# The Cost of Increasing Carbon Stock in a Coastal Douglas-fir Stand by Extending Forest Rotation

FRST 497 Graduating Essay

**Vojtech Prilesky**

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**Primary Advisor: Dr. John Nelson**
**Secondary Advisor: Dr. Gary Bull**

# Abstract

The effect on climate of extending forest rotations is similar to that of afforestation/reforestation projects. This study attempts to model the opportunity cost that would have to be covered by carbon revenues (ie. ‘carbon cost’) to make delayed forest harvest economically viable. This is considered for an even-aged Douglas-fir (*Pseudotsuga menziesii*) stand in coastal British Columbia. Sensitivity of carbon costs to parameters such as site productivity, log prices, discount rates, and risk buffers are examined. Results find that carbon costs for all scenarios rise with greater rotation extensions but eventually “plateau” in the future. Sites of higher productivity have higher carbon costs. Higher log prices also cause carbon costs to rise. Higher discount rates cause carbon costs to rise more quickly with length of rotation extension, but plateau carbon costs do not vary greatly between discount rates. Risk buffers cause carbon costs to rise more than the proportion of the risk buffer. Assuming a market price of \$5.00/t$CO_2$e, rotation extensions could only be viable for scenarios with depressed log prices. Short rotation extensions have poor economy of scale and would likely be unable to cover enough of a project’s fixed costs to make it feasible.



# Key Words

Carbon, stock, forest, rotation, extension, cost, log, price, discounting, productivity, harvest, Douglas-fir, net present value, viable, risk.

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# Introduction

Forests can store a large amount of carbon in soils and biomass, though they are a dynamic system acting simultaneously as carbon sinks and carbon stores. Depending on their state, forests can cause either net carbon sequestration or net carbon emission.

The past decade has seen the rapid development of regulated and non-regulated carbon markets. These carbon markets were made to create incentive to reduce global greenhouse gas emissions by the lowest cost. Just about any project that can prove to create a net sequestration of carbon can be eligible to receive payment through these markets. Since forests are such a large part of the global carbon cycle, forest landowners and forest managers all over the world are considering how to manage their forests to better sequester carbon.

The most common forest carbon sequestration projects to date are afforestation and reforestation projects (Hamilton *et al.* 2009). There are, however, other methods of increasing forest carbon storage. Avoiding deforestation is a powerful method of preventing carbon from ever reaching the atmosphere, as is changing clearcut harvest systems to selective systems or leaving greater retention areas. Extending forest rotations is another means to hold more carbon in forests and is the subject of this study.

Longer forest rotations can reduce the greenhouse gas emissions by sequestering and storing carbon in biomass for a greater amount of time. The additional sequestration may seem moot considering that the stand would be eventually harvested; after all, the clearcut of a 50 year old stand holds about as much carbon as the clearcut of a 100 year old stand. However, there is nonetheless a net emission reduction. If one were to consider the implementation of such a project over an entire landscape, then there would be a net increase in forest biomass overall (Harmon and Marks 2002); ie. there would be bigger trees standing for a longer period of time. Moreover, longer rotations also have a lower harvest rate – reducing the rate of fossil fuel consumption; and larger diameter logs – resulting in lower decay rates of the wood products.

## *Objective*

The objective of this study is to test the feasibility of sequestering carbon by extending forest rotations by modeling the cost of carbon with harvest age, in units of dollars per ton of $CO_2$ equivalent; $/t$CO_2$e. In other words, what is the price of carbon necessary to make up for the opportunity cost of a delayed harvest? This question is considered for Douglas-fir (*Pseudotsuga menziesii*) stands typical of the University of British Columbia's Malcolm Knapp Research Forest in Maple Ridge, BC. Stands of varying productivity will be considered along with differing log prices, discount rates, and risk buffers.

TIPSY (Table Interpolation Program for Stand Yields) and CBM-CFS3 (Carbon Budget Model for the Canadian Forest Sector version 3) will be used to model growth and yield, carbon stocks, and net present values for all scenarios. These parameters will allow us to establish a baseline for each scenario and then calculate the price of carbon necessary to cover the opportunity costs of extending rotations beyond the baselines. A detailed description of this process can be found in the Methods section. The Results section presents the model outputs and attempts to explain the trends and anomalies that are found. A comparison of the results of this study to current market conditions and other studies is given in the Discussion section.

# Methods

To model stand growth and yield and change in forest value with harvest age, the TIPSY 4.1 model was used. The Table Interpolation Program for Stand Yields (TIPSY) is a stand-level growth and yield model developed by the BC Ministry of Forests and is commonly used by BC forest managers to model stands for decision support. TIPSY growth and yield curves are based on permanent sample plots in mostly single-species even-aged stands (Mitchell *et al.* 2007). This makes it a relevant tool for modeling similar stands under varying management regimes, especially for modeling changes to the stand with increasing age. For these reasons TIPSY was chosen for this project to model the changes to forest carbon stock and its relation to the stand financial value.

Growth and yield data were input to the Carbon Budget Model for the Canadian Forest Sector (CBM-CFS3) developed and freely distributed by the Canadian Forest Service (Kurz *et al.* 2009). Specific details on how the modeling program was used are described in the Methods section of this report.

Three Douglas fir stands were defined by their productivity; a high quality site (Site Index: 30), a medium site (SI: 24), and a poor site (SI: 18). Models were extended to 290 years, which is the limit of TIPSY projections.

## *Modelling*

To model stand growth, TIPSY requires a number of input variables to describe the stand. A hypothetical single-species even-aged Douglas fir (*Pseudotsuga menziesii*) stand in the Coastal Western Hemlock biogeoclimatic zone was chosen as a typical stand in the Malcolm Knapp Research Forest.

Table 1 outlines the necessary inputs to get a growth and yield curve based on growth curves by D. Bruce (1981). Operational Adjustment Factors (OAF) are factors that reduce the modeled productivity of stands to realistic levels. OAF 1 adjusts the model to consider areas of low productivity in the stand or "gaps" such as those created by rocky soils or wet ground; in this case the volume of the stand is reduced by 15% due to areas of low productivity. This reduction is constant for all ages. OAF 2 considers the decrease in volume attributable to disease, pests, and breakage. It is not constant for all ages but rather indexed to 100 years. Therefore, in this case OAF 2 reduces stand volume by 5% at 100 years; the reduction is lesser at younger ages and greater at older ages (Mitchell *et al.* 2007).

**Table 1: Input variables used in TIPSY models.**

| | | |
|---|---|---|
| Site slope | 10% | * Operational Adjustment Factor 1<br>** Operational Adjustment Factor 2 |
| Site Index | 30, 24, 18 | |
| Regeneration | Planted | |
| Regeneration Delay | 1 year | |
| Initial Density | 1600 sph | |
| OAF 1* | 0.85 | |
| OAF 2** | 0.95 | |

The financially optimal harvest age was assumed to be that which produces the greatest net present value (NPV). For TIPSY to output NPV estimates, economic specifications such as a discount rate, log prices, and harvest and silviculture costs are needed. Four discount rates were considered: 3%, 4%, 5%, and 6%. Average log prices from the period of November 1st 2010 to January 31st 2011 were used (Table 2). To test the sensitivity of carbon prices to log prices, real annual log price changes of -2%, -1%, 0%, +1%, +2%, and +4% were considered.

**Table 2: Log prices for BC coast Douglas-fir grades (BC Ministry of Forests, Mines and Lands 2011).**

| Log Grade | H | I | J | U | X | Y |
|---|---|---|---|---|---|---|
| Price/$m^3$ | $133.67 | $70.76 | $58.07 | $47.50 | $36.94 | $29.05 |

Higher value grades for Douglas fir – such as grades B, C, D, and F – were not included in the economic analysis because they require a minimum of 25% clear wood (ie. without knots), which is very unlikely to be achieved in a second growth stand without pruning (Mitchell *et al.* 2007).

Other economic specifications were included based on average harvest and silviculture costs in the Malcolm Knapp Research Forest. These costs were $2500 for planting and manual brushing (brushing performed in year 3), and $27/$m^3$ for harvesting, stump to dump (Cheryl Power, RPF, pers. comm. 2011).

Stands were defined as second-growth established after clearcutting, so it was assumed that roads previously established for harvest and silviculture activities would still be in place, therefore requiring no additional road building costs. $1154/ha of road maintenance costs were included in the NPV calculations.

TIPSY calculated the NPV of the stand at varying harvest rotations in single year increments. The >17.5cm dbh merchantable volume yield curve was input into CBM to produce the carbon stock curves (tonnes of carbon per hectare).

The tables created by TIPSY and CBM – estimating the NPV and total forest carbon stock, respectively – was imported into spreadsheets where further calculations could take place.

Table 3 summarizes inputs used for 36 carbon cost scenarios. Default values for all stands were assigned as 0% change in log price, 4% discount rate, and 0% risk buffer. These were the values held constant during the sensitivity analysis of each other factor. For example, while testing the sensitivity of carbon revenues to discount rates, the 0% change in log price and 0% risk buffer were held constant.

**Table 3: Summary of values used in scenarios modeled.**

| | |
|---|---|
| Site Index | 18, 24, 30 |
| Annual Log Price Change | -2%, -1%, 0%, 1%, 2%, 4% |
| Discount Rates | 3%, 4%, 5%, 6% |
| Risk Buffers | 0%, 10%, 20%, 30% |

### *Carbon Price Calculations*

The maximum NPV was determined for each carbon scenario. This was set as the baseline harvest age, even for scenarios whose maximum NPV was negative (the grand majority of scenarios). Any extra carbon sequestered by extending the rotation beyond this baseline age was considered additional and eligible for carbon offset payments.

A hypothetical payment schedule was designed in which the forest owner would be paid at the beginning of each one-year period beyond the baseline harvest age. For example, if the baseline harvest age is determined to be 60 years, the forest owner would be paid at year 60 for delaying harvesting and sequestering carbon for that year. The next year, year 61, he would receive another payment for not harvesting that year. The payment would be proportional to the amount of CO2e sequestered in that year.

The loss of NPV was calculated for each harvest age beyond the baseline year. This amount is equal to $NPV_c$, the minimum net present value that must be derived from carbon offset payments to make the extended rotation financially feasible; in other words $NPV_c$ is the project's opportunity cost.

The marginal carbon sequestration was calculated for each year beyond the baseline year and was converted to $CO_2$ equivalent by multiplying by a factor of 44/12 – the atomic mass of $CO_2$ (44) divided by the atomic mass of carbon (12).

Equation 1 was used to determine carbon costs.

$$NPV_c = p/(1+r)^n \qquad [1]$$

where $NPV_c$ is the opportunity cost, $p$ is the carbon offset payment at year $n$, and $r$ is the discount rate.

Any payment given for carbon will depend on the additional carbon sequestered in each period (Equation 2).

$$p = \rho \times C \qquad [2]$$

where ρ is the price per ton of $CO_2$e and $C$ is the marginal $CO_2$e stock sequestered in a given period. ρ is assumed to remain constant for all periods in each scenario.

Since the carbon offset payments are given periodically, the total $NPV_c$ will be the sum of all payments received until harvest ($h$) (Equation 3):

$$NPV_c = \rho\left[\frac{C_1}{(1+r)^{n1}} + \frac{C_2}{(1+r)^{n2}} + \cdots \frac{C_h}{(1+r)^{nh}}\right] = \rho \times \sum_{t=1}^{h} \frac{C_n}{(1+r)^{n_t}} \qquad [3]$$

Solving Equation 3 for ρ yields Equation 4:

$$\rho = NPV_c\left[\frac{C_1}{(1+r)^{n1}} + \frac{C_2}{(1+r)^{n2}} + \cdots \frac{C_h}{(1+r)^{nh}}\right]^{-1} = NPV_c \times \left[\sum_{t=1}^{h} \frac{C_n}{(1+r)^{n_t}}\right]^{-1} \qquad [4]$$

This methodology is identical to the "Levelization/Discounting Method" described by Richards and Stoke (2004). This is not the only method used to calculate the costs of carbon sequestration, and results can vary significantly between methods; the Levelization/Discount Method has been observed to have produced higher unit costs for carbon by a factor of 5 to 10 (Van Kooten *et al.* 1992 cited in Richard and Stoke 2004). This method, unlike others, discounts carbon sequestration as well as opportunity costs, therefore stressing the value of sequestering carbon sooner rather than later. These factors make this methodology conservative and it is the method recommended by Boyland (2006).

To mitigate risks to permanence, risk buffers were calculated and analyzed. The amount of carbon equivalent available for offset sale was decreased by each given proportion.

Results were summarized in tables showing the viable rotation extension – expressed in years and as a percent of the baseline rotation age – created by assuming a carbon price of $5.00/t$CO_2$e. This value is considered to be an average price for forest carbon projects sold in North American voluntary markets, which is argued in the Discussion section of this report.

# Results

## *Log Price Change*

As expected, Figures 1, 2, and 3 show that the price of carbon rises with longer rotation extensions and higher log prices. This makes sense because with time, stands accumulate larger, more valuable timber as well as more carbon. Higher future log prices mean that forest owners would have to be paid more for carbon to be convinced not to harvest the stand.

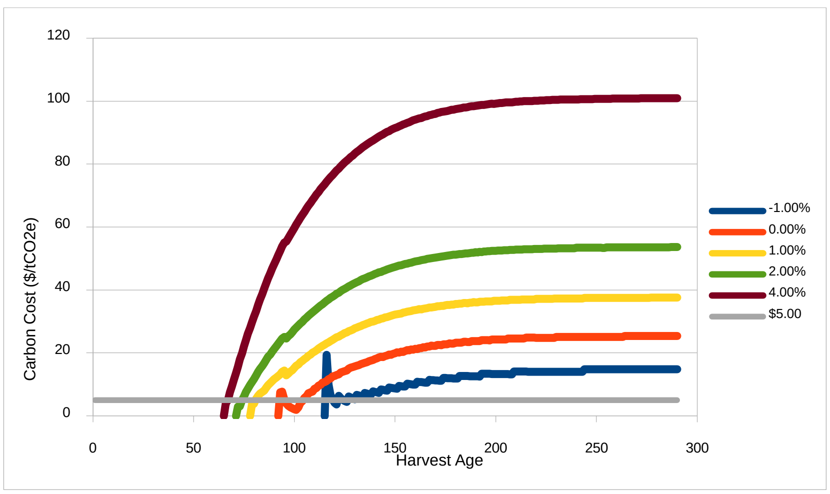


**Figure 1: Carbon cost curves for SI 18 with real annual log price changes of -1%, 0%, 1%, 2%, and 4%.**

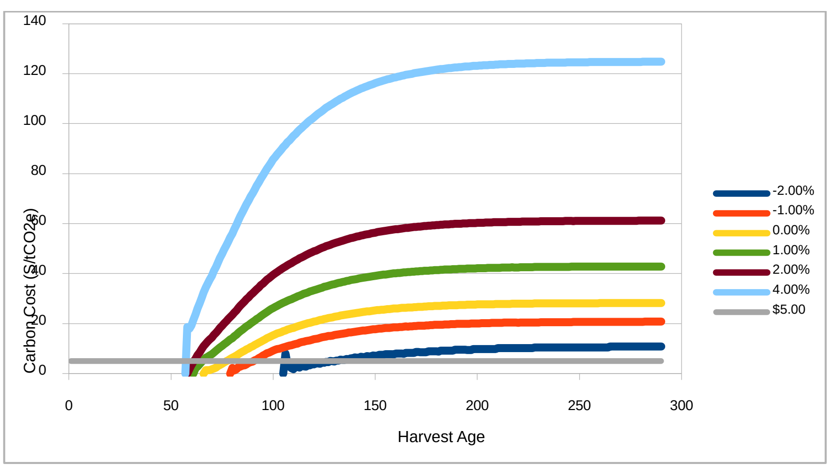


**Figure 2: Carbon cost curves for SI 24 with real annual log price changes of -2%, -1%, 0%, 1%, 2%, and 4%.**

The baseline harvest year also varied with log price. High log prices shortened rotations whereas low prices extended rotations. This can be seen in Figures 1-3 as the curves for low prices begin at a later rotation age.

Site Index also influenced the baseline year, with rotations being shorter for stands of higher SI. This influence of Site Index and log prices on the baseline age resulted in the elimination of the SI 18, -2% price change scenario; the highest NPV occurred at year 290, therefore making the stand inoperable. The scenario therefore does not appear in Figure 1 or Table 4.

One can notice that for some curves, especially the lower cost curves, there is a spike near the beginning of the curve. This is an artifact of the distant payment periods. Since the first payment is made far into the future, the $1/(1+r)^n$ factor is very small, making the carbon cost at that age very large. With the addition of more periods, and an $NPV_c$ value that hardly changes (once again, a

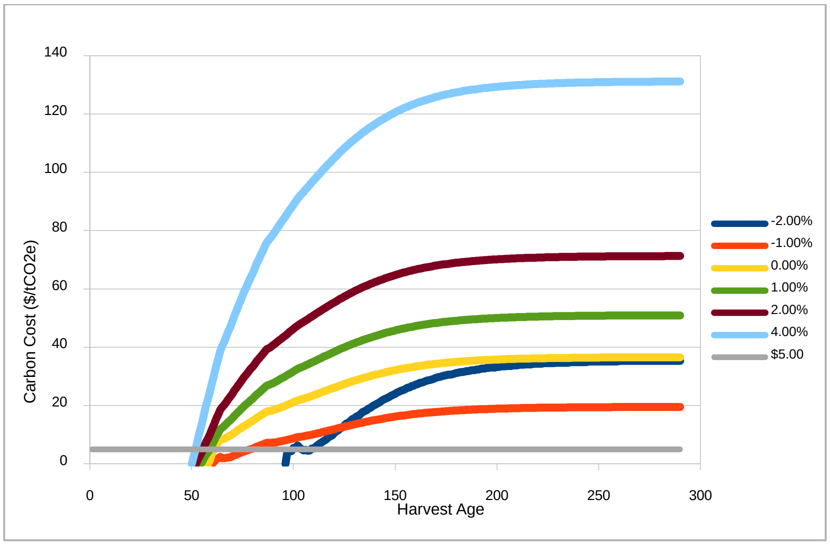


**Figure 3: Carbon cost curves for SI 30 with real annual log price changes of -2%, -1%, 0%, 1%, 2%, and 4%.**

result of the length of time into the future being considered), the carbon cost decreases to a more acceptable level.

It is interesting to note that in all scenarios, the cost of carbon eventually "plateaus". This is interpreted as the cost of carbon necessary to halt any future harvest. This plateau is a result of discounting; events far off into the future have less effect on NPV. After several centuries, carbon sequestration slows and eventually becomes insignificant, while potential economic activities far into the future also lose influence on present-day NPV.

The SI 30, -2% change in log price scenario was anomalous, as is evident in Figure 3. Like other low price curves, it spikes at the beginning and recovers, but then, unlike others, the curve rises substantially and plateaus above the -1% log price curve and almost on-par with the 0% log price curve. This behaviour might be explained by the very large baseline year gap between the -2% curve and others; the baseline year shifts from 60 years for the -1% scenario to 96 years for the -2% curve. This means that the first carbon offset payment would arrive 36 years later than in the -1% scenario.

However, this explanation does not explain why this behaviour does not appear in the lower Site Index scenarios. For example, the baseline year gap for SI 24 is 26 years but the -2% curve does not even approach the -1% curve.

Besides this one anomaly, there is a readily apparent positive relationship between the cost of carbon and real annual log price increases.

Assuming an average price of $5.00/tCO_2e$, Table 4 shows that small rotation extensions are viable for all sites. Lower log prices generally allow for greater rotation extensions. All scenarios that involve any real log price increase are the least feasible; viable rotation extensions are below 6 years. It is interesting to note that for almost all log price scenarios, the low productivity site (SI 18) has viable rotation extensions that are comparable to the higher productivity sites in real terms, but consistently lower in terms of percentage. This is due to the fact that the baseline years are much greater for SI 18.

**Table 4: Viable rotation extensions [years (%)] with real annual log price changes of -2%, -1%, 0%, 1%, 2%, and 4%, and a carbon price of $5.00/tCO2e.**

| **Log Price Change** | **-2.00%** | **-1.00%** | **0.00%** | **+1.00%** | **+2.00%** | **+4.00%** |
|---|---|---|---|---|---|---|
| **SI 18** | | 11 (9.57%) | 12 (13.04%) | 2 (2.56%) | 2 (2.82%) | 1 (1.54%) |
| **SI 24** | 25 (23.81%) | 11 (13.92%) | 11 (16.67%) | 4 (6.56%) | 3 (5.17%) | 0 (0.00%) |
| **SI 30** | 12 (12.50%) | 18 (30.00%) | 2 (3.45%) | 5 (9.26%) | 3 (5.77%) | 1 (2.00%) |

## *Discount Rate*

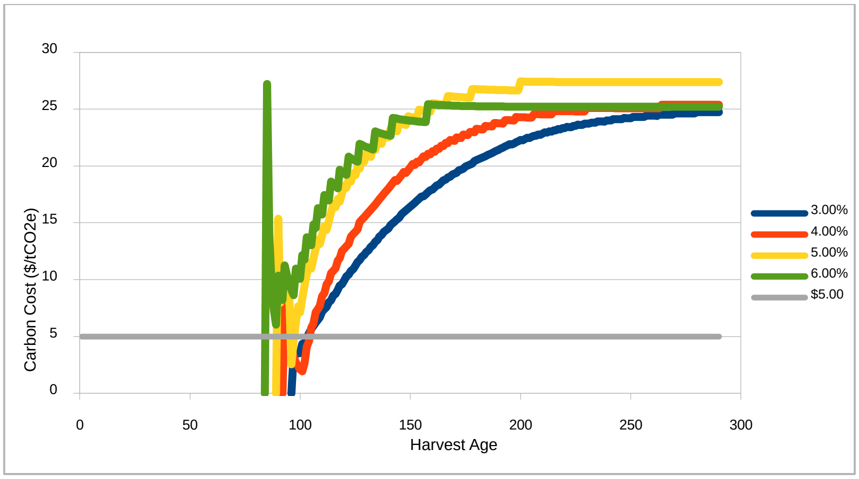


**Figure 4: Carbon cost curves for SI 18 with discount rates of 3%, 4%, 5%, and 6%.**

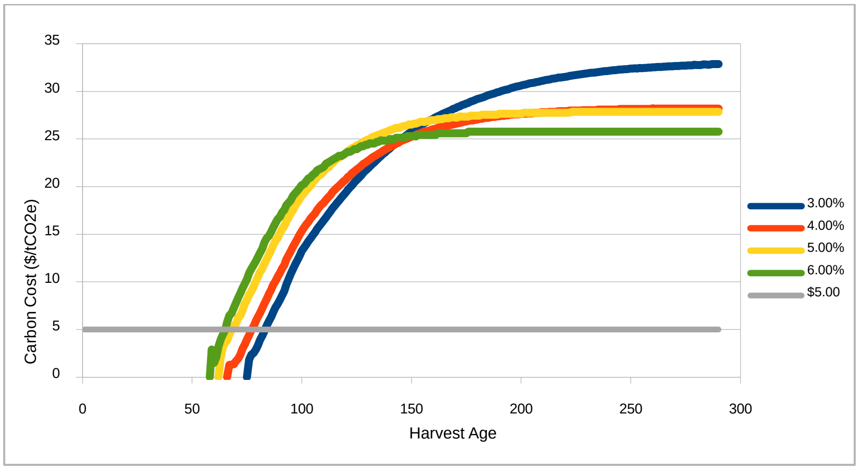


**Figure 5: Carbon cost curves for SI 24 with discount rates of 3%, 4%, 5%, and 6%.**

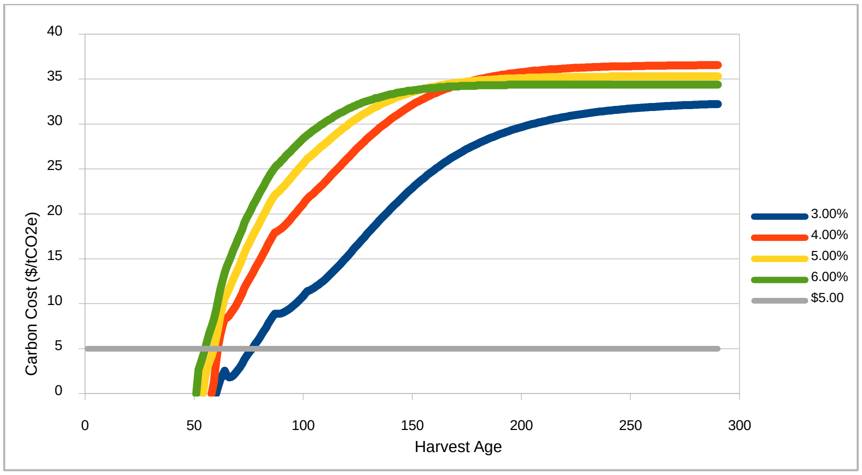


**Figure 6: Carbon cost curves for SI 30 with discount rates of 3%, 4%, 5%, and 6%.**

Figures 4, 5, and 6 display the sensitivity of carbon prices to discount rates for the three Site Indexes. The most apparent trend is that higher discount rates create steeper curves. Higher discount rates cause the cost of carbon to increase quickly and plateau sooner than lower discount rates. Discount rates, like Site Index and log price, affect the baseline harvest age. One can see that for all Site Indexes, higher discount rates cause baseline ages to shorten; the opposite being the effect of low discount rates.

In Figure 4 it is interesting to note that the curves for the SI 18 stand spike highly near the beginning of the curves, which does not appear as strong for SI 24 and SI 30 scenarios. This can once again be explained by the later baseline year, which in itself is caused by the low productivity of the stand. The later baseline year causes the $1/(1+r)^n$ factor to be very small, greatly increasing the cost of carbon for the first period. This is especially true for higher discount rates, which make the $1/(1+r)^n$ factor even smaller. Note that the carbon price curve for the 3% discount rate has a very small spike.

The curves in Figure 4, especially the higher discount rate curves, also have a peculiar slanted step-ladder shape where the carbon cost spikes periodically followed by several years where it decreases, then spikes again. This can be explained as an artifact of the rounding of NPV values output by TIPSY. TIPSY produces only whole-number NPV calculations, and with high discount rates, the difference in NPV between one year and the next far off into the future is minimal. In fact, for the SI 18, 6% discount rate scenario, it is not uncommon to have 5 or more years with the same NPV value, and this creates the 'step' seen in the curve. In these 'steps', the NPV difference does not change, whereas the $\sum_{t=1}^{h} \frac{C_n}{(1+r)^{n_t}}$ factor increases with each year causing the cost of carbon to decrease, until the NPV moves up another step. This phenomenon can be seen in curves for other Site Indexes, but is most notable for the SI 18 curves.

The inconsistent curves appearing in the SI 30 scenarios are a manifestation of undulations in the stand's carbon stock. These undulations are a series of years with a decreased carbon sequestration rate which later picks up again, causing deformations in the carbon price curve. These undulations in carbon sequestration rate are more pronounced in the SI 30 carbon stock curve than in the other Site Indexes.

It is interesting to note that discount rates do not seem to greatly affect plateau carbon costs; there is no readily apparent relationship between final plateau carbon cost and discount rate (Figures 4, 5, and 6), though the 6% discount rate did not result in the highest plateau carbon costs in any scenario. Likewise, there is no clear relationship between discount rate and the length of any viable rotation extension assuming a carbon price of \$5.00/t$CO_2$e (Table 5). Short rotation extensions are viable for all scenarios except for the SI 18, 6% discount rate scenario.

**Table 5: Viable rotation extensions [years (%)] with discount rates of 3%, 4%, 5%, and 6%, with a carbon price of \$5.00/tCO2e.**

| Discount rate | 3.00% | 4.00% | 5.00% | 6.00% |
|---|---:|---:|---:|---:|
| **SI 18** | 7 (7.29%) | 12 (13.04%) | 8 (8.99%) | 0 (0.00%) |
| **SI 24** | 8 (10.67%) | 11 (16.67%) | 6 (9.68%) | 7 (12.07%) |
| **SI 30** | 16 (26.67%) | 2 (3.45%) | 5 (9.26%) | 3 (5.88%) |

## *Risk Buffers*

As expected, higher risk buffers increase the cost of carbon (Appendix A, Figures 9, 10, 11, and 12). Carbon cost curves track the shape of the default 0% curve (from which they are derived) but are stretched vertically. Risk buffers caused a cost increase that was of the same proportion for all stands; 10% risk buffers raised carbon costs by 11.11%, 20% buffers raised costs by 25.00%, and 30% buffers raised costs by 42.86%. Table 6 shows that higher risk buffers also decrease the length of viable rotation extensions for all sites besides SI 30, which shows no change from risk buffers.

**Table 6: Viable rotation extensions [years (%)] with risk buffers of 0%, 10%, 20%, and 30%, and a carbon price of \$5.00/tCO2e.**

| Risk Buffer | 0.00% | 10.00% | 20.00% | 30.00% |
|---|---|---|---|---|
| **SI 18** | 12 (13.04%) | 11 (11.96%) | 10 (10.87%) | 10 (10.87%) |
| **SI 24** | 11 (16.67%) | 10 (15.15%) | 9 (13.64%) | 8 (12.12%) |
| **SI 30** | 2 (3.45%) | 2 (3.45%) | 2 (3.45%) | 2 (3.45%) |

## Discussion

There were a number of assumptions implicit in this study. The first major assumption was that the project was taking place on and adjacent to private land, and that the owner would manage the forest to derive the maximum net financial benefit. It was assumed that leakage would not be a major factor. Depending on the relative size of the project area to the timber supply area, the leakage caused by supply and demand dynamics might become a factor to consider and in any case should be included in any comprehensive project proposal.

Climate change was not directly considered in this study. Although quite uncertain, it is conceivable that climate change could influence not only growth and yield curves and carbon cycling data used in this study, but also the market price for logs. All these factors combined would drastically change the results of this study, but the sheer complexity of the exercise would it make far beyond the scope of this essay.

This study did not account for the costs associated with establishing a carbon offset project. These costs cover project development, modeling, auditing, registration, and monitoring. Monitoring is a cost necessary for carbon projects to verify actual sequestration taking place and is usually performed by measuring permanent sample plots within the project boundaries. The cost depends on fixed and variable monitoring costs, discount rates, and the variability of stands; Cacho *et al.* (2004), estimated monitoring costs (including all fixed establishment costs) to be between $0.12/tCO2e and $0.58/tCO2e for tropical hardwood plantations in Indonesia with areas of 500 to 1000 hectares. These costs would likely be greater for a coastal BC forest of similar size due to the complexity of the ecosystem and higher labour costs.

It was assumed that forest owners would receive payment every year beyond the maximum NPV harvest, with the payment being given at the beginning of the year. This may be quite different from actual payment regimes, and may be unique to each contract, for "[t]here are... countless ways to structure and implement a [Clean Development Mechanism] project, and to value and transact the resultant [Certified Emission Reductions]" (Wilder and Willis 2007). The same is true for transactions in non-regulated markets. For each scenario, determining the price per Certified Emission Reduction unit (CER; also known as a carbon 'credit' and equivalent to 1 metric ton of $CO_2$e) would require a different formula therefore yielding different results from those presented in this study. Although calculated prices per unit of $CO_2$e will vary between payment regimes, it is expected that the trends shown in the sensitivity analyses would not.

Considering the wide variety of potential contracts, especially regarding the assumption of risk and the stage of project development when credits are bought, it is difficult to fairly compare prices. Average prices can be as low as $2.60/tCO2e for a geological sequestration project being sold in over-the-counter (OTC) voluntary markets (Hamilton *et al.* 2009), to a peak average of over €31/tCO2e for EUA credits (European Union Allowance; emission allowances that effectively carry no risk) on the European Union's Emissions Trading System (the world's largest regulatory carbon market) in mid-2008 (Kossoy and Ambrosi 2010). In 2008, afforestation/reforestation (A/R) plantation projects in OTC markets received an average price of $6.40/tCO2e, but had a large degree of variation with a maximum price of over $45/tCO2e (Hamilton *et al.* 2009). Forest management projects in OTC markets received an average price of $7.70/tCO2e and a maximum of about $11/tCO2e in 2008 (*ibid*.). Currently CERs are trading on the EU ETS regulated market for around €13.00/tCO2e, or $18.08/tCO2e (ICE 2011). It is important to note that these are the prices of secondary transactions and do not reflect the actual prices received by primary carbon suppliers, which are not as commonly reported and can be several dollars less. The World Bank reports in its "State and Trends of the Carbon Market 2010" report that the average price that primary carbon suppliers received in North American OTC markets in 2009 was \$4.90/tCO2e (Kossoy and Ambrosi 2010). This is the basis for the use of \$5.00/t$CO_2$e in this study. Most analysts expect carbon prices in all markets to rise as the market matures and emissions caps become more restrictive and global economic growth gets back on track.

If we assume a price of \$5.00/tCO2e for this carbon project, the results suggest that sequestering carbon by extending forest rotations could only be viable for very short rotation extensions. It would be most viable for scenarios of depressed log prices and small risk buffers; the longest possible rotation extension was determined to be the SI 24, -2% log price change scenario which could be viably extended by 25 years (24%). One must consider economies of scale and incorporate the project development costs into the calculations to determine whether the project would truly be viable. A large volume of carbon would need to be sequestered to cover the project's fixed costs, which would be difficult to attain with very short rotation extensions.

If carbon prices were to increase in the future, the feasibility of sequestering carbon by rotation extension would not only increase, but at a rate greater than carbon prices. As cost curves become less steep farther into the future, the increase in rotation extension length – as well as total sequestered carbon – will increase greater relative to marginal increases in carbon price.

A number of studies have been published over the last two decades attempting to model the carbon sequestration costs associated with forest practices. Methodologies and land bases have varied so much between studies that they are difficult to compare (Richards and Stoke 2004; Boyland 2006), and most have focused on A/R projects rather than alternative forest management projects. Von Kooten *et al.* (1995), however, conducted a similar study and estimated that for coastal BC forests, harvest rotations would be extended by about 20% if carbon were priced at \$20/tC (\$5.45/t$CO_2$e) and wood were to have a (net) price of \$15/$m^3$. Similar to this study, they found the cost of carbon to increase and rotation length to shorten with increased wood prices.

## Conclusion

This study was designed to test the feasibility of sequestering carbon by the extension of forest rotations. The actual cost of such a project varies according to the length of the extension, size of the project, discount rate, site productivity, log prices, and risk buffers. The price for carbon that project designers can expect to receive also varies due to natural market variability, changes in the regulatory environment, perceived risk, and payment regime. In general, the models presented here suggest that short rotation extensions could be feasible considering current prices for carbon, especially for scenarios assuming decreasing log prices. However, economies of scale must be seriously considered and short rotation extensions are not likely to produce a large enough increase in carbon stock to cover the fixed costs of the project. Higher carbon prices are necessary to make these types of carbon projects viable.

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# Appendix A – Supplemental Figures

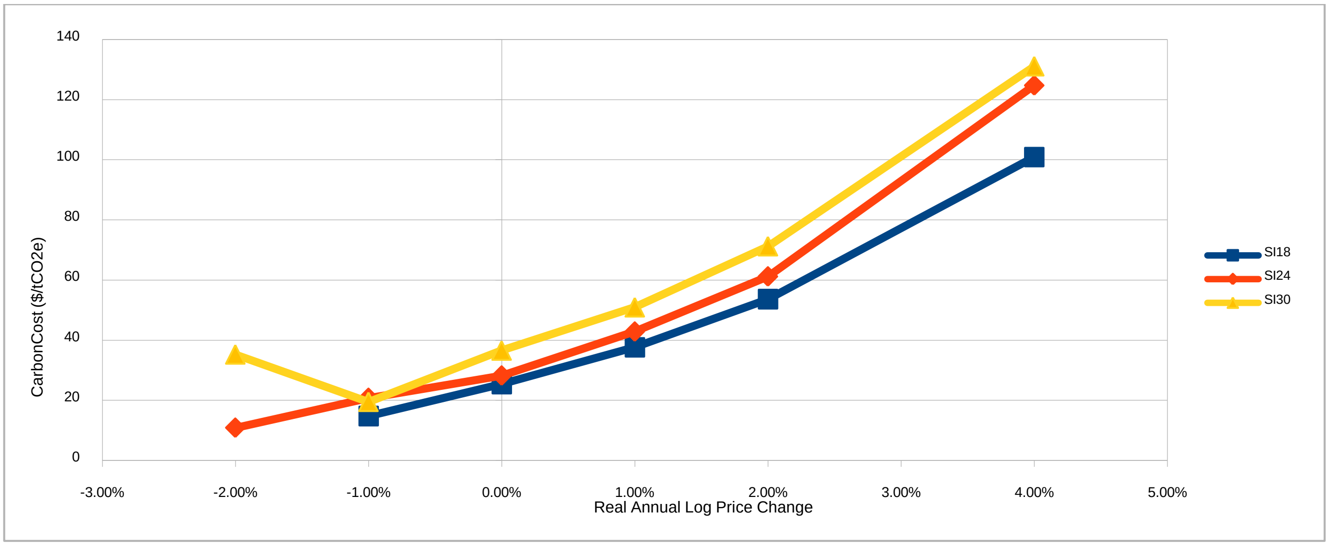


**Figure 7: 'Plateau' carbon costs at different real annual log price changes for stands of Site Index 18, 24, and 30.**

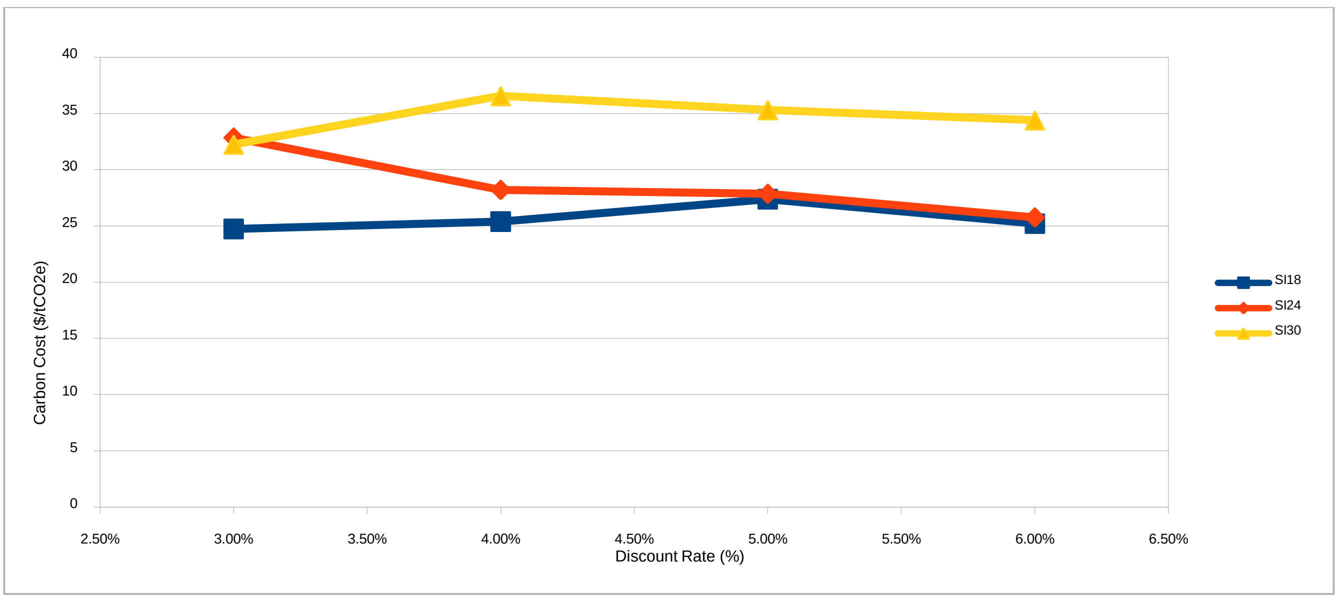


**Figure 8: 'Plateau' carbon costs at different discount rates for stands of Site Index 18, 24, and 30.**

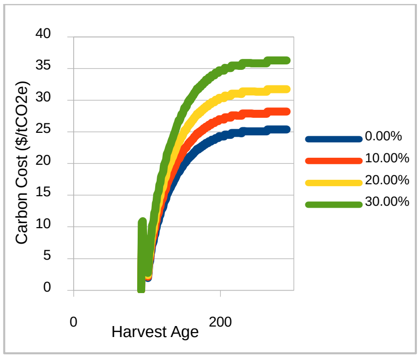


**Figure 9: Carbon cost curves with risk buffers of 0%, 10%, 20%, and 30% for stands of Site Index 18.**

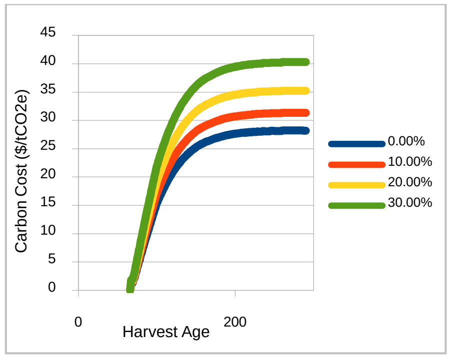


**Figure 10: Carbon cost curves with risk buffers of 0%, 10%, 20%, and 30% for stands of Site Index 24.**

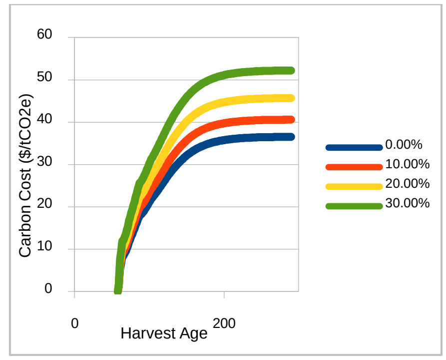


**Figure 11: Carbon cost curves with risk buffers of 0%, 10%, 20%, and 30% for stands of Site Index 30.**

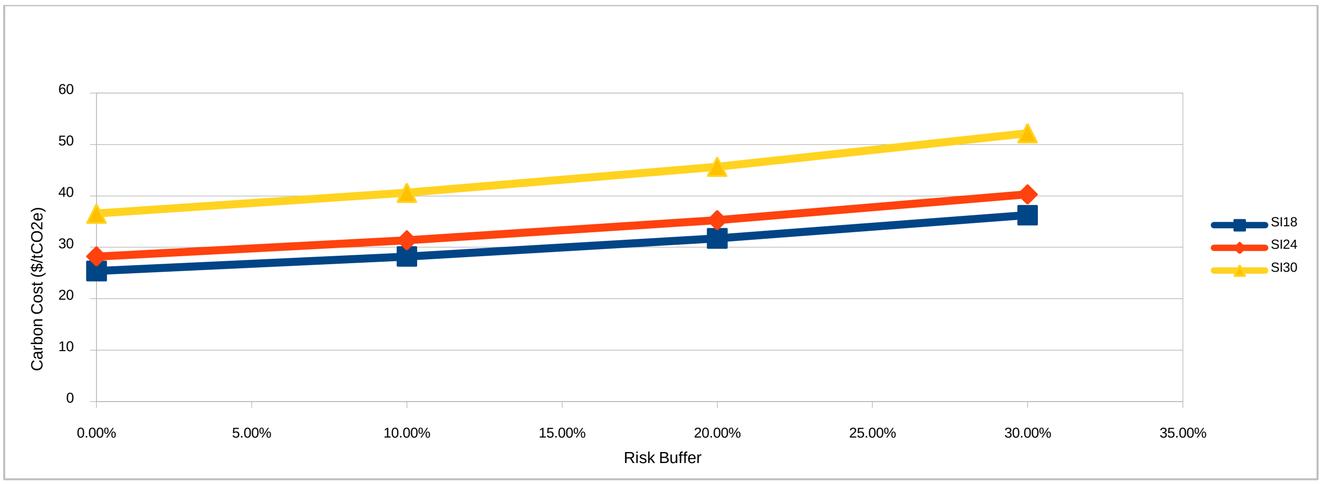


**Figure 12: ‘Plateau’ carbon costs with different risk buffers for stands of Site Index 18, 24, and 30**