Estimating and Monitoring the Long-Term Growth and Productivity of Boreal Forests on Reclaimed Oil Sands Sites: Preliminary Results and Future Outlook

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Abstract
Alberta is the largest supplier of oil to the U.S. Oil sands mining companies in Alberta are required to use effective conservation and reclamation measures to ensure that land disturbed in oil sands mining is reclaimed to achieve an equivalent capability to what was present prior to mining. It is crucial that in areas designed to support forests, the productivity of the forests is maintained. Site index is the most common metric in forest models for assessing the long-term growth and productivity of forests. Comparing undisturbed natural site index with post-reclamation site index is an important component of demonstrating equivalent forest growth and productivity on pre- and post-reclamation sites. Based on tree sectioning data from 60 plots at 20 of the oldest reclaimed sites that cover three main boreal tree species, detailed stem analysis is performed. Preliminary results show that site index and post-reclamation growth of all three species are comparable to those on undisturbed natural sites. Future outlook of this study in terms of collecting additional data, performing further analyses and monitoring the long-term outcome on reclaimed landscapes, is discussed.

Key Words: Forest growth, oil sands, reclamation, monitoring, site index

1. Introduction

North America's largest known oil reserves are in Canada's oil sands in Alberta (Alberta Energy 2014). Alberta ranks third, after Saudi Arabia and Venezuela, in terms of proven global crude oil reserves. In 2011, Alberta's total proven oil reserves were 170.2 billion barrels, or about 11 percent of total global oil reserves (1,523 billion barrels).

Of Alberta's total oil reserves, 168.7 billion barrels (about 99 percent) come from the oil sands. The U.S. imports about 1.9 million barrels of oil a day from Canada, about 1.4 million of which from the Alberta oil sands (Alberta Energy 2014). Alberta supplies approximately 15 percent of U.S. crude oil imports, or 7 percent of U.S. oil consumption. This makes Alberta the largest supplier of oil to the U.S.

Alberta's oil sands underlie 142,200 km^2 (Alberta Energy 2014). It has been continuously developed by private enterprise since 1967, regulated by independent agencies, and subject to policies and laws developed by government. To date, about 767 km^2 of land have been disturbed by oil sands activity (about 0.2% of Alberta's boreal forests).

By law, proponents of oil sands development projects in Alberta are required to use effective conservation, remediation and reclamation measures to ensure that land disturbed in oil sands mining is reclaimed to achieve an equivalent capability to what was present prior to mining. Remediation is the process of removing, reducing or neutralizing contaminants in soil, sediments or water to prevent or minimize any adverse effects on the environment currently or in the future. Reclamation is the process of returning disturbed land to the state of natural productivity that existed prior to the start of industrial activity. It differs depending on what types of activity took place on the land, but it generally includes: a) reshape land and landform to a natural appearance and function; b) re-establish topsoil and subsoil; and c) reforest or replant with species native to the area to support a sustainable ecosystem.

As of 2013, over 77 km^2 of disturbed lands in the oil sands region are in the process of being reclaimed (Alberta Energy 2014, http://www.oilsands.alberta.ca/reclamation.html). If an area meets stringent requirements for reclamation, such as soils are tested, tree and shrub growth is monitored for 15+ years, and ecological trends are achieved, regulators will issue a final certification. In March 2008, the Alberta government issued its first and only reclamation certificate so far to Syncrude Canada for the 104-ha parcel of land known as Gateway Hill, north of Fort McMurray. Several reclamation certificate applications for oil sands projects are expected within the next 10 years.

To date, oil sands companies have planted more than 12 million tree seedlings towards reclamation efforts. They used local tree species to target the return of a local boreal forest ecosystem to achieve an equivalent forest productivity to what was present before mining. Many of the seedlings have been growing on reclaimed sites for more than 30 years. They have become young boreal forests, which enable a more robust assessment of the forest productivity than was possible at an earlier age.

In spite of the observed progress, the science and practice of oil sands reclamation is still relatively new, and a full return to a self-sustaining ecosystem present before mining is a long and complex process. The main objectives of this study therefore focus only on three specific aspects: 1) assess the height growth and productivity of three main boreal tree species grown on reclaimed sites; 2) compare their growth and productivity to those from natural sites in the same ecoregion; and 3) identify potential areas of improvement in collecting additional data, performing further analyses, monitoring the long-term outcome, and elevating the scientific understanding of biological processes on reclaimed sites to enhance existing and guide future work.

2. Materials and Methods

2.1 Study Area and Sampling Procedures

The study area covers the oldest oil sands mining sites in Suncor and Syncrude licensing areas, located about 35 km north of Fort McMurray (Figure 1). It is in the northeastern part of Alberta’s boreal forest, in the central mixedwood (CM) natural subregion (Natural Regions Committee 2006). The CM natural subregion (also called ecoregion) is characterized by short, warm summers and long, cold winters. Gently undulating plains with some hummocky upland inclusions are the primary landforms in this subregion.

Elevations of the subregion range from 200 m along the Peace River in the northeast to 1050 m in the extreme south. The CM natural subregion is covered by boreal forests consisting of a mosaic of aspen (*populus tremuloides*, AW) dominated deciduous forests, aspen-white spruce (*picea glauca*, SW) forests and white spruce forests on uplands, with extensive areas of mainly treed fens in central areas and jack pine (*pinus banksiana*, PJ) forests on coarser materials to the east. This explains why this study focused on the three main boreal tree species in the subregion: aspen, white spruce and jack pine.

Figure 1. Study areas located in the reclaimed oil sands mining sites approximately 35 km north of Fort McMurray (map source: Alberta Energy 2014).

A total of 60 plots were sampled, 30 in the Suncor area and 30 in the Syncrude area. They fall within 20 stands, 10 in the Suncor area and 10 in the Syncrude area. Three plots were randomly laid out in each stand following standard forest inventory field procedures. GPS coordinates of each plot were recorded and plotted on maps (available but not shown here). All plots were located in reclaimed areas older than 15 years total age.

Each of the three plots established in the stands is 300 m^2 and circular in shape, with a radius of 9.77 m. Each plot was assessed to determine site characteristics by collecting the depth of the litter-fermented humus (LFH) layer, soil texture, slope position, slope, aspect, land capability classification, soil moisture regime and eco-site classification. A concentric 100 m^2 subplot (with a radius of 5.64 m) was established within each 300 m^2 plot for the purpose of measuring stand density and average tree conditions. All live trees taller than 1.30 m in the 100 m^2 subplot were measured for species, diameter at breast height (DBH) and total tree height (HT).

2.2 Tree Sectioning and Stem Analysis

The largest DBH aspen, white spruce and jack pine trees within each 300 m^2 plot were felled at the ground level (or as close to the ground as possible) if they were present in the plot. In addition, felled trees must satisfy these conditions: a) live and healthy looking; b) no broken or dead top; c) no severe leaning ≥20^0, not a wolf tree or of obvious poor form (e.g., crook, sweep, fork); and d) no severe damage to more than 1/3 of the bole, crown and/or root. If the largest DBH tree for a species did not satisfy these conditions, no replacement tree was sampled for that species. Tree disks were cut along the stem at 0.0, 0.3, 1.3, 2.3, 3.3, 4.3 m and then every 2 m after that to the top of the tree. Each disk was labeled, stored and processed at the Canadian Forest Service (CFS) lab in Edmonton. Table 1 lists a summary of the sample trees.

Table 1. A summary of felled trees for stem analysis.

Species	# trees	# disks	Variable	Mean	Min	Max	SD
AW	43	353	Tree height (m)	10.69	5.92	16.28	2.71
			Total age (years)	26.51	13.00	36.00	5.89
			Stump age (years)	25.17	11.50	34.50	5.86
			Breast height age (years)	21.97	10.50	29.50	5.03
SW	42	320	Tree height (m)	8.87	3.60	12.12	2.11
			Total age (years)	28.24	18.00	35.00	3.51
			Stump age (years)	24.40	14.50	29.50	3.78
			Breast height age (years)	19.14	9.50	25.50	4.51
PJ	36	268	Tree height (m)	8.76	5.05	11.35	1.74
			Total age (years)	29.00	15.00	33.00	4.61
			Stump age (years)	26.22	13.50	29.50	4.19
			Breast height age (years)	22.03	10.50	27.50	3.95

Notes: Min, Max and SD are minimum, maximum and standard deviation, respectively.

On each smoothly sanded disk, the long axis (A) and the perpendicular short axis (B) through the pith were marked. The A and B axis diameter measurements were used to determine the average growth radius, which was located and marked on the disk to serve as the annual growth increment sample line to be scanned and imported into the dendrochronology program CooRecorder/CDendro 7.7 to determine the annual growth increments. Distinct annual growth increment patterns that may indicate periods of defoliation or reduced moisture availability were used as common markers to assist in date validation. Figure 2 shows an example of annual growth increment patterns for a white spruce disk. Each disk was cross-dated against the other disks from within the same sample tree to ensure that each ring and each annual growth increment was accounted for and accurately measured.

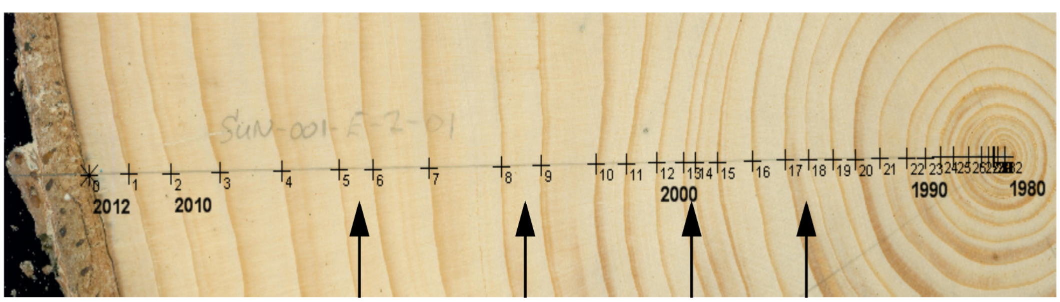

Figure 2. An example of cross section markers and measurements for a white spruce disk. The arrows indicate the annual growth increments for 2007 (ring 6), 2004 (ring 9), 1999 (ring 14) and 1995 (ring 17) that served as cross-dating markers.

2.3 Site Index Estimation

From the ring count measurements on disks and the heights above ground corresponding to the disks, height-age pairs along each sectioned tree were obtained as a part of the standard stem analysis procedure. They were used to predict site indices for each sectioned tree, based on the most recent site index equations developed as a part of the GYPSY model commonly used in Alberta (Huang et al. 2009):

[1] $$HT = SI_t \times \left(\frac{1+\exp(b_1 + b_2\sqrt{\ln(1+50)} + b_3[\ln(SI_t)]^2 + b_4\sqrt{50})}{1+\exp(b_1 + b_2\sqrt{\ln(1+totage)} + b_3[\ln(SI_t)]^2 + b_4\sqrt{50})} \right) \text{ (AW)}$$

[2] $$HT = SI_t \times \left(\frac{1+\exp(b_1 + b_2\sqrt{\ln(1+50^2)} + b_3[\ln(SI_t)]^2 + b_4\sqrt{50})}{1+\exp(b_1 + b_2\sqrt{\ln(1+totage^2)} + b_3[\ln(SI_t)]^2 + b_4\sqrt{50})} \right) \text{ (SW)}$$

[3] $$HT = SI_t \times \left(\frac{1+\exp(b_1 + b_2\sqrt{\ln(1+50)} + b_3\ln(SI_t) + b_4\sqrt{50})}{1+\exp(b_1 + b_2\sqrt{\ln(1+totage)} + b_3\ln(SI_t) + b_4\sqrt{50})} \right) \text{ (PJ)}$$

where HT is total tree height (m), totage is the total age (years) from the point of germination, SI_t is totage-based site index (i.e., HT at 50 years total age), and b_1-b_4 are estimated model coefficients (listed in Huang et al. 2009). Equations [1]-[3] are total age based site index models. Corresponding breast height age (bhage) based site index models are mathematically embedded in [1]-[3], as illustrated in Figure 3.

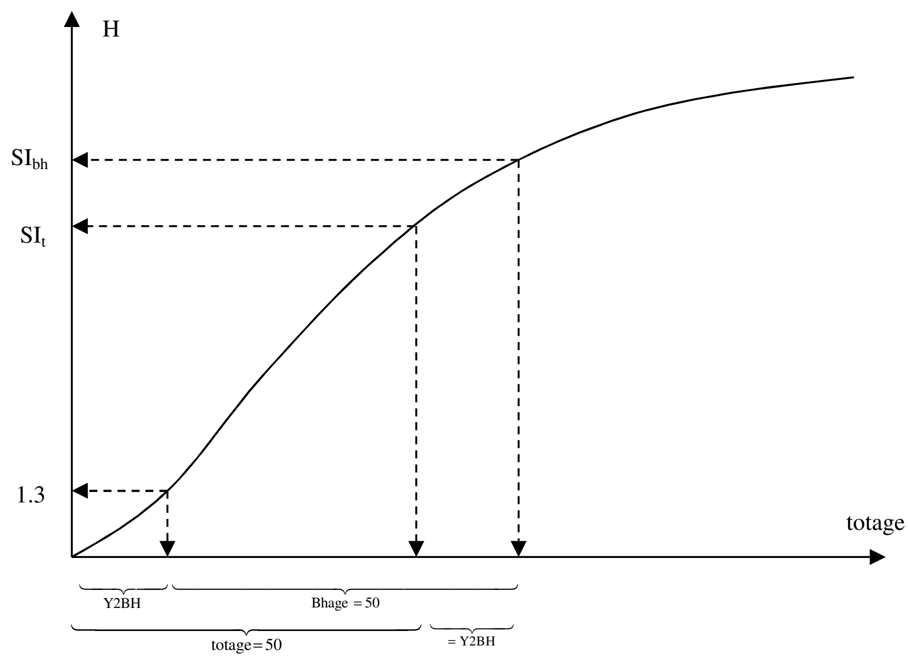

Figure 3. An illustration of the relationships among total age (totage), breast height age (bhage), totage-based site index (SI_t), and bhage-based site index (SI_{bh}). Y2BH is the number of years needed to reach breast height (1.3 m above ground).

The fact that the corresponding bhage-based site index models are embedded in the totage-based site index models is an important one that has often been overlooked in literature. It allows for the calculation of and conversion between totage-based site index (SI_t, i.e., HT at 50 years totage) and bhage-based site index (SI_{bh}, i.e., HT at 50 years bhage). As an example, model [1] for aspen can be written as [1a] for the specific height-age pair of HT=1.3 (m) and totage=Y2BH, where Y2BH is the number of years needed to reach the breast height of 1.3 m above ground:

$$[1a] \qquad 1.3 = SI_t\left(\frac{1+\exp(b_1 + b_2\sqrt{\ln(1+50)} + b_3[\ln(SI_t)]^2 + b_4\sqrt{50})}{1+\exp(b_1 + b_2\sqrt{\ln(1+Y2BH)} + b_3[\ln(SI_t)]^2 + b_4\sqrt{50})}\right)$$

Given HT and totage or bhage (totage=Y2BH+bhage), the two unknown variables (SI_t and Y2BH) in the two-equation system of [1] and [1a] can be solved (a program is available to interested readers). Once SI_t and Y2BH are known, and recognizing SI_{bh} is HT at 50 years bhage, the specific height-age pair of HT=SI_{bh} and totage=Y2BH+50 (see illustration in Figure 3) can be substituted into [1] to predict SI_{bh}:

$$[1b] \qquad SI_{bh} = SI_t\left(\frac{1+\exp(b_1 + b_2\sqrt{\ln(1+50)} + b_3[\ln(SI_t)]^2 + b_4\sqrt{50})}{1+\exp(b_1 + b_2\sqrt{\ln(1+Y2BH+50)} + b_3[\ln(SI_t)]^2 + b_4\sqrt{50})}\right)$$

Similarly, models [2] and [3] can also be used to derive compatible SI_t and SI_{bh}. Some readers may immediately recognize that totage-based site index models also encompass stump age based site index models. Totage-based site index models can verily be used to derive compatible site index predictions regardless of the type of age used.

In this study, we focused on the standard bhage-based site index SI_{bh}. SI_{bh} values were calculated using the height-totage pairs along each sectioned tree. The number of height-totage pairs from a sectioned tree determines the number of SI_{bh} values available for that tree. Following the standard practice in Alberta, only the SI_{bh} values corresponding to five years or older in bhage were used for further analysis.

2.4 The Stability of Site Index Estimates Over Time

By definition, site index should be a constant stand or plot level attribute. It should not change over time. One of the greatest concerns regarding the estimation of site index from young stands is the stability of site index estimates over time. The concern centres around whether or not the site index obtained from the early height growth is maintained through to maturity.

The stem analysis data were used to examine the stability of site index estimates over time. Successive site index estimates obtained from the height–age pairs were connected for each sectioned tree and plotted against bhage. A simple linear model was fitted on the site index-bhage trajectories to examine the site index-bhage relationship:

$$[4] \qquad SI_{bh} = a + b \cdot \text{bhage}$$

where SI_{bh} is bhage-based site index, and a and b are model parameters to be estimated.

The overall significance of the site index-bhage relationship is assessed by the *F*-value from analysis of variance (ANOVA). The significance of the b value (slope) is assessed by the *t*-value of the estimate. A significant slope implies the instability of site index estimates over time. Two other statistics from the fit of [4], root mean square error (RMSE) and coefficient of determination (R^2), are also calculated:

[5] $$\text{RMSE} = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{n - 2}} \qquad R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \overline{y})^2}$$

where y_i and $\hat{y}_i$ denote original and predicted SI_{bh} values, respectively, $\overline{y}$ denotes the average of original SI_{bh} values, n is the number of observations, and the summation is from 1 to n (i=1, 2, …, n).

2.5 Comparison to Natural Height Growth and Site Index

The stem analysis data obtained on reclaimed oil sands sites were compared to the stem analysis data collected as a part of the permanent sample plots (PSPs) located in the fire-origin natural stands in the same CM natural subregion. Since this natural subregion is fairly large (Natural Regions Committee 2006), the comparison was also narrowed to using only a part of the PSP stem analysis data from the northeastern (NE) portion of the CM subregion (confined by meridian=4 and 65<=township<=100). The NE portion of the CM subregion is geographically and ecologically closest to the oil sands mining sites (it encompasses the oil sands mining sites), therefore, the comparison to the data from this portion of the CM subregion is considered more pertinent.

A summary of the stem analysis data from PSPs is listed in Table 2. All sectioned trees from PSPs were felled outside the PSPs but inside the PSP buffers. More detailed descriptions about the PSP program are provided in Alberta Environment and Sustainable Resource Development (2005).

Table 2. A summary of stem analysis data from permanent sample plots.

Species	Region	# trees	# disks	Variable	Mean	Min	Max	SD
AW	CM-all	113	1162	Tree height (m)	18.13	6.60	29.38	5.00
				Stage (years)	56.31	12.50	118.50	23.29
				Bhage (years)	51.93	11.50	116.50	22.90
	CM-NE	43	419	Tree height (m)	15.54	6.60	25.74	4.03
				Stage (years)	45.66	12.50	91.50	15.74
				Bhage (years)	41.03	11.50	85.50	15.37
SW	CM-all	65	702	Tree height (m)	20.51	8.29	31.30	5.70
				Stage (years)	90.52	30.50	170.50	40.78
				Bhage (years)	83.27	21.50	159.50	39.82
	CM-NE	23	222	Tree height (m)	18.55	9.60	28.10	5.44
				Stage (years)	72.41	30.50	129.50	31.53
				Bhage (years)	65.28	25.50	123.50	30.88
PJ	CM-all	87	757	Tree height (m)	15.19	4.70	21.73	3.80
				Stage (years)	59.35	28.50	152.50	29.75
				Bhage (years)	54.78	21.50	145.50	29.22
	CM-NE	81	705	Tree height (m)	15.12	4.70	21.73	3.92
				Stage (years)	60.78	28.50	152.50	30.36
				Bhage (years)	56.17	21.50	145.50	29.82

Notes: CM-all and CM-NE denote all and northeastern central mixedwood (CM) natural subregion, respectively, Stage is stump age at 0.3 m above ground, Bhage is breast height age at 1.3 m above ground, Min is minimum, Max is maximum and SD is standard deviation.

Since all stem analysis trees from PSPs were felled at 0.3 m above ground, there is no observed total age for these trees. Only stump age at 0.3 m above ground and breast height age at 1.3 m above ground are available (Table 2). Site indices (at 50 years bhage) for these trees were calculated from the height-bhage pairs at the sectioning points, based on the procedures described earlier.

3. Results and Discussion

Observed height-age trajectories from sectioned trees on reclaimed oil sands sites are shown in Figure 4 (left-hand side graphs). Species-specific site index curves generated from equations [1]-[3] with site index (SI_{bh}) values of 6, 11, 16, 21 and 26 m are overlaid on the height-age trajectories. A visual inspection of the graphs suggests reasonable conformity between the height-age trajectories and site index curves.

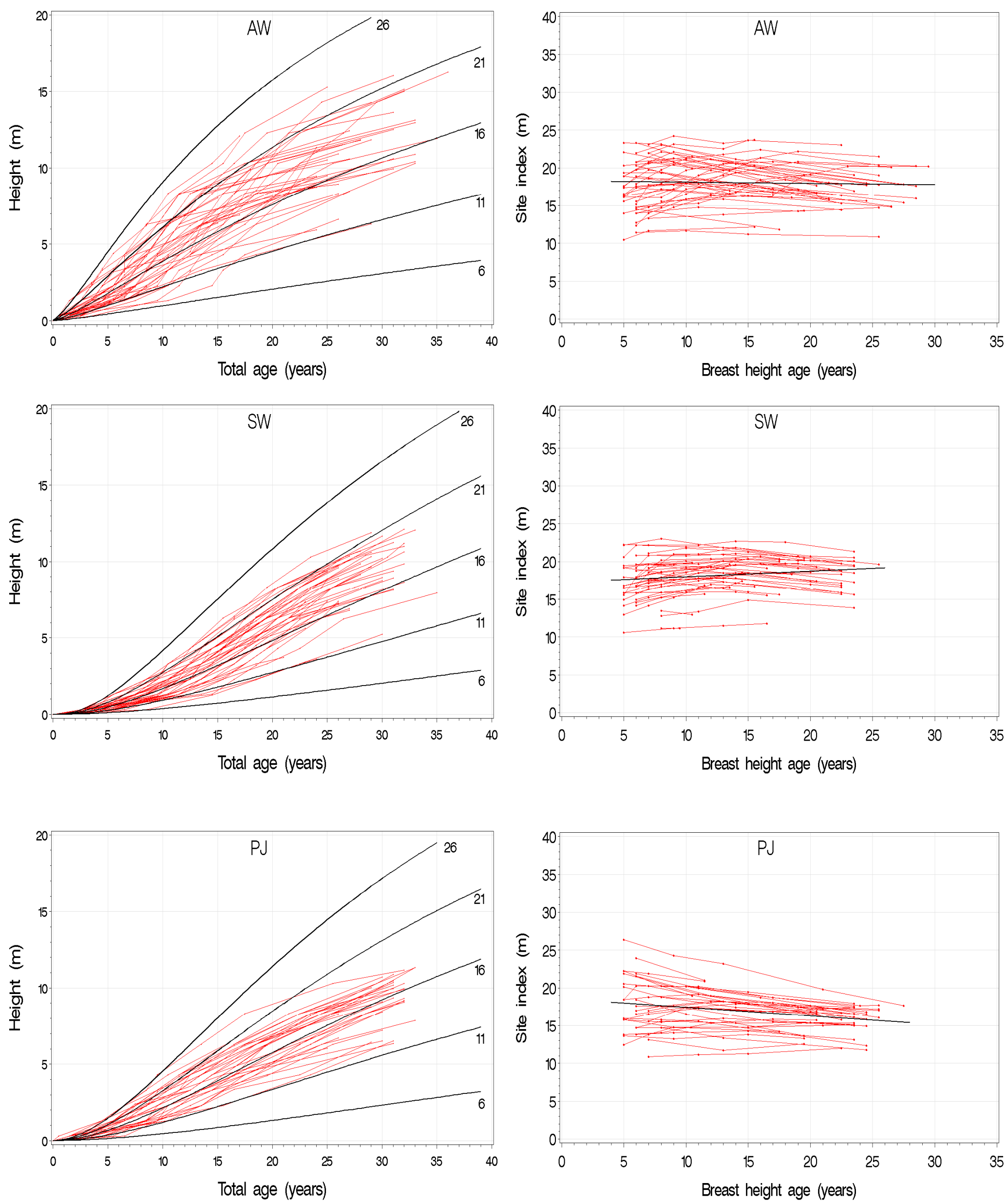

Figure 4. Left-hand side graphs are observed height-age trajectories from sectioned trees on reclaimed oil sands sites overlaid on species-specific site index curves generated from site index (SI_{bh}) values of 6 m (bottom), 11, 16, 21 and 26 m (top). Right-hand side graphs are site index trajectories (>=5 years bhage) corresponding to the height-age trajectories. The black line in each right-hand side graph represents the fit from equation [4].

The right-hand side graphs in Figure 4 show SI_{bh} trajectories corresponding to the height-age trajectories on the left. Successive site index estimates were calculated using equations [1]-[3] and summarized in Table 3, based on the observed height-age pairs at the sectioning points. They are connected for each sectioned tree and plotted against bhage, then overlaid for all trees (Figure 4). Graphs of the SI_{bh} trajectories provide the most intuitive means for assessing the stability of site index estimates over time. A visual inspection of the SI_{bh} trajectories in Figure 4 suggests that successive site index estimates for AW and SW are generally stable over time. But for PJ, a downward trend is noticeable, which could suggest that the site index estimates for PJ may not be stable.

Table 3. Site index values from sectioned trees from different data sources.

Species	Data	Region	# trees	Site index (m)						
				n	Mean	Min	Max	SD	MD	MD%
AW	Oil Sands	CM-NE	43	179	18.09	10.50	24.23	2.98		
	PSPs	CM-all	113	853	17.36	6.78	30.02	3.45	0.73	4.2
		CM-NE	43	309	16.66	8.37	25.64	3.29	1.43	8.6
SW	Oil Sands	CM-NE	42	187	18.15	10.57	23.04	2.49		
	PSPs	CM-all	65	558	15.00	6.07	27.51	3.17	3.15	21.0
		CM-NE	23	172	15.52	8.35	20.87	2.82	2.63	16.9
PJ	Oil Sands	CM-NE	36	152	17.05	10.88	26.38	2.75		
	PSPs	CM-all	87	534	15.90	5.47	40.32	4.03	1.15	7.2
		CM-NE	81	496	15.63	5.47	40.32	3.95	1.42	9.1

Notes: CM-all and CM-NE denote all and northeastern CM, n represents the number of site index predictions, and Min, Max and SD are minimum, maximum and standard deviation. MD is the difference and MD% is the percent difference between mean site indices from oil sands and PSPs (e.g., for AW and PSPs (CM-all), MD=18.09-17.36=0.73, and MD%=0.73/17.36=4.2%).

The stability of site index estimates over time was checked by fitting equation [4]. Results of the fits are listed in Table 4. Based on the results, it can be seen that for AW, the slope of the SI_{bh}-bhage relationship is negative but not significantly different from zero (p=0.6001) at α=0.05. This suggests that the site index estimates for AW can be considered stable over time.

Table 4. Parameter estimates and ANOVA results for model [4].

Spec.	Parameter estimates					ANOVA		RMSE	R^2
	Par.	Estimate	Std Err	t	$p > \|t\|$	F	$p > F$		
AW	a	18.3153	0.4794	38.21	<.0001	0.28	0.6001	2.99	0.002
	b	-0.0174	0.0330	-0.53	0.6001				
SW	a	17.2307	0.4227	40.76	<.0001	5.80	0.0170	2.46	0.030
	b	0.0758	0.0315	2.41	0.017				
PJ	a	18.5490	0.4792	38.71	<.0001	12.29	0.0006	2.65	0.076
	b	-0.1121	0.0320	-3.51	0.0006				
Comb	a	18.14319	0.27194	66.72	<.0001	1.91	0.1680	2.78	0.004
	b	-0.0263	0.01905	-1.38	0.168				

Notes: spec. denotes species, comb denotes all species combined, par. denotes model parameter, ANOVA denotes analysis of variance summary statistics, and RMSE and R^2 are defined in [5].

For SW, the overall SI_{bh}-bhage relationship and the slope of the fit (b=0.0758) are significant at α=0.05. The slope is positive, which is different from that for AW, and which suggests that SW site index estimates are increasing with the increasing bhage. This can be considered a desirable nuisance because it implies that long term outcomes for SW will be better than the initial estimates. If we take a conservative approach and consider the fact that the slope of the fit has a p=0.017, we could regard the site index estimates for SW as stable over time. For PJ, the overall SI_{bh}-bhage relationship and the slope of the fit is significant at α=0.05 (p=0.0006). The slope of the fit has a negative value (b=-0.1121), suggesting that the site index for PJ decreased with the increasing bhage. When all three boreal species are combined, the SI_{bh}-bhage relationship and the slope of the fit (b=-0.0263) become statistically insignificant (p=0.1680), suggesting that the overall SI_{bh}-bhage relationship for combined boreal species is insignificant and the site Index estimates can be considered stable over time.

Figure 5 shows the site index trajectories obtained from reclaimed oil sands sites compared to those from the PSPs located in the fire-origin natural stands of the same natural subregion (CM-all) and the northeastern part of the same natural subregion (CM-NE). Summary statistics of the actual site index values are listed in Table 3.

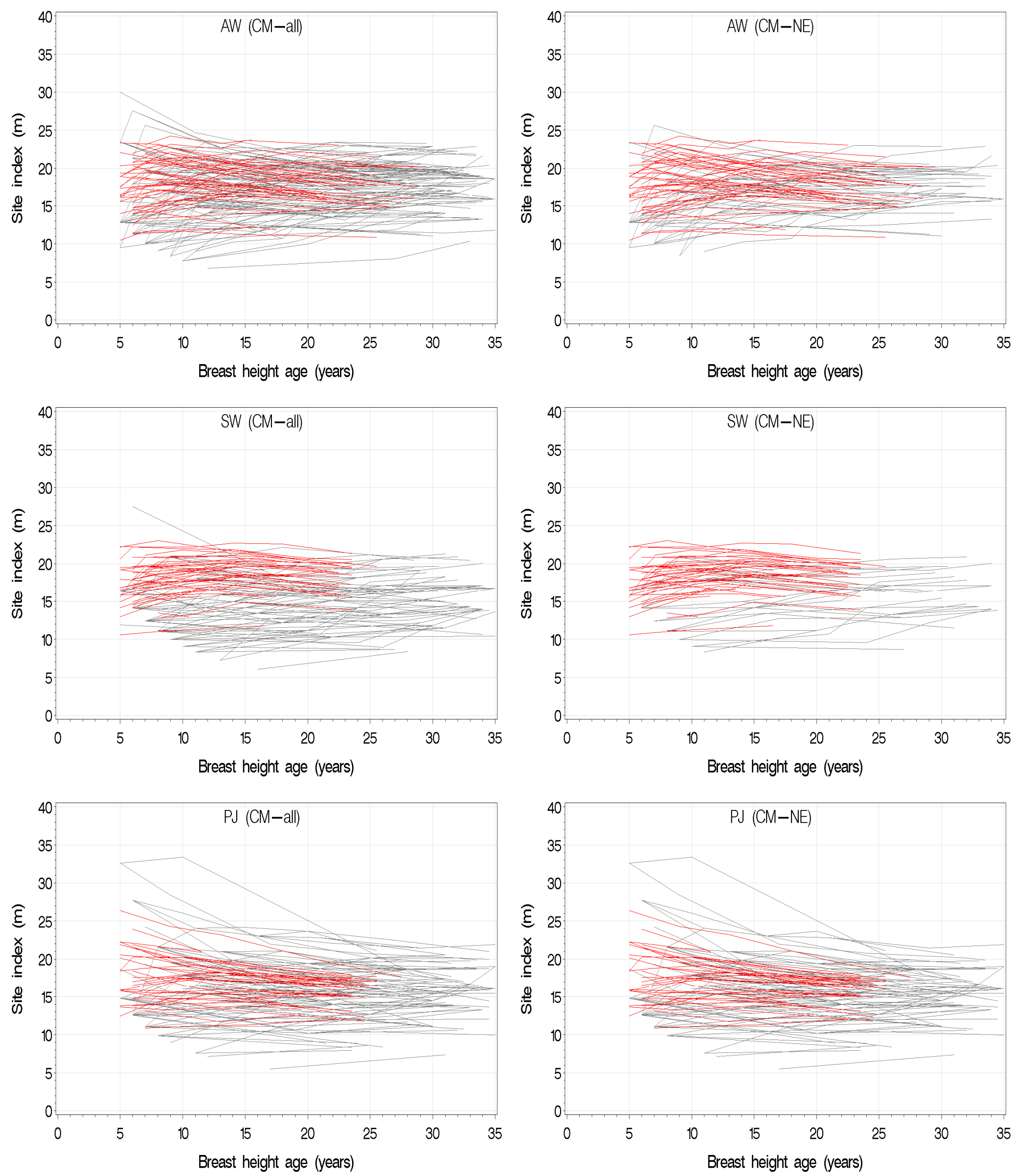

Figure 5. Site indices from reclaimed oil sands sites (red) and PSPs (grey) in the CM natural subregion (CM-all) and northeastern CM natural subregion (CM-NE).

The results shown in Table 3 suggest that the mean site indices obtained on reclaimed oil sands sites for AW, SW and PJ are 4.2%, 21.0% and 7.2% more than their respective counterparts from the PSPs in the CM natural subregion, and 8.6%, 16.9% and 9.1% more than those in the northeastern CM natural subregion. On average (weighted by sample sizes), the site index obtained on reclaimed sites is about 10% higher than the site index from the natural PSPs when all three boreal species are combined.

Observed height growth trajectories from reclaimed oil sands sites and natural PSPs are compared to see whether there is any difference in early height growth between the trees on reclaimed and natural sites (Figure 6). A visual inspection suggests that the differences are obvious for AW and SW, but less so for PJ. Early height growth on reclaimed sites appears to tilt more heavily towards the upper portion of the height growth from PSPs. This is consistent with higher average site indices on reclaimed sites.

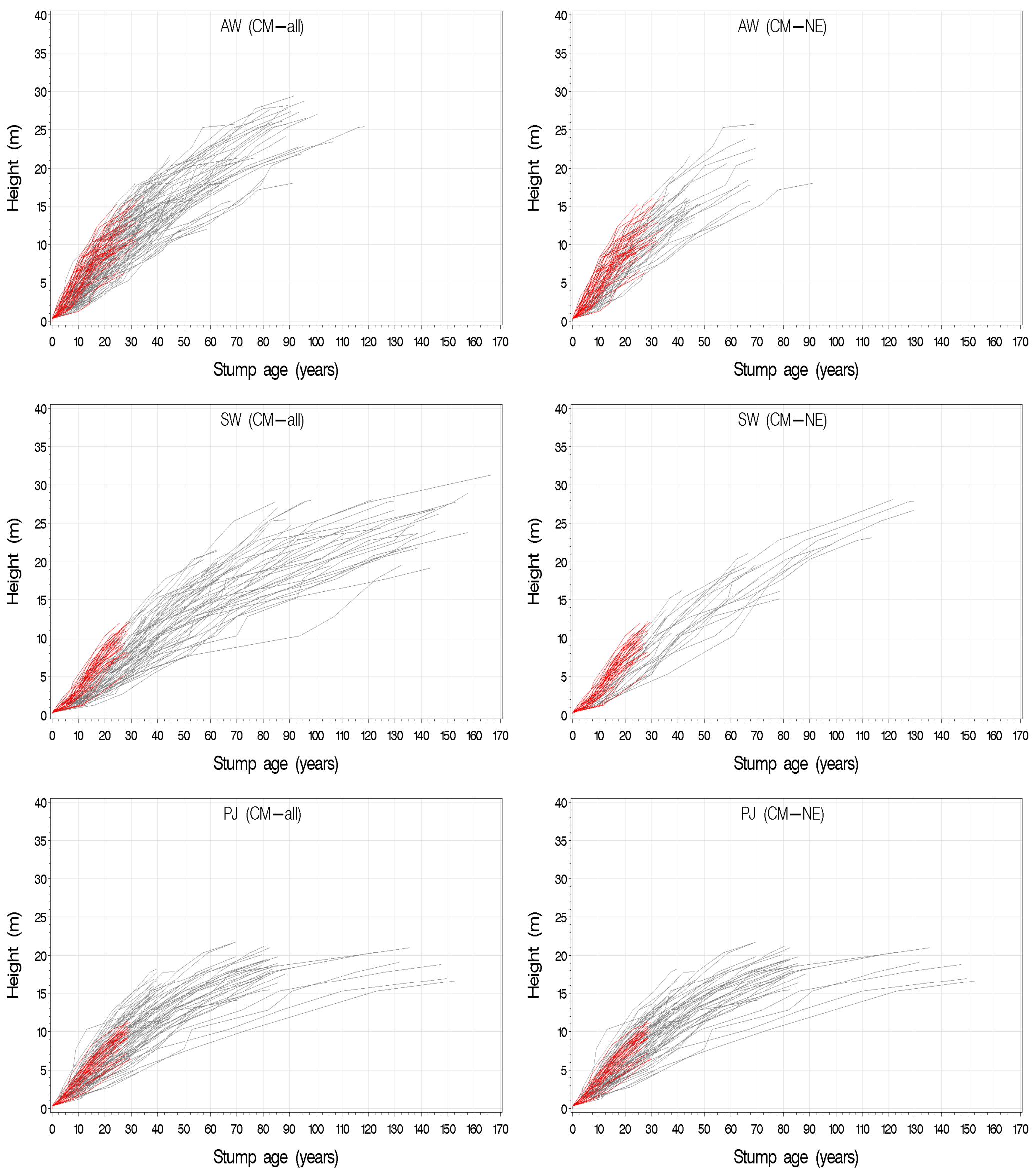

Figure 6. Height-age trajectories from reclaimed oil sands sites (red) and PSPs (grey) in the CM natural subregion (CM-all) and northeastern CM natural subregion (CM-NE).

The analysis of the tree sectioning data from reclaimed oil sands sites suggested that, while the exact amount was different for different species, site index values of the reclaimed oil sands sites were found to increase for all three boreal species relative to those from the fire-origin natural PSPs in the same ecoregion (Table 3). White spruce achieved the biggest increase (16.9 to 21.0%), followed by jack pine (7.2 to 9.1%), and aspen (4.2 to 8.6%). Overall, reclaimed oil sands site index was about 10% higher than fire-origin site index from PSPs. This followed similar trends to those reported in other independent studies that compared natural and managed second-growth forests (e.g., Stirling 1997, Karjalainen et al. 1999, Huang et al. 2004), although the observed increases in this study were generally lower than those reported in other studies.

In addition, it was observed that the site index estimates on reclaimed oil sands sites were reasonably stable over time for aspen and white spruce, but not for jack pine. A stable site index estimate over time is a prerequisite for differentiating a real change in site productivity from any fleeting spurt that might have occurred momentarily in reclaimed young stands. It is also a critical element in long-term forest modeling and timber supply analysis, which typically require a constant site index estimate through the rotation age or the entire planning horizon. The fact that a stable site index estimate over time was not achieved for jack pine suggested that while the current reclaimed site index value for jack pine appeared to be higher than that from comparable natural sites, we could not extend the result into the future. Consequently, caution must be exercised when interpreting the result for jack pine. Additional longer term data and further analysis would be helpful in this regard.

While increases in site index on reclaimed oil sands sites were found for all three boreal tree species, the underlying causes for such increases were not exactly understood and could be varied, with soil, density, age, stocking and stand conditions all considered important. Besides, site preparation methods and treatment techniques, and silvicultural practices could also play an important role in expediting tree growth on reclaimed sites. Foresters typically have the capability to identify the limiting factors on a site that impede growth, then apply appropriate site preparation methods and treatment techniques to create the preferred site conditions for expedited growth. When executed properly, the physical quality of reclaimed sites can be improved through the preferred soil and site treatment combination. The increases in reclaimed site index observed in this study may in turn imply that the existing site preparation methods and treatment techniques are reasonably adequate, even though continued improvements to these methods and techniques for better growth can still be made.

One of the other potential reasons for increased site index on reclaimed sites may be climate change. This perspective can sometimes be controversial, contentious and even contradictory. By definition, site index reflects the inherent productive capacity of a site. It is specific to the species grown on the site, and is determined by the carrying capacity of the surrounding environment and the genetic makeup of the species. Where the environmental attributes such as climate of a site change, it is possible that site index is also changed as a result.

Evidences of increased site productivity due to climate change have become more apparent in North America (e.g., Jenkins et al. 2000). In Europe, various studies have showed that forest growth and site productivity have increased considerably in recent decades, in some cases by 50% or more (e.g., Spiecker 1999, Pretzsch et al. 2014). Many researchers have found that higher CO_2 concentrations (and possibly greater levels of nitrogen deposition) related to climate change act like a fertilizer, enhance water use efficiency, and increase the site productivity through accelerated growth and increased biomass accumulation (e.g., Jenkins et al. 2000). But the overall realization of the increases is likely complicated and multifaceted. It needs to be balanced by other constraints on a broader scale, such as increased fire, insects and disease, and moisture stress (flood and drought) resulting from climate change.

4. Additional Data Collection and Further Analysis

Despite the fact that the available data showed that the site productivity of reclaimed oil sands sites is increased, we still need to take a conservative approach. It is worthwhile to emphasize that the science and practice of oil sands reclamation is relatively new. We do not have long-standing experience that spans to forest maturity. Our ability to fully understand forest growth and productivity on reclaimed sites is constrained by the lack of long-term measurement data, and by an incomplete knowledge of biological processes on reclaimed landscapes. We used an accepted variable (site index) as a measure of site productivity on reclaimed sites, and compared it to those obtained from the closest existing natural sites (PSPs) within the same ecoregion. But those closest natural sites may still not be close enough to the reclaimed sites. Hence, we need to collect additional data in natural stands that are ecologically matching and geographically closest possible to the reclaimed sites as in a paired-plot setting (Huang et al. 2004). We expect the data currently being collected from localized matching sites will shed further insights.

In addition, oil sands lease holders need to have enough long-term plots to continuously monitor forest growth and productivity on reclaimed sites. Data collected from repeatedly measured long-term plots will be extremely valuable as they become available over time.

While site index is the most common measure of site productivity, the overall biomass and volume productivity of reclaimed sites may also be affected by changed radial growth on reclaimed sites. This is illustrated in Figure 7 for one tree from detailed tree sectioning data available but not analyzed in the current study. Such data allow for other analyses on biomass and radial growth and their linkage to climate and climate change (e.g., Monserud et al. 2006, Chhin et al. 2008).

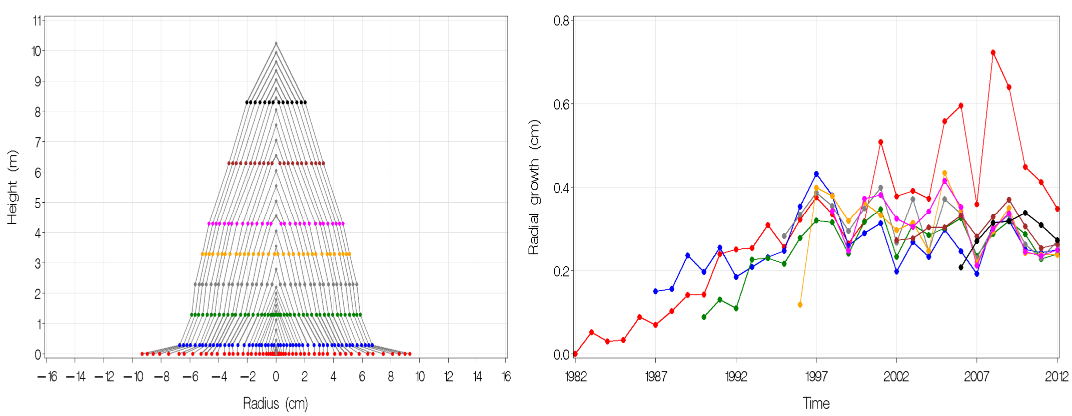

Figure 7. Observed annual radial growth along the stem of a sectioned tree (left, where for a graphical purpose the centre of the stem has an x-value of zero). The right graph shows colour-coordinated actual values of the annual radial growth at the sectioning points along the stem.

Additional data available on site and soil characters such as shallow surface soils, soil layering, mineral soil additions, soil texture, slope, aspect, and soil moisture and nutrient regimes should also be assessed (e.g., Wang et al. 2004). The effects of reclaimed landform and landform materials such as overburden, interburden, tailings sands, lean oil sands and other salvageable reclamation materials should also be looked at. Comparisons to regenerated forest growth and productivity on adjacent sites from forest management agreement holders, and to pre-oil sands mining growth and productivity on the same sites, should also be made where possible. Together they may provide a more holistic picture about the overall productivity of reclaimed sites. More importantly, they may also reveal the potential causes that resulted in the apparent increases in reclaimed site productivity. Clearly, these are fertile grounds for further analyses.

Conclusions

Analysis and comparison of the tree sectioning data from reclaimed oil sands sites suggested that, on average, forest productivity of the reclaimed oil sands sites in terms of site index is increased (4.2 to 21%, with an average of about 10%) after some rigorous soil replenishment, site treatments, and reforesting. While this increase is very desirable for maintaining the inherent productivity of the forests on the land, caution still needs to be exerted when interpreting the results, especially within the general context of identifying the likely causes and determining what kind of techniques can best be used to restore and enhance site productivity after oil sands mining. Additional comparison to natural and regenerated sites of similar ecological conditions adjoining the reclaimed oil sands sites should be made to help determine if the site index gain observed in this study is tangible and consistent over time. The continued long-term monitoring of the forest growth and productivity on reclaimed sites, particularly under assumed changes in bio-geo-climatic conditions, is very important in assessing if the final productivity of the boreal forests on reclaimed sites is fully maintained or enhanced over time.

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