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ACCOUNTING FOR CARBON DIOXIDE EMISSIONS FROM CLEARCUT LOGGING IN THE CANADIAN BOREAL FOREST

I. INTRODUCTION

Mature boreal forests are important sinks for atmospheric carbon dioxide (CO_2). Left undisturbed, they can continue to sequester CO_2 for hundreds of years,[1,2,3] mitigating global climate change. Forest disturbances, such as clearcut logging, convert localized boreal forest ecosystems from net carbon sinks to net carbon sources, suggesting a negative impact on the global climate. For up to three decades during forest regrowth following a clearcut, the forest acts as a CO_2 source due to relatively smaller CO_2 uptake from net primary production and a relative increase in CO_2 emissions from soils and forest litter due to enhanced heterotrophic respiration and decomposition.[4,5] Over time, forest succession and recovery presumably returns the logged forest to a net CO_2 sink. However, significant uncertainties exist regarding how quickly and effectively a boreal forest regenerates following intensive logging. Furthermore, the amount of CO_2 sequestration that, in the absence of logging, would have occurred during the forest regrowth time frame is uncertain, as is the carbon balance effect of large-scale cumulative logging disturbances that have been taking place annually over several decades.

Logging is a significant industry in Canada. An estimated 717,059 hectares (ha) of forest were clearcut in 2014.[6] The carbon life cycle and the full carbon impacts associated with forestry operations remain poorly understood and are confounded by the debate around the fate of carbon in wood products and the amount of time required for a forest to recover. Logging activities are sometimes assumed to be carbon neutral or climate beneficial, with proponents of this view arguing that harvested wood products act as a net carbon sink as new forests regenerate and sequester atmospheric CO_2.[7] However, this is far from proven, and some studies have shown: that "no management" (i.e., no logging) leads to greater carbon storage than any degree of logging activity, including clearcutting.[8] This paper addresses one element of this uncertainty, focusing primarily on understanding and quantifying site specific CO_2 emissions caused by clearcut logging disturbances within the boreal forest in Canada.

The objective of this research is to model published net ecosystem productivity data to 1) quantify CO_2 emissions per hectare from clearcut disturbances, 2) estimate total CO_2 emissions based on average yearly clearcut areas across the Canadian boreal forest, and 3) predict the cumulative CO_2 emissions impact of annual logging operations over an 85-year time frame.

Results and estimates are expressed in terms of net ecosystem productivity (NEP). NEP is defined as the difference between the gross ecosystem productivity (carbon fixation) and ecosystem respiration (CO_2 release).[9,10] In other words, NEP quantifies whether CO_2 is being emitted or sequestered within a given area and measures the changes in concentration of carbon within that area over time. The NEP values used in our model were derived from data collected and analyzed via eddy covariance flux towers.[4,9] These flux towers collect time-series data for localized environmental and climate parameters to understand the magnitude and direction of CO_2 fluctuations in these areas.

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2. METHODS

2.1 Data Collection and Modeling NEP over Time

Peer-reviewed studies have published NEP data for several sites throughout the Canadian boreal. These studies generated original data based on empirical measurements collected from eddy covariance flux towers at multiple sites in different regions.[4,9] It is important to note that the data presented represent a single year of NEP data for single forest stands impacted by a clearcut disturbance. There has been no longer-term collection of eddy covariance flux data, so the data were collected as an innovative approach to comparing multiple sites and inferring results about carbon flux over decades, where long term data are not available. One limitation of this approach is that it inherently assumes that all sites' carbon trajectories will be similar, regardless of localized ecosystem differences such as climate, soil, and species mix.

Two different forest recovery models were used to reflect the carbon balance of a jack pine (JP)-dominant ecosystem (Saskatchewan NEP data) and a black spruce (BSp)-dominant ecosystem (Quebec NEP data). The specifics of these ecosystems are explained in detail in Grant et al. 2010. For brevity, these descriptors, JP and BSp, will be used to define the models. However, data from these models are not necessarily representative of the carbon balance responses to clearcut disturbances across all black spruce or jack pine forests.

The forest recovery function f(t), where t = time in years after clearcut, was modeled using equation 1[11] (Eq. 1) to quantify changes to NEP over time. In Eq. 1, f(t) is the modeled NEP function (gC/m^2*year) over time, and Q, P, R, and S represent the fitting parameters. The forest recovery function established in this work generally agrees with measured data[4,12] and conceptual models of NEP recovery.[13]

Eq. 1 $$f(t) = Q * e^{p*t} + R * e^{s*t}$$

Experimental NEP data were collected and modeled from various sources,[4,8] and fitting parameters were established by minimizing the residual sum of squares (RSS; results in

FIGURE 1: EXAMPLE OF FOREST RESPONSE FUNCTION ANALYSIS FROM JP BOREAL FOREST ECOSYSTEMS (SASKATCHEWAN NEP DATA[4])

The different-colored regions describe the fundamental concepts of the carbon emission budget (CEB) curve analysis. Blue: carbon sequestration; green: undisturbed sequestration; red: CO_2 emissions. Eq. 1 was used to model the forest response curve.

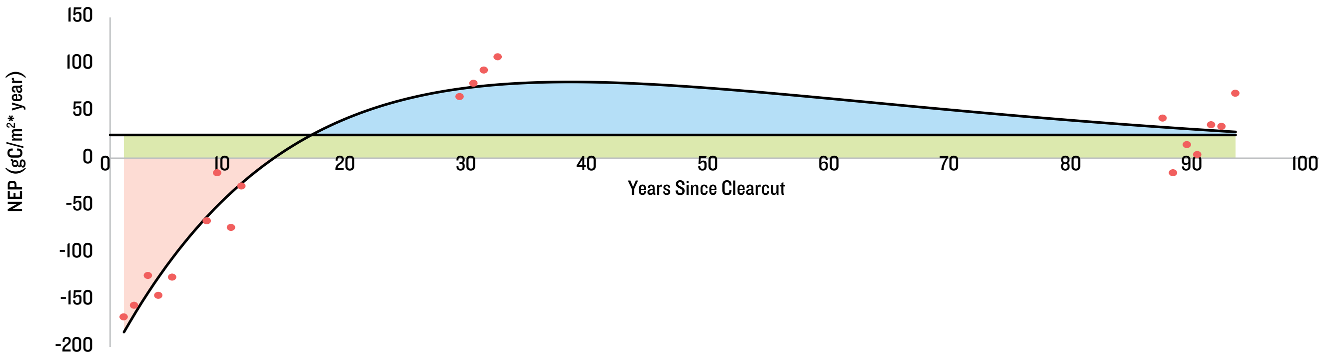


FIGURE 2: EXAMPLE OF FOREST RESPONSE FUNCTION ANALYSIS FROM BSP BOREAL FOREST ECOSYSTEMS (QUEBEC NEP DATA[4,9])

The different-colored regions describe the fundamental concepts of the carbon emission budget (CEB) curve analysis. Blue: carbon sequestration; green: undisturbed sequestration; red: CO_2 emissions. Eq. 1 was used to model the forest response curve.

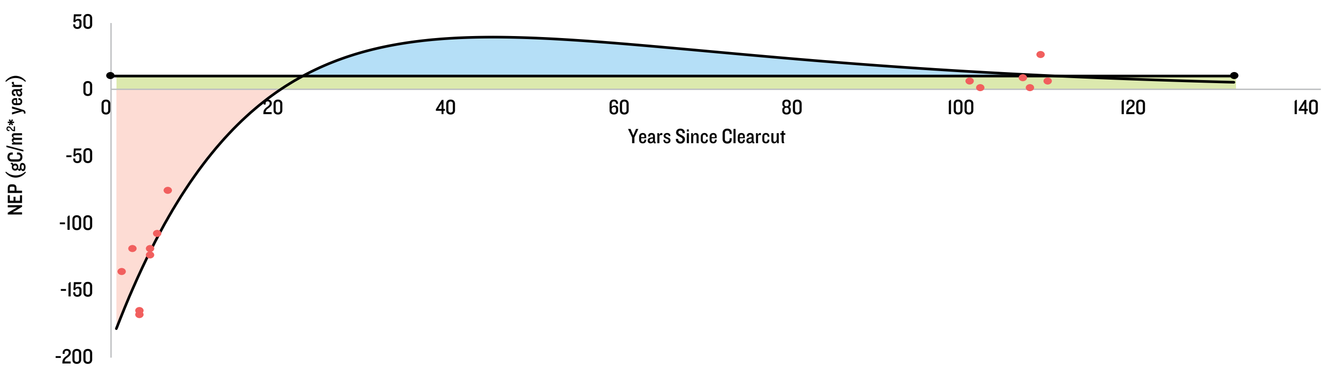


TABLE 1: FITTING PARAMETERS FOUND FROM MINIMIZATION OF RSS OF EQUATION 1					
MODEL	FOREST RECOVERY RATE	FITTING PARAMETERS			
		Q	P	R	S
Jack Pine (SK)	High	3804.491213	−0.03359	−3985.9015	−0.03769
	Moderate	1921.796697	−0.03694	−2130.1326	−0.04464
	Low	3812.808551	−0.04593	−4049.0739	−0.04970
Black Spruce (QC)	High	6420.481039	−0.03986	−6643.7683	−0.04235
	Moderate	6426.112845	−0.04013	−6621.9448	−0.04164
	Low	6438.582378	−0.03999	−6621.5956	−0.04104

table 1). For the BSp model (figure 2), the lack of mid-term NEP data (15-100 years after clearcut) resulted in a range of fitting values based on hypothetical NEP values to model high, moderate, and low NEP recovery scenarios (see figure 8).

Background, long-term NEP average values (NEP_{ave}) were the mean of the data points available for mature boreal forests. The mean range of NEP_{ave} in this study was consistent with published long-term boreal forest NEP values.[3] Throughout the remainder of this paper, the term "undisturbed" will be used to explain constant NEP values of an undisturbed, mature boreal forest.

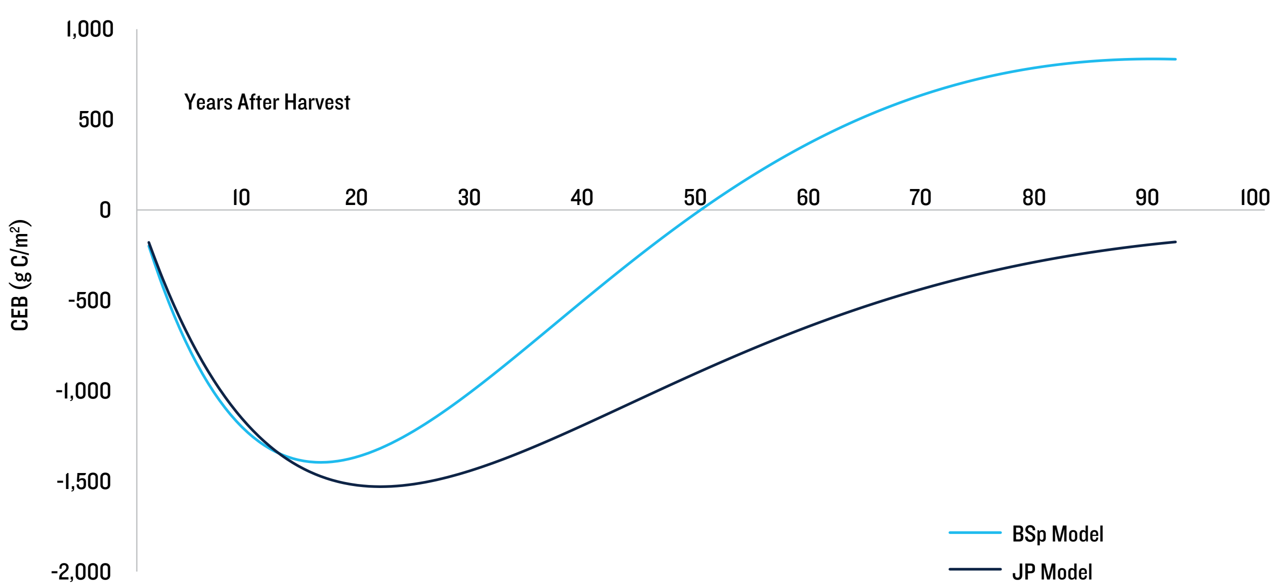
2.2 Quantifying NEP Curves with the Carbon Emissions Budget (CEB) Function

To compare post-harvest CO_2 emissions with a non-harvest condition, a new function, carbon emissions budget (CEB), was defined as the carbon sequestered in an undisturbed mature forest compared with carbon emitted during the initial years following a logging disturbance. Cumulative emissions were considered over an 85-year period. Furthermore, average yearly clearcut data over a 10-year period for each respective province[19] was used to estimate the total CO_2 emissions due to clearcut harvesting and the total loss of CO_2 that was not sequestered during that time frame.

The CEB function (units: g C/m^2) was defined as the difference between the forest recovery function (NEP(t)) and the undisturbed NEP for a given ecosystem integrated over a given time frame (Eq. 2, figure 3). A positive CEB meant that the forest stand exhibited net CO_2 sequestration over the time period considered, and when negative, the forest stand acted as a source of CO_2 emissions. Eq. 2 was used to define the CEB curve for a single clearcut disturbance:

Eq. 2 $$\boldsymbol{CEB(t) = NEP_{ave} * \Delta t - \int_{t_o}^{t} f(t)\,dt}$$

FIGURE 3: CEB CURVES FOR FOREST ECOSYSTEMS IN JP AND BSP MODELS. CEB CURVES WERE ESTABLISHED FROM THE MODEL DATA SHOWN IN TABLE 1



To understand the contribution of repeated logging year after year on the cumulative carbon budget, CEB curves were summed to quantify the long-term cumulative impacts to the carbon budget (Eq. 3). The cumulative function assumes that yearly CEB curves are equal, forest response curves are equal across years, and area clearcut each year remains constant.

Eq. 3

$$CEB_{cumulative}(t) = \sum CEB(t) + CEB(t+1) + CEB(t+2) + \cdots \ldots CEB(t+n)$$

3. RESULTS AND DISCUSSION

3.1 Post-Harvest CO_2 Emissions

Post-harvest CO_2 released to the atmosphere was evaluated by integrating the initial CO_2 released in the forest response curves (see total red area and green area above, figure 1 and figure 2). The JP model predicted total CO_2 emissions of 44.5 tons CO_2/ha over a 13-year period (table 2) when including the long-term NEP values (see green area, figure 1). The BSp model predicted relatively higher total CO_2 emissions per area at 67.9 tons CO_2/ha over a ~27-year period (table 2).

It is important to note that the carbon was not emitted instantaneously but rather over several years. As the model predicted, the time since harvest at which NEP shifted from negative to positive (i.e., when the forest shifted from being a net CO_2 source to a net CO_2 sink) was 13 years for the JP model and 27 years for the BSp model. This extended NEP negative-to-positive recovery time is generally consistent with literature finding that NEP values remain negative for up to 20 years following forest harvest.[16,17] While our results showed slightly longer recovery times in some instances (BSp model), these results were acceptable because 1) they were based on the specific model interpolation results; 2) the seven years of CO_2 emissions during years 20 to 27 were overwhelmingly smaller in magnitude, compared with the emissions from year 0 to year 20; and 3) other research has shown that NEP recovery may oscillate for several years between source and sink due to interannual variability.[12]

Results for CO_2 emissions per area (table 2) were multiplied by the 10-year average clearcut area in each province (2006–2015) to estimate provincial CO_2 emissions due to yearly clearcut disturbances. The BSp model was used to estimate CO_2 emissions per area for Quebec, Ontario, and Newfoundland, while the JP model was used to estimate carbon emissions per area for Alberta, Manitoba, and Saskatchewan. The results predict the highest emissions attributable to average annual clearcutting for Quebec, Ontario, and Alberta (11.2 million, 8.7 million, and 3.4 million tons CO_2, respectively), with emissions occurring over the recovery time frames (figure 4, table 2). As discussed above, these are not yearly emissions, but the total emissions that will occur over the time it takes for the forest to recover to a positive NEP. However, because clearcut logging is an ongoing occurrence, clearcutting will continue to produce new sources of emissions—a cumulative emissions phenomenon described in the subsequent sections.

TABLE 2: TOTAL CO_2 EMISSIONS FOR FOREST ECOSYSTEMS OVER THE INITIAL 13-27 YEARS FOLLOWING A CLEARCUT DISTURBANCE

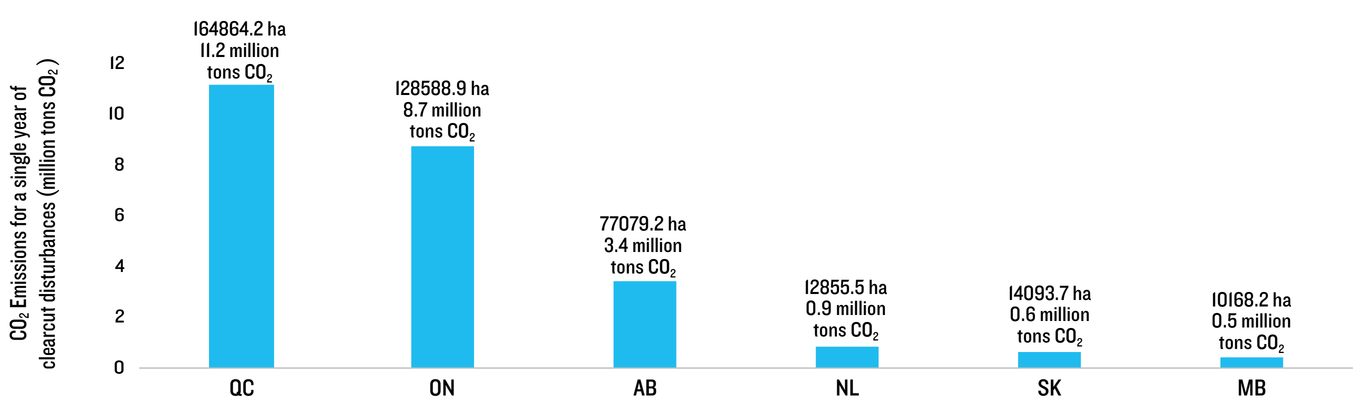
	CO_2 EMISSIONS PER AREA (TONS CO_2/HA)
FOREST RECOVERY MODEL	HARVESTED + UNDISTURBED NEP^
JP Model (SK)	44.5
BSp Model (QC)	67.9

Net source to net sink recovery times were 13 years (Sk) and 27 years (Qc).

Long-term NEP considers the positive NEP flux *over the forest recovery time frame of a* clearcut disturbance. Long-term NEP values of 25 g C/m^2*year and 50 g C/m^2*year were used for the Jack Pine model, and 10 g C/m^2*year and 30 g C/m^2*year were used for the Black Spruce model.[18]

FIGURE 4: CO_2 EMISSIONS BY PROVINCE BASED ON THE 10-YEAR AVERAGE YEARLY CLEARCUT AREA (2006–2015[19]) AND CO_2 EMISSIONS MODEL PREDICTIONS IN TABLE 2

These are not yearly CO_2 emissions but represent the total amount of CO_2 released over a 13- to 27-year period, for an average year of clearcut disturbances. NL: Newfoundland; QC: Quebec; ON: Ontario; MB: Manitoba; SK: Saskatchewan; AB: Alberta. The JP model was used for MB, SK, and AB. The BSp model was used for NL, QC, and ON.



3.2 Cumulative Carbon Balance over Successive Years

The CEB curves discussed in the previous section were produced for a hypothetical 85-year period and summed to predict the long-term impacts of clearcut logging disturbances in Canada's boreal forest. While this analysis provides a framework for understanding the long-term impact of clearcut logging on the carbon balance in Canada's boreal forest, measurements taken at precise areas and over precise time periods would provide a more accurate picture of CO_2 emissions than the extrapolations we present here. While the certainty of any prediction decreases with time, this analysis provides a basis for understanding how yearly clearcuts and forest NEP recovery relate to the overall climate budget impacts of clearcutting. Importantly, this analysis is not a life cycle analysis and does not consider other sources of CO_2 emissions (or storage) throughout a wood product's life cycle. It focuses solely on quantifying the biological CO_2 emissions that are observed at a specific site, via NEP values, after a clearcut disturbance.

Analysis of cumulative and successive CEB curves over an 85-year time frame suggest that yearly disturbances compound CO_2 emissions and delay the CEB recovery for both the JP model (figure 5) and the BSp model (figure 6). In other words, these results suggest that clearcutting year after year generates a "carbon debt," which is quantified for various NEP recovery scenarios and presented in section 3.3. Importantly, these results also suggest that if cutting at current rates continues beyond our hypothetical 85-year time frame, CEB recovery will continue to be negatively impacted until the rate of cutting drops significantly.

FIGURE 5: SEQUENTIAL CEB CURVES FROM THE JP MODEL, WHERE HARVESTING OCCURS YEAR AFTER YEAR, ILLUSTRATE THE LONG-TERM CUMULATIVE CARBON BALANCE

The black line corresponds to the sum of the yearly CEB curves over time, and its units are on the right vertical axis. CEB curves for years 11-85 are not shown here but were used to construct the cumulative CEB curve.

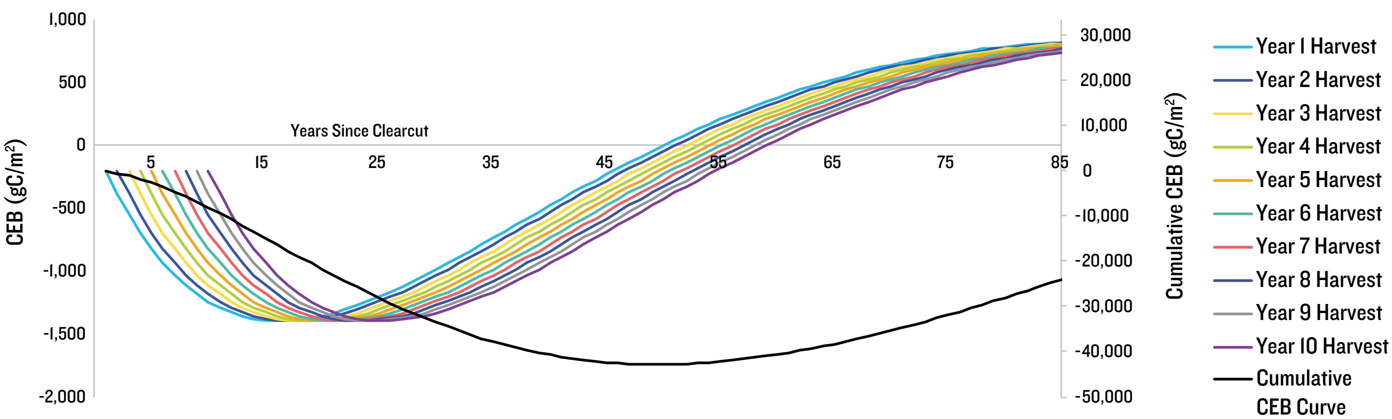
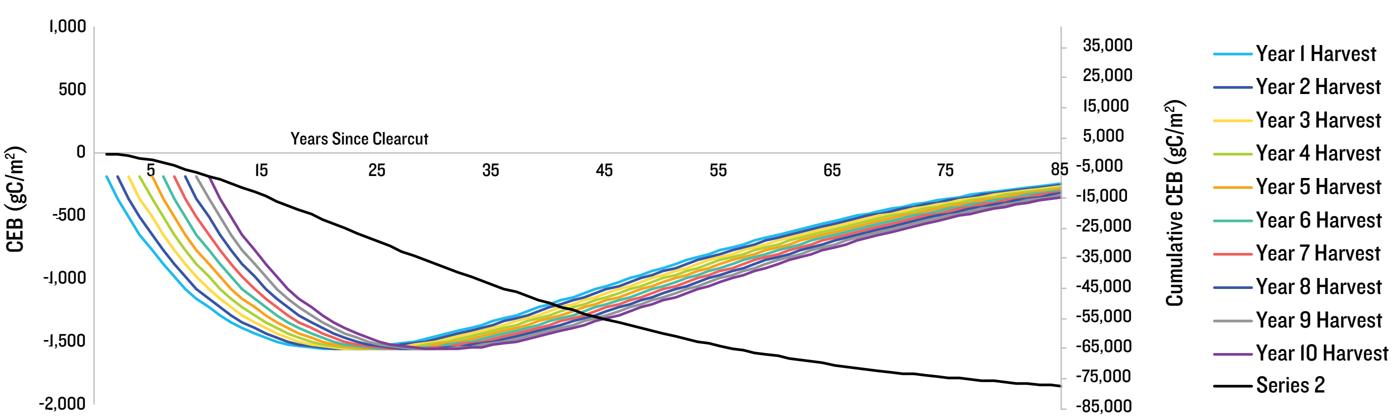


FIGURE 6: SEQUENTIAL CEB CURVES FROM BSP MODEL, WHERE HARVESTING OCCURS YEAR AFTER YEAR, ILLUSTRATE THE LONG-TERM CUMULATIVE CARBON BALANCE

The black line corresponds to the sum of the yearly CEB curves over time, and its units are on the right vertical axis. CEB curves for years 11-85 are not shown here but were used to construct the cumulative CEB curve.



3.3 Carbon Dioxide Emissions Estimations After 85 Years Under Various Forest Recovery Scenarios

Due to uncertainties with NEP trajectory, scenarios based on low, moderate, and high forest recovery (regeneration) rates were analyzed. Two long-term NEP scenarios were used to assess the impact of clearcut logging in Canada's boreal on the carbon budget relative to an undisturbed boreal forest stand over that time frame.

Four NEP data points were available at around 30 years post-harvest for the JP model (Figure 7). To estimate the upper and lower bounds of the rate of forest recovery, the standard deviation established from the residuals of the moderate fitting parameters was used to create high and low recovery scenarios.

The BSp model had limited mid-term NEP data available. Grant et al. 2010 published data for the initial years following the disturbance and around 100 years; however, no NEP data were recorded between those years. Therefore, three post-harvest recovery scenarios were considered—high, moderate, and low—to shed light on the carbon budget under various NEP trajectories (figure 8). The low scenario was fit to the existing data, using the regression model presented with equation 1. These results show relatively larger CO_2 emissions initially and a slower NEP recovery (see figure 2). To estimate the mid-term forest response for the moderate and high recovery scenarios, theoretical data points were added for years 40, 45, and 50 (moderate: 30, 40, 35 gC/m^2 year; high: 80, 100, 90 gC/m^2 year). The data points used in the high recovery scenario are consistent with data observed from the JP model during that time frame.

FIGURE 7: FOREST RECOVERY SCENARIOS DISPLAYING NEP TRAJECTORY UNDER HIGH, MODERATE, AND LOW RECOVERY SCENARIOS FOR THE JP MODEL

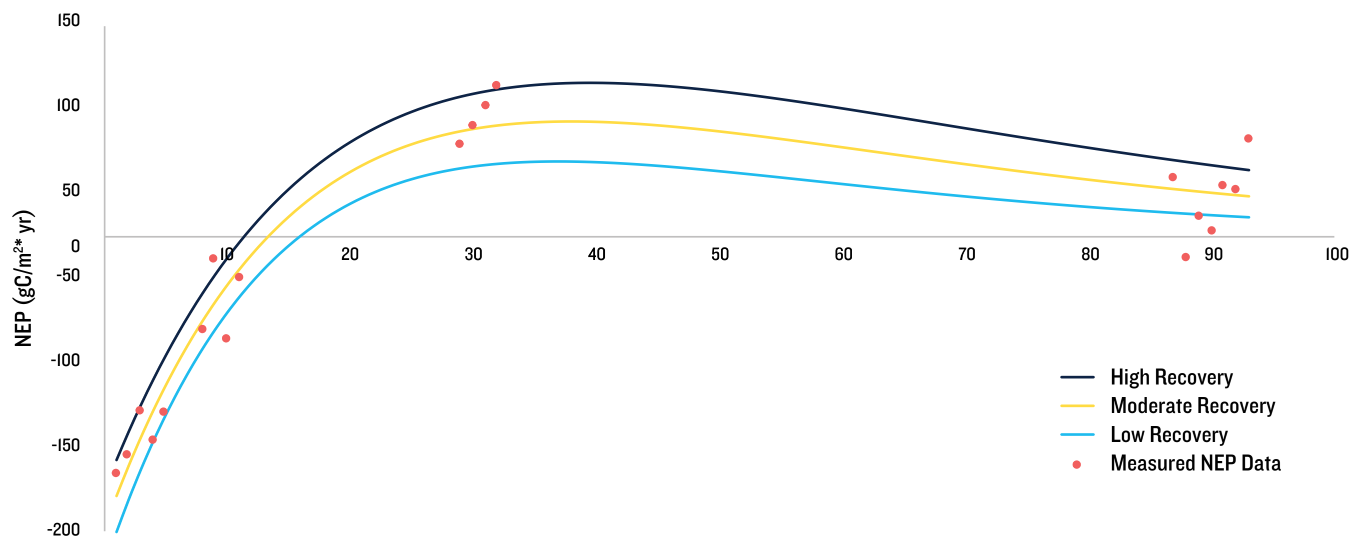


FIGURE 8: FOREST RECOVERY SCENARIOS DISPLAYING NEP TRAJECTORY UNDER HIGH, MODERATE, AND LOW RECOVERY SCENARIOS FOR THE BSP MODEL

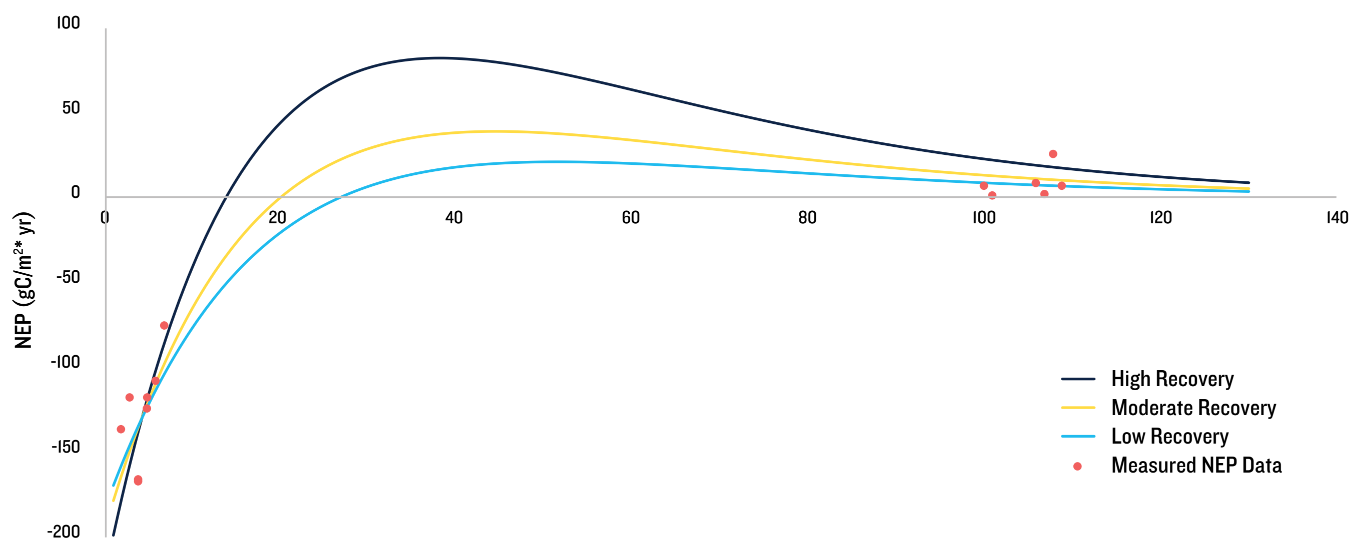


FIGURE 9: RESULTS FOR CO_2 EMISSIONS FOR THREE FOREST RECOVERY SCENARIOS (LOW, MODERATE, AND HIGH) FOLLOWING CLEARCUT LOGGING IN THE JP MODEL. LONG-TERM NEP FOR AN UNDISTURBED FOREST AREA WAS ASSUMED TO BE 25 g/m²

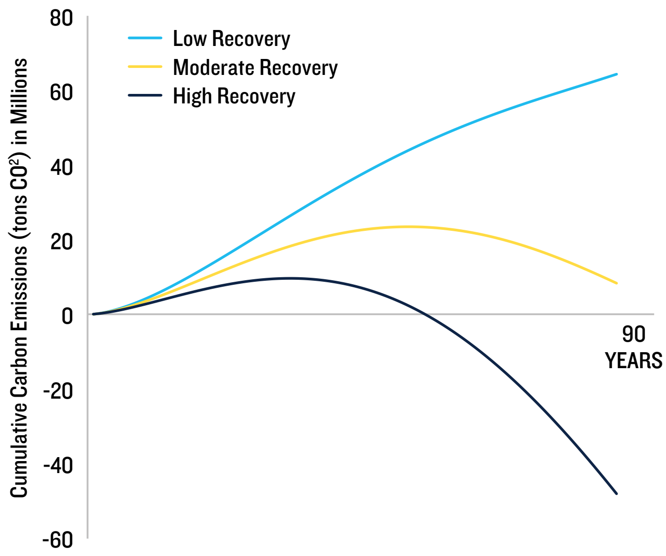


FIGURE 10: RESULTS FOR CO_2 EMISSIONS FOR THREE FOREST RECOVERY SCENARIOS (LOW, MODERATE, AND HIGH) FOLLOWING CLEARCUT LOGGING IN THE JP MODEL. LONG-TERM NEP FOR AN UNDISTURBED FOREST AREA WAS ASSUMED TO BE 50 g/m²

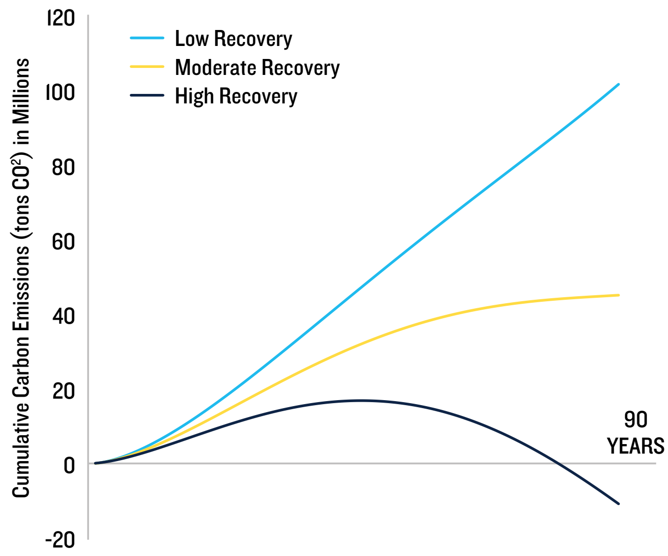


FIGURE 11: RESULTS FOR CO_2 EMISSIONS FOR THREE FOREST RECOVERY SCENARIOS (LOW, MODERATE, AND HIGH) FOLLOWING CLEARCUT LOGGING IN THE BSP MODEL. LONG-TERM NEP FOR AN UNDISTURBED FOREST AREA WAS ASSUMED TO BE 10 g/m²

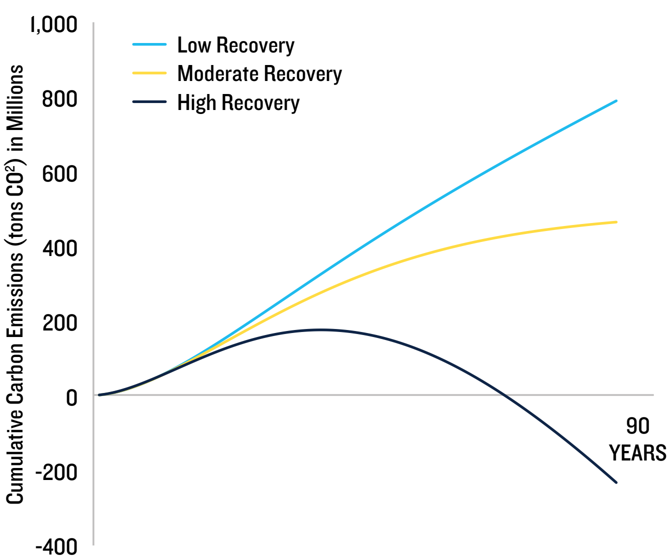
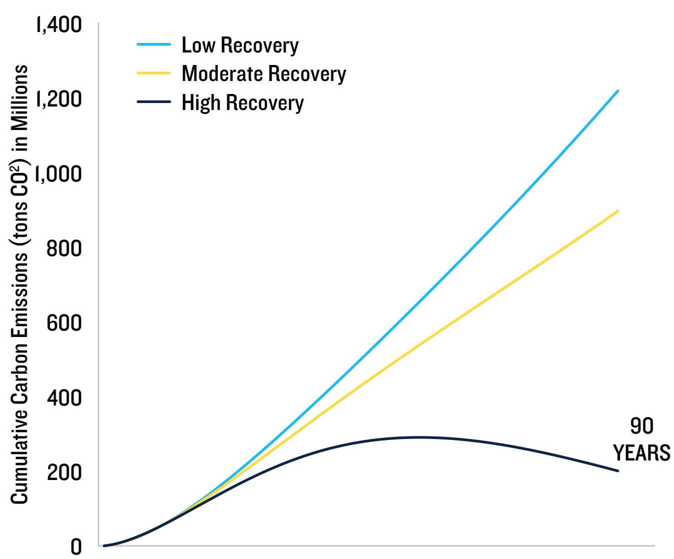


FIGURE 12: RESULTS FOR CO_2 EMISSIONS FOR THREE FOREST RECOVERY SCENARIOS (LOW, MODERATE, AND HIGH) FOLLOWING CLEARCUT LOGGING IN THE BSP MODEL. LONG-TERM NEP FOR AN UNDISTURBED FOREST AREA WAS ASSUMED TO BE 30 g/m²



The results from the CEB analysis for various forest recovery scenarios, presented in figures 9 through 12, can be interpreted in two ways. First, the results can be viewed as a straightforward presentation of total CO_2 emissions values by year for a given theoretical forest recovery scenario. This interpretation could be useful by directly accounting for the CO_2 emissions over a given time. Under this interpretation, several observations about the results can be made:

- The highest emissions from clearcutting were observed for the low forest recovery scenario in the BSp model that had relatively high long-term NEP (30 g/m^2). For this scenario, after 85 years the total CO_2 emissions associated with the clearcut area in Quebec were predicted to be approximately 1.2 billion tons CO_2 total (figure 12), or roughly 14.4 million tons/year (approximated linearly).
- Only under high recovery scenarios did we find that harvested forests fully sequester initial CO2 emissions (figures 9, 10, 11). In addition, the only moderate recovery scenario anticipated to eventually sequester initial CO2 emissions is the JP model with a low undisturbed NEP value (figure 9), though this event takes place after the time period modeled here. In all events, it is important to note that a site's return to carbon neutrality and a net carbon sink would only occur if logging were to end after the 85-year period examined.
- The relative difference in emissions magnitudes is largely due to size variability in the 10-year average clearcut areas for Quebec (164,864 ha) and Saskatchewan (14,094 ha).

The second, and perhaps the more intriguing, way to view these results is to assume that the rate of forest recovery has been hindered by clearcut logging. This assumption is supported by observations regarding clearcutting's contribution to the degradation of soil organic carbon, decreased NEP trajectories after multiple disturbances, and the inability of the forest to recover initial stand biomass.[21] Thus, under this interpretation, the notable difference between forest recovery scenarios demonstrates how clearcutting can obstruct the carbon recovery budget. Thus, because of clearcutting's hindering of the recovery process, the true carbon impact of ongoing clearcutting can be understood as the difference between emissions under the high recovery scenario and under the low recovery scenario. For example, under this interpretation, even the most optimistic carbon recovery curve (low undisturbed NEP, high recovery, figure 11) would be carbon neutral after ~67 years. However, a reduced NEP trajectory due to clearcutting would lead to a NEP curve that resembled a moderate forest recovery scenario. At the same recovery time of 67 years, the moderate scenario had observed net CO_2 emissions of roughly 431 million tons, significantly higher than the high scenario, and representing a significant loss of forest carbon sequestration capacity. This also suggests that carbon budgets are highly sensitive to minor changes in the NEP trajectory during mid-term and long-term forest recovery. In other words, if forest stands do not fully recover biomass (represented here by depressed NEP) relative to an undisturbed state, then significant emissions will be observed relative to an unaltered stand.

Regardless of whether the implications of clearcutting on forest recovery rates is taken into account, these results suggest that CO_2 emissions from annual clearcutting activities in the boreal forest have profound and detrimental climate implications. Even under the most optimistic forest recovery scenario, the results show that the carbon budget would remain in a deficit for at least 67 years, an estimate that does not even account for the full carbon life cycle of logging and the carbon impact of the manufacture of wood products.

To put this in context, if the cumulative emissions time line began in 2017, that would mean carbon neutrality from forest regeneration would not be reached until 2084. This implies emissions from clearcut logging would cause a CO_2 deficit well into the period when predictions suggest the most dramatic, irreversible, and negative environmental, social, and economic consequences of human-induced climate change will occur. Worse, if forest recovery resembles the low or moderate scenarios, then over that time frame the CO_2 emissions from clearcut logging activities will be an even more significant contributor to the global atmospheric CO_2 budget. This is particularly disturbing given that these emissions are not currently being quantified, assessed, or accounted for in any meaningful policy application.

4. CONCLUSIONS AND IMPLICATIONS

The results suggest, under the conditions and assumptions for this analysis, that biological CO_2 emissions from clearcut logging activities contribute substantial atmospheric CO_2 emissions. A single clearcut disturbance in the BSp and JP models was estimated to emit between 44.7 and 68.9 tons CO_2/ha between the initial disturbance and the time when NEP measurements become net positive (i.e., the area returns to a net sink versus a net source). These estimations were used to establish provincial CO_2 emissions for an average year of clearcut logging based on historic logging data for each Canadian province with significant boreal forest cover. The estimated total CO_2 emissions from clearcut logging for each of the six boreal provinces examined ranged from 0.5 million to 11.2 million tons of CO_2. Quebec, Ontario, and Alberta had the highest CO_2 emissions from clearcut logging, mainly due to the relatively large area that is clearcut each year. The total emissions for all six provinces was 25.3 million tons of CO_2 for each year disturbances occurred, released over the time frame when NEP values remained negative.

To put this in perspective, the average CO_2 emissions for a passenger automobile are approximately 4.8 tons/year.[22] This suggests that one hectare of clearcut forest produces CO_2 emissions equivalent to the total CO_2 emissions of one vehicle operating for roughly 9-14 years. And each year of new clearcuts is akin to a new wave of vehicles on the road that will operate over that time frame.

Additionally, several pieces of evidence suggest that these results are likely underestimating the CO_2 emissions from clearcut logging—and should thus be viewed as conservative figures. We used relatively low estimates of long-term NEP values (10 g/m^2 and 30 g/m^2), whereas mean boreal semiarid evergreen values were 40±30 g/m^2 and boreal humid evergreen values were 131±79 g/m^2.[18] Furthermore, it is important to state that there are substantial uncertainties and complexities involved in predicting long-term forest recovery and interannual NEP dynamics.[12,20] These complexities are compounded by the fact that research suggests that historically disturbed sites may not fully recover NEP relative to the trajectory of an undisturbed site,[21] perhaps due to the loss of soil organic carbon[15] and other nutrients.[20] Similarly, it is unclear to what extent carbon fluxes observed in mature forests resemble fluxes in disturbed sites that do not achieve 100 percent regeneration of the stand's original biomass. In addition, this study does not consider the full carbon life cycle of logging and the carbon impact of the manufacture of wood products. However, it should be noted that there is substantial uncertainty about assumptions for modeling mid-term NEP values, scaling across time and space, and uncertainties regarding undisturbed NEP which may impact the CO_2 emission budget.

Finally, this work proposes that repeated yearly clearcuts increase both the magnitude of CO_2 emissions and the theoretical time frame for harvested areas to reach net carbon neutrality for CO_2 emissions. The cumulative impact of sequential clearcuts, year after year, results in a compounding effect of net CO_2 emissions over the time frame used in this study.

These results suggest clearcutting in the boreal forest has resulted in the release of considerable biological CO_2 emissions to the atmosphere that are not being fully reclaimed via the process of forest carbon sequestration. Substantial spatial and temporal complexities and lack of mid-term forest response data necessitate significantly more research to understand the intricacies, including localized conditions impacting carbon fluxes and limitations in extrapolating this data to a larger area. However, these results suggest that, at a minimum, CO_2 emissions from continued and increased clearcut harvesting in the boreal must be accounted for in climate models and assessments of anthropogenic greenhouse gas emissions in order to craft policies that will effectively reduce these, and other, emissions over time.

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