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**Cost to produce carbon credits through fluctuating harvest levels in British Columbia,
Canada.**

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carbon offsets, forest management, management strategies, vegetation simulator.

Abstract

The forest inventory of an actively managed forest estate in the Coast forest region of British Columbia was used to investigate the potential of fluctuating harvest levels to produce carbon credits. Fluctuating harvest levels allowed the target harvest level to fluctuate between the baseline and a starting target harvest level (set at a lower level than the baseline) over the 25-year life of the carbon project. Carbon credits continued to be produced for 4-15 years following the harvest adjustment from the starting level to the baseline level. Carbon credits production for the fluctuating harvest schedules was highest when the starting harvest level was held for 10-15 years and the baseline level for the remaining of the carbon project life. Carbon credit production was sensitive to the initial age class structure of the forest estate, the harvest priority algorithm, the starting target harvest level, and the timing of harvest adjustment from the starting level to the baseline level. The cost to produce carbon credits using fluctuating harvest levels for the studied forest estate varied between \$32.2 and \$41.1 tCO₂e⁻¹ (at 0% discount rate), which is 14-17% lower than using a constant reduced harvest level.

48 Introduction

49 The role of forest ecosystems to mitigate anthropogenic global climate change continues
50 to be recognized at the international scale (Intergovernmental Panel on Climate Change 2014). It
51 has been argued that forest management techniques can be used to increase the carbon storage in
52 forest ecosystems (i.e., carbon sequestered from the atmosphere by the aboveground vegetation
53 and stored in the forest ecosystem) (Cooper 1983; Smith et al. 1993; Parker et al. 2000) while
54 continuing to meet the society's demand for timber, fiber, and energy (Kurz et al. 2002). The
55 additional carbon storage can be converted to carbon credits (i.e., one metric tonne (t) of CO₂e¹
56 stored in addition to the baseline level) and if these carbon credits are sold, they can generate
57 additional revenues. Two general strategies to increase carbon storage include increasing the
58 growth rate (e.g., fertilization, use of genetically improved planting stock) and reducing the
59 harvest (e.g., harvest reduction to a fixed target level, increased minimum harvest ages, increased
60 area in reserves). It has been shown that in temperate forests, the harvest reduction strategies
61 have a significantly higher potential to increase carbon storage than the increased growth rate
62 strategies (Seely et al. 2002; Harmon and Marks 2002; Man et al. 2013). Moreover, out of the
63 harvest reduction strategies mentioned above, the harvest reduction to a fixed target level is
64 better able to adapt to changing markets and natural disturbances (Man et al. 2013). However,
65 the opportunity cost due to harvest reduction (i.e., the cost of leaving the forest standing to
66 produce carbon credits as opposed to generate revenue from selling the timber) can account for
67 58-97% of the total cost to produce carbon credits (Man et al. 2015).

¹ 1 t of CO₂e (e-equivalent) indicates the global warming potential of 1 t of various greenhouse gases relative to the Carbon Dioxide as defined in the Assessment Report 5 of the Intergovernmental Panel on Climate Change (2014). In a forest ecosystem, the carbon storage is estimated in t of carbon and then converted to t of CO₂e (1 t of carbon is 3.667 tCO₂e).

In this study, we continue the analysis conducted by Man et al. (2013) and Man et al. (2015) on the potential of the harvest reduction strategies to produce carbon credits in British Columbia. Man et al. (2013) explored the potential of alternate forest management strategies to sequester and store carbon in two actively managed forest estates in British Columbia. Man et al. (2013) found strategies that reduce harvest levels significantly outperformed strategies that increase stand growth. Man et al. (2015) estimated the costs to produce carbon credits using strategies that reduce harvest levels over the first 25-year period for three significantly different and actively managed forest estates in British Columbia. The inclusion of the opportunity cost due to harvest reduction significantly increased the cost to produce carbon credits (higher cost for higher value stands).

The relatively high opportunity cost due to harvest reduction results in the question, can harvest levels be fluctuated so that the opportunity cost is reduced while still producing carbon credits? For this strategy to work, the production of carbon credits must have inertia. In this context, inertia means once a forest estate is given a carbon credit production trajectory by reducing the harvest below the baseline level, carbon credit production will continue after the harvest is returned to the baseline level. The time length for which the carbon credit production continues after the harvest is returned to the baseline level is defined as the inertia period. The implementation of fluctuating harvest levels is a complex problem determined by the factors affecting the carbon credit production rate (e.g., determining the starting target harvest level (STHL) which gives the forest estate a carbon credit production trajectory) and by the factors affecting the length of the inertia period (e.g., timing of the harvest return to the baseline level). It is important to understand these factors and their interactions when fluctuating harvest levels are implemented, particularly in the case of forest estates actively managed for profit where

lowering the opportunity costs due to harvest reduction should decrease the cost to produce carbon credits.

The objectives of this study are to determine if carbon credit inertia can be produced in an actively managed forest estate, and to examine the effect of important variables on the length of the inertia period, the number of carbon credits produced during the inertia period, and the cost to produce carbon credits when fluctuating harvest levels are implemented.

Methods

Many of the methods used in this study are detailed in Man et al. (2013) and Man et al. (2015), yet for clarity and convenience critical information is included here.

Study area and simulation models

The Malcolm Knapp Research Forest (MKRF) was used to conduct the analysis. The MKRF is located approximately 60 km East of Vancouver within the Coast forest region of British Columbia. The timber supply analysis was conducted with a spatially explicit forest-level planning model (Forest Planning Studio (FPS-ATLAS) (Nelson 2003)), the carbon stock dynamics within the forest ecosystem were modelled with a spatial reference stand and landscape level model (the Carbon Budget Model for Canadian Forest Sector (CBM-CFS3) (Kurz et al. 2009)), and the estimation of carbon credits produced followed the guidance of the Protocol for the Creation of Forest Carbon Offsets in British Columbia (British Columbia Ministry of Environment 2011). Detailed description of the MKRF, and assumptions used in FPS-ATLAS and CBM-CFS3 are found in Man et al. (2013), while detailed carbon credits accounting methodology is found in Man et al. (2015).

Fluctuating harvest level scenarios

In British Columbia, a carbon project (i.e., a course of action undertaken to achieve greenhouse gas reduction) is required to run for at least a minimum of 25 years (British Columbia Ministry of Environment 2013). In a fluctuating harvest schedule, a starting target harvest level (STHL) is followed for a period of years and then, at some point before the end of the carbon project, the harvest level is increased to the baseline level. The baseline harvest level of the MKRF was determined to be 33 000 m³ year⁻¹ (as the long term sustainable yield to be achieved for 100 years into the future). A minimum acceptable harvest level was determined to be 11 000 m³ year⁻¹ (33% of the baseline level) in order to achieve a minimum set of objectives (e.g., research, wildfire protection, and a minimum volume for the onsite sawmill). Starting with the baseline FPS-ATLAS database and keeping the same set of constraints (e.g., minimum harvest ages) as for the baseline scenario, three sets of five scenarios were simulated. Each of the three sets was defined by the STHL, which was set at 33%, 50%, and 70% of the baseline level. For each of these three sets, five scenarios were simulated by holding the cut constant at STHL for 5, 10, 15, 20, and 25 years (the harvest reduction period) and then adjusting the harvest to the baseline level (Table 1). The simulations were run for 100 years in order to allow sufficient time to observe how carbon credit production is affected once the harvest has been adjusted from the STHL to the baseline level. In addition, to provide a reference in exploring the important variables affecting the inertia period, three harvest reduction scenarios were simulated where the annual harvest was held constant at 33%, 50%, and 70% of the baseline level for the entire 100-year planning horizon.

136 The total break-even carbon credit price (P) was calculated using Eq. (1) derived by Man
 137 et al. (2015) with its two components; P_H , the component of the total break-even carbon credit
 138 price due to the opportunity cost of the reduced harvest (Eq. (2)) and P_{CC} , the component of the
 139 total break-even carbon credit price due to the carbon project cost (Eq. (3)). Here, P , P_H , and P_{CC}
 140 are assumed to be constant over the 25-year carbon project and P is the sum of P_H and P_{CC} . Eq.
 141 (1) is identical to the levelization equation from Richards and Stokes (2004) and to the
 142 discounted carbon equation from Boyland (2006).

$$P = \frac{\sum_{t=0}^n \frac{(H_{Bt} - H_{Ct}) \cdot TNR + CC_t}{(1+r)^t}}{\sum_{t=0}^n \frac{C_t}{(1+r)^t}} \quad 1)$$

$$P_H = \frac{\sum_{t=0}^n \frac{(H_{Bt} - H_{Ct}) \cdot TNR}{(1+r)^t}}{\sum_{t=0}^n \frac{C_t}{(1+r)^t}} \quad 2)$$

$$P_{CC} = \frac{\sum_{t=0}^n \frac{CC_t}{(1+r)^t}}{\sum_{t=0}^n \frac{C_t}{(1+r)^t}} \quad 3)$$

143 Here, H is the harvested volume (B - baseline, C -carbon project), TNR is the average timber net
 144 revenue per cubic meter (the difference between the timber revenue and the harvesting cost,
 145 estimated at \$35 m⁻³ for the last 10 years of financial data for MKRF (Man et al. 2015)), C is the
 146 number of carbon credits produced for the 25-year carbon project life, CC is the carbon project
 147 cost which includes the initial establishment and validation cost (estimated at \$5.61 ha⁻¹ from
 148 Galik et al. (2012)) and ongoing 5-year frequency verification cost (estimated at \$1.52 ha⁻¹ from

Galik et al. (2012)), r is the discount rate (0-16% real rates once inflation has been removed), t is the year of the planning horizon, and n is the total number of years of the planning horizon (i.e., the 25-year carbon project).

For each scenario, the annual change of carbon storage (i.e., carbon storage difference between two consecutive years) was tracked for the entire 100-year planning horizon and four metrics were quantified: 1) the length of time (in years) that the carbon credits continue to be produced following the harvest adjustment from the STHL to the baseline level, this is termed the carbon credits inertia period (CCI), 2) the number of carbon credits produced during CCI, 3) C , and 4) P .

Results

In the case of the baseline scenario, the annual change of carbon storage had an irregular pattern, generally declining for the first 26 years of the 100-year planning horizon, then increasing for the next 38 years (until year 64 of the 100-year planning horizon), and then decreasing again for the remaining 36 years of the 100-year planning horizon (Figure 1). The irregular pattern is explained by the initial age class structure of the MKRF, where over 52% of the timber harvest land base was older than 80 years (Man et al. 2013), and by the oldest-first harvest priority algorithm used to simulate the harvest schedule. In the beginning of the planning horizon, the harvesting of the oldest stands first reduced the carbon storage in the forest ecosystem and consequently, the annual change of carbon storage declined. At the stand level, when the tree cover was removed there was an immediate significant loss of carbon stored in the dead organic matter pool (Figure 2) which caused the annual change of carbon storage for the entire stand (i.e., total stand in Figure 2) to decline for the first year of the stand development.

Following year 1 of the stand development (Figure 2), the growing biomass pool overcame the initial loss of stored carbon and the annual change of carbon storage of the entire stand increased to a peak value at year 57. At the forest estate level (Figure 1), as the area of older stands was depleted by harvesting and the regenerated stands had higher yields than the stands they replaced, the annual change of carbon storage increased gradually after year 26 and by year 64 of the planning horizon it reached a higher value than the value at the beginning of the planning horizon. Following year 64 of the planning horizon, the cycle repeated at a lower scale because the forest was gradually transitioning to a younger age class structure where the oldest stands were 120 years old (i.e., the highest minimum harvest age).

In the case of the harvest reduction scenario where the STHL was set to 33% of the baseline for the entire 100-year planning horizon, the annual change of carbon storage was irregular as well, generally increasing for the first 32 years and then decreasing for the remainder of the 100-year planning horizon (Figure 1). Here, the carbon credit production occurred for the entire 100-year planning horizon because the annual change of carbon storage for the harvest reduction scenario (i.e., STHL set at 33% of the baseline for the entire 100-year planning horizon) was above the annual change of carbon storage of the baseline scenario. Note that the carbon credit production was higher when the two patterns of annual change of carbon storage (baseline and harvest reduction scenario) were more divergent. Similar patterns of the annual change of carbon storage were observed for the harvest reduction scenarios where the STHL was set to 50% and 70% of the baseline level for the entire 100-year planning horizon.

In the case of the fluctuating harvest level scenarios where the STHL was set to 33%, 50%, and 70% of the baseline level, the annual change of carbon storage declined sharply at the start of the CCI (i.e., when the harvest level was adjusted from the STHL to the baseline level)

(Figure 1). The decline of the annual change of carbon storage for the fluctuating harvest level scenarios continued for a number of years until it fell under the annual change of carbon storage of the baseline scenario. At this point, the carbon credit production ceased and CCI ended. Note that as the timing of harvest level adjustment from the STHL to the baseline level (i.e., the harvest reduction period) approached year 25 of the 100-year planning horizon, the CCI extended past the 25-year carbon project life.

The CCI for the fluctuating harvest level scenarios was between 4 and 15 years and carbon credit production during CCI was between 8 and 103 thousand tCO₂e (Figure 3). The STHL (33%, 50%, or 70% of the baseline level) did not affect the patterns of the CCI period or carbon credit production during the CCI period, but it had a visible effect on the scale of carbon credit production during the CCI period (which was highest when the STHL was set to 33% of the baseline level). Regardless of the STHL, the CCI and carbon credit production during the CCI were at the highest levels when the harvest reduction period was between 10 and 15 years. Recall, the annual change of carbon storage for the baseline scenario was generally increasing after year 26 of the planning horizon and reduced the CCI for fluctuating harvest level scenarios with harvest reduction periods longer than 15 years (Figure 1). It was also observed that CCI was highly sensitive to the irregular patterns of the annual change of carbon storage for the baseline scenario. For example, between year 26 and 29, the annual change of carbon storage for the baseline scenario slightly increased and between year 29 and 35 it slightly decreased (Figure 1). This subtle variation resulted in slightly lower CCI values for the 15-year harvest reduction period compared to the 10- and 20-year harvest reduction periods when STHL was set at 33% of the baseline level (Figure 3). Similarly, when STHL was set at 50% of the baseline level, the CCI was lower for the 20-year harvest reduction period compared to the 15- and 25-year harvest

reduction periods. Thus, CCI was highly sensitive not just to the STHL and the harvest reduction period, but also to the interplay of the annual change of carbon storage between baseline and fluctuating harvest level scenarios.

The CCI and the carbon credit production during the CCI were also sensitive to the initial age class structure of the forest and the harvest priority algorithm. Recall, the initial age class structure of the MKRF where over 52% of the timber harvest land base was older than 80 years caused the annual change in carbon storage for the baseline scenario to decline for the first 26 years. Had the initial age class structure been younger, the annual change in carbon storage for the baseline scenario would have had an increasing trend because the annual change of carbon storage is higher in younger stands compared to older stands (Figure 2). The use of any other harvest priority algorithm than oldest-first would have harvested more stands at younger ages in the beginning of the planning horizon. Harvesting of younger stands in the beginning of the planning horizon would have resulted in a lower decrease of the annual change in carbon storage for the baseline scenario compared to the oldest-first harvest priority algorithm. Thus, the annual change in carbon storage difference between the baseline and the fluctuating harvest level scenarios would have been lower in a forest estate with a higher percentage of the area in younger age classes than the MKRF or when using another harvest priority algorithm (i.e., not oldest first). Consequently, the CCI and carbon credit production during CCI would have been lower.

The number of carbon credits produced for the first 25-year carbon project life (C) by the range of fluctuating harvest level scenarios analyzed here was 8% to 88% of the maximum (Table 2). In Table 2, for the fluctuating harvest level scenarios where the annual change of carbon storage fell under the baseline (Figure 1), C values accounted for the carbon credits loss

during the first 25 years of the 100-year planning horizon (e.g., 5- or 10-year harvest reduction periods). The maximum C was achieved when the STHL was set to 33% of the baseline level for the entire 25-year carbon project life (i.e., the scenario identified as max in Table 2). The large variation from the max was explained by the STHL, the harvest reduction period, and to a lesser extent by the CCI and the carbon credit production during CCI. Higher C values (over 67% of max) were achieved when the STHL was at lower levels (e.g., 33% or 50% of the baseline level) and the harvest reduction period was longer than 20 years. Recall, in order to maximize the advantages of the CCI and the carbon credit production during CCI, the harvest reduction period should be 10 to 15 years (Figure 3). Fluctuating harvest level scenarios with the STHL for 10 to 15 years achieved C values of 21% to 70% of the max. For example, C values of approximately 50% of max could be achieved if STHL was set to 1) 33% of the baseline level for 10 years, 2) 50% for 15 years, or 3) 70% for 25 years (Table 2).

A second, third, or fourth 25-year carbon projects could be developed during year 26-50 of the 100-year planning horizon, year 51-75, or year 76-100, respectively. However, as noted in Figure 1, the CCI loses momentum and carbon credits production stops before year 50 of the 100-year planning horizon. Only a constant harvest reduction level continued to produce carbon credits past year 50, 75, or 100. Therefore, once the previous 25-year carbon project comes to an end, a new strategy needs to be developed for the next 25-year carbon project.

The total break-even carbon credit price (P) at 0% discount rate for the range of fluctuating harvest level scenarios analyzed here varied between \$32.2 and \$41.1 $\text{tCO}_2\text{e}^{-1}$ (Table 2). The highest P reduction from max (17%) occurred for the fluctuating harvest level scenario where STHL was set to 50% of the baseline level for 10 years. Similar P reductions from max (14% to 16%) occurred when the STHL was set to 1) 33% of the baseline level for 10 to 15

years, 2) 50% for 15 years, or 3) 70% for 10 years. These results correlate well with the advantages of the CCI and carbon credit production during CCI observed in Figure 3. A somewhat surprising result was that P could only be reduced by 17% from the max despite implementing the baseline harvest level for the last 15 years of the carbon project life. Man et al. (2015) found that P was relatively independent of the target harvest level because of the high proportion of P_H (over 96% in the case of the MKRF). In the case of the fluctuating harvest level scenarios with the highest P reduction from max (17%), the value of the opportunity cost was reduced from $\$19.0 \times 10^6$ to $\$5.7 \times 10^6$ (30% of the max), but P_H still represented a high proportion of P (99%, $\$31.8$ out of $\$32.2 \text{ tCO}_2\text{e}^{-1}$) (Table 2). Thus, P reduction through implementing fluctuating harvest levels was limited by the scale difference between the opportunity cost and the carbon project cost. In the case of the MKRF, the scale difference between $\$10^6$ for the opportunity cost and under $\$10^4$ for the carbon project costs was relatively large.

When the discount rate was increased from 0% to 4%-6%, the P reductions from max shown in Table 2 were reduced by half (Figure 4). The P reductions from max became less than 2% when the discount rate was increased to more than 14%. The effect the discount rate had on P reductions from max is explained by Eq. (1). When the STHL was held constant over the 25-year carbon project life, P (as a constant value) needed to increase with an increasing discount rate. This was because the denominator of Eq. (1) (which includes the annual carbon credit production) was more sensitive to the discount rate increase than the numerator (which includes the annual total cost). When the harvest level fluctuated over the 25-year carbon project life, once the STHL was adjusted to the baseline level, the total costs were reduced to only the carbon project costs (i.e., the opportunity cost was zero) while the carbon credit production continued. Here, the numerator in Eq. (1) became less sensitive to the discount rate due to the sharp cost

reduction. Thus, a higher discount rate resulted in higher increase of P for the fluctuating harvest level scenarios and consequently a smaller P reduction from max.

The value of discount rate to be used in financial analyses is heavily debated in the literature. Arguments for higher discount rates include the opportunity cost of investment funds (i.e., the real rate of return on alternate investments), the time preference for earlier over later consumption, diminishing marginal utility (i.e., discounting only products and services that are known to be more abundant for future generations), and risk (Price 2014). The arguments for low discount rates (<1%) include intergenerational fairness (Stern 2007; Howarth 2009; Price 2014), decision-makers' behaviour on capital markets (Howarth 2009), and supporting aggressive steps to stabilize the anthropogenic global climate change (Cline 1992). Specific to forestry, higher discount rates favour maintenance of current silvicultural systems and delays adopting new regimes with the potential to yield higher timber volumes or improved ecosystem services (Price 2014). In the case of carbon projects on public land, relatively low discount rates may be warranted for the following reasons; 1) generating public goods, 2) relatively a long term horizons, 3), intergenerational fairness, 4) faster transition to regimes that favour ecosystem services, and 5) help stabilizing the anthropogenic climate change.

When developing a carbon project, the fluctuating harvest levels can be used to take advantage of the CCI and consequently produce carbon credits at lower prices. Carbon credit prices in the range of \$5 to \$16 tCO₂e⁻¹ were reported for the improved forest management type projects on the voluntary carbon markets (Peters-Stanley et al. 2013; Hamrick and Goldstein 2015) which are in line with the reduced timber harvesting abatement curves (McKinsey and Company, 2009). In the case of the MKRF, the timber net revenue (TNR) was \$35 m⁻³, and the P reductions from max shown in Table 2 were not sufficient to produce carbon credits within the

310 market price range. However, assuming a TNR of \$15 m⁻³, a fluctuating harvest level scenarios
311 with STHL set to 33% of the baseline for 10 years would have produced carbon credits at prices
312 within the market price range whereas a constant reduced harvest level scenario (i.e., STHL set
313 to 33% of the baseline for 25 years) would have not (Figure 5).

314 The TNR is sensitive not only to the timber market fluctuations, but also to the flexibility
315 a forest manager has on the annual operational plans. In the case of the MKRF, the last 10-year
316 financial data used to derive the TNR indicated a relatively constant timber revenue stream. The
317 constant stream revenue is explained by the flexibility the forest manager had to adjust the
318 harvest schedule to the timber market fluctuations. For example, favourable prices for cedar
319 poles encouraged harvesting of 80-90 years old cedar stands. In the case of the forest estates with
320 reduced operational flexibility, the TNR is expected to be more sensitive to the timber market
321 fluctuations than the MKRF. Thus, the current carbon credit market range in Figure 5 could be
322 more favourable in developing carbon projects for forest estates other than MKRF.

323 Some of the limitations of this study with potential large impacts on *P* include simulation
324 of stand-replacing natural disturbances and substitution benefits of carbon in harvested wood
325 products. In the case of the MKRF, the impact of stand-replacing natural disturbances (if they
326 occur) is relatively low because of its location (near Vancouver in the Coast forest region of
327 British Columbia). In the case of other forest estates located in more remote and drier areas, the
328 stand-replacing disturbances with shorter cycles than the Coast forest region reduce the LTSY,
329 and consequently the carbon credit production. The substitution of greenhouse gas emissions-
330 intensive products (e.g., steel, concrete, and plastic) with low emissions renewable harvested
331 wood products is considered by many an essential carbon accounting tool to mitigate emissions
332 from the forest sector (e.g., Lemprière et al. 2013). Because the baseline scenario has a higher

level than any reduced harvest level scenarios, the substitution benefits are higher for the baseline scenario. Consequently, the carbon credit production due to storage in manufactured products is lower when substitution benefits are accounted. Thus, both limitations are expected to increase P because for the same TNR the carbon credit production is lower.

The financial benefits accrued from carbon credits present an opportunity for social justice as they are distributed to improve the livelihoods of remote communities with positive socio-economic impacts. For example, the Great Bear Rainforest carbon project was designed to share the financial benefits between First Nations and the British Columbia Government (Offsetters 2016)). However, a conservative approach to reduce harvesting for a relatively long time may reduce the forest adaptability to climate change. The current relatively old stands were regenerated by stand-replacing natural disturbances (e.g., wildfires) and they may not have the capacity to adjust quickly enough to the forecasted changes in species habitat due to climate change (Hamann and Wang 2006) and the forecasted carbon credit benefits may be reduced. Our study presents an alternative to accrue carbon credit benefits while increasing the forest adaptability to the forecasted changes in species habitat due to climate change. The fluctuating harvest levels strategies described here give the forest estate a trajectory capable to deliver financially-viable carbon projects and replace the less adaptable stands by increasing the harvest level at a later time during the planning horizon.

Conclusions

The fluctuating harvest level strategies triggered a CCI of 4 to 15 years during which carbon credit production was 8 to 103 thousand tCO₂e. The annual change of carbon storage difference between the baseline and the fluctuating harvest level was the most important variable

that affected the CCI and carbon credit production during the CCI. The annual change of carbon storage difference between the baseline and the fluctuating harvest level was sensitive to the initial age class structure of the forest estate, the harvest priority algorithm, the STHL, and the timing of harvest level adjustment from the STHL to the baseline level (i.e., the harvest reduction period). A lower STHL gave the carbon credit production a higher inertia which resulted in longer CCI and higher carbon credit production during CCI. The highest levels of CCI and carbon credit production during the CCI were achieved when the harvest reduction period was between 10 and 15 years.

The fluctuating harvest level scenarios with the STHL for 10 to 15 years were able to achieve 21% to 70% of the maximum number of carbon credits produced for the 25-year carbon project life. The maximum number of carbon credits was achieved when the STHL was set to 33% of the baseline level for 25 years. The total break-even carbon credit prices (P) at a 0% discount rate were between \$32.2 and \$41.1 $\text{tCO}_2\text{e}^{-1}$ for the fluctuating harvest level scenarios. The highest P reductions from the maximum at a 0% discount rate (14% to 17%) were achieved when the STHL was held for 10 to 15 years, which correlated well with the results of the CCI and carbon credit production during CCI. The P reductions from the maximum were reduced by half when the discount rate was increased from 0% to 4-6%.

Another option to reduce the opportunity costs due to harvest reduction is to implement carbon projects in forest estates with lower timber net revenues. This study compared P between fluctuating and constant reduced harvest level scenarios. It was found that implementation of fluctuating harvest level scenarios where timber net revenue was set to \$15 m^{-3} resulted in P below the carbon credits market range. For the same timber net revenue of \$15 m^{-3} , the constant reduced harvest level scenarios resulted in P above the carbon credits market range. The

challenge of forest carbon projects proponents is to find forest estates with lower timber net revenues where a carbon project can yield higher financial returns than the timber revenues. However, this challenge is highly sensitive to forest condition (i.e., inventory and growth) and financial markets fluctuations. Further research is needed to test the financial viability of carbon projects in actively managed forest estates where timber net revenues are low relative to carbon credit prices.

This study complements the analysis conducted by Man et al. (2013) and Man et al. (2015) on the potential of the harvest reduction strategies to produce carbon credits in British Columbia. In actively managed forest estates, strategies that reduce harvest levels are more efficient at storing carbon in the forest ecosystem than strategies that increase stand growth (e.g., fertilization, use of genetically improved planting stocks) (Man et al. 2013). In the case of strategies that reduce harvest levels, the inclusion of the opportunity cost due to harvest reduction increases significantly the cost to produce carbon credits (Man et al. 2015). One alternative to reduce the opportunity cost due to harvest reduction, and consequently reduce the cost to produce carbon credits, is to utilize the inertia property of the carbon credit production by implementing fluctuating harvest levels strategies. Lastly, the financial viability of strategies that increase stand growth in actively managed forest estates needs to be addressed further.

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Table 1. Change of STHL to the baseline level for one set of five scenarios. Each of the three sets of five scenarios is defined by the STHL set at 33%, 50%, and 70% of the baseline level.

Scenario (1 set of 5)	Harvest level between year:					
	1-5	6-10	11-15	16-20	21-25	>25
1	STHL	Baseline	Baseline	Baseline	Baseline	Baseline
2	STHL	STHL	Baseline	Baseline	Baseline	Baseline
3	STHL	STHL	STHL	Baseline	Baseline	Baseline
4	STHL	STHL	STHL	STHL	Baseline	Baseline
5	STHL	STHL	STHL	STHL	STHL	Baseline

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Table 2. Number of carbon credits produced (*C*), total break-even carbon credit price (*P*), and opportunity cost (*P_H*) for the first 25-year carbon project life at 0% discount rate and 5-year carbon project verification frequency

Harvest reduction period (years)	<i>C</i>		<i>P</i>		Opportunity cost		
	t CO ₂ e	% of <i>max</i>	\$ tCO ₂ e ⁻¹	% reduction from <i>max</i>	<i>P_H</i> (\$ tCO ₂ e ⁻¹)	Value (\$ 10 ⁶)	Value % of <i>max</i>
STHL at 33% of the baseline level							
5	105 523	21%	35.6	8%	34.9	3.7	19%
10	228 421	46%	32.6	16%	32.3	7.4	39%
15	344 061	70%	33.0	15%	32.8	11.3	59%
20	433 963	88%	35.1	9%	34.9	15.2	80%
25	492 283	100%	38.7	0%	38.6	19.0	100%
STHL at 50% of the baseline level							
5	80 798	16%	35.6	8%	34.7	2.8	15%
10	180 419	37%	32.2	17%	31.8	5.7	30%
15	261 154	53%	32.5	16%	32.3	8.4	44%
20	331 465	67%	34.9	10%	34.7	11.5	61%
25	376 255	76%	38.0	2%	37.8	14.2	75%
STHL at 70% of the baseline level							
5	38 152	8%	41.1	−6%	39.3	1.5	8%
10	105 061	21%	33.4	14%	32.8	3.4	18%
15	153 072	31%	34.3	11%	33.9	5.2	27%
20	194 768	40%	35.3	9%	34.9	6.8	36%
25	227 039	46%	38.5	1%	38.2	8.7	46%

Figure 1. Comparing the annual change of carbon storage between the baseline scenario and the fluctuating harvest level scenarios: STHL is starting target harvest level.

Figure 2. Annual change of carbon storage over time by ecosystem components in a typical stand at MKRF. The stand replacing disturbance in year 0 resulted in a significant loss of carbon storage in year 1.

Figure 3. Comparing the carbon credit inertia periods (CCI) at MKRF when the starting target harvest level (STHL) is held constant for a range of harvest reduction periods

Figure 4. The effect of the discount rate on the total break-even carbon credit price (P) reduction from max when STHL is set to 50% of the baseline level for 10 years (highest P reduction from maximum): max value occurs when the starting target harvest level (STHL) is held constant over 25-year carbon project life.

Figure 5. Comparing the carbon credit market price range to the total break-even carbon credit price (P) (0% discount rate) for a range of timber net revenues (TNR) when the starting target harvest level (STHL) is set at 33% of the baseline level for 10 years (fluctuating harvest level) and 25 years (constant reduced harvest level)