	183	204	223	236	245	250	252	252	252
		MP	174	168	179	197	214	227	235	241	243	243	243
	W	G	188	180	190	213	232	247	256	261	262	263	263
		MP	173	167	178	197	214	227	235	240	241	242	242
bFsP	N	G	169	173	187	203	213	219	223	226	227	228	228
		M	146	141	149	163	176	187	195	199	202	203	204
		P	144	141	149	163	175	184	191	196	199	200	201
	W	G	173	167	178	196	213	226	234	240	241	242	242
		MP	149	145	155	172	186	198	205	209	210	211	211
sP	N	All	147	141	147	157	166	175	183	190	196	200	203
	W	All	155	148	153	164	176	186	195	202	208	212	215

bF = balsam fir; sP = Spruce; bFsP = fir spruce; wB = white birch;

MSW = mixedwood with softwood leading; MHW = mixedwood with hardwood leading

N = Northern Ecoregion; W = Western Ecoregion; NW = Northern and Western Ecoregion

G = Good Site; MP = Medium and Poor Sites; All = All Sites

Table 4-7. Domestic harvest levels within GMNP harvest blocks from 1993 to 2015

	Cubic Metres Harvested by Block										
	BL 1	BL 3	Bl 4	Bl 5	Bl 6a	Bl 6B	Bl 7A	Bl 7B	Bl 8	Bl 9	Total
1993	9	1758	2535	0	52	302	45	0	1426	838	6964
1994	45	1938	2004	0	61	254	0	24	1129	610	6066
1995	104	657	1235	38	50	203	284	98	676	982	4326
1996	0	365	971	4	0	140	65	0	324	52	1920
1997	21	635	707	0	41	221	91	101	825	640	3281
1998	0	671	603	101	75	159	94	0	339	626	2667
1999	0	995	420	280	31	150	52	0	237	296	2462
2000	0	988	477	496	0	129	38	0	667	534	3329
2001	20	1515	492	119	0	161	35	5	871	634	3851
2002	0	1191	616	391	5	13	39	0	804	320	3380
2003	309	1212	1212	316	33	53	45	0	909	584	4673
2004	0	1114	603	163	0	100	38	112	928	725	3784
2005	127	862	520	27	0	48	34	128	218	452	2416
2006	0	1037	640	0	0	12	0	181	297	499	2666
2007	82	1105	783	0	0	0	32	115	593	571	3281
2008	79	1126	443	0	4	95	0	112	243	338	2439
2009	192	1388	345	0	0	138	0	89	206	431	2788
2010	0	315	1021	4	4	13	0	9	23	118	1507
2011	0	802	514	13	5	10	0	0	180	291	1816
2012	0	813	370	0	0	7	0	0	127	386	1702
2013	0	979	215	0	0	18	0	48	186	462	1908
2014	216	860	545	0	0	38	0	14	332	432	2437
2015	245	726	488	0	0	32	94	127	367	291	2371
total	1449	23051	17760	1954	360	2298	985	1162	11905	11111	72035

Table 4-8. Modeling objectives and constraints for the S_C1 - baseline, S_C2 - Domestic harvesting, S_C3 - Wind disturbance, S_C4 - Planting, S_C5 - Maximize Carbon, S_C6 - Maximize Harvesting wood supply scenarios.

Constraint	S_C1 - Base	S_C2 - DH	S_C3 - Plant	S_C4 - Max Carbon	S_C5 - Max Harvest
Harvesting	--	Even Flow	--	Even Flow	
Planting	--	--	Even Flow	Even Flow	Even Flow
Maximize Function	TGS[1]	Harvest	Planting	Carbon	Harvest

[1] *Total growing Stock*

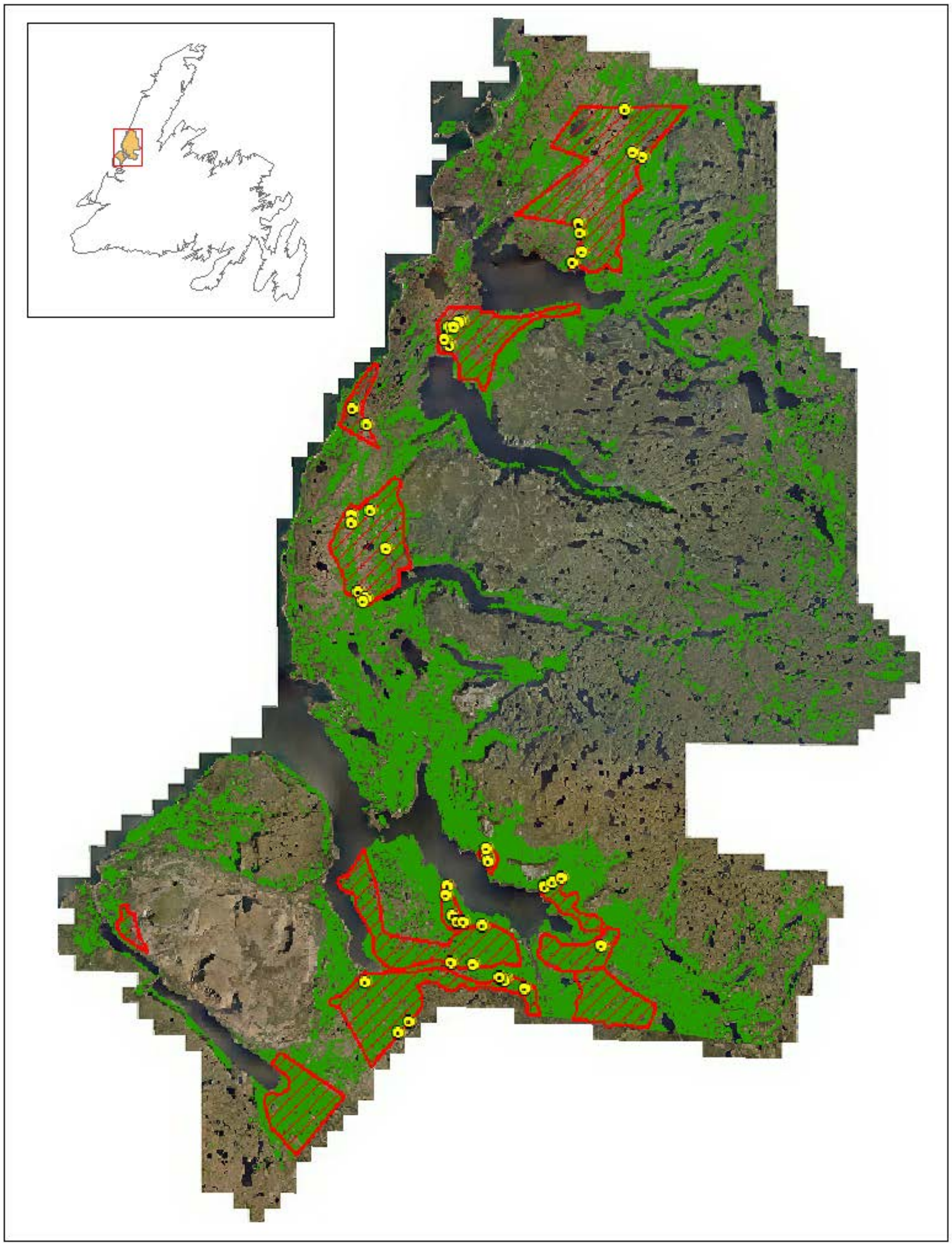

Figure 4-1. Locations of GMNP domestic harvest blocks (red), displaying their positions within the productive forest zone within the park. Regeneration-survey plots are displayed as yellow dots.

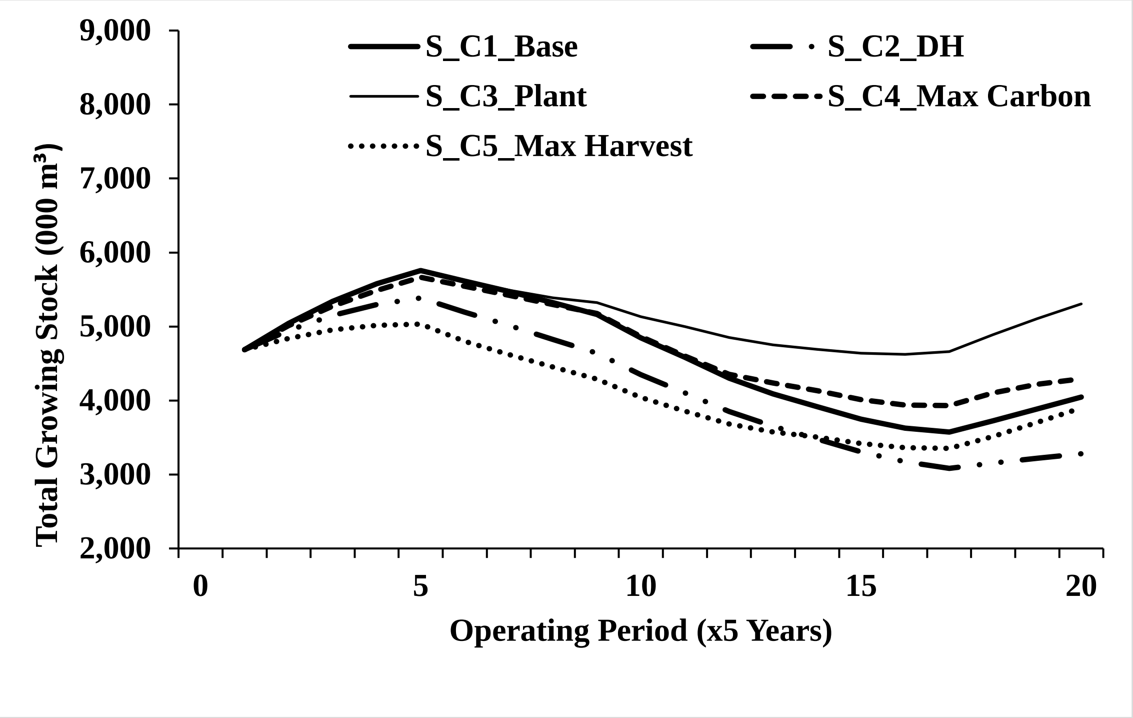

Figure 4-2. Total Growing stock changes from modeling combination of forest management objectives including domestic harvesting (S_C2_DH), planting (S_C3_Plant), maximizing carbon (S_C4_Max Carbon), and maximizing harvest level (S-C5_MaxHarvest), compared against a base scenario (S_C1_Base). Refer to Table 4-8 for scenario description

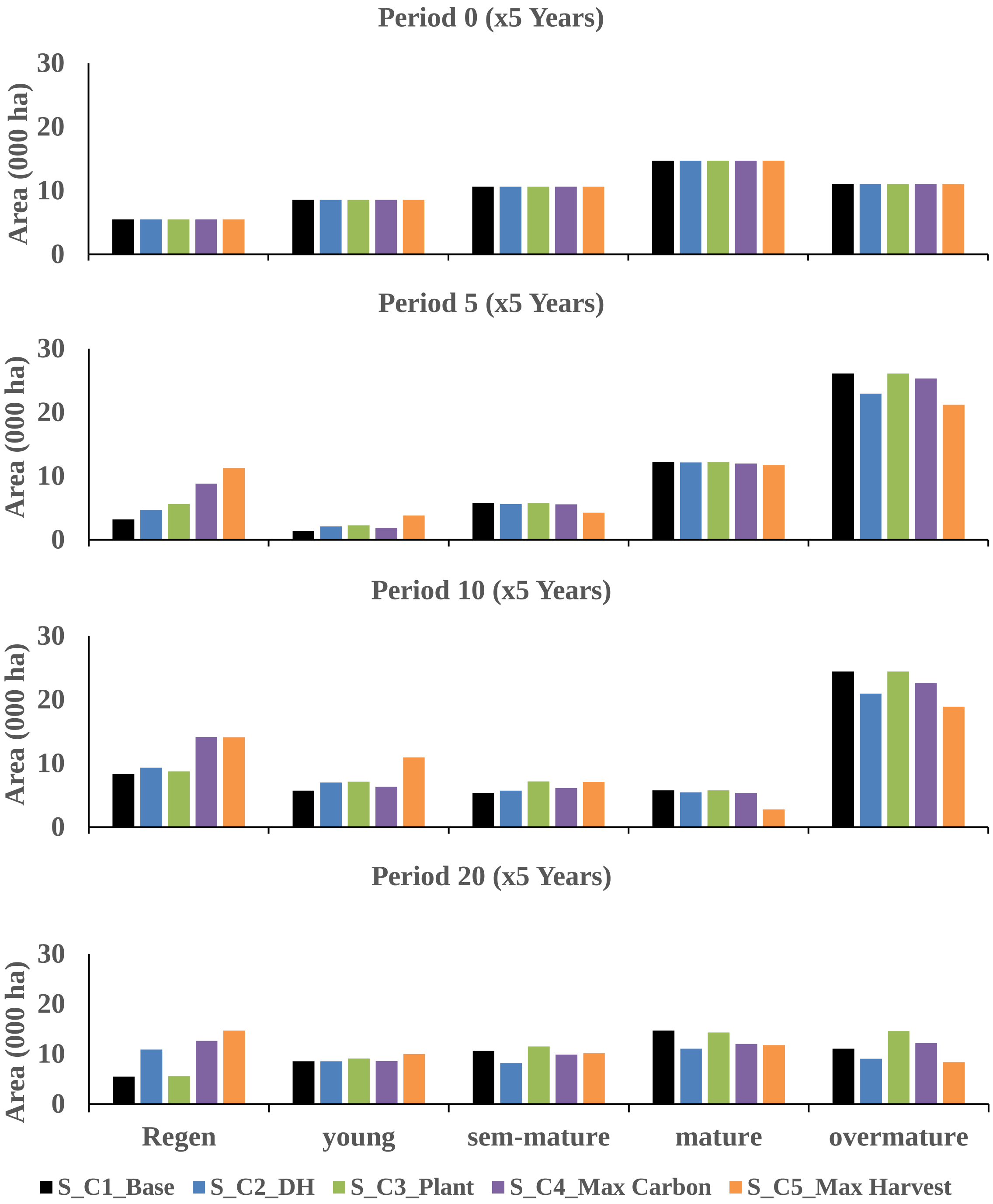

Figure 4-3. Area in each development stage indicating age class structure for periods 0, 5, 10 and 20 from modeling combination of forest management objectives including domestic harvesting (S_C2_DH), planting (S_C3_Plant), maximizing carbon (S_C4_Max Carbon), and maximizing harvest level (S-C5_MaxHarvest), compared against a base scenario (S_C1_Base). Refer to Table 4-8 for scenario description

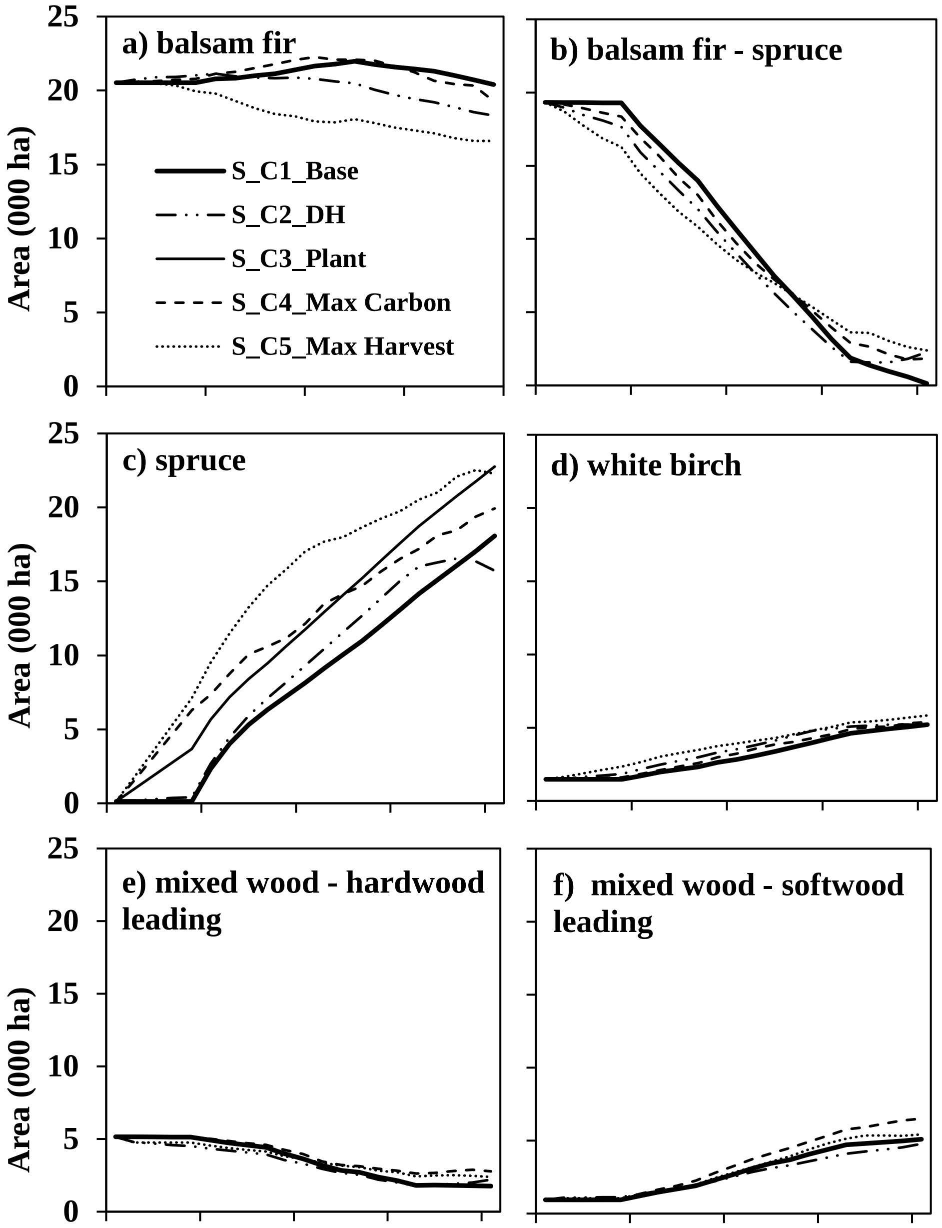

Figure 4-4. Area of balsam fir, balsam fir-spruce, spruce, white birch, mixedwood with hardwood leading and mixedwood with softwood leading forests under forest management scenarios including domestic harvesting (S_C2_DH), planting (S_C3_Plant), maximizing carbon (S_C4_Max Carbon), and maximizing harvest level (S-C5_MaxHarvest), compared against a base scenario (S_C1_Base). Refer to Table 4-8 for scenario description.

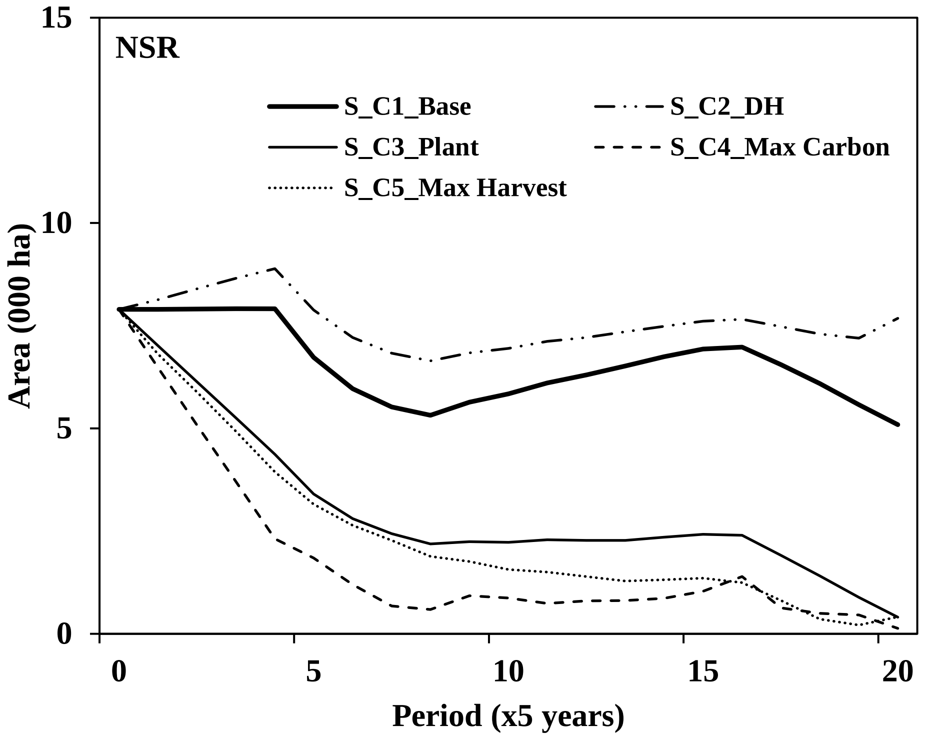

Figure 4-5. “Not sufficiently regenerated” (NSR) area under forest management scenarios including domestic harvesting (S_C2_DH), planting (S_C3_Plant), maximizing carbon (S_C4_Max Carbon), and maximizing harvest level (S-C5_MaxHarvest), compared against a base scenario (S_C1_Base). Refer to Table 4-8 for scenario description.

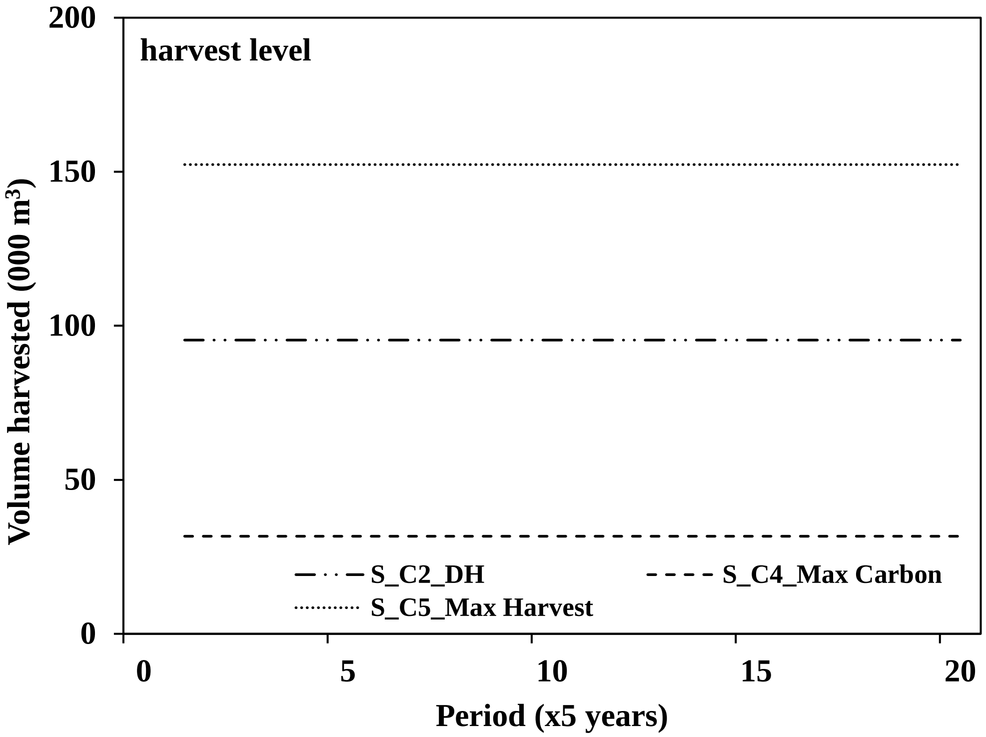

Figure 4-6. Sustainable even flow harvest level under forest management scenarios where harvesting is permitted including domestic harvesting (S_C2_DH), maximizing carbon (S_C4_Max Carbon), and maximizing harvest level (S_C5_Max Harvest). Refer to Table 4-8 for scenario description.

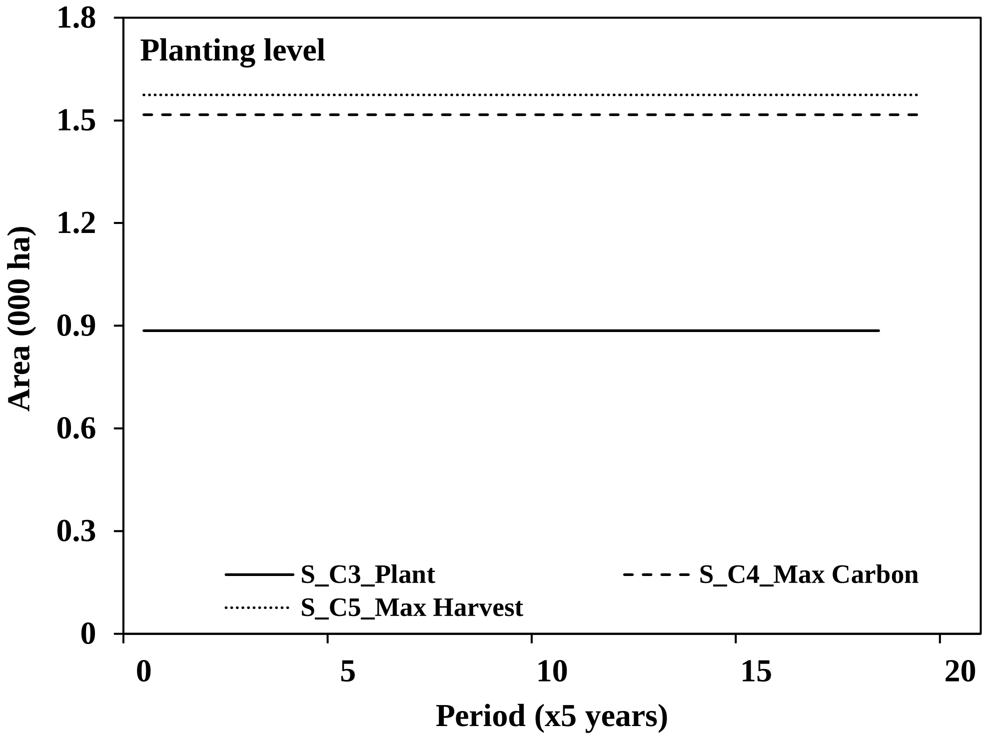

Figure 4-7. Planted area under forest management where planting is permitted including scenarios for planting (S_C3_Plant), maximizing carbon (S_C4_Max Carbon), and maximizing harvest level (S_C5_MaxHarvest. Refer to Table 4-8 for scenario description.

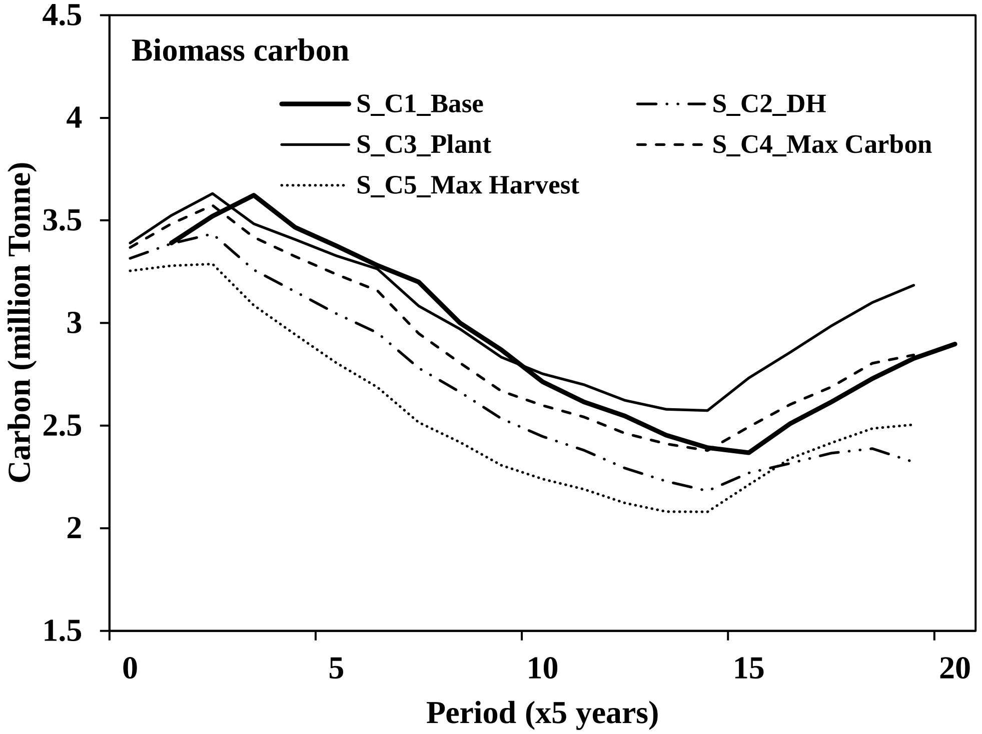

Figure 4-8. Total biomass carbon under forest management scenarios including domestic harvesting (S_C2_DH), planting (S_C3_Plant), maximizing carbon (S_C4_Max Carbon), and maximizing harvest level (S-C5_MaxHarvest), compared against a base scenario (S_C1_Base). Refer to Table 4-8 for scenario description.

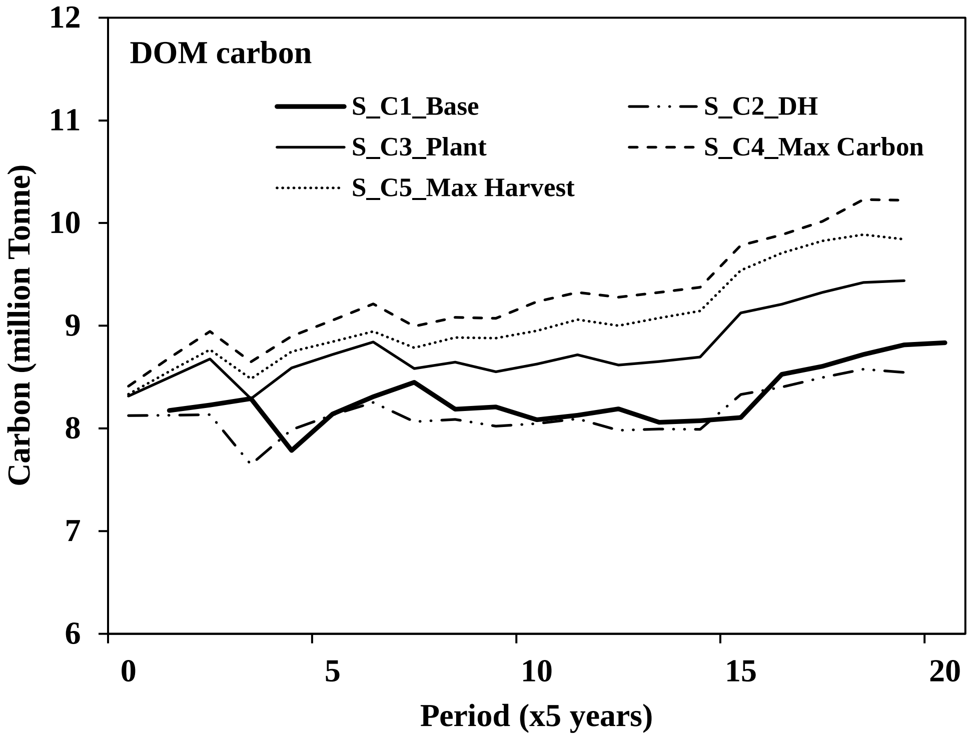

Figure 4-9. Total Dead Organic Material (DOM) carbon under forest management scenarios including domestic harvesting (S_C2_DH), planting (S_C3_Plant), maximizing carbon (S_C4_Max Carbon), and maximizing harvest level (S-C5_MaxHarvest), compared against a base scenario (S_C1_Base). Refer to Table 4-8 for scenario description.

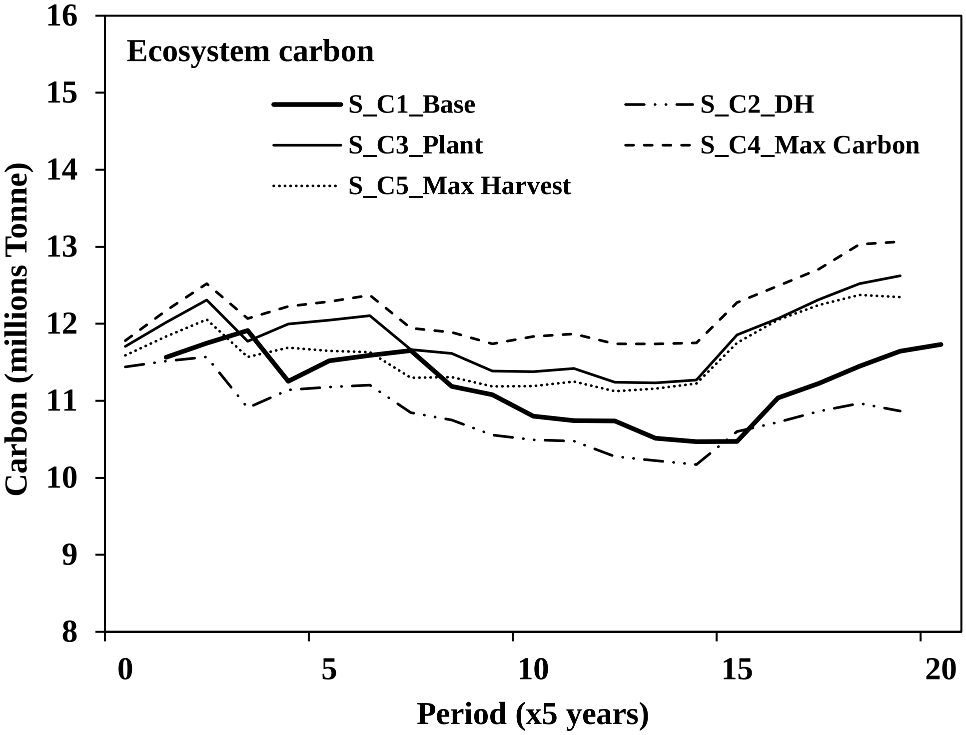

Figure 4-10. Total ecosystem carbon under forest management scenarios including domestic harvesting (S_C2_DH), planting (S_C3_Plant), maximizing carbon (S_C4_Max Carbon), and maximizing harvest level (S-C5_MaxHarvest), compared against a base scenario (S_C1_Base). Refer to Table 4-8 for scenario description.

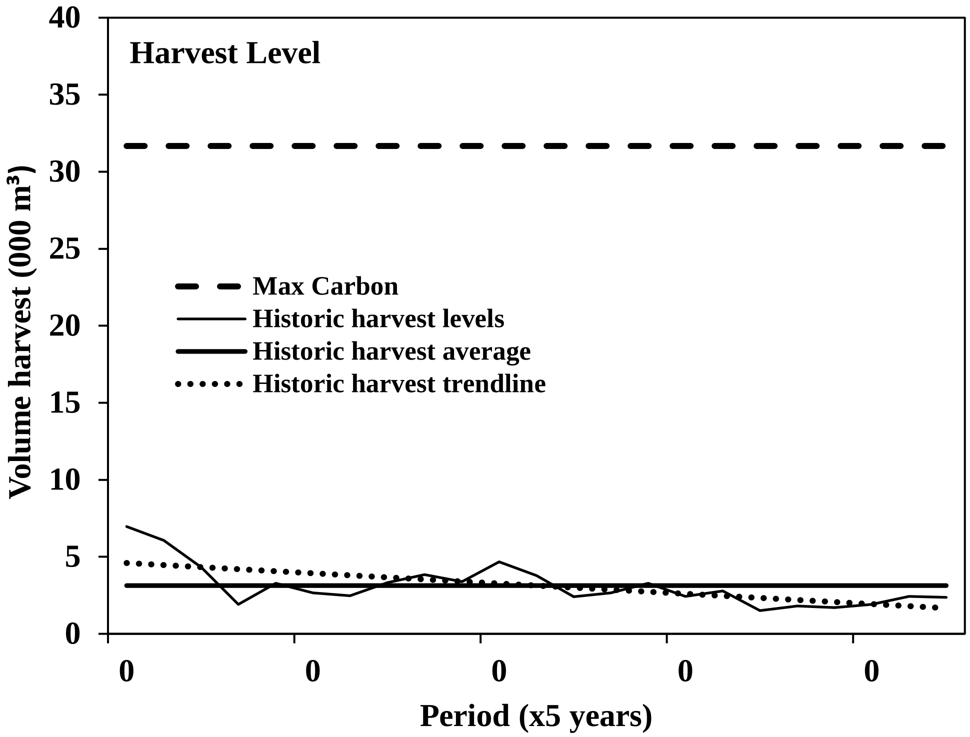

Figure 4-11. Harvest levels comparison between historical total harvest levels within GMNP harvest blocks, the average historical level, the historical harvest level trendline, and maximizing carbon storage on the GMNP land base.

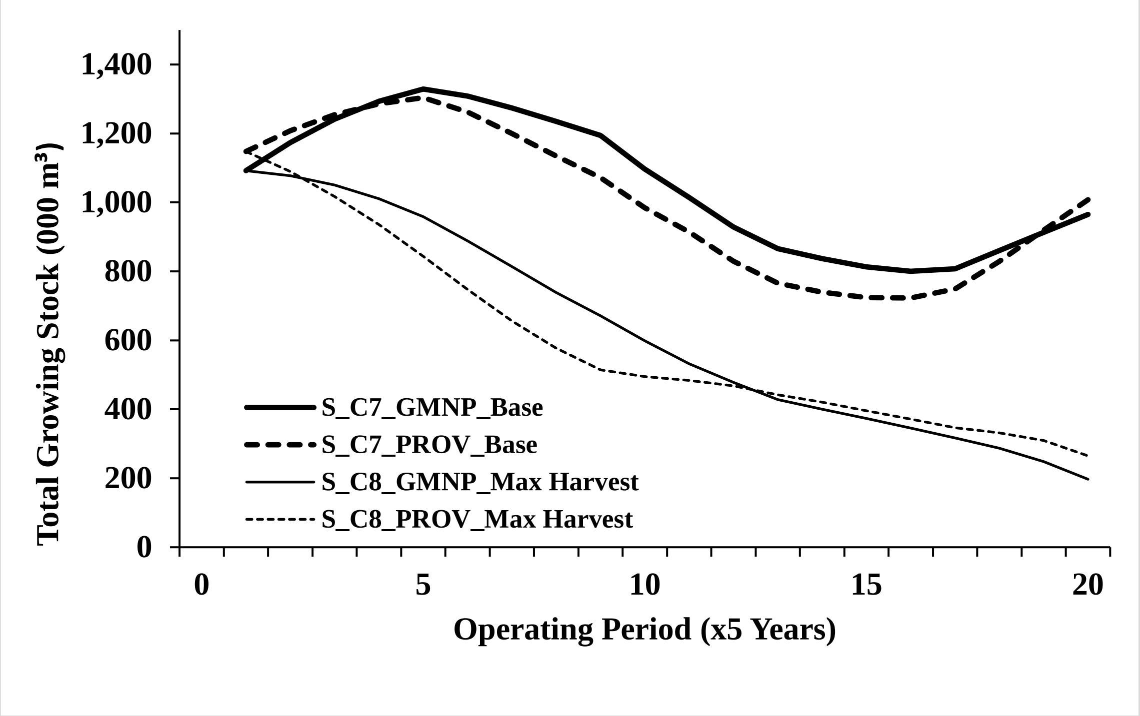

Figure 4-12. Total Growing stock comparisons between GMNP specific model and the provincial standard model from modeling combination of forest management objectives including a base inventory projection scenario (S_C7) and maximum sustainable harvest level scenarios (S_C8). GMNP assumes heaving moose browsing while provincial model assumes light moose browsing.

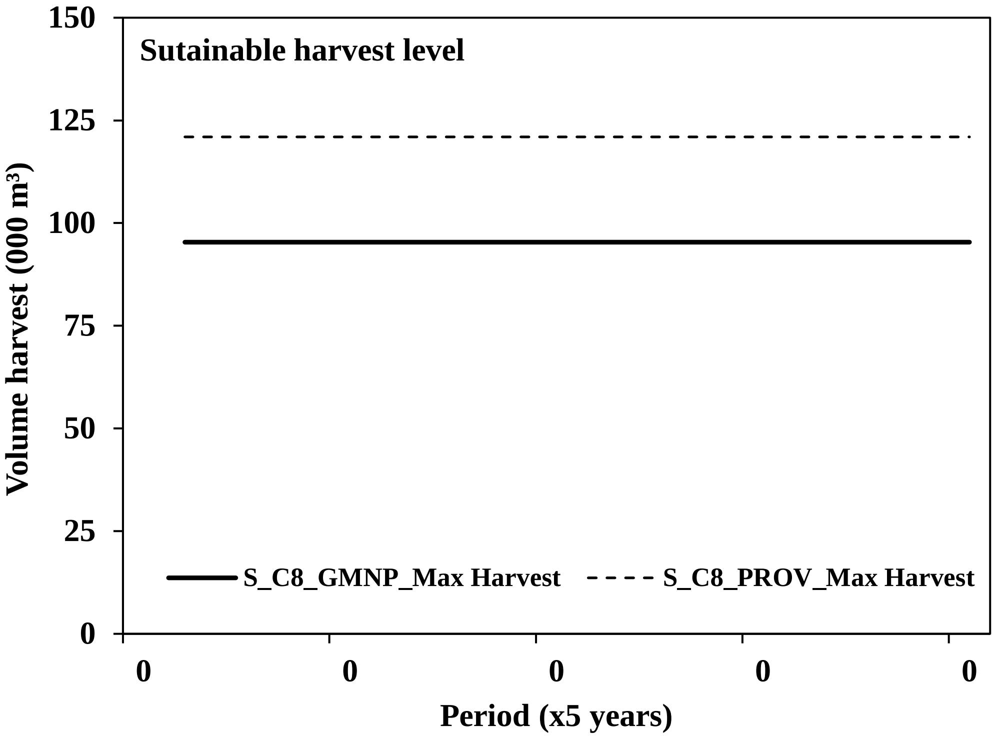

Figure 4-13. Harvest levels comparison between GMNP specific model and the provincial standard model from modeling combination of forest management objectives including a base inventory projection scenario (S_C7) and maximum sustainable harvest level scenarios (S_C8). GMNP assumes heaving moose browsing while provincial model assumes light moose browsing.

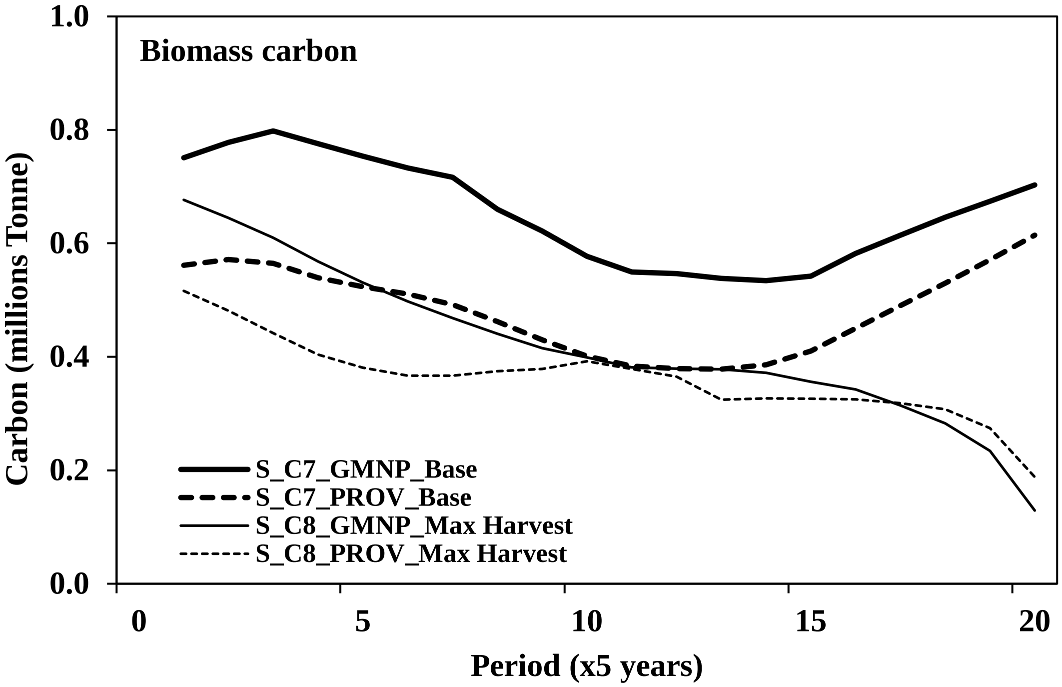

Figure 4-14. Total biomass carbon comparison between GMNP specific model and the provincial standard model from modeling combination of forest management objectives including a base inventory projection scenario (S_C7) and maximum sustainable harvest level scenarios (S_C8). GMNP assumes heaving moose browsing while provincial model assumes light moose browsing.

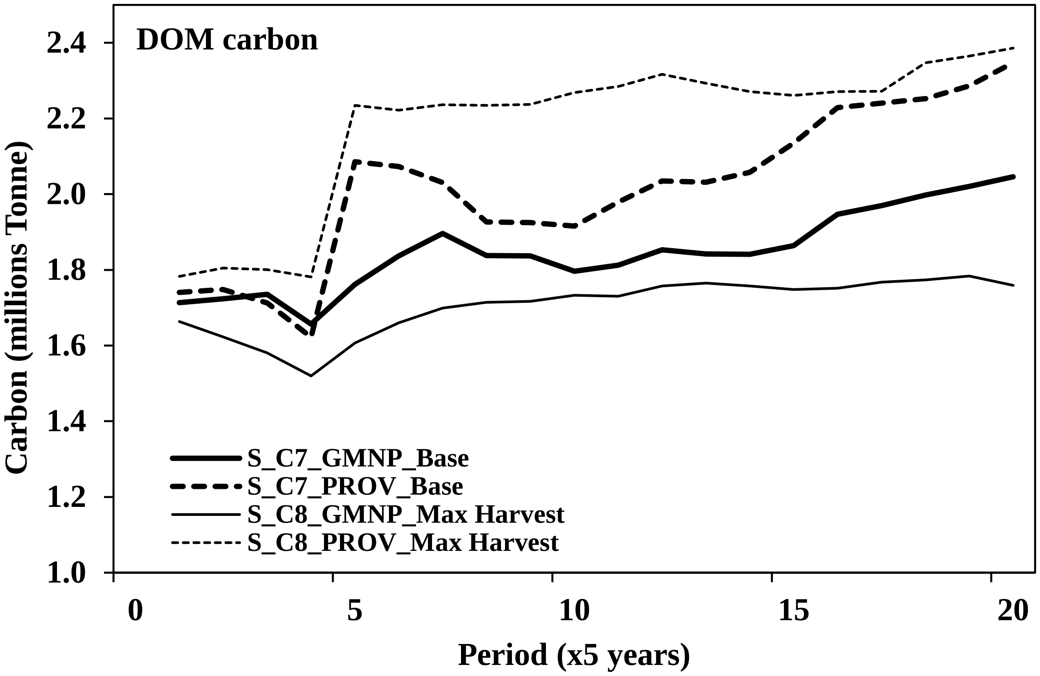

Figure 4-15. Total Dead Organic Material (DOM) carbon comparison between GMNP specific model and the provincial standard model from modeling combination of forest management objectives including a base inventory projection scenario (S_C7) and maximum sustainable harvest level scenarios (S_C8). GMNP assumes heaving moose browsing while provincial model assumes light moose browsing.

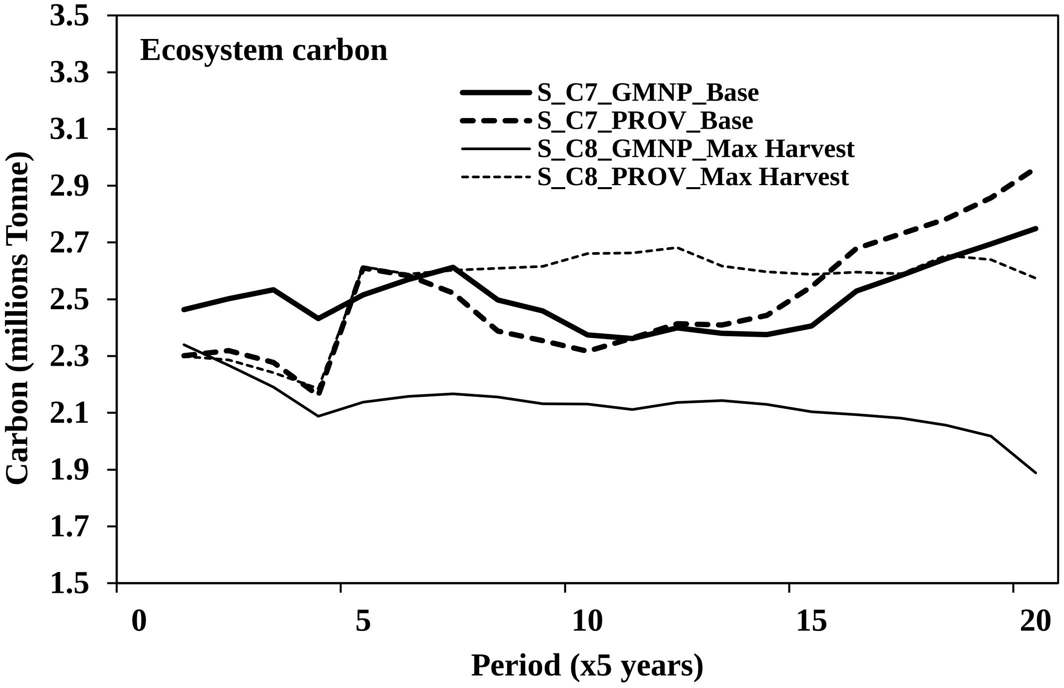

Figure 4-16. Total ecosystem carbon comparison between GMNP specific model and the provincial standard model from modeling combination of forest management objectives including a base inventory projection scenario (S_C7) and maximum sustainable harvest level scenarios (S_C8). GMNP assumes heaving moose browsing while provincial model assumes light moose browsing.

5 Concluding remarks

The focus of this study was to investigate and quantify harvesting and moose impacts on forest regeneration, growth and development, and carbon storage to help advance our understanding of forest health within the park. Objectives under this focus included in Chapter 2 to advance understanding of regeneration success following hyperabundant moose browsing in Gros Morne National Park by developing stocking rates for tree species within recently disturbed stands suppressed by moose browsing and to use temporary sample plot data (TSP) to develop GMNP-specific yield curves for each of the ecoregions within the park. Chapter 3 included using state-of-the-art forest-estate modeling and the latest regeneration stocking levels and forest inventory to explore impacts of moose browsing and domestic harvesting levels within GMNP to assess moose browsing and domestic harvest impacts on park-forest development through a range of disturbance levels and forest restoration strategies by implementing programs of moose population control and reforestation. Chapter 4 incorporating carbon yields within a forest-estate model to evaluate the changes in carbon by evaluating the impact on carbon due to the domestic harvesting program within the park and the impact of heavy and light moose browsing on carbon storage within GMNP.

Chapter 2 highlighted the fact that high moose browsing levels within GMNP has resulted in a significant portion of regenerating areas to fall within the “not sufficiently regenerated”. At high moose browsing levels, this study found that forest stands will have lower growth and yield expectations, when compared to lightly browsed areas.

Chapter 3 has shown that using the transitions rules and growth and yield information developed in Chapter 2 that under heavy browsing in pure balsam fir stands that regenerating balsam fir stocking levels are high enough to perpetuate balsam fir dominance in those stands. However, in stands where balsam fir is co-dominant, the amount of balsam fir is drastically reduced, which causes balsam fir to eventually be replaced by spruce. Modeling results indicate that tree planting can be an effective tool to improve regeneration success within GMNP. Planting non-palatable spruce may help accelerate the landscape-level conversion from balsam fir dominance and could potentially be a problem for park managers trying to maintain current species distribution. Chapter 3 results emphasize the importance of reducing moose densities in the park as a necessary first step to return the park's forest to its natural balsam fir-dominated state.

Chapter 4 indicates that using historical disturbance levels of harvesting carbon stores within GMNP forested ecosystem will hinder the shift to a net carbon source. Using planting strategies implemented in Chapter 3 could be used to mitigate degradation of forest integrity due to hyperabundant moose and domestic harvesting and transition the park to a net carbon sink. Using carbon as the primary management objective for the park could provide ongoing domestic harvesting opportunities, make the forest more resilient against heavy moose browsing, maintain a healthy forest ecosystem, all the while becoming a net sink for carbon.

The surveys and modeling results in this study have been developed to better understand the impacts of moose, domestic harvesting and carbon storage within the GMNP forest ecosystem, and to that end we feel that this study has further our understanding of their interactions/dynamics at the landscape level.

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Publications:

Leblon, B., Alexander, M., Chen, J., White, S. 2001. Monitoring fire danger of northern boreal forests with NOAA-AVHRR NDVI images. International Journal of Remote Sensing, 22:14, 2839-2846.

White, S., Zhu, X., Meng, F., Taylor, S., and Bourque, C. P. A. (2020) Intensive moose browsing and small-scale domestic woodcutting impacts on forest successional trajectories in Gros Morne National Park, Canada, The Forestry Chronicle (Submitted)

Presentations:

White, S., Moose Browsing Impacts on Gros Morne National Park. Graduate Seminar, March, 31, 2016. Fredericton, NB. (This Thesis, Ch. 1–2).

White, S., Moose Browsing Impacts on Gros Morne National Park. Graduate Seminar, November, 17, 2016. Fredericton, NB. (This Thesis, Ch. 2).

White, S., Moose Browsing Impacts on Gros Morne National Park. Master Proposal, March, 14, 2017. Fredericton, NB. (This Thesis).

White, S., Moose Browsing Impacts on Gros Morne National Park. Graduate Seminar. April 6th, 2017. Fredericton, NB. (This Thesis).

White, S., Moose Browsing Impacts on Gros Morne National Park. Presentation at Gros Morne National Park, October 26th, 2017, Rocky Harbor, NL (This Thesis, Ch. 2–3).

White, S., Modelling of Gros Morne Forest. Presentation at Gros Morne National Park, June 27th, 2018, Corner Brook, NL (This Thesis).