Cost to produce Carbon credits by reducing the harvest level in British Columbia, Canada.

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Abstract

This paper uses the inventory of three actively managed forest estates located in the Coastal, Central Interior, and Northern Interior forest regions in British Columbia to estimate the cost to produce Carbon credits ($ per Carbon credit) when the harvest is reduced below the baseline level. The financial analysis was conducted over a range of discount rates (0-16%) and the total cost included the opportunity cost due to harvest reduction and the Carbon project cost (the Carbon project initial establishment and validation cost and the ongoing verification cost for two frequencies (1-year and 5-year)). When the opportunity cost was not included, the cost per Carbon credit was similar to previous findings (lower cost per Carbon credit for higher site index (i.e. top height in meters at age 50)). However, when the opportunity cost was included the cost per Carbon credit was higher for higher site indices. The reversal of trends is the result of the average timber net revenue being higher for higher site indices which resulted in a higher opportunity cost. The opportunity cost represented 58% to 97% of the cost per Carbon credit. Compared to the 5-year verification, the 1-year verification frequency increased the total cost per Carbon credit by 1% to 22%, with the smallest increase being when the Carbon project cost represented a small percent of the total cost. The estimates for the three forest estates analyzed here represent three points from a larger spectrum, and they identify the cost per Carbon credit over a range of site indices (14.7 to 25.6 meters top height at age 50) and timber net revenues ($4 to $35 m^{-3}). Further research is required to determine if the trends found in this study hold over a more densely populated spectrum.

1. Introduction

The IPCC (2007) suggests forests can be used to store additional Carbon producing Carbon credits (where a Carbon credit equals one Mg of CO_2e) to help offset recent human induced global warming. Management strategies used to enhance the amount of Carbon stored in existing forests can be organized into two major categories; (1) harvest reduction and (2) increased forest growth strategies. Harvest reduction strategies have a higher potential for producing Carbon credits in the short term (25 to 50 years). Man et al. (2013) found little difference in the number of Carbon credits produced between different harvest reduction strategies, and suggested that reducing the harvest level to a fixed target below the baseline provides the forest manager with more flexibility. Strategies to increase forest growth rates above the baseline levels include fertilization and planting genetically improved stock; however, these strategies store significantly less Carbon than the harvest reduction strategies (Man et al., 2013) and pose the risk of not being able to deliver the projected growth increase. The past financial analyses conducted on theoretical forests developed indicators to determine the financial viability of forest based Carbon projects (Richards and Stokes, 2004; van Kooten, 2009). Given the large number of factors involved in developing such indicators (Golden et al., 2011; Greig and Bull, 2011; Galik and Cooley, 2012) there is still a debate on which financial indicators are best suited for forest based Carbon projects.

A useful indicator to determine the financial viability of forest based Carbon projects is the Carbon supply curve (i.e. plotting the Carbon credits produced against the marginal cost to produce them) (Boyland, 2006). Marginal cost to produce Carbon credits at a landscape level has been estimated between $0 to over $200 depending on the location and the forest management strategy used (van Kooten et al., 2009). Usually, only the average costs and revenues are available in a financial analysis of a forest estate (e.g. timber price, harvesting cost, Carbon project costs, and Carbon credit price). The marginal costs derived from the average costs and revenues can be misleading because they can overestimate the number of Carbon credits that can be produced at a given Carbon credit price (Boyland, 2006). An alternate strategy to determine the financial viability of forest based Carbon projects where the average costs and revenues are known is to compare the market price of a Carbon credit to the break-even Carbon credit price (i.e. the total cost of the project divided by the number of Carbon credits produced). The average

Carbon credit market price for improved forest management projects (i.e. IFM) in 2012 varied between \$5 and \$16 depending on the contract type and project stage (Peters-Stanley et al., 2013). Richards and Stokes (2004) and Boyland (2006) discussed in detail the equations used to determine the break-even Carbon credit price. Typically, the total cost of the project includes harvesting, silviculture, opportunity, Carbon project initial establishment and validation, and Carbon project verification costs. In the case of the harvest reduction strategies, the opportunity cost of the timber left standing, as opposed to generating revenue from harvesting, is not always included in the financial analysis. For example, Huang and Kronrad (2001) did not include the opportunity cost and this resulted in lower average costs to store one additional Mg of Carbon for stands with higher site index (i.e. top height in meters at age 50). In a different study that analyzed the increased forest growth strategies, which do not have opportunity costs due to harvest reduction, Bull (2010) also found lower break-even Carbon credit prices for higher site indices.

Financial analyses of forest based Carbon projects that include the opportunity cost due to harvest reduction are needed in order to provide better estimates for the break-even Carbon credit price when considering actual forest estates. However, using site index as the universal measure of site productivity can be problematic when comparing different forest estates composed of different species and site conditions. Thus, it is necessary to develop a metric that represents the opportunity cost of reducing harvests in favor of storing Carbon. This new metric will have to be sensitive to site productivity, tree species, and log quality.

In this study, three small-scale actively managed forest estates located in the Coastal, Central Interior, and Northern Interior forest regions in British Columbia that cover a wide range of species, forest types, and timber net revenues are considered. The objectives of this study are; (1) to propose a new metric that represents the opportunity cost of reducing harvests in favour of storing Carbon, (2) to determine the break-even Carbon credit price for three small-scale actively managed forest estates when reducing the harvest below the baseline level, and (3) to examine how the break-even Carbon credit price varies with the new metric developed in (1) for the three forest estates. These are important questions for jurisdictions such as British Columbia where there are large tracts of publicly owned forests that might be considered for Carbon projects.

2. Methods

2.1. Forest estates

Three actively managed forest estates were used to conduct the analysis in this paper. The Alex Fraser Research Forest (AFRF) (average site index of 22.1 (range 15-26)) located in the Central Interior forest region of British Columbia and the Malcolm Knapp Research Forest (MKRF) (average site index of 25.6 (range 20-40)) located in the Coastal forest region of British Columbia are described in detail in Man et al. (2013). The third forest estate (FE3) is 14920 ha in size and is located in the boreal plains, approximately 40 km South East of Dawson Creek, British Columbia. It falls entirely into the Boreal White and Black Spruce Biogeoclimatic Ecosystem Classification (BEC) zone, with the Western third in the dry cool subzone and the rest in the moist warm subzone. Lodgepole pine (*Pinus contorta*) covers approximately half of the landbase while the other half is covered by mixed stands of white spruce (*Picea glauca*), black spruce (*Picea mariana*), and trembling aspen (*Populus tremuloides*). Mountain pine beetle (*Dendroctonus ponderosae*) disturbed most of the lodgepole pine stands since 2003 at an average attack rate of 30%. Wildfires and forest harvesting since 1978 have created a mosaic of even aged stands, 76% of the landbase being covered by 80 to 160 years old stands. The average site index at FE3 estimated from the existing inventory excluding all non-forested areas is 14.7 (range 6-22).

2.2. Simulation models

Two forest-level models (the Forest Planning Studio (FPS-ATLAS) (Nelson, 2003) and the Carbon Budget Model for Canadian Forest Sector (CBM-CFS3) (Kurz et al., 2009)) were used to forecast the timber supply, standing volume, and Carbon stocks. The growth and yield curves were either extracted from the Timber Supply Area Analysis Reports where the forest estate resides (British Columbia Ministry of Forests, 2001; British Columbia Ministry of Forests, 2002; British Columbia Ministry of Forests, 2003) or developed from the existing inventory using stand level yield prediction systems. The Variable Density Yield Prediction (VDYP) was used to generate the growth and yield curves for the stands regenerated naturally following a stand replacing disturbance (e.g. wildfire) and the Table Interpolation Program for Stand Yields (TIPSY) was used to generate the growth and yield curves for the stands regenerated artificially following harvesting-planting events (British Columbia Ministry of Forests, Lands and Natural

Resource Operations, 2012). The methodology used to build the timber supply model in FPS-ATLAS and transferring the disturbance schedule into CBM-CFS3 to estimate Carbon stocks were documented in Man et al. (2013) for AFRF and MKRF. A similar methodology was used in the case of the FE3 where 2737 spatially explicit polygons were grouped into 32 stand types based on species composition, regeneration type (natural or artificial through planting), BEC, and site index. In order to increase forest response flexibility to predicted climate changes (Burton and Cumming, 1995; Hamann and Wang 2006; Swift and Ran, 2012), lodgepole pine dominated stands with small pockets of trembling aspen and white spruce were promoted at FE3.These factors combined with the management objective of timber production determined the implementation of the clearcut system (one cut at age 60-170 depending on site productivity and quality of harvested products) on the entire timber harvest land base.

2.3. Forest Management Strategies to generate Carbon credits

2.3.1. Baseline determination

Using the approach detailed by Man et al. (2013), the baseline long term sustainable yields for 100 years were determined to be 14800 m^3 $year^{-1}$ at AFRF, 27000 m^3 $year^{-1}$ at FE3, and 33000 m^3 $year^{-1}$ at MKRF, while satisfying a series of constraints imposed by the forest management objectives of the forest estates (e.g. minimum harvest ages, protected areas, retention levels, and harvesting priorities).The simulations were run for 100 years with the harvesting algorithm being programmed to treat oldest stands (and infested mountain pine beetle stands at FE3) first and the commercial thinning before final cuts (e.g. clearcuts, shelterwood, uneven aged management system).

2.3.2. Reduced Harvest to a Fixed Target Level

The various strategies to reduce the harvest below the baseline level have been investigated in the past (Harmon and Marks, 2002; Seely et al., 2002; Peng et al., 2002; Harmon et al., 2009; Nunery and Keeton, 2010) and little difference in Carbon stocks has been found between these strategies (Man e al., 2013). Man et al. (2013) suggested that reducing the harvest to a fixed target level offers more flexibility to the forest manager since it poses fewer constraints than increasing rotation ages or increasing area is reserves. Thus, this study uses harvest reduction to a fixed target level for analysis. In order to continue to meet the objectives of the actively managed forest estates considered in this paper, a minimum accepted harvest level had to be determined. For the three forest estates analyzed in this paper, the minimum accepted harvest level varied between 50% and 30% of the baseline harvest level. To permit comparison between the forest estates considered in this study the minimum accepted harvest level was set to 30% of the baseline harvest level for all the estates. Seven scenarios were simulated by gradually reducing the target harvest level in steps of 10% down to 30% of the baseline level. The management constraints (e.g. minimum harvest ages) were kept identical to the baseline scenario and the target harvest level was constant throughout the 100-year planning horizon.

2.4. Calculation of Carbon credits

Estimating the number of Carbon credits that can be claimed by a project proponent in British Columbia is complicated by the numerous factors involved (e.g. duration of the project, baseline determination and proof of additionality, estimates of the Carbon pools and related emissions, leakage, risk assessment, buffer pool release schedule, and verification frequency) (Grieg and Bull, 2011; British Columbia Ministry of Environment, 2011). Guidance to account for these factors is usually found in a protocol document (e.g. Verified Carbon Standard, 2012a; British Columbia Ministry of Environment, 2011), yet each protocol has different accounting rules resulting in significant differences for the claimable Carbon credits (Newell and Stavins, 2000; Pearson et al., 2008; Galik and Cooley, 2012). Given the location of the three forest estates analyzed here, the Protocol for the Creation of Forest Carbon Offsets in British Columbia (FCOP) (British Columbia Ministry of Environment, 2011) was selected to estimate the claimable Carbon credits. It should be noted the FCOP is seeking formal recognition under the international Verified Carbon Standard (VCS) (Pacific Carbon Trust, 2012).

The controlled and affected Carbon pools and related Carbon sources considered by FCOP include; (1) live and dead forest Carbon pools, (2) Carbon stored in harvested wood products in use and in landfill, (3) emissions due to fossil fuel production and combustion for vehicles, equipment, transport of material, equipment, inputs, and personnel to site, (4) emissions due to processing the harvested wood products, (5) emissions due to the anaerobic decay of the harvested wood products in landfill, and (6) external harvest shifting leakage due to harvest reduction. In addition to the controlled and affected Carbon pools and related Carbon sources, every forest Carbon project carries a risk of reversal as forests are subject to natural disturbances that reduce forest growth and Carbon storage. In order to mitigate the risk of reversal, the offset programs (i.e. regulatory bodies that have registration and enforcement systems and rules for Carbon accounting, monitoring, reporting, verification, and certification) create a buffer pool of Carbon credits corresponding to the risk of reversal. The Carbon credits in the buffer pool cannot be sold immediately by the project proponent; instead the project proponent must follow a release schedule. This study uses the VCS (Verified Carbon Standard, 2012a) buffer pool release schedule, which releases 15% of the buffer pool every 5 years. The number of Carbon credits held back due to the risk of reversal has been assessed at 10% of the credits produced for all three forest estates analyzed in this study, using the VCS tool for AFOLU Non-Permanence Risk Analysis and Buffer Determination (Verified Carbon Standard, 2012b).

Ongoing verification events need to be conducted periodically in order to allow the project proponent to sell the Carbon credits. Most of the offset programs require that at least one verification event should occur every 5 years for the improved forest management strategies (e.g. Verified Carbon Standard, 2012c). The verification frequency, payment strategy (ex-ante or ex-post) and payment schedule are established through negotiations between buyers and producers and are specific to each project. Since the verification frequency has a significant effect on the number of Carbon credits that can be claimed and thus on the break-even Carbon credit price, the financial analysis was conducted for two levels of verification, 1-year and 5-year. The two levels permit the Carbon credits to be sold as soon as they are generated (1-year verification) or the cumulated Carbon credits at 5 years intervals (5-year verification).

2.5. Calculation of the break-even Carbon credit price

The total present net revenue for the baseline scenario ($TPNR_B$) and the total net present revenue for the Carbon project ($TPNR_C$) for an entire planning horizon of n years are

$$TPNR_B = \sum_{t=0}^{n} \frac{H_{Bt} \cdot TNR}{(1+r)^t} \tag{1}$$

$$TPNR_C = \sum_{t=0}^{n} \frac{H_{Ct} \cdot TNR + P_t \cdot C_t - CC_t}{(1+r)^t} \tag{2}$$

Here, H is the harvested volume ($_B$ - baseline, $_C$-Carbon project), TNR is the average timber net revenue per cubic meter (i.e. the difference between the average timber revenue (i.e. average market timber selling price) and the harvesting cost), *P* is the price per Carbon credit, *C* is the number of Carbon credits, *CC* is the Carbon project cost which includes the initial establishment and validation cost and ongoing verification cost, *r* is the discount rate, and *t* is the year. Set $TPNR_B$ equal to $TPNR_C$ and isolate the sum containing *P*

$$\sum_{t=0}^{n}\frac{P_t \cdot C_t}{(1+r)^t}=\sum_{t=0}^{n}\frac{(H_{Bt}-H_{Ct})\cdot TNR+CC_t}{(1+r)^t} \tag{3}$$

The right hand side of Eq. (3) represents the total cost needed to generate C_t in year zero dollars for a given *r*. In order to determine the break-even Carbon credit price, solve for *P* in Eq. (3) assuming that *P* is a constant over the planning horizon of *n* years

$$P=\frac{\sum_{t=0}^{n}\frac{(H_{Bt}-H_{Ct})\cdot TNR+CC_t}{(1+r)^t}}{\sum_{t=0}^{n}\frac{C_t}{(1+r)^t}} \tag{4}$$

In the following analysis *P* is calculated using Eq. (4). *P* is defined as the total break-even Carbon credit price (year zero $ per Carbon credit), and it is assumed to be a constant value for the entire planning horizon of *n* years. Eq. (4) is identical to the levelization equation from Richards and Stokes (2004) when using the same discount rate for the cash flows (numerator) and Carbon credits (denominator) and to the discounted Carbon equation from Boyland (2006).

The right hand side of Eq. (4) can be expanded in order to calculate two components of the total break-even Carbon credit price.

$$P_H=\frac{\sum_{t=0}^{n}\frac{(H_{Bt}-H_{Ct})\cdot TNR}{(1+r)^t}}{\sum_{t=0}^{n}\frac{C_t}{(1+r)^t}} \tag{5}$$

$$P_{CC}=\frac{\sum_{t=0}^{n}\frac{CC_t}{(1+r)^t}}{\sum_{t=0}^{n}\frac{C_t}{(1+r)^t}} \tag{6}$$

Here P_H is the component of the total break-even Carbon credit price due to the opportunity cost of the reduced harvest, and P_{CC} is the component of the total break-even Carbon credit price due to the Carbon project cost. Note the total break-even Carbon credit price (P) calculated in Eq. (4) is the sum of P_H and P_{CC}.

In previous financial analyses on Carbon cost (e.g. van Kooten et al., 2009), *n* was assumed to be the entire life of the project. In the case of British Columbia, the contract term for forest Carbon projects is 25 years with the option of renewal, yet permanence of the emissions offsets should be ensured for 100 years after the end of each contract period (British Columbia Ministry of Environment, 2013). This is expected to be achieved by not harvesting more than the baseline harvest level set prior to the forest Carbon project. In this study, *n* is defined as the break-even period and is set to 25 years. It is assumed that all costs are expenses at the time of occurrence.

The present day costs and revenues used in the financial analysis are detailed in Table 1; these were considered to increase with inflation rate over the 25-year life of the Carbon project. In the case of the AFRF and MKRF, the average timber revenue (i.e. average market timber selling price) and harvesting cost are averaged from the last 10 years of financial data, while in the case of the FE3 these were averaged from 8 cutting permits from last 5 years typical for the area where FE3 resides. Table 1 also shows the site index (i.e. top height in meters at age 50) of the three forest estates and the metric representing the opportunity cost of reducing harvest expressed as the average value per hectare harvested (AVHH) and as the net value per hectare harvested (NVHH). The AVHH is calculated for each forest estate as the average timber revenue multiplied by the 25-year average harvested volume per hectare per year determined for the baseline scenario. Recall, the baseline scenario uses the LTSY approach to determine the harvest level which represents the potential of the forest to produce a non-declining yield. The average harvested volume per hectare per year is the average over the 25-year Carbon project life of the annual harvested volume divided by the annual effective treated area. The effective treated area excludes the in-block retentions (10-20%) in the case of the clearcuts, includes only 30% of the area of each polygon treated in the case of the partial cuts, and includes only 40% of the area of each polygon treated in the case of commercial thinnings. The NVHH is calculated as the TNR multiplied by the 25-year average harvested volume per hectare per year. Given the variety of species, forest types, and timber qualities of the three forest estates, the use of the AVHH to represent the opportunity cost of reducing harvests is more appropriate for the purpose of this study because it takes into account the timber value which is a function of species, forest type, and wood quality. Site index does not take into account the timber value and wood quality, while the NVHH requires information about harvesting cost which is not always available.

Location Table 1

For many years it has been debated what discount rate (*r*) should be used in the financial analysis of forestry projects, for example Row et al. (1981). More recent financial analyses on forest based Carbon projects have used discount rates (i.e. real rates once inflation rate has been removed) of 2.5% to 15% (Richards et al., 1993; Newell and Stavins, 2000; Huang and Kronrad, 2001; Galik and Cooley, 2012). However, the discount rate used in the financial analysis can be lower than 2% (Stern, 2007) or much higher than 15% (Covell, 2011). This study considered discount rates between 0% and 16% to evaluate the effect on the total break-even Carbon credit price.

3. Results

The number of Carbon credits produced and the total break-even Carbon credit price (P) with its two components (P_H and P_{CC}) are presented in Table 2, at 0% and 16% discount rates. It can be seen that P_H is relatively independent of the target harvest level (i.e. percent reduction of the baseline harvest level) because in Eq. (5) both the opportunity cost, and the number of Carbon credits produced, increase at similar rates as the target harvest reduces from 90% to 30% of the baseline harvest level. The implication of this result is P_H is a function of TNR; a higher TNR (e.g. MKRF) results in a higher P_H. It can be seen that P_{CC} drops slightly as the target harvest level reduces; this is because in Eq. (6) the Carbon project cost (i.e. initial establishment and validation cost and verification cost) is constant while the number of Carbon credits produced increases. The overall effect is that P is relatively independent of the target harvest level because P_H is much larger than P_{CC} and so it dominates this relationship. When setting the discount rate to 0% it can be seen that P_H represents more than 58% of P at FE3, more than 79% of P at AFRF, and more than 97% of P at MKRF. The exception observed at AFRF, where P is not independent of the target harvest level for target harvest levels that are 60%-90% of the baseline level, is explained by the reduced number of Carbon credits produced. As the target harvest reduces from 90% to 60% of the baseline harvest level, Carbon credit production at AFRF increases at a slower rate than the opportunity cost and thus, P_H and ultimately P, decrease instead of being relatively constant.

Location Table 2

Figure 1 presents the total number of Carbon credits produced over the life of the project divided by the forest area for each of the forests considered in this study. It can be seen that AFRF produces fewer Carbon credits per hectare over the life of the project than FE3 or MKRF for all target harvest levels. The numbers presented in Figure 1 for the MKRF align with the estimates found by Harmon and Marks (2002) for a similar forest type in the Pacific Northwest. This difference can in part be explained by the productivity of the forest estates. The current average standing volume per hectare is 497 m^3 ha^{-1} for MKRF, 194 m^3 ha^{-1} for AFRF, and 172 m^3 ha^{-1} for FE3 (at MKRF the current average standing volume per hectare is 2.9 times larger as compared to FE3 and 2.6 times larger as compared to AFRF). When the target harvest is reduced to 30% of the baseline level, the Carbon credits produced per standing volume is 0.18 Mg CO_2e m^{-3} for FE3, 0.16 Mg CO_2e m^{-3} for MKRF, and 0.05 Mg CO_2e m^{-3} for AFRF (at FE3 the Carbon credits produced per standing volume is 1.1 times larger as compared to MKRF and 3.4 times larger as compared to AFRF). The reason for the much lower performance of AFRF is that 83% of the timber harvesting land base is managed under uneven aged systems, which has been showed to result in higher Carbon stocks for the baseline (Taylor et al., 2008; Harmon et al., 2009; Man et al. 2013). Thus, the target harvest has to be at a lower level in order for AFRF to produce a large number of Carbon credits.

Location Figure 1

An unexpected result in Table 2 is that P_H and P_{CC} increase with increasing discount rate, except at AFRF for the 70-90% target harvest levels. On viewing Figure 2 it can be seen that the annual production of Carbon credits at MKRF is greater in the later years of the contract, while the annual total cost (i.e. opportunity cost of timber revenue and the Carbon project cost) is constant over the life of the project. Note on the left hand side of Eq. (3) that a larger number of Carbon credits are produced later in the project, while on the right hand side the costs are uniformly distributed over the life of the project, this makes the left hand side more sensitive to an increase in the discount rate. In order to preserve the equality in Eq. (3) as the discount rate is increased, it is necessary to increase P when P is considered a constant value. The exception observed at AFRF for 60-90% target harvest levels is explained by the higher percentage of Carbon credits being produced in the earlier years of the project. Recall that AFRF uses uneven aged systems on 83% of the timber harvest land base, and a lower target harvest level is needed in order to produce an increasing number of Carbon credits throughout the project life.

Location Figure 2

The average site index of the MKRF, AFRF, and FE3 is respectively 25.6, 22.1, and 14.7 while the AVHH of the MKRF, AFRF, and FE3 is respectively 63.7, 22.9, and 12.2 thousands \$ ha^{-1} $year^{-1}$ (Table 1). For the three forest estates considered in this study, a higher site index corresponds to a higher AVHH. However, this is not always the case. For example, high timber value species (e.g. yellow cedar (*Chamaecyparis nootkatensis*)) growing on low site indices can have a high AVHH. The average value per cubic meter harvested follows a similar trend as the site index and AVHH, and for the MKRF, AFRF, and FE3 it is respectively \$35 m^{-3}, \$16 m^{-3}, and \$4 m^{-3}. Figure 3 presents the total break-even Carbon credit price as a function of AVHH and site index, and compares the trends when the opportunity cost of a reduced harvest is not included in the calculation of the total break-even Carbon credit price (Panel A), and when it is included (Panel B). Recall that a significant portion of the AFRF uses uneven aged systems which results in low Carbon credit production and high total break-even Carbon credit prices when the target harvest is 60-90% of the baseline harvest level. The effect of the uneven aged system becomes less when the target harvest is reduced to 50% of the baseline harvest level. Thus, to use the MKRF, AFRF, and FE3 in an analysis of the sensitivity of the total break-even Carbon credit price to AVHH and site index, the target harvests were set to 30% of the baseline level. When the opportunity cost is not included the trend shown in Figure 3 (Panel A), where the total break-even Carbon credit price is lower for the forest estates with higher site index and higher AVHH, is similar to that found by Huang and Kronrad (2001). In contrast, when the opportunity cost is included in the analysis (Figure 3, Panel B), the trend is reversed and the total break-even Carbon credit price increases as the AVHH and site index of the forest estate increases. This is explained by the higher average timber net revenue for higher site index forest estates (Table 1), which results in a higher opportunity cost and higher AVHH. In addition, even a 90% reduction of the TNR (Figure 4) which drives the opportunity cost, does not show the trends found by Huang and Kronrad (2001). It should be noted in the case of the AFRF, the total break-even Carbon credit price has the potential to be lower if an even aged system is used instead of the uneven aged system. In a separate analysis conducted at AFRF, the uneven aged system was changed to an even aged system and the target harvest was set at 30% of the baseline level. This resulted in a total break even Carbon credit price at 0% discount rate of $14.1 per Carbon credit ($P_H$ = $13.9 and P_{CC} = $0.2). The trends in Figure 3 become clearer when these values are used for AFRF (shown in gray color in Figure 3). The opportunity cost is not always important in the financial analysis of a forest based Carbon project. For example, the TimberWest Strathcona Ecosystem Conservation Project (Pacific Carbon Trust, 2011) and the Darkwoods Forest Carbon Project (The Nature Conservancy of Canada, 2011) have been established on the premises that preservation of the current forest structure is more important than the financial return. Where the financial return is the main objective, the opportunity cost of a reduced harvest has to be taken into account when conducting a financial analysis; in such cases, the opportunity cost has a dramatic effect on the total break-even Carbon credit price which increases for forest estates with higher AVHH.

Location Figure 3

Location Figure 4

The current market prices for improved forest management (IFM) projects are between $5 and $16 per Carbon credit, with a slight increase since 2006 (Peters-Stanley et al., 2013). Compared to the *P* values in Table 2, only FE3 could profitably undertake a Carbon project. The AFRF and MKRF would have to wait for the Carbon credit market prices to increase or for the log prices to decrease. Forecasting Carbon credit market prices into the future is a difficult task and contradictory arguments are found in the literature. While Sohngen and Mendelsohn (2003) argue towards an increase of the Carbon credit market prices towards the end of the century due to higher accumulated Carbon concentrations in the atmosphere, most arguments are towards a decrease of Carbon credit market prices because the Carbon sequestration is viewed as a short time strategy to allow for new technologies to emerge (Feng et al., 2002) or because of the decreased attractiveness of Carbon sequestration (Stavins, 1999). Despite the uncertainty, forest based Carbon projects can still be profitably undertaken (Haim et al., 2014), an optimal time path being the immediate implementation of the projects and maintained until the atmospheric Carbon concentration is stabilized (Feng et al., 2002). In order to implement immediately financially feasible IFM projects at AFRF and MKRF at the current Carbon credit market prices, the TNR should be 60%-80% less (at 0% discount rate) (Figure 4) than the values shown in Table 1. The lowest value for the TNR in the last 10 years of financial data from AFRF and MKRF was 18% less than the values shown in Table 1. The British Columbia timber market reports for the last 10 years (British Columbia Ministry of Forests, Lands and Natural Resource Operations, 2014) indicate the lowest timber prices were 32%-34% less than the average timber prices for the same period. Thus, a balance between timber and Carbon credit market prices that would permit the implementation of financially feasible IFM projects at AFRF and MKRF seems difficult to reach in the near future. In the case of the forest estates with low productivity and relatively low TNR (similar to FE3), the forest managers should consider immediate implementation of IFM projects in order to be as close as possible to the optimal time path suggested by Feng et al. (2002).

The 1-year verification frequency might be preferred in order to sell Carbon credits annually to offset the opportunity cost of a reduced harvest. Using the verification cost from Table 1, it was determined that compared to a 5-year verification frequency, the 1-year verification frequency increases the Carbon project cost (initial establishment and ongoing verification) by 3.30 times at 0% discount rate and by 2.14 times at 16% discount rate. Using the increased Carbon project cost due to the 1-year verification frequency in Eq. (4), the total break-even Carbon credit price in Table 2 increased by 22% ($0.8 per Carbon credit) at FE3, by 7% at AFRF ($2.3 per Carbon credit), and by 1% at MKRF ($0.1 per Carbon credit) when the target harvest is set to 30% of the baseline level and discount rate at 0% (Table 3). The highest percent increase for the total break-even Carbon credit price was observed in the case of the FE3 because the Carbon project cost represents a large percent of the total cost (recall at FE3, P_H represents more than 58% of P while P_{CC} represents up to 42% of P). At the other extreme is MKRF where the Carbon project cost is less than 3% of the total cost, and the added cost by adopting the 1-

year verification frequency increases the total break-even Carbon credit price by the lowest percent. When the discount rate is set at 16%, the percent increase for the total break-even Carbon credit price is similar to 0% discount rate for the AFRF and MKRF and lower at FE3 because P_{CC} represents a higher proportion of P and it is discounted more. Thus, the 1-year verification frequency can be more advantageous where the Carbon project cost represents a relatively small percent of the total cost so the added verification cost has little effect on the total break-even Carbon credit price.

Location Table 3

4. Conclusions

Three actively managed forest estates were analyzed in this study, each representing one of the main forest regions in British Columbia; the Coast (MKRF), Southern Interior (AFRF), and Northern Interior (FE3). For each of these forest estates the total break-even Carbon credit price was estimated. When the opportunity cost due to harvest reduction was included in the analysis, it represented 58% to 97% (at 0% discount rate) of the total break-even Carbon credit price. The total break-even Carbon credit price ($ per Carbon credit) was $3.9 at FE3, $32.1 at AFRF, and $40.8 at MKRF when the target harvest was reduced to 30% of the baseline level and for 0% discount rate. Under the current Carbon market prices, only FE3 could profitably undertake a forest Carbon project that reduces the harvest below the baseline level. The total break-even Carbon credit price was relatively independent of the target harvest level (i.e. percent reduction of the baseline harvest level) because when the target harvest decreased from 90% to 30% of the baseline harvest level, the portion of the opportunity cost which represents the largest portion of the total cost, increased at a similar rate to the number of Carbon credits produced. In addition, a higher discount rate increased the total break-even Carbon credit price because the number of Carbon credits produced was larger in the later years of the 25-year project life, while the annual total cost was constant over the project life. However, when the number of Carbon credits produced was larger in the beginning of the project (e.g. AFRF, harvest target at 60-90% of the baseline level), a higher discount rate decreased the total break-even Carbon credit price.

The forests considered in this study provide 3 points from a larger spectrum; the range in site index (i.e. top height in meters at age 50) was 14.7 to 25.6, range in average value per hectare harvested (i.e. the metric representing the opportunity cost of reducing harvests) was 12.2 to 63.7 thousand \$ ha^{-1} $year^{-1}$, and the range in average timber net revenue was \$4 to \$35 m^{-3}. The results of this study indicate that inclusion of the opportunity cost due to harvest reduction results in higher total break-even Carbon credit prices for forests with higher average value per hectare harvested (which corresponded to higher site indices for the three forest estates analyzed here). However, when the opportunity cost was not included in the analysis, the total break-even Carbon credit price drops as the site index increases, and this is similar to previous findings. Further research is required to populate this spectrum with more points from various forest regions in order to be able to generalize about the potential to manage for both timber products and Carbon credits.

The 1-year verification frequency could be considered where the verification cost represents a low percent of the total cost. For projects following an ex-post payment schedule it is necessary to validate and verify periodically the Carbon credits produced before payment is made. Thus, moving to a 1-year verification frequency can supply a more uniform revenue stream. However, care must be taken to ensure the benefits of a more uniform revenue stream outweigh the increased cost incurred due to the more frequent verification events. This is another area that requires more research as the result is likely to be strongly dependent on the financial model of the forest.

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List of symbols and acronyms

AFRF	Alex Fraser Research Forest
AVHH	Average Value per Hectare Harvested, the average timber revenue (i.e. the timber selling price averaged from the last 5-10 years of financial records) multiplied by the 25-year average harvested volume per hectare per year (thousand \$ ha^{-1} $year^{-1}$)
BEC	Biogeoclimatic Ecosystem Classification in British Columbia
C	The number of Carbon credits produced (Mg CO_2e)
CBM-CFS3	Carbon Budget Model for Canadian Forest Sector
CC	Total Carbon project cost, includes initial establishment and validation and ongoing verification cost (\$)
CO_2e	Carbon dioxide equivalent, one Mg of CO_2e indicates the global warming potential of one Mg of Carbon Dioxide for various greenhouse gases as defined in ISO 14064-1(2006). In a forest ecosystem, the Carbon storage is estimated in Mg of Carbon and then converted to Mg of CO_2e (1 Mg of Carbon is 3.667 Mg of CO_2e).
FCOP	The Protocol for the Creation of Forest Carbon Offsets in British Columbia
FE3	Third Forest Estate
FPS-ATLAS	Forest Planning Studio, a spatially explicit forest-level planning model
H	Harvested volume ($_B$ - baseline, $_C$-Carbon project) (m^3 $year^{-1}$)
NVHH	Net Value per Hectare Harvested, TNR multiplied by the 25-year average harvested volume per hectare per year (thousand \$ ha^{-1} $year^{-1}$)
MKRF	Malcolm Knapp Research Forest
n	Duration of the planning horizon and the break-even period for which a break-even Carbon credit price can be calculated (years)
P	Total break-even Carbon credit price ($P= P_H + P_{CC}$) (\$ Mg CO_2e^{-1})
P_{CC}	The component of *P* due to the total Carbon project cost (initial project establishment and validation and ongoing verification) (\$ Mg CO_2e^{-1})
P_H	The component of *P* due to the opportunity cost of the reduced harvest (\$ Mg CO_2e^{-1})
r	Discount rate
t	Simulation year
TIPSY	Table Interpolation Program for Stand Yields of managed stands
TNR	Average Timber Net Revenue, calculated as the difference between the average timber revenue (i.e. the timber selling price averaged from the last 5-10 years of financial records) and the average harvesting cost rom the last 5-10 years of financial records (\$ m^{-3})
TPNR	Total Present Net Revenue ($_B$ - baseline, $_C$-Carbon project)
VCS	Verified Carbon Standard
VDYP	Variable Density Yield Prediction for unmanaged stands

Table 1. Site index, revenues, and costs.

Site index, revenues, or costs	Forest Estates AFRF	FE3	MKRF
Average Site Index (top height in meters at age 50)	22.1	14.7	25.6
Average Timber Revenue ($ m^{-3})	67	48	85
Harvesting Cost ($ m^{-3})[a]	51	44	50
TNR (Average Timber Revenue less Harvesting Cost) ($ m^{-3})	16	4	35
Carbon Project Establishment and Validation ($ ha^{-1})[b]	5.61 (all forest estates)		
Verification ($ ha^{-1} $event^{-1}$)[b]	1.52 (all forest estates)		

[a] includes tree to truck, hauling, road construction, road deactivation, road maintenance, silviculture, scaling, administrative overhead, stumpage (at FE3 and AFRF), and fire protection (at AFRF and MKRF).
[b] costs estimated from Galik et al. (2012).

Table 2. The total break-even Carbon credit price and its two components for a 25-year project life with all costs assumed to be expenses for a 5-year verification frequency.

THL*	Carbon Credits (Mg CO_2e 10^3)	0% Discount Rate			16% Discount Rate		
		P_H (\$ $MgCO_2e^{-1}$)	P_{CC} (\$ $MgCO_2e^{-1}$)	$P = P_H + P_{CC}$ (\$ $MgCO_2e^{-1}$)	P_H (\$ $MgCO_2e^{-1}$)	P_{CC} (\$ $MgCO_2e^{-1}$)	$P = P_H + P_{CC}$ (\$ $MgCO_2e^{-1}$)
AFRF							
90%	1	326.5	87.9	414.4	132.6	95.5	228.1
80%	9	125.0	14.1	139.1	69.8	17.4	87.2
70%	30	59.8	4.4	64.1	48.4	8.1	56.5
60%	46	48.8	2.8	51.6	47.9	6.8	54.7
50%	89	32.7	1.5	34.2	38.4	3.9	42.3
40%	114	31.0	1.1	32.1	39.2	3.1	42.3
30%	129	31.1	1.0	32.1	38.4	2.7	41.2
FE3							
90%	79	3.5	2.5	6.0	4.7	7.4	12.2
80%	177	3.2	1.1	4.3	4.6	3.5	8.1
70%	257	3.2	0.8	4.0	4.6	2.4	7.0
60%	333	3.2	0.6	3.8	4.7	1.9	6.6
50%	407	3.3	0.5	3.8	4.8	1.5	6.3
40%	477	3.4	0.4	3.8	4.9	1.3	6.2
30%	538	3.5	0.4	3.9	5.0	1.1	6.1
MKRF							
90%	67	40.6	1.0	41.6	56.4	2.9	59.3
80%	128	40.7	0.5	41.3	58.9	1.6	60.4
70%	175	42.1	0.4	42.4	59.7	1.1	60.8
60%	255	45.1	0.3	45.4	61.4	0.8	62.2
50%	321	44.4	0.2	44.6	60.9	0.6	61.5
40%	393	44.2	0.2	44.4	60.7	0.5	61.2
30%	501	40.7	0.1	40.8	59.5	0.4	60.0

*THL, target harvest level shown as % of the baseline harvest level

Table 3. The total break-even Carbon credit price increase at 0% discount rate from a 5-year to a 1-year verification frequency.

	AFRF		FE3		MKRF	
THL*	+$	+%	+$	+%	+$	+%
90%	202.2	49%	5.7	96%	2.3	6%
80%	32.3	23%	2.6	60%	1.2	3%
70%	10.0	16%	1.8	45%	0.9	2%
60%	6.4	12%	1.4	36%	0.6	1%
50%	3.4	10%	1.1	29%	0.5	1%
40%	2.6	8%	1.0	25%	0.4	1%
30%	2.3	7%	0.8	22%	0.3	1%

*THL, target harvest level shown as % of the baseline harvest level

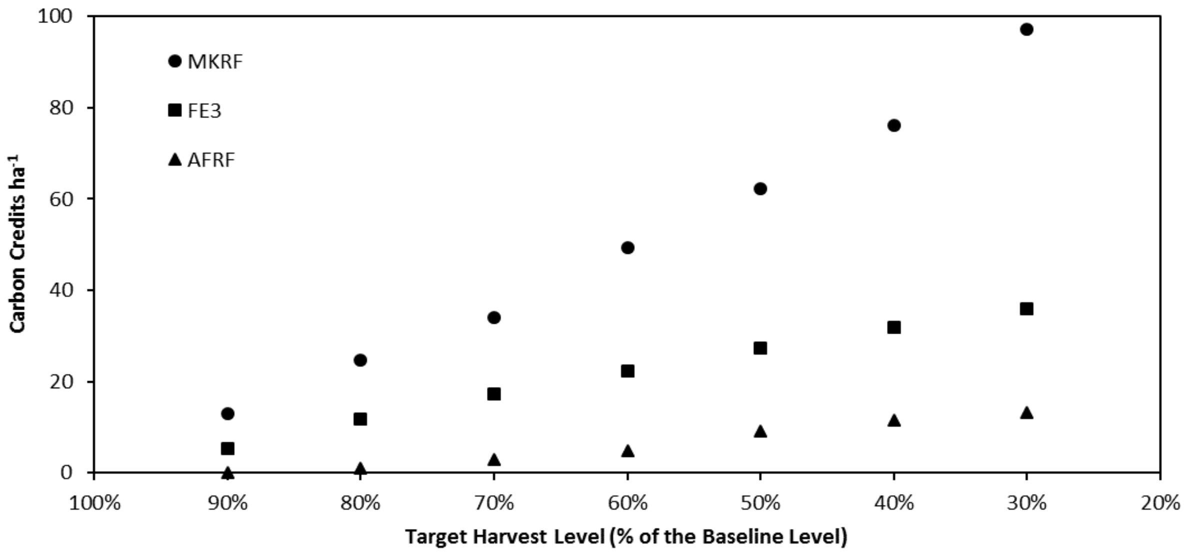

Figure 1. Carbon credits produced per hectare over the life of the project.

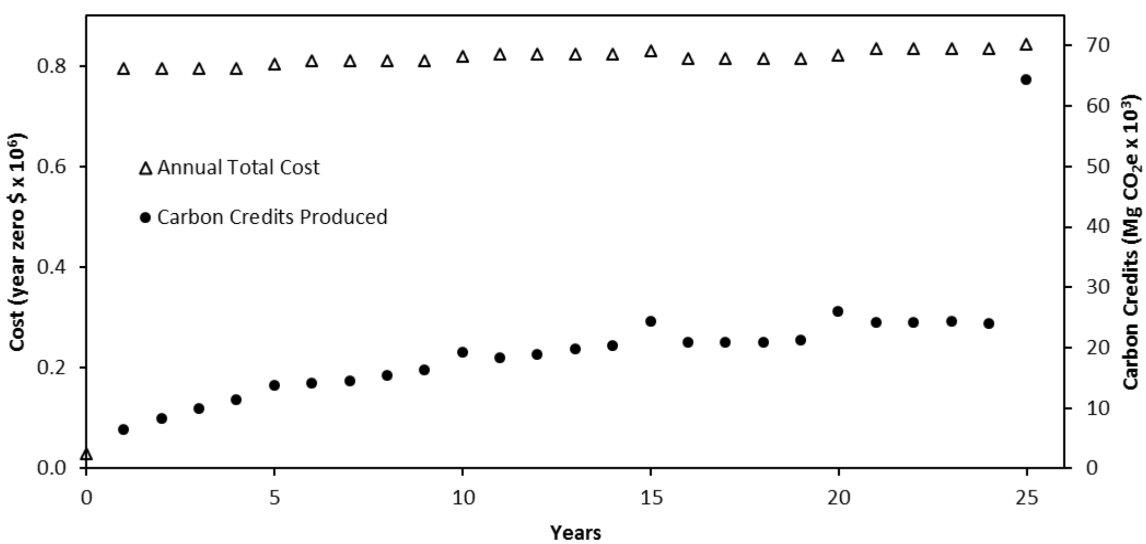

Figure 2. Annual total cost (i.e. sum of opportunity and Carbon project costs) and Carbon credits produced over the life of the project at MKRF for 30% target harvest level (i.e. minimum accepted level). Costs are shown at 0% discount rate.

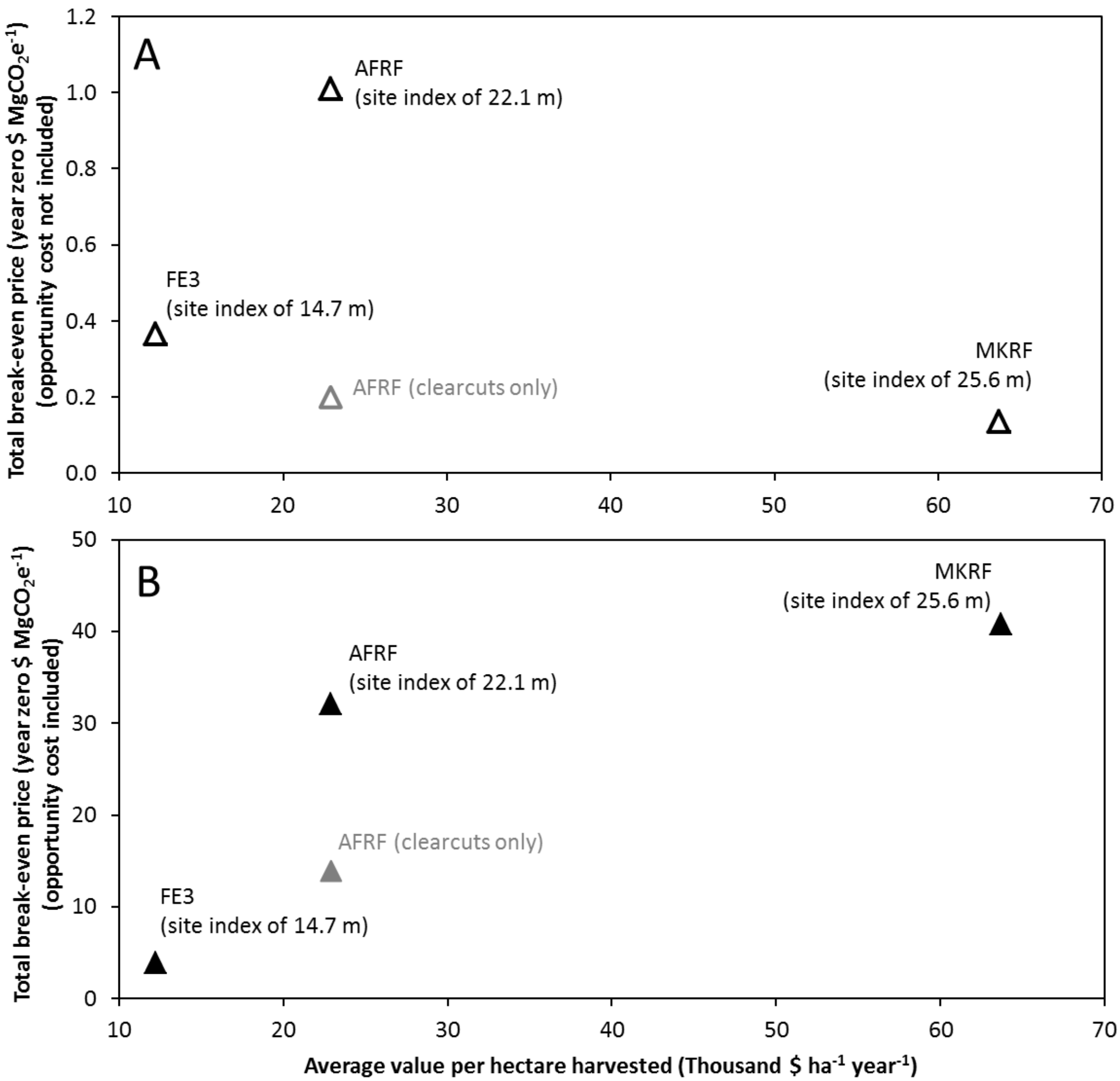

Figure 3. Comparing the total break-even Carbon credit price at 0% real discount rate over a range of average values per hectare harvested per year (12.2 at FE3, 22.9 at AFRF, and 63.7 thousand $ ha^{-1} year^{-1} at MKRF) at 30% target harvest of the baseline level when the opportunity cost due to harvest reduction is not included (Panel A) and included (Panel B) in the financial analysis. The values in the brackets represent the average site index for each forest estate.

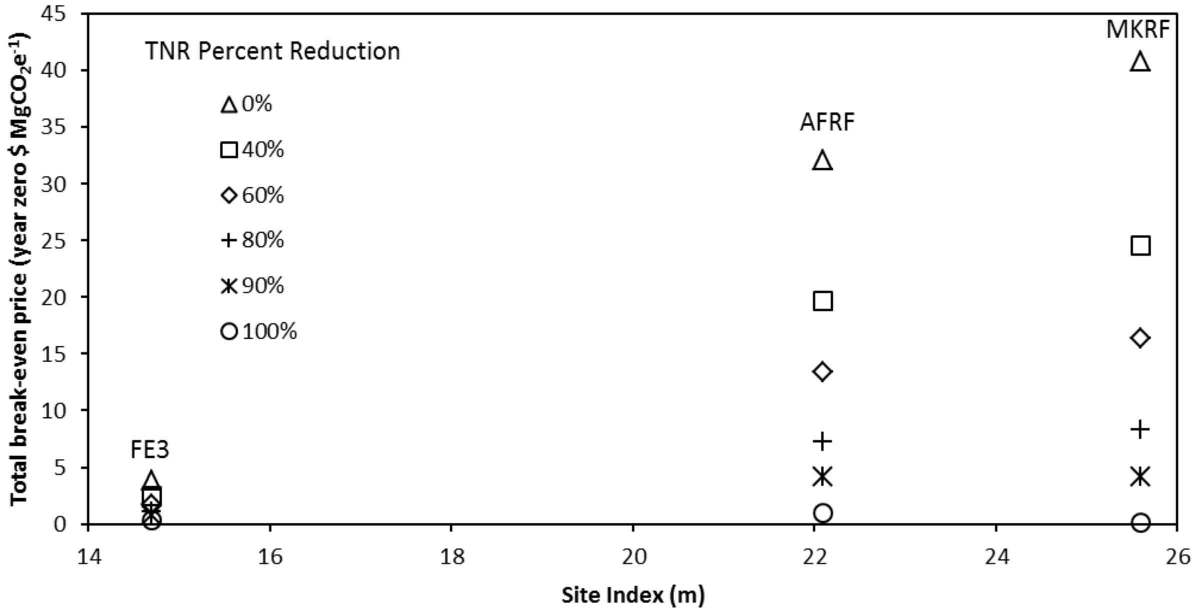

Figure 4. Comparing the total break-even Carbon credit price at 0% real discount rate over a range of site indices (corresponding to three forest estates) at 30% target harvest of the baseline level when percent reductions are applied to the Timber Net Revenues (TNR).