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Article

Effects of Boreal Well Site Reclamation Practices on Long-Term Planted Spruce and Deciduous Tree Regeneration

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Abstract: Well site development associated with oil sands exploration is common in boreal mixedwood forests of northern Alberta, Canada, and necessitates reforestation to accommodate other land uses. Little is known about the impact of soil and debris handling strategies during well site construction on long-term forest regeneration. This study addresses the impact of soil disturbance intensity, debris treatment, soil storage, and planting on the reforestation of 33 well sites reclaimed prior to 2006. Data on the survival and growth of planted white spruce (*Picea glauca* (Moench) Voss) and the regeneration density of deciduous trees, including trembling aspen (*Populus tremuloides* Michx), are presented from 2014 to 2015. The survival of planted spruce increased from 81% to 88% at well sites with a high relative to low soil disturbance. The total tree densities were lower in most treatments ($\leq$2.69 stems m^{-2}) than those in clear cuts (5.17 stems m^{-2}), with the exception of root salvage areas where clear cuts had greater balsam poplar (*Populus balsamifera* L.) densities (2.05 stems m^{-2} vs. <0.71 stems m^{-2} on all other treatments). Aspen densities were up to five times greater at well sites with low disturbance when compared to those with high disturbance, and this was further aided by shallow mulch at low disturbance sites. Spruce growth did not respond to well site treatments. Aspen growth (diameter and height) remained similar between well site disturbance regimes; aspen exposed to high disturbance underperformed relative to low disturbance well sites and clear cut controls. With high disturbance, progressive soil piling led to increases in the density of aspen and birch (*Betula papyrifera* Marshall). Few long-term changes in soil were found due to well site development, with a greater soil pH in high disturbance sites compared to low disturbance sites. Overall, these results indicate that the nature of well site construction, including the extent of soil removal, soil piling, and debris treatment, may collectively alter forest re-establishment, with associated implications for forest management.

Keywords: boreal forest; planting; reforestation; tree density; well site reclamation

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1. Introduction

Large areas of boreal forest in northeastern Alberta are subject to oil sands exploration, with eight to 20 well sites, each approximately 0.7 ha^2 in size, established per square mile across the landscape. These well sites are exploratory and do not lead to permanent infrastructure. Where they occur in forest management agreement areas, these well sites are jointly managed for timber production with a requirement for reclamation that promptly returns these landscapes to productive harvest rotation [1].

It remains unclear whether and how reforestation on upland boreal oil sands exploration sites may be supported during the construction and/or reclamation phases of well site development to aid forest recovery.

Prior to the 1990s, post-harvest operations focused on the monoculture establishment of white spruce (*Picea glauca* (Moench) Voss) to meet the projected market demand for softwoods. White spruce is commonly planted after disturbance as its natural regeneration patterns are temporally erratic. The main reproductive strategy of white spruce is wind dispersed seed, with abundant seed production only occurring in mast years. Seeds germinate in newly disturbed areas on exposed mineral soil, humus, and woody substrates [2–5]. Under developed forest canopies, seedlings establish on woody debris in various stages of decay [6–9] and among feather mosses [10]. At open sites, naturally regenerating spruce seedlings often perish due to water stress [11]. White spruce growth and survival in boreal regions is impacted by frost damage, snow press, excess moisture, browsing by wild ungulates and small mammals, and competition from trembling aspen (*Populus tremuloides* Michx) and bluejoint (*Calamagrostis canadensis* (Michx) Beauv), a common grass in the boreal forest [11–14].

The management of mixed trembling aspen and white spruce stands is increasingly important for public land in Alberta [15], to accommodate biodiversity and associated social values, and to meet the increased market demand for hardwoods [16–20]. Trembling aspen can reproduce by wind dispersed seed on mineral substrates, but requires continuous moisture for seedlings to establish [21]. Aspen is clonal, vigorously resprouting following harvest and natural disturbances such as fire [22]. Resprouting is attributable to the removal of above ground biomass and the hormonal triggering of sucker growth from roots, which can produce high densities of robust clones under warm soil conditions at sites with favourable drainage [13,23]. Defoliating insects severely impact trembling aspen in the western boreal, especially with drought [24]. Regeneration densities of aspen are reduced by root severing and fragmentation [13]. Similar to spruce, aspen is prone to suppression by bluejoint, due to competition and the soil cooling associated with its thick litter [25].

Other regional pioneer tree species include balsam poplar (*Populus balsamifera* L.) and paper birch (*Betula papyrifera* Marshall). Birch sheds abundant wind dispersed seed in fall through winter [26]. Seeds germinate the following spring on exposed mineral or organic-mineral soil, and require continuous moisture for seedling establishment. Paper birch resprouts from root collars after stem removal, often forming pure stands or co-dominating with aspen [26]. Balsam poplar establishes after disturbance at sites with favourable moisture and nutrients through seeding, suckering, and sprouting from stem and branch pieces [27]. Prolific seed dispersal in balsam poplar occurs in early spring before bud flush and seeds germinate in exposed mineral soil. Partially buried branches can form new trees and suckering is common after soil disturbance; suckers of poplar are more vigorous than those of aspen [27].

Little is known about the long-term effects of oil sands well site exploration on the survival and growth of planted spruce, density and growth of naturally regenerating trees, and associated physical and chemical properties of boreal forest soils. Exploration well operations are small but numerous, creating many disturbances across a large area with spatially and seasonally limited access. Better guidelines are needed on the optimal construction and reclamation techniques for mixedwood forest recovery following well site establishment. For example, the use of low soil disturbance techniques may minimize undesirable soil property changes; separating soil layers in excavation and storage may reduce soil horizon mixing, thereby limiting the alteration of soil physical and chemical properties [28]. Improved soil handling may prevent the deep burial of seeds and propagules important for the revegetation [28], and retention of roots and woody debris may increase the opportunities for tree re-establishment [7,13,26,29]. Re-entering sites to amend a past reclamation project generates more disturbance and is financially undesirable.

This research was conducted to better understand the impact of soil management practices during well site construction, storage, and reclamation phases, including how these practices impact long-term (10 year) tree survival, regeneration, and reforestation. Reforestation success was defined as successional development convergent with the surrounding forest, or similar areas subject to clear cut forest harvest. Therefore, all sites were exposed to the common disturbance of tree removal during the same general period, and clear cuts provided a good reference for the physical characteristics of natural boreal vegetation in the absence of soil disturbance. A-priori use of well site treatments during construction and reclamation allowed for a direct comparison of conventional well site development methods with alternative construction and revegetation methods thought to reduce the impacts on existing vegetation, remaining plant propagules, and associated soil. Conventional construction methods include tree salvage, topsoil and subsoil stripping (high disturbance site levelling), and storage, typically in a single (progressive) pile, with coarse woody debris at the bottom. Following sequential soil layer replacement, coarse woody debris is placed on the soil surface and revegetation is undertaken when necessary. Salvage materials are normally stored for several weeks within the same season prior to reclamation. Occasionally, storage is carried over into the following winter as work primarily occurs under frozen conditions. All of the sites in our study were reclaimed in the same season. This study specifically addressed how planted white spruce survival and growth, together with hardwood tree regeneration and growth, responded to industry and prescribed experimental practices, including soil disturbance (low and high disturbance, duff stripping, root salvage), forest debris and mulch processing (whole slash, shallow mulch, deep mulch), and soil piling methods (single, progressive) with high disturbance treatments. The way in which these treatments altered the soil chemical and physical properties was also evaluated.

2. Materials and Methods

2.1. Study Areas

Thirty-three well sites established and reclaimed between 2004 and 2006 (Table 1) were examined during 2014 and 2015 in the boreal forest near Anzac, Alberta, within the Central Mixedwood Natural Subregion [30]. The site locations spanned approximately 500 km^2 SE of Fort McMurray, Alberta (Figure 1). Four cut blocks harvested and planted with white spruce in 2004 were also examined as a reference community in the absence of soil disturbance.

Table 1. Summary of 33 well sites and associated construction and reclamation treatments investigated during 2014 and 2015, 9 to 10 years after well site development and reclamation.

Year	Number of Sites	Soil Treatment	Soil Excavation		Soil Storage Method		Woody Material Management			Tree Planting	
			No	**Yes**	**Progressive Pile**	**Separate Piles**	**Spread Mulch**	**Spread Whole Slash**	**Wind-Rowed Whole Slash**	**Non-Planted**	**Planted**
2004	3	Low disturbance	√		n/a		√ *			√	√
2004	5	Low disturbance	√		n/a		√			√	√
2005	2	Low disturbance	√		n/a			√	√	√	√
2006	3	Low disturbance	√		n/a		√			√	√
2004	5	High disturbance		√	√			√		√	√
2005	2	High disturbance		√	√			√	√	√	√
2006	1	High disturbance		√	√			√	√	√	√
2006	3	High disturbance		√		√		√	√	√	√
2006	3	Duff-stripped		√ **	√			√		√	√
2006	6	Root salvage		√		√		√		√	

* Both shallow and deep mulch treatments were applied; ** Duff-stripping led to minimal disturbance of mineral soil. n/a = not applicable.

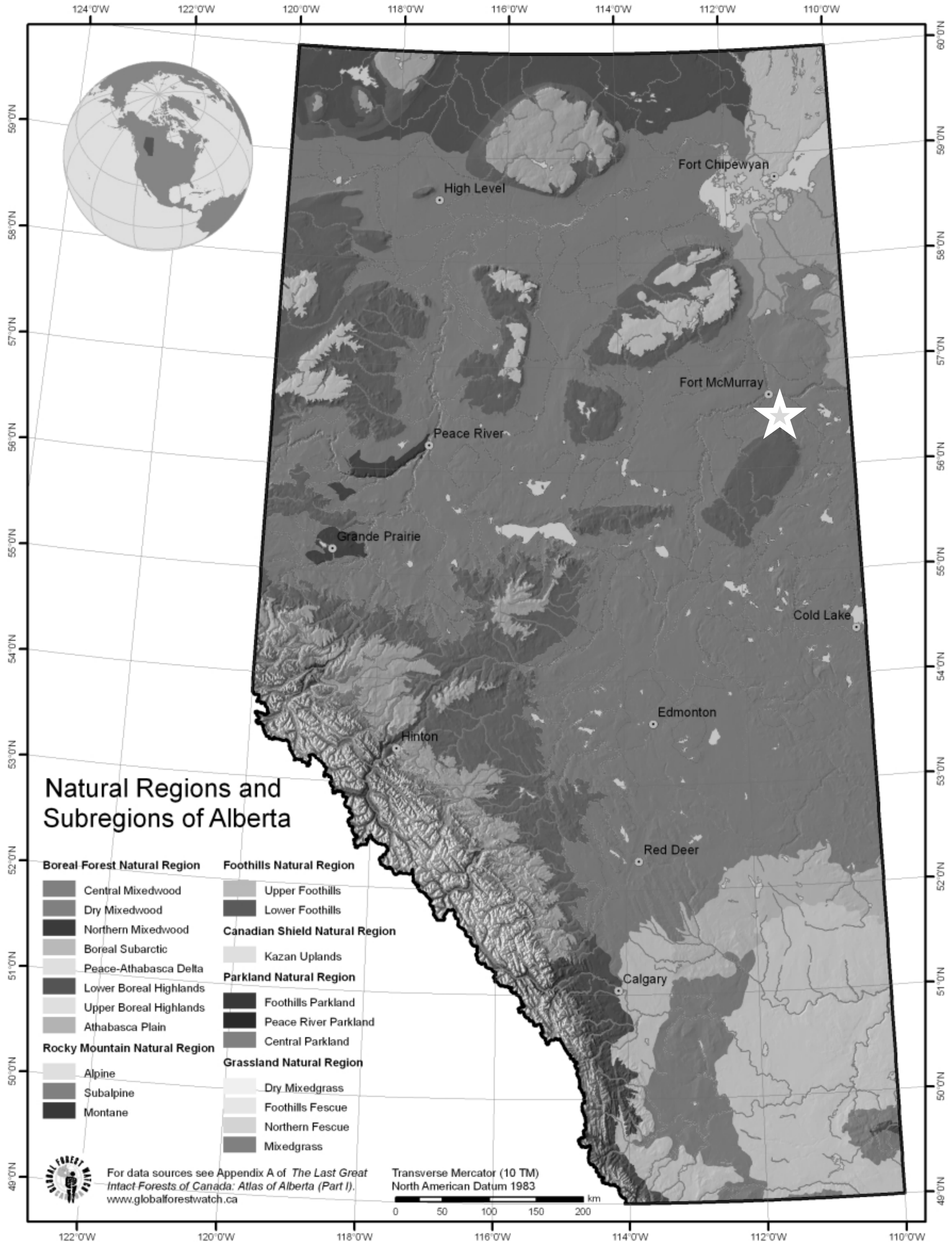
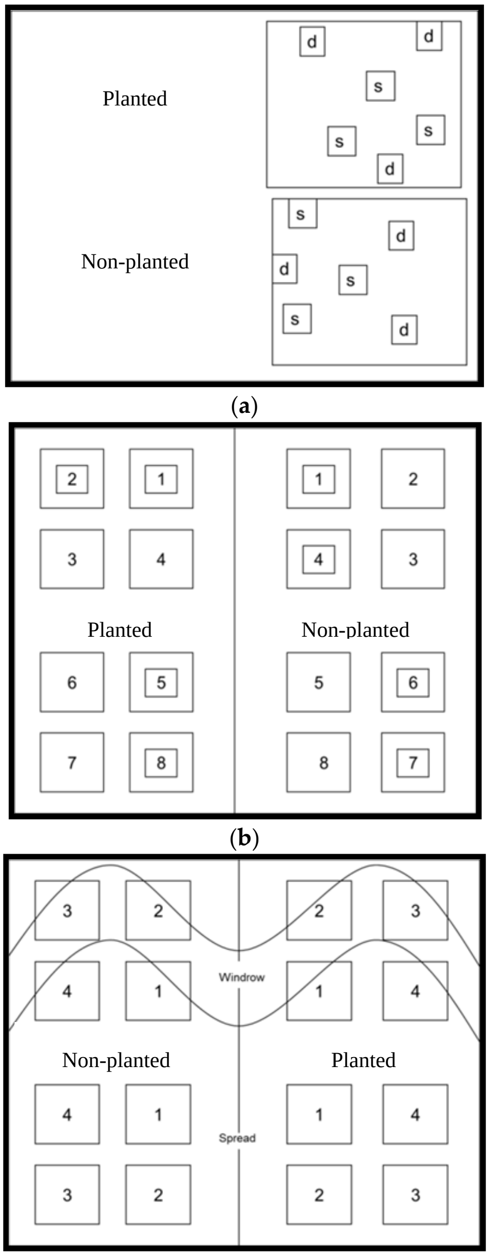


Figure 1. Location of the study region in the boreal mixedwood forest of NE Alberta, adapted from Global Forest Watch Canada [31].

The region is characterized by gently rolling to hummocky moraine receding to lacustrine flats underlain by Cretaceous shales [30,32]. Sites were mid to late seral boreal forest prior to well site establishment, with mesic to sub-mesic aspen or aspen—white spruce mixes in variable proportions on Gray Luvisolic soils of varying texture. Ecotypic understory species ranged from low bush cranberry (*Viburnum edule* (Michx) Raf), wild rose (*Rosa acicularis* Lindl), green alder (*Alnus viridis* (Chaix) DC), and red-osier dogwood (*Cornus sericea* L.), to Labrador tea (*Ledum groenlandicum* Oeder), ericaceous shrubs, and feather mosses.

2.2. Experimental Design and Treatments

All well sites were developed for oil sands exploration and subsequently reclaimed during winter months using different soil handling and woody debris management methods (Table 1). Each treatment group consisted of two to three well sites, with each site combining soil and woody debris treatments. Well sites were at least 70 m × 70 m, with four plots established in each treatment per site. Plots established in 2004 were 10 m × 10 m, and those established in 2005 and 2006 were 12 m × 12 m; the exception was mulch depth treatments with three 3 m × 3 m plots for each treatment at each site (Figure 2).



(**a**)

(**b**)

(**c**)

Figure 2. Site schematic for (**a**) shallow [s] and deep [d] mulch subplots in areas with and without planting within well sites; (**b**) a site with one woody debris treatment, further split into planted and non-planted treatments; and (**c**) a site with two woody debris treatments and planted and non-planted treatments.

Thirteen well sites were constructed with the most common low disturbance (iced-in) method, in which limited soil disturbance occurred. Mulch, snow, and ice were pushed over the top of the site to build a level platform. On eight of these, non-merchantable vegetation was mulched and spread at variable depths according to standard management methods during reclamation (Table 1). At three sites, mulch was spread to depths of ≤ 5 cm and ≥ 10 cm in alternating 10 m wide strips (hereafter shallow and deep mulch treatments, respectively). On the remaining two low disturbance sites, residual woody debris was spread as whole slash on half the site and windrowed on the other half (Figure 2). Five sites established with the low disturbance methods were compared with five high disturbance sites constructed and reclaimed in the same year.

Eleven sites were constructed with high disturbance (conventional) methods and reclaimed (Table 1). During construction, soils were stripped by a dozer in two passes. The first pass removed the LFH (organic) layer and the second underlying mineral Ae horizon, usually with some B horizon when the Ae horizon was <15 cm depth. Stripped soils were stored at the edge of the site, usually for three to four weeks, and were then replaced. At five sites, salvaged slash was evenly spread across the site. At six sites, slash was windrowed on half the site and spread evenly across the other half at reclamation.

Soil was stored at eight high disturbance sites with single (progressive) piles, in which removed material (woody debris, LFH, top soil, then subsoil) was sequentially placed on top of each other. Space limitations occasionally required the use of one progressive pile. Three of these sites were compared to three others at which LFH and surface soil were piled separately from subsoil during storage; the latter replaced the first during reclamation. Although attempts were made to replace all soils according to their originating depth, the substantial mixing of layers likely occurred in progressively piled soils.

Three sites were constructed with a duff stripping method, removing the LFH layer and occasionally a small amount of mineral A horizon. Stripped material was stored in a single pile with residual slash. The duff stripping treatment used the same design as the 2004 high and low disturbance sites (Figure 2b). Since duff stripping seemed to be of an intermediate disturbance intensity, between high and low, we compared the response of duff stripping in those two extremes.

Root salvage treatments were applied at the remaining six sites (Table 1), and compared to five conventionally constructed reference sites established using progressive soil piles. Conventional two-pass soil stripping is often performed using soil colour as an indicator of stripping depth. However, aspen roots are mostly located where a soil colour change occurs at the interface of the LFH and Ae horizons [28]. The first pass therefore excavated soil at a greater depth to prevent root damage by the equipment. During storage, aspen roots were generally bound within larger soil aggregates than at conventional sites. A second excavation pass removed the lower Ae and some B horizon to level the site prior to well establishment. Soils from the second pass were piled separately and measures were taken to reduce the sorting of roots from soil during soil replacement.

Except for six root salvage sites where excavation was designed to examine natural tree regeneration, the sites were planted in early summer following reclamation with 150 to 200 trees on a randomly selected half of the site (Figure 2a). Trees were grid planted at 2 m spacing, with a planting density of 3300 trees ha^{-1}. In 2004, alternating rows of trembling aspen, balsam poplar, and white spruce were planted. Sites reclaimed in 2005 and 2006 were planted with the same species, plus rows of paper birch. Twelve individuals of each species were planted in each plot (three of each species in deep and shallow mulch treatments).

2.3. Planted Spruce Assessment

Planted spruce were readily identifiable, exhibiting more regular spacing and a greater size than volunteer spruce, although multiple individuals of a similar size occurring at expected spacing for planted deciduous trees prevented the identification of planted deciduous trees. Therefore, the assessment of planted tree performance was restricted to spruce. Spruce planted in 2004 and 2005 were assessed in May and June 2014, while spruce planted in 2006 were assessed in 2015. After being relocated, the trees were assessed as live, damaged, or missing; for those alive, root the crown diameter and diameter at breast height were measured with calipers (trees < 20 cm diameter) or diameter tape (trees > 20 cm). The height was measured for each tree with a tape (trees up to 5 m) or Suunto clinometer (trees > 5 m).

2.4. Regenerating Tree Density Assessment

The density of trees was assessed at each site during the same year as the planted spruce were assessed. At each site, five 1 m × 1 m quadrats were randomly located in each plot for a total of 20 quadrats per treatment. In deep and shallow mulch treatments, four 1 m × 1 m quadrats were randomly located in each plot for a total of 12 quadrats per treatment. To sample the well sites with a single woody material treatment (mulched or spread), transects were established from one corner of a reference plot to its opposite corner. At sites with woody material spread on one half and windrowed on the other, transects radiated from the centre. Transects thus crossed both shaded and lit portions of each plot, and crossed windrows where present. All trees in quadrats, including aspen, birch, poplar, white spruce, *Picea mariana* (Mill) Britton, Sterns and Poggenb (black spruce), *Larix laricina* (Du Roi) K Koch (tamarack), *Abies balsamea* (L.) Mill (balsam fir), and *Pinus banksiana* Lamb (jack pine) were counted. The height and diameter at breast height for all trees were recorded in size classes (Table 2) and averaged to expedite sampling.

Table 2. Summary of diameter at breast height (DBH) and height classes used to assess regenerating aspen trees.

DBH Class	DBH (cm)	Height Class	Height (m)
1	0–2	1	0–0.5
3	2–4	2	0.5–1.3
5	4–6	3	1.3–3
7	6–9	4	3–5
9	9–12	5	5+

Reporting was limited to spruce, aspen, birch, and balsam poplar because the other species were not present at all sites. The occurrence of four conifers other than white spruce was controlled by the location and proximity to seed sources; black spruce, jack pine, tamarack, and balsam fir. Populations were site specific and did not significantly contribute to the total density relative to any treatment, ranging from 1% in cut blocks, 2% in high disturbance, 3% in root salvage, and 6% in low disturbance, to 9% in duff stripping; the latter being higher than others where treatment resulted in significant hardwood regeneration losses.

Cut blocks, from 30 to 156 ha in size, were sampled in a similar manner to the well sites. Transects were established 20 m from the edges, with one transect in each cardinal direction. Five 1 m × 1 m quadrats were randomly located 15 to 20 m apart along each transect ($n = 20$ per cut block). Areas clearly disturbed since the harvest (recreational vehicle use) and those in lowland or riparian ecotypes were avoided to ensure comparability.

2.5. Soil Sampling and Laboratory Analyses

In 2015, soil was sampled from six root salvage sites. Six subsamples were obtained on and off the site at random locations and were at least 20 m apart. For each core, the overlying organic layer was removed and samples were taken with a 7.5 cm diameter × 7.5 cm long Uhland corer at 0 to 15 and 15 to 30 cm depths. Samples were stored in coolers, weighed fresh, and then air dried and reweighed to determine the water content. Soils were then sieved, the rocks and roots were removed, and the final volume was determined to calculate the bulk density [33]. Subsamples from each site and paired control were amalgamated in a treatment and depth class.

Soil at other sites was sampled the summer following reclamation. Three subsamples were taken at 6 and 30 cm depths from each of the four locations, and an equal number were collected from offsite reference areas. Samples from each onsite treatment community and each forest control were amalgamated in each depth class before being sent to the laboratory. Soils in cut blocks were not sampled.

Physical and chemical soil analyses for the initial samples between 2004 and 2006 included the available nitrate, determined by calcium chloride solution and colourimetry [34], phosphorus and potassium by modified Kelowna solution and colourimetry [35], and the available sulfur by calcium chloride solution and inductively coupled plasma atomic emission spectroscopy [34]. The total carbon and nitrogen were quantified by dry combustion [36] and inorganic carbon by acid digestion [37]. The soil pH and electrical conductivity were assessed using a saturated paste (2:1 soil to water slurry) with a pH meter [38] and particle size determination with the hydrometer method [39].

2.6. Statistical Analyses

Analyses of tree densities and growth (height and DBH), spruce survival, and soil properties were performed using *R* 3.2.5 software [40]. All data were checked for normality and homoscedasticity prior to analysis. Planted spruce survival followed a Poisson distribution and was arcsine square root transformed to attain normality. Square and fourth root transformations were conducted on regenerating tree densities and aspen growth parameters (height, DBH). Soil electrical conductivity was log transformed. All data presented are original means and standard errors for interpretative purposes.

Statistical approaches for analysis included ANOVA and contrasts to assess the fixed effects of well site treatment with REML. To assess the impact of each well site construction method (low disturbance, high disturbance, duff stripping, root salvage) and adjacent clear cuts on the tree responses, ANOVA was used to analyse the total tree densities and the density of aspen, paper birch, and balsam poplar. The large sample of aspen trees allowed for an assessment of the diameter and height in this species. In this analysis, the five main treatments were considered fixed effects, with each well site (or clear cut) sample considered random. The significance of the main effects was set at $p < 0.10$ to minimize the risk of type 2 errors, with post-hoc comparisons conducted using an alpha of 5%. Contrasts were used to assess the differences between cut blocks and high and low disturbance, and between treatments (not including cut blocks) relative to conventional (high disturbance) well site construction methods. A second set of data pertaining to the performance of planted spruce, including height, DBH, and survival, was compared for those treatments subject to planting, and included low disturbance, high disturbance, and duff stripping (no spruce were planted in the root salvage treatment).

Other contrasts were performed within low disturbance well sites to assess the specific impact of debris management (whole slash retention vs. mulching) and depth of mulch (deep > 10 cm; shallow < 5 cm). Similarly, within high disturbance well sites, contrasts were performed to compare the effect of soil piling (progressive vs. separate piles) and the role of spreading vs. windrowing of slash. An alpha value of 0.10 was used due to the limited sample sizes for these treatments (whole slash, duff stripping, mulch depth, separate piles; $n = 2$–3).

3. Results

3.1. Spruce Responses

The survival of planted white spruce averaged 81.4% across all treatments, and was greater ($p = 0.068$) with high disturbance (87.9 ± 6.4%) than low disturbance (80.2 ± 6.4%). Spruce survival was greater ($p = 0.09$) with high disturbance subject to progressive soil piling (91.9 ± 7.8%) than where soil was piled separately (76.7 ± 7.8%). The mean DBH ($p \geq 0.15$) and height ($p \geq 0.19$) did not differ for planted white spruce in relation to soil disturbance, debris handling, or soil piling (data not shown), although the height and diameter of spruce trees with high disturbance (224.5 and 19.2 cm, respectively) exceeded those with low disturbance (191.8 and 13.9 cm, respectively). Across all well sites, spruce height averaged 198.8 cm after 10 years of growth, and DBH averaged 15.1 cm.

There was no effect of planting on the spruce density. The white spruce density, including planted and naturally regenerating trees, was higher ($p = 0.09$) with low disturbance (0.52 ± 0.25 trees m^{-2})

than high disturbance (0.25 ± 0.25 trees m^{-2}). With high disturbance, spruce density was greater ($p = 0.03$) where slash had been windrowed (0.28 ± 0.08 trees m^{-2}) than where spread across the site (0.21 ± 0.08 trees m^{-2}).

3.2. Deciduous Tree Responses

The aspen densities in all well site treatments were lower ($p < 0.05$) than in clear cut areas (Table 3); low disturbance aspen density ($p < 0.05$) remained more than five-fold higher than high disturbance. The height of aspen responded similarly, remaining shorter in all well sites relative to clear cuts, with the exception of low disturbance treatments (Table 3), where aspen were 20–45% taller than those in the other well site treatments. Differences in the aspen DBH values were not as pronounced among treatments (Table 3), with high disturbance, root salvage, and duff stripping well sites having aspen trees of a smaller diameter than clear cuts; aspen DBH was similar ($p = 0.17$) between low disturbance well sites and clear cuts.

Table 3. Results of ANOVA comparing mean aspen, paper birch, and balsam poplar tree density, and aspen diameter at breast height (DBH) and height class, among clear cuts and various well site construction treatments in the boreal mixedwood.

Treatments (*n*)	**Aspen DBH Class**		**Aspen Height Class**		**Aspen Density (Trees m^{-2})**		**Paper Birch Density (Trees m^{-2})**		**Balsam Poplar Density (Trees m^{-2})**	
ANOVA *p*-values	0.019		0.022		<0.001		0.089		<0.001	
Clear cuts (4)	2.1	A	3.6	A	1.64	A	3.19	A	0.01	C
Low disturbance (10)	1.5	AB	3.1	AB	**0.86**	B	**0.82**	B	0.36	BC
High disturbance (11)	**1.2**	B	**2.6**	BC	**0.16**	C	0.86	AB	**0.71**	B
Root salvage (6)	**1.3**	B	**2.2**	C	**0.23**	C	**0.29**	B	**2.05**	A
Duff stripping (3)	**1.0**	B	**2.3**	C	**0.36**	C	**0.08**	B	0.26	BC
SEM	0.2		0.2		0.27		0.84		0.49	

Within a column, means with different letters differ at $p < 0.05$; Well site treatments different from clear cuts are bolded.

The densities of paper birch were lower with low disturbance, root salvage, and duff stripping than clear cutting (Table 3). Balsam poplar densities were very low in clear cuts, particularly relative to root salvage and high disturbance well site treatments. Balsam poplar densities with root salvage were at least 2.8 times greater than with all other treatments (Table 3).

The total deciduous density was highest in clear cuts (Figure 3). Among well site treatments, the deciduous density was not significantly different among low disturbance, high disturbance, and root salvage. The deciduous density was lowest for duff stripping, which did not differ from low and high disturbance.

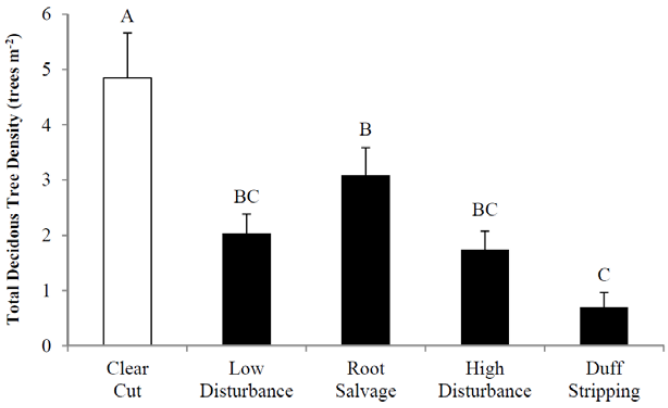


Figure 3. Comparison of total deciduous tree densities on clear cuts and well sites constructed with four soil surface disturbance methods. Bars represent 1 standard error. Means with different letters differ at $p < 0.05$.

With low disturbance well site treatments, mulching had relatively few effects on deciduous tree regeneration (Table 4). While trembling aspen tended to have a greater density ($p = 0.09$) with shallow mulch compared to deep mulch, the opposite was evident for balsam poplar ($p = 0.09$), which displayed a greater density with deeper mulch. Aspen height and DBH did not vary with mulching treatment ($p \geq 0.34$; Table 4). Planting did not alter the aspen density in most well site treatments [41] ($p > 0.40$) (data not shown), with the exception of the low disturbance, where planting marginally increased the aspen density (planted = 4.99 vs. non-planted = 3.64 ± 2.08 trees m^{-2}; $p = 0.07$).

Table 4. Comparison of deciduous tree density, aspen height, and diameter responses in relation to woody debris and soil piling surface treatments in upland boreal well sites in northern Alberta. SEP indicates within separate soil pile treatment and PROG indicates within progressive soil pile treatment.

Treatment Grouping	**Mean Comparison**				**p-Value**
			Aspen Height Class		
Within Low Disturbance					
Whole slash ($n = 2$)	3.2 (±0.4)	VS.	Mulching ($n = 8$)	3.1 (±0.4)	0.86
Shallow mulch ($n = 3$)	3.7 (±0.6)	VS.	Deep mulch ($n = 3$)	3.0 (±0.6)	0.34
Within High Disturbance					
Separate piles ($n = 3$)	2.8 (±0.4)	VS.	Progressive piles ($n = 8$)	2.5 (±0.4)	0.57
Spread slash ($n = 11$)	2.3 (±0.3)	VS.	Windrowed slash ($n = 6$)	1.9 (±0.3)	0.15
			Aspen Diameter at Breast Height Class		
Within Low Disturbance					
Whole slash ($n = 2$)	1.3 (±0.4)	VS.	Mulching ($n = 8$)	1.6 (±0.4)	0.52
Shallow mulch ($n = 3$)	3.1 (±1.0)	VS.	Deep mulch ($n = 3$)	2.3 (±1.0)	0.48
Within High Disturbance					
Separate piles ($n = 3$)	1.2 (±0.2)	VS.	Progressive piles ($n = 8$)	1.2 (±0.2)	0.95
Spread slash ($n = 11$)	1.3 (±0.2)	VS.	Windrowed slash ($n = 6$)	0.8 (±0.2)	**0.024**
			Aspen Density (trees m^{-2})		
Within Low Disturbance					
Whole slash ($n = 2$)	1.16 (±0.34)	VS.	Mulching ($n = 8$)	0.79 (±0.34)	0.31
Shallow mulch ($n = 3$)	0.85 (±0.11)	VS.	Deep mulch ($n = 3$)	0.51 (±0.11)	**0.094**
Within High Disturbance					
Separate piles ($n = 3$)	0.05 (±0.08)	VS.	Progressive piles ($n = 8$)	0.21 (±0.08)	**0.083**
Spread slash ($n = 11$)	0.15 (±0.10)	VS.	Windrowed slash ($n = 6$)	0.20 (±0.10)	0.57
SEP: Spread slash ($n = 3$)	0.02 (±0.03)	VS.	Windrowed slash ($n = 3$)	0.08 (±0.03)	**0.005**
PROG: Spread slash ($n = 8$)	0.20 (±0.21)	VS.	Windrowed slash ($n = 3$)	0.33 (±0.21)	0.81
			Paper Birch (trees m^{-2})		
Within Low Disturbance					
Whole slash ($n = 2$)	1.57 (±0.87)	VS.	Mulching ($n = 8$)	0.63 (±0.87)	0.31
Shallow mulch ($n = 3$)	1.58 (±0.42)	VS.	Deep mulch ($n = 3$)	1.01 (±0.42)	0.25
Within High Disturbance					
Separate piles ($n = 3$)	0.05 (±0.60)	VS.	Progressive piles ($n = 8$)	1.17 (±0.60)	**0.03**
Spread slash ($n = 11$)	0.83 (±0.08)	VS.	Windrowed slash ($n = 6$)	0.46 (±0.08)	**0.085**
			Balsam Poplar (trees m^{-2})		
Within Low Disturbance					
Whole slash ($n = 2$)	0.15 (±0.43)	VS.	Mulching ($n = 8$)	0.41 (±0.43)	0.48
Shallow mulch ($n = 3$)	0.01 (±0.13)	VS.	Deep mulch ($n = 3$)	0.29 (±0.13)	**0.096**
Within High Disturbance					
Separate piles ($n = 3$)	0.99 (±0.61)	VS.	Progressive piles ($n = 8$)	0.60 (±0.61)	0.20
Spread slash ($n = 11$)	0.72 (±0.44)	VS.	Windrowed slash ($n = 6$)	1.10 (±0.44)	0.67

Aspen density varied with debris and piling treatment; Bolded values indicate those with $p < 0.10$.

With high disturbance, balsam poplar densities did not vary with soil piling or debris treatment ($p \geq 0.20$); however, the paper birch densities were greater where soil was progressively rather than separately piled ($p = 0.03$), and where slash was spread rather than windrowed (Table 4). Similarly, aspen densities were greater ($p = 0.08$) with progressive rather than separate piling (Table 4). The aspen density response to debris treatments differed between soil piling treatments ($p = 0.005$); windrowing slash led to greater aspen densities when combined with the separate, not progressive, piling of soil (Table 4). Although aspen height was not influenced by these treatments with high disturbance well sites ($p \geq 0.15$), the windrowing of debris led to aspen that had a smaller DBH ($p = 0.02$) relative to those growing where slash had been spread (Table 4).

3.3. Aggregate Forest Densities

The total tree densities differed among main disturbance treatments ($p = 0.002$). They were greater ($p < 0.05$) with clear cuts than with other treatments, with the exception of root salvage well sites, and duff stripping led to the fewest trees. Tree densities did not differ with contrasting soil piling ($p = 0.24$), slash treatment ($p = 0.56$), or mulching ($p \geq 0.30$).

3.4. Soil Responses

Well sites constructed using high disturbance (soil removal) techniques had greater ($p = 0.07$) soil nitrogen levels (0.14 ± 0.04 mg kg^{-1}) than low disturbance sites (0.08 ± 0.04 mg kg^{-1}). Parallel results were evident for the organic matter content of mineral soils, which were greater ($p = 0.003$) with high disturbance well sites (5.10 ± 1.25%) than low disturbance sites (1.65 ± 1.25%).

No differences in soil texture were evident among well site treatments ($p \geq 0.19$), with similar results for electrical conductivity ($p \geq 0.20$). In contrast, the soil pH differed markedly among treatments. Soils with high disturbance had a higher pH (6.07 ± 025) ($p = 0.01$) than those with low disturbance (5.42 ± 0.25), but remained below ($p = 0.03$) those with root salvage (6.57 ± 0.21). Within low disturbance well sites, whole slash application areas had a lower ($p = 0.08$) soil pH (4.78 ± 0.41) than mulched areas (5.54 ± 0.41); shallow mulch areas generally had a lower pH ($p = 0.05$) (5.32 ± 0.07) than deep mulch areas (5.52 ± 0.07).

4. Discussion

The good planted spruce survival on disturbed sites likely resulted from the increased nutrient availability from soil disturbance and mixing. Nitrogen mineralization is common after forest soil disturbance [42,43] and mechanical site preparation [44,45]. Soil mixing during construction and reclamation can introduce organic carbon from forest surface materials to underlying mineral soil, particularly if the stored soil layers are piled on top of one another without separating barriers. Disturbance effects on nitrogen and organic matter may be short-lived [46], although planted spruce likely benefitted from the initially improved nutrient availability of disturbed soils, which was especially evident where soil materials were stored in single, progressive piles when the mixing of soil layers was more difficult to avoid.

Spruce can be suppressed by deciduous tree competition [13,15], although the deciduous tree density did not differ between the high and low disturbance treatments. Differential competition from woody species was therefore not likely a factor. However, the soil storage method within disturbed treatments may have influenced spruce survival. Microorganism and micro faunal populations can be lost with exposure and soil desiccation [47]. Soils stored in separate piles with greater surface area to volume ratios than single large piles provided less protection, potentially leading to greater losses in soil microorganisms and a reduced soil productivity.

The construction and reclamation practices studied represent varying soil and propagule disturbance levels, with mitigative effects from higher disturbance. Soil excavation results in the severing, wounding, and displacement of suckering roots [48], exposing them to freezing, desiccation, and equipment traffic [28,49], and thereby severely diminishing their suckering ability. Low disturbance methods reduce such damage by avoiding excavation; root salvage can avoid root losses by retaining larger pieces of roots, providing a better protection of roots from exposure during storage, and preventing the sorting of roots to the surface during soil replacement. Separating soil components in storage avoids the mixing of soil layers, while duff stripping was an attempt to minimize excavation, possibly preserving topsoil.

Although the deciduous tree density was expected to be greatest where the disturbance was lowest, with some variation among high disturbance mitigation practices, it did not differ greatly between well site treatments. Treatments appeared to differentially benefit tree species, with balsam poplar highly favoured at root salvage sites and birch at clear cuts. Capable of reproducing from seed, root suckers, stump sprouts, and buried branches, balsam poplar has a greater regenerative versatility than aspen, and soil disturbance tends to exploit this versatility [50]. With greater vigour [27] and more opportunity for vegetative regeneration, poplars likely took greater advantage of the protective measures on root salvage sites and dominated the initial population of regenerating trees, possibly impeding further aspen establishment. Both aspen and poplar have fairly stringent seedling establishment requirements [50], although the differences in local seed abundance and dispersal timing and duration may have favoured poplar seedlings over aspen. However, vegetative stems are more vigourous than seedlings [50], and therefore, vegetative poplars would have been more competitive than aspen seedlings.

The progressive piling of soil components may have benefitted aspen more than root salvage. The smaller surface area to volume ratio of progressive piles likely resulted in fewer aspen root fragments lost to desiccation and freezing during soil storage, resulting in a four-fold increase in the density over separate piles. The same might be true for birch seeds, as the birch density was more than twenty times higher at sites with progressive piles than separate piles. Combining progressive soil piling with root salvage might have yielded a higher overall tree density than either of these practices separately. While aspen densities were very low at sites with separately piled soils in general, they were improved by windrowing slash. Aspen seedling establishment may have benefitted from increased mineral soil exposure and a higher soil temperature within the inter-windrow spaces of these treatments. Birch seeds dispersed in autumn prior to site construction may have been buried within windrows, thereby resulting in a lower birch density than spread slash treatments.

By producing abundant seed and having a broad soil water tolerance once established, birch can rapidly colonize post disturbance [26], possibly explaining the ubiquity of birch among treatments. Climate and insect stressors have increasingly affected North American aspen populations [51,52]. Drought was widespread in central and northern Alberta in 2009 and 2010 [53], and widespread forest tent caterpillar defoliation occurred in the study area from 2007 to 2009 [54]. The competitiveness of naturally regenerating aspen at clear cuts and oil sands exploration well sites might have thus been reduced. A higher birch abundance for clear cuts and low disturbance treatments may have been related to the soil pH, as birch prefer soils with a pH < 5.3 [55].

The further aspen reduction on low disturbance sites relative to clear cuts may have resulted from incomplete apical dominance release and residual shading. Harvest induces aspen suckering by soil warming and the removal of apical dominance [50]; suckering is significantly reduced in partial cuts [23]. Cutting only a small area can limit the release of apical dominance [13] and residual shade, which limits soil warming on the small well site openings and may have contributed to a lower density of deciduous trees. Aspen clones vary in their suckering ability [50], potentially resulting in reduced suckering on a well site by chance. Deeper mulch at low disturbance sites would further impede aspen suckering by insulating the soil and delaying soil warming [56,57], in turn delaying the sucker emergence and reducing the competitive advantage [13]. Poplar is more tolerant than aspen to cooler, moister conditions [50], thus responding favourably to deeper mulch. The aspen density, which was marginally greater in the planted portion of the low disturbance treatment, was likely influenced by planting occurring randomly on the shallower half of sites where mulch application was used to correct slight slopes [54].

The seemingly minor disturbance of duff stripping produced the greatest tree density reduction. Some suckering roots would have been removed with LFH material and suffered mechanical damage similar to other high disturbance treatments. The smaller volume of material compared to root salvage or progressively piled soils provided far less protective insulation during storage, resulting in a greater loss of regenerative ability. The regenerative capacity of roots remaining in the mineral soil would have diminished from the increased exposure caused by the removal of the insulating LFH layer. Tree establishment from seeds might have been affected. The mixing of LFH during removal and replacement could stimulate the germination of weaker seeds previously buried deep within the seed bank, while burying the youngest, most viable seeds and preventing their germination. Tree seeds are more prone to desiccation than the seeds of other plants [58]. Therefore, factors reducing root fragment viability could reduce tree seed viability. Loosening caused by removing and replacing LFH could reduce its water retention, thereby reducing the establishment success of germinated trees [59].

Minimizing soil disturbance remains a preferred option for maintaining forest productivity at oil sands exploration well sites. While the tree density was not highest at low disturbance sites, aspen were larger, possibly because of regeneration from suckering roots rather than seedlings. Species composition, including herb and shrub vegetation [41] (data not shown), was closer to expectations from timber harvest or fire, and herb and shrub vegetation was most similar to clear cuts [41]. A reduced soil disturbance reduces the risk of invasive species introduction and is usually less costly than site excavation [28]. Forest productivity losses due to soil excavation can be mitigated by practices that protect suckering roots, including deep first passes that collect roots with abundant soil for burial; preventing root sorting to the surface when replacing soil, such as using an excavator rather than a dozer [28]; and piling stored soil layers on top each other rather than piling them separately to minimize the surface area to volume ratio of exposed soils. Certain practices and locally available seed sources may alter the species composition of regenerating trees, requiring supplemental planting or actions targeting the protection or conservation of specific propagules.

There may be a cultural resistance to reducing excavation among drilling and construction operators, retaining bias from construction practices on non-forested lands, as demonstrated by duff stripping. Duff stripping sites were level and a safe drilling platform could have easily been constructed from snow and available woody debris without excavation. The limited excavation may have been a sincere attempt to preserve topsoil, but also demonstrated a resistance to avoid excavation. Excavation is a common method for conserving non-forested soils, but constructing well sites over topsoil without excavation is becoming more common at non-forested sites. That forest productivity was poorest at duff stripping sites demonstrated that topsoil protection is not always achieved by its removal and that this practice should be avoided.

Windrowing was only beneficial in combination with separately piled soils. However, woody debris loads were not high at any of the sites. Windrows may be of benefit at sites where slash loads are detrimental to tree establishment, but not at sites with low to moderate slash loads. Deep wood chip mulch can be detrimental to tree regeneration. Windrowing could be used to manage mulch, but keeping woody debris whole rather than chipping it will reduce the volume associated with a given weight of woody debris, thereby reducing the blanketing effect.

5. Conclusions

There were many sites where planted spruce and regenerating aspen achieved simultaneous reforestation, although it was difficult to manage soil disturbance and woody debris in favour of both species. Although low disturbance methods were cost effective for industry and the environment, high disturbance methods may be necessary for site construction. Soil disturbance augmented the early growth of spruce, but not regenerating aspen. Planted spruce growth was only favourable where soil mixing occurred, although survival was greater at well sites with high soil disturbance. The tree species composition at regenerating oil sands exploration sites remained inconsistent with regeneration at comparably disturbed areas associated with forest harvest (clear cutting). The total deciduous tree densities were lower for most well site treatments than for clear cuts, with the exception of root salvage areas which had greater balsam poplar densities. Aspen densities were greater at well sites with low disturbance than with high disturbance and increased with shallow mulching or woody debris when compared to mulch. Aspen regeneration was favoured by low disturbance methods; aspen growth was similar for high and low well site disturbances. With high disturbance, progressive soil piling led to increases in the aspen and birch density, likely due to the protection of roots and seeds not afforded by piling soils separately. Few changes in soil were found due to well site development, with a soil pH that was greater at high disturbance sites than low disturbance sites.

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