Effects of woody debris and cover soil types on soil properties and vegetation 4–5 years after oil sands reclamation

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Woody debris is a critical component of natural forests, with an important function in land reclamation to control erosion and enhance diversity and function of newly developing ecosystems. Combined with cover soils, woody debris can play a significant role in plant community development, as cover soil is a source of inexpensive and ecologically adapted propagules. As we develop woody debris application as a land reclamation tool, its impacts on cover soils over time need to be documented. This study assessed how woody debris volume, types (Picea mariana, Populus tremuloides), and size influenced soil properties, and vegetation structure and composition in forest floor-mineral mix (FFM) and peat-mineral mix (PMM) cover soil types 4–5 years after oil sands reclamation. Soil chemical and physical properties were significantly affected by cover soil types, whereas no woody debris effects were evident. FFM cover soil was associated with greater vegetation cover, plant species richness, composition, and woody plant density than PMM. Nonmetric multi-dimensional scaling and multi-response permutation procedures revealed plant community compositional differences only for cover soil types. Presence of early-to-late and mid-to-late seral species 4–5 years after reclamation in FFM and PMM indicated community development trajectories were following typical early successional processes of boreal forests of the region. Woody debris type, size, and volume application had small or no impact on vegetation development. Although FFM cover soil was more effective than PMM, further long-term research to evaluate impacts of woody debris on vegetation development would be important to affirm its use for reclamation.

Key words: boreal forest, cover soil, forest restoration, land reclamation, oil sands, plant community

Implications for Practice
- Four to five years after reclamation, plant community development can be affected more by cover soil type than by woody debris.
- Forest floor-mineral mix can be a more effective reclamation cover soil than peat-mineral mix for plant community development.
- Although woody debris had positive impacts on vegetation 2 years after reclamation in the earlier study, small or no impacts were evident after 4–5 years; this may change over time.
- Presence of early-to-late and mid-to-late seral species 4–5 years after reclamation indicates the community development trajectory can follow the typical early successional recovery process of boreal forests.

Introduction
Reclamation strategies depend on the nature of ecosystem degradation or land-use history (Hobbs & Harris 2001; Dhar et al. 2018), and the outcomes of reclamation that influence ecosystem development are often dependent on cover soil and revegetation (Macdonald et al. 2015; Dhar et al. 2018; Dhar et al. 2020a, 2020b, 2020c). Cover soil types can play significant roles in plant community development. In post-oil sands mining reclamation in Canada, the most commonly used cover soil types are peat-mineral mix (PMM) (peat to mineral soil at 3:2 to 3:4 by volume) and forest floor-mineral mix (FFM) (forest floor materials mixed with underlying mineral soil during salving at 1:1 to 1:5 ratio) (Alberta Environment and Water 2012). Historically, PMM was the most common cover soil type because of its availability; recently it is being replaced by FFM, which can provide greater plant cover, richness, and

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... and age effect, which would provide important information for debris species, size, decay class, charring, volume application, and time since reclamation (e.g., Tropek et al. 2013; Dhar et al. 2018; Luna Wolter et al. 2021).

Woody debris is a critical component of forest ecosystems and can directly contribute to plant community structure, productivity, microhabitat diversity, water retention, erosion control, nutrient and mineral cycling, energy fluxes, and soil formation (Odor et al. 2006; Brown & Naeth 2014; Pinno & Das Gupta 2018). Woody debris can influence microclimate conditions such as light, soil temperature, air humidity, and soil nutrients and protects soils against wind, light, and drought (Botting & DeLong 2009; Dhar et al. 2018). These conditions, along with wood decay rate, and plant and microbial population growth, dispersal, and colonization, can increase microhabitat variability for vascular and non-vascular plants (Crites & Dale 1998) and influence forest ecosystem development. Therefore, understanding ecological successional relationships among woody debris, soils, and plants is important for reclamation and management of disturbed landscapes.

Oil sands mining in boreal forests completely removes forest ecosystems (Audet et al. 2015; Macdonald et al. 2015; Dhar et al. 2018) and companies are mandated by the Environmental Protection and Enhancement Act (EPEA) of Alberta to reclaim disturbed ecosystems to equivalent land capability (Alberta Government 2005). Successful reclamation is influenced by activities relating to each step and how they work together (Macdonald et al. 2015; Dhar et al. 2018). During reclamation, woody materials such as snags, logs, stumps, limbs, and large branches can be spread on top of cover soils during reclamation. Using woody debris in reclamation can mimic natural ecological succession by providing conditions that could facilitate development of plant communities on the disturbed site (Botting & DeLong 2009). Mining companies have developed their own woody debris handling practices; many are based on trial and error and have been directed to erosion control without necessarily considering ecological benefits for the plant community and soil.

A few studies focused on woody debris application and its effects on ecosystem recovery after disturbance and subsequent reclamation have shown some impacts such as increased plant cover, changes in soil microbial community composition and respiration, and changes in soil chemical and physical properties (Brown & Naeth 2014; Kwak et al. 2015a, 2015b; Pinno & Das Gupta 2018). However, none of these studies quantified woody debris species, size, decay class, charring, volume application, and age effect, which would provide important information for adopting woody debris application as a viable land reclamation tool. This study was a continuation of the Brown and Naeth (2014) work to address some of those shortfalls (woody debris species, size, volume application, time since application effects) and to highlight changes that can occur in the critical 5-year period after reclamation. This study was conducted to determine ecological effects of two cover soil types (FFM and PMM) and woody debris (types, size, volume, cover) on vegetation (understory plants) and soil (nutrient availability, physical properties) 4–5 years after reclamation. Ecological impacts of woody debris on vegetation and soil properties were hypothesized to differ between cover soils with woody debris types and volume application and to provide ecological value as found in an initial study by Brown and Naeth (2014).

Methods

Study Area

The study area was located approximately 30 km north of Fort McMurray in the Athabasca Oil Sands Region of the Mixedwood Boreal Forest. Climate is continental with short, warm summers and long, cold winters. Mean annual temperature is 0.7°C, with maximum 23.7°C in July and minimum −22.5°C in January (Government of Canada 2019). Mean annual precipitation is 418 mm, 24.4% as snow. Topography is undulating plains with minor inclusions of hummocky uplands. Soils are dominated by organic Mesisols, with Fibrisols, Cryosols, and Orthic and peaty Gleysols. Upland forests are dominated by *Picea glauca* (Moench) Voss, *Populus tremuloides* Michx., and mixed stands with *Abies balsamea* (L.) Mill., *Betula papyrifera* Marsh., *Populus balsamifera* L., and *Pinus banksiana* Lamb. Wetlands are dominated by *Picea mariana* bogs and fens, with *Salix* (willow) and sedge species.

Experimental Design

The upland reclaimed site was approximately 3 ha in size; sites were cleared in 1999 and had been used as a saline sodic overburden dump until 2004. The research plots were established on a southeast-facing mid-slope of 6–11% between November 2007 and February 2008. The area was divided into two rows; each row had 18 plots with each 10 × 30 m in size. In total, 36 plots were established and half the plots had 20 cm of FFM applied over 30 cm of B and C horizon subsoil and 100 cm of clean overburden. The other half had 30 cm of PMM applied over 100 cm of clean overburden. Plots were separated by 5 m and rows by 10 m, with a 10-m buffer from the edge.

The experimental design for this study consists of two cover soils (FFM and PMM), with three woody debris treatments: no woody debris (control), woody debris from *P. mariana,* and woody debris from *P. tremuloides.* Woody debris types were selected based on abundance in surrounding, easy accessible areas. There were three replicates of each of the six treatment combinations (two cover soils × three woody debris levels), randomly assigned to the plots within each row. Rows were placed horizontally. For each cover soil type, six plots had pure
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P. mariana woody debris, six had P. tremuloides mixed woody debris, and six controls had no woody debris. P. tremuloides mixed woody debris contained approximately 70% P. tremuloides, 30% P. glauca, and traces of B. papyrifera (Brown & Naeth 2014). All debris was placed to provide maximum contact with the soil surface and debris pieces were scattered far enough apart that it was still possible to sample areas within each plot that were free of woody debris cover. Mean woody debris cover after construction was 11% for P. tremuloides mixed wood treatments and 20% for P. mariana treatments due to greater abundance of small and fine sized woody debris. Woody debris was divided into four size classes based on diameter: fine woody debris with diameter <2 cm, small woody debris with diameter 2–4.9 cm, medium woody debris with diameter 5–15 cm, large woody debris with diameter >15 cm.

Soil Sampling and Analyses
Soil was sampled with an auger in each plot 4 years after reclamation in July at 0–20 cm depth. In each woody debris plot, three soil samples were collected and composited from each of under large woody debris, under small woody debris, and in areas with no woody debris. Samples were refrigerated (4°C) until analyzed at a commercial laboratory. Available nitrogen was determined by extraction; available phosphorus and potassium by modified Kelowna extraction; available sulfate by inductively coupled plasma atomic emission spectrophotometry; total nitrogen and total carbon by dry combustion; inorganic carbon by CO$_2$ release; total organic carbon by calculation; electrical conductivity, sodium adsorption ratio, and pH in saturated paste; particle size (sand, silt, clay) by hydrometer (Carter & Gregorich 2008).

Woody Debris Cover and Volume Estimation
Woody debris volume was assessed in August 4 years after its application. Every large (>15 cm diameter) and medium (5–15 cm diameter) piece of woody debris in each plot was measured. Length was measured with a measuring tape; diameter was estimated using a caliper near both ends of each woody debris piece. Volume was calculated using Smalian’s formula for volume of a cylinder per m$^3$ as $\pi \times (\text{diameter of top end}/2)^2 + \pi \times (\text{diameter of base end}/2)^2 \times \text{length of the woody debris piece}$ and then converted to volume per hectare. For flattened woody debris pieces, the volume was reduced or halved based on field notes. Covers of all size classes of woody debris in each vegetation assessment quadrat were summed and a mean per plot was used to quantify cover application rate.

Vegetation Assessment
Vegetation was assessed in 1 m$^2$ permanent quadrats during July 2011 (4 years after reclamation) and August 2012 (5 years after reclamation). Three permanent line transects with five evenly spaced quadrats (15 quadrats per plot) were established without moving woody debris. Transects were spaced 3 m apart, with a 2-m buffer strip from edge of the plot. In each plot, seven quadrats were randomly selected from the first, third, and fifth rows for vegetation assessments 4 years after reclamation; all 15 quadrats were assessed 5 years after reclamation. Four temporary 1 m$^2$ quadrats were randomly placed in each plot 5 years after reclamation to assess woody debris size class impact on vegetation, with one quadrat for each of fine-, small-, medium-, large-size debris. Vegetation cover was visually assessed in each quadrat, by species where possible, of all growth forms (trees, shrubs, forbs, graminoids, bryophytes), woody debris types and size classes, and bare ground. Woody plant density was assessed by counting individual plants or stems in each quadrat for each tree and shrub species. In some cases where identification to the level of species was not possible, genera were used instead. Species richness and Shannon diversity (Magurran 2004) were calculated for each woody debris treatment (two cover soils × three woody debris × six plots). Woody debris overlapped by vegetation was included, thus cover could be greater than 100%. Covers less than 0.5% were recorded as trace. Only vegetation rooted inside quadrats and Fragaria (strawberry) runners were included. Species nomenclature followed Moss (1994).

Statistical Analyses
A mixed model analysis was used for soil chemical and physical properties and vegetation parameters within treatment combinations with three factors (block, cover soil, woody debris) using SAS statistical software (version 9.2, SAS Statistical Institute). Rows were treated as blocks and each plot as an experimental unit. Treatment types (cover soil, woody debris) were fixed factors and block was a random factor. Vegetation data were analyzed separately by year due to the irregular number of quadrats (year 4 = 7 per plot, year 5 = 15 per plot). When data failed assumptions for analysis of variance (ANOVA), non-parametric permutational ANOVA was performed with PERMANOVA v.1.6. Procedure entries were selected based on the PERMANOVA user guide; block was selected as a random factor, while cover soil (two levels: FFM and PMM) and woody debris type (three levels: P. tremuloides, P. mariana, and control) were selected as fixed factors. Bray–Curtis dissimilarities distance was used during analysis. Post hoc comparisons were conducted using Tukey’s test if means were significantly different with ANOVA. The Shapiro–Wilk test was used to determine if residuals of treatment combinations were normally distributed and Levene’s test to assess homogeneity of variance. Significance level for parametric and non-parametric ANOVA was $\alpha = 0.05$.

Nonmetric multidimensional scaling ordination (NMDS) was conducted to illustrate variation in plant community composition between cover soil types and among woody debris treatments. To quantify multivariate differences in species composition, a non-parametric multivariate test multi-response permutation procedure (MRPP) was used. The ordination and MRPP were conducted using the package vegan 2.4–2 (Oksanen et al. 2017) in R (R Core Team 2020). The affinity of species to particular treatment units was evaluated using indicator
species analysis using the package *indicspecies* version 1.7.5 (De Cáceres 2020).

**Results**

No significant interactions occurred between cover soils and woody debris treatments for soil or vegetation response; therefore, results of main effects are presented based on 4- and 5-year growing seasons.

**Soil Properties**

Soil texture was loam or sandy loam throughout the plots. Four years after reclamation, available nitrate and ammonium were often below detection limits (Table 1). Available phosphorus ($p < 0.001$), potassium ($p = 0.001$), C:N ratio ($p = 0.014$), and silt ($p < 0.001$) were significantly higher with FFM than PMM. Available sulfate ($p = 0.014$), inorganic carbon ($p = 0.002$), sodium adsorption ratio ($p = 0.011$), electrical conductivity ($p = 0.003$), pH ($p < 0.001$), and clay ($p < 0.001$) were significantly higher on PMM than FFM. Woody debris type, size class (large and small), or its presence or absence had no significant effects on soil properties. Available phosphorus, potassium, and sulfate were generally greater under small woody debris than large for both *Populus tremuloides* and *Picea mariana* types (data not shown).

**Plant Community Composition**

In total, 119 species were found: 5 trees, 17 shrubs, 56 forbs, 27 graminoids, 14 bryophytes; with 21 forbs, 11 graminoids, 5 shrubs, 2 trees, and 7 bryophytes in all treatments, and 17 species only in single treatments (Table S1). Species number was greatest in PMM *P. tremuloides* (82 species), followed by FFM control (77 species), PMM *P. mariana* (76 species), and FFM *P. tremuloides* (68 species). The highest numbers of species of bryophytes were on PMM *P. tremuloides* (12 species) and lowest on PMM *P. mariana* (eight species). In total, 107 native and 14 non-native species (12 in FFM, 13 in PMM) were identified (Table S1).

While plant community composition varied between FFM and PMM (MRPP: $A = 0.108, p = 0.001$), no differences were observed among woody debris types. Similarly, the NMDS ordination yielded a two-dimensional solution and explained 73.3% of total variation in the original data matrix and strong compositional separation between FFM and PMM (Fig. 1). Indicator species analysis showed more species were associated with FFM (seven) than PMM (five) (Table 2) and most were either perennial shrub, forb, or graminoid. Two non-native indicator species, *Chenopodium album* L. and *Agrostis stolonifera* L., were found only in FFM cover soil.

Although most species were early successionsals frequently found in disturbed areas, a number of early-to-late successional (shrubs: *Ribes hudsonianum* Richards, *Ribes oxyacanthoides* L., *Rosa acicularis* Lindl.; forbs: *Lathyrus ochroleucus* Hook., *Mertensia paniculata* (Ait.) G. Don, *Petasites frigidus* var. *palmatus* (Ait.) Cronq.; and most graminoids) and several mid-to-late successional (shrubs: *Arctostaphylos uva-ursi* (L.) Spreng., *Lonicera villosa* (Michx.) Schult.; forbs: *Cornus canadensis* L., *Viola adunca* Sm., Graminoid: *Oryzopsis pungens* (Torr. ex Spreng.) Dorn; moss: *Pleurozium schreberi* (Br.) Mitt.) species were found in both cover soils and woody debris types.

**Vegetation Cover, Diversity, and Density**

Four years after reclamation, forb ($p = 0.014$) and bryophyte ($p < 0.001$) covers were greater on PMM than FFM; graminoid ($p < 0.001$) and shrub ($p < 0.001$) covers were greater on FFM than PMM (Fig. 2A). Five years after reclamation, shrub ($p < 0.001$) and graminoid ($p < 0.001$) covers were greater on FFM than PMM; only bryophyte ($p < 0.001$) cover was greater on PMM than FFM (Fig. 2B). While native species cover was

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**Table 1.** Mean chemical and physical soil properties 4 years after reclamation by cover soil types ($n = 18$). Numbers are means followed by standard errors in parentheses. Different superscript letters denote significance between cover soil types at $α = 0.05$. Most available nitrate and available ammonium values were below detection limits.

| Parameter                        | Unit | Forest Floor-Mineral Mix | Peat-Mineral Mix |
|----------------------------------|------|--------------------------|------------------|
| Available nitrate                | mg/kg| BDL                      | BDL              |
| Available ammonium               | mg/kg| BDL                      | BDL              |
| Available phosphorus             | mg/kg| 35.7 (2.7)$^a$           | 14.0 (2.0)$^b$   |
| Available potassium              | mg/kg| 227.9 (33.3)$^a$         | 120.6 (10.5)$^b$ |
| Available sulfate                | mg/kg| 90.7 (34.3)$^a$          | 201.1 (25.2)$^a$ |
| C:N ratio                        |      | 33.1 (0.7)$^a$           | 31.3 (0.4)$^a$   |
| Total organic carbon             | %    | 7.34 (1.30)              | 6.62 (0.50)      |
| Total inorganic carbon           | %    | 0.29 (0.10)$^b$          | 0.76 (0.04)$^a$  |
| Total nitrogen                   | %    | 0.24 (0.04)              | 0.23 (0.02)      |
| Hydrogen ion activity            | pH   | 6.4 (0.1)$^b$            | 7.4 (0.0)$^a$    |
| Electrical conductivity          | dSm | 1.1 (0.2)$^b$            | 1.7 (0.1)$^a$    |
| Sodium adsorption ratio          |      | 0.6 (0.1)$^b$            | 1.1 (0.1)$^a$    |
| Sand                             | %    | 51.4 (1.0)               | 50.1 (0.9)       |
| Silt                             | %    | 35.7 (0.6)$^a$           | 31.5 (0.6)$^b$   |
| Clay                             | %    | 12.9 (0.6)$^b$           | 18.4 (0.4)$^a$   |
| Bulk density                     | mg/m$^3$ | 0.82 (0.06)           | 0.89 (0.04)      |
greater \((p = 0.002)\) on FFM than PMM, non-native species cover was greater \((p < 0.001)\) with PMM than FFM (Fig. 2C & D). None of the growth forms was affected by woody debris treatment except bryophytes, which exhibited significantly greater cover on the control than both \(P. mariana\) \((p = 0.002)\) and \(P. tremuloides\) \((p = 0.014)\). \(P. mariana\) woody debris had less bryophyte cover than \(P. tremuloides\) (Fig. 2A,B).

None of the growth forms showed cover soils and woody debris treatment effects on species richness, except shrubs, which were significantly greater \((p = 0.029)\) on PMM than FFM 5 years after reclamation (Fig. 3A & B). Overall species richness was slightly greater in year 5 than in year 4 in both cover soil types, being greatest for forbs followed by graminoids and shrubs. Although non-native species richness was significantly greater on FFM than PMM in year 4 \((p = 0.002)\) and year 5 \((p < 0.001)\), no woody debris effects were observed (Fig. 3C & D). Relative to year 4 non-native species richness was low in year 5 in both cover soil types with greater magnitude in FFM than PMM (Fig. 3C & D).

Plant density was significantly greater \((p = 0.041)\) on FFM than PMM 5 years after reclamation, whereas no difference was observed in year 4 (Fig. 4B). Higher woody plant density was found in year 5 in both FFM and PMM. Among the woody debris treatments \(P. mariana\) had higher plant density than \(P. tremuloides\) and controls (Fig. 4A & B). Although woody debris and cover soil types had no significant effects on species Shannon diversity, overall diversity was slightly higher in year 5 (Fig. 4C & D).

**Woody Debris Cover Volume and Size Class Effect on Vegetation**

Five years after application, total estimated woody debris cover and volume did not differ significantly between cover soils and woody debris types. Mean estimated woody debris cover and volume for \(P. mariana\) were 16.0% 59 m²/ha on PMM, and 12.9%, 45 m²/ha on FFM; for \(P. tremuloides\) 13.8%, 73 m²/ha on PMM and 10.3%, 74 m³/ha on FFM. Woody debris application rates ranged from 32.0 m³/ha on a \(P. mariana\) plot to 117.9 m³/ha on a \(P. tremuloides\) plot, and PMM had more woody debris cover and volume than FFM. Five years after reclamation, no woody debris volume and cover effects on vegetation were observed. Due to lack of sample size, no statistical analyses were conducted for woody debris size class (fine, small, medium, large) against vegetation response. We included descriptive information to show its potential impact on vegetation. Total vegetation cover was slightly greater with large woody debris than fine, small, or medium for \(P. mariana\) and \(P. tremuloides\) (data not shown). Woody plant density was slightly greater with small debris on FFM for both \(P. mariana\) and \(P. tremuloides\) and \(P. mariana\) for PMM cover soil (Fig.S1A & B).

![Figure 1. Nonmetric multidimensional scaling (NMDS) ordination of plant community by cover soil and woody debris type. FMM, forest floor-mineral mix; PMM, peat-mineral mix.](image)

![Table 2. Significant \((\alpha = 0.05)\) indicator species association by cover soil types. Stat is the association statistic and \(p\) value is the permutational test (*non-native species).](table)

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Discussion

Low nitrate and phosphorus in this study and the earlier study of Brown and Naeth (2014) were likely due to woody debris being in early-stage decomposition (Auerswald & Weigand 1996; Kuehne et al. 2008) and soil nitrogen had not likely to immobilize. Relative to Brown and Naeth (2014), the influence of woody debris application on soil chemical properties did not change 4 years after reclamation. The decrease in available nitrogen was consistent with patterns found in other studies where this change was related to reduced mineralization (Kayahara et al. 1996; Laiho & Prescott 1999; Kwak et al. 2015). When woody debris begins to decompose, it immobilizes nitrogen in the soil, which can have direct negative impacts on early plant growth. Wells and Boddy (1990) reported nitrogen immobilization occurs when saprotrophic fungi utilize soil nutrients to decompose woody debris, indicating physical breakdown of bark and small woody debris was likely occurring 4 years after application although biochemical decomposition was slow.

When comparing this study with the earlier Brown and Naeth (2014) findings from this site, shrub and bryophyte cover were higher for both cover soil and woody debris treatments, with corresponding declines in forbs and graminoids (except PMM) cover. These covers resemble those in the natural boreal forest ecosystem after recovery from natural disturbance of this region (Hart & Chen 2006). The greater cover, species richness, and diversity with woody debris in FFM than PMM support the conclusions of previous research that FFM provides better growing conditions (Mackenzie & Naeth 2010; Brown & Naeth 2014; Pinno & Das Gupta 2018; Dhar et al. 2020d). Vegetation differences between cover soil types were likely associated with seed banks in the materials, microorganisms, and favorable microsites due to woody debris (Mackenzie & Naeth 2010; Dhar et al. 2018). Mackenzie and Naeth (2010) found forest floor- and peat-mineral donor soil propagule banks contained 9,000 and 3,600 seeds/m. Some visual differences in vegetation parameters observed between the years might be due to influence of precipitation, as year 4 (106.8 mm) had less summer month (June to August) precipitation than year 5 (182.8 mm).

The presence of greater shrub cover (especially in FFM) in this study was higher than in the earlier Brown and Naeth (2014) and other studies where woody debris was not used (Pinno & Hawkes 2015; Dhar et al. 2019, 2020d). According to these studies, shrub cover was ≤5% after 5 years and ~ 10% after 15–20 years of reclamation. Greater shrub cover in FFM could be linked to better microsites created by woody debris or greater propagules in the cover soil. Adding wood debris can increase variation in microtopography and provide increased protection for seedlings from desiccation, wind, and frost damage (Vinge & Pyper 2012). Greater shrub cover can be a good indicator of reclamation success (Dhar et al. 2018) as it accelerates
forest floor development; facilitates tree establishment through snow retention; and reduces drought, temperature stress, and seeding mortality from browsing (Rowland et al. 2009). The nitrogen-fixing native shrub *Shepherdia canadensis* ((L.) Nutt.) was found in most reclamation treatments, which can be another indication of reclamation progression. This shrub can increase soil nitrogen pools and organic matter (Mummey et al. 2002), which could improve soil chemical and biological properties of reclaimed sites (Rowland et al. 2009).

Compared to the initial post-reclamation findings of Brown and Naeth (2014), our study showed that non-native species cover had declined in both soil cover types (FFM: 10.4–4.2% and PMM: 15.2–5.9%). Other studies also reported a non-native species decline with time (Pinno & Hawkes 2015; Dhar et al. 2019, 2020a, 2020b). This decline indicates other conditions may influence the probability that the native plant community could exclude all or most non-native species as succession progresses. The presence of non-native species in disturbed ecosystems is often problematic as they could alter community composition, biodiversity, and nutrient cycling (MacDougall & Wilson 2011), requiring monitoring of potential long-term impacts of non-native species on reclaimed ecosystems.

The successional groups to which the species belong can influence the successional trajectory of reclamation sites (Dhar et al. 2018). Brown and Naeth (2014) could not find any mid-to-late successional species 2 years after reclamation at these sites. In our study, many species found on the sites were early-to-late successional upland forests species or mid-to-late successional species; most of the indicator species were perennial forbs or shrubs. Their presence in year 5 following reclamation indicates the trajectory of community development follows the typical early successional pattern or recovery process of boreal forests (from ruderal and annual to perennial communities) (Lieffers et al. 1999; Hart & Chen 2006).

Presence of late seral bryophytes *Pleurozium schreberi* (Brid.) Mitt., *Pohlia nutans* (Hedw.) Lindb., *Polytrichum juniperinum* Hedw., and *Pylaisiella polyantha* (Hedw.) Grout in our study also suggests successional progression (Shaughnessy 2010; Dhar et al. 2018; USDA Forest Service 2021).

Depending on treatment and year, woody debris cover was 10–16% in the study area and showed minimal effects on the plant community and soil, although Brown and Naeth (2014) found a significant positive relationship between woody plant density and woody debris cover 2 years after reclamation. Similarly, other studies suggested application rates of 10–25%
(Vinge & Pyper 2012) or <30% (Pinno & Das Gupta 2018) can be useful for maintaining native plant species diversity and abundance. In this study, application rate of woody debris was wider (32.0 to 117.9 m$^3$/ha) in range than those recommended by Vinge and Pyper (2012) (60–100 m$^3$/ha) and showed little or no evidence of woody debris impact on vegetation. The findings of this study contradict other previous studies, which suggest woody debris plays an important role in plant community development on reclaimed areas in the boreal forest (Vinge & Pyper 2012; Brown & Naeth 2014; Pinno & Das Gupta 2018). The difference might be due to the negative effects of nutrient immobilization or the benefits of woody debris may only apply in the very short term (Brown & Naeth 2014). Considering the lifespan of a boreal forest, 5 years post-treatment is short to make an accurate conclusion about woody debris implication on reclamation success. Boreal forest woody debris could be important later when nitrogen is no longer immobilized; therefore longer-term research to evaluate impacts of woody debris in mid-to-late stages of decay would be important to affirm its use for reclamation.

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LITERATURE CITED
Alberta Environment and Water (2012) Best management practices for conservation of reclamation materials in the mineable oil sands region of Alberta. Her Majesty the Queen in Right of the Province of Alberta, Edmonton, Alberta, Canada
Alberta Government. (2005) Government of Alberta mineable oil sands strategy. Available from https://open.alberta.ca/dataset/56e72a34-7d20-46b4-97da-073c525fcbb/resource/cc203ce6-10c3-4b6c-bcd0-67fa9643c75b/download/a9r92b-goa-mineable-oil-sands-strategy-for-discussion.pdf. (accessed 12 Jun 2021)
Audet P, Pinno BD, Thiffault E (2015) Reclamation of boreal forest after oil sands mining: anticipating novel challenges in novel environments. Canadian Journal of Forest Research 45:364–371
Auerswald K, Weigand S (1996) Ecological impact of dead-wood hedges; release of dissolved phosphorus and organic matter into runoff. Ecological Engineering 7:183–189
Botting RS, DeLong C (2009) Macro-lichen and bryophyte responses to woody debris characteristics in sub-boreal spruce forest. Forest Ecology and Management 258S:85–94
Brown RL, Naeth MA (2014) Woody debris amendment enhances reclamation after oil sands mining in Alberta, Canada. Restoration Ecology 22:40–48
Carter MR, Gregorich EG (2008) Pages 1–224. Soil sampling and methods of analysis. 2nd edition. Canadian Society of Soil Science. Taylor & Francis Group, Boca Raton, Florida

Figure 4. (A–D) Mean woody plant density and Shannon diversity 4 and 5 years after reclamation by cover soil and woody debris types. Bars illustrate mean (±SE). FFM, forest floor-mineral mix; PMM, peat-mineral mix.
Kuehne C, Donath C, Muller-Using SI, Bartsch N (2008) Nutrient
Hart SA, Chen HYH (2006) Understory vegetation dynamics of North American
Hobbs RJ, Harris JA (2001) Restoration ecology: repairing the earth
Laiho R, Prescott CE (1999) The contribution of coarse woody debris to carbon,
Kwak JH, Chang SX, Naeth MA, Vassov R (2018) Plant community development following reclamation of oil sands mine sites in the boreal forest: a review. Environmental Reviews 26:286–298
Dhar A, Comeau PG, Karst J, Pinno B, Chang S, Naeth MA, Vassov R, Bamfylde C (2020) Plant community development following reclamation of oil sands mine sites in northern Alberta. Restoration Ecology 28:82–92
Dhar A, Comeau PG, Naeth MA, Pinno B, Vassov R (2020a) Plant community development following reclamation of oil sands mines using four cover soil types in northern Alberta. Restoration Ecology
Dhar A, Comeau PG, Naeth MA, Vassov R (2020d) Early boreal forest under-
Dhar A, Naeth AM, Jennings PD, Gamal El-Din M (2020b) Perspectives on envi-
Dhar A, Naeth AM, Jennings PD, Gamal El-Din M (2020c) Geothermal energy resources: potential environmental impact and land reclamation. Environmental Reviews 7:415–427
Government of Canada (2019) Canadian climate normals 1981–2010 station data. http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnName&txtStationName=Fort+McMurray&stnID=2982124&dispBack=1 (accessed 02 Mar 2020)
Hart SA, Chen HYH (2006) Understory vegetation dynamics of North American boreal forests. Critical Reviews in Plant Sciences 25:381–397
Hobbs RJ, Harris JA (2001) Restoration ecology: repairing the earth’s ecosys-
tems in the new millennium. Restoration Ecology 9:239–246
Kawahara GI, Klinka K, Lavkulich LM (1996) Effects of decaying wood on elu-
viation, podzolization, acidification, and nutrition in soils with different moisture regimes. Environmental Monitoring Assessment 39:485–492
Kuehne C, Donath C, Muller-Using SI, Bartsch N (2008) Nutrient fluxes via leaching from coarse woody debris in a Fagus sylvatica forest in Solling Mountains, Germany. Canadian Journal of Forest Research 38:2405–2413
Kwak JH, Chang SX, Naeth MA, Schaaf W (2015a) Coarse woody debris increases microbial community functional diversity but not enzyme activities in reclaimed oil sands soils. PLoS One 10:e0143857
Kwak JH, Chang SX, Naeth MA, Schaaf W (2015b) Coarse woody debris extract decreases nitrogen availability in two reclaimed soils in Canada. Ecological Engineering 84:13–21
Laiho R, Prescott CE (1999) The contribution of coarse woody debris to carbon, nitrogen, and phosphorus cycles in three Rocky Mountain coniferous for-
esta. Canadian Journal of Forest Research 29:1592–1603
Lieffers, VJ, Messier, C, Gendron, F, Stadl, KJ & Comeau, P (1999) Predicting and managing light in the understory of boreal forests. Canadian Journal of Forest Research, 29:796–811.
Luna Wolter G, Dhar A, Naeth MA (2021) Response of three native grass species on mature fine tailings reclamation substrate amended with petroleum coke. Journal of Environmental Quality, 50:384–395
Macdonald SE, Snively AEK, Fair JM, Landhauser SM (2015) Early trajectories of forest understory development on reclamation sites: influence of forest floor placement and a cover crop. Restoration Ecology 23:698–706
MacDougall AS, Wilson SD (2011) The invasive grass Agropyron cristatum dou-
bles belowground productivity but not soil carbon. Ecology 92:657–664
Mackenzie DD, Naeth MA (2010) The role of the forest soil propagule bank in assisted natural recovery after oil sands mining. Restoration Ecology 18:418–427
Mackenzie MD, Quideau SA (2012) Laboratory-based nitrogen mineralization and biogeochemistry of two soils used in oil sands reclamation. Canadian Journal of Soil Science 92:131–142
Magurran AE (2004) Measuring biological diversity. Blackwell Publishing, Malden, Maryland
Moss EH (1994) Flora of Alberta: a manual of flowering plants, conifers, ferns and fern allies found growing without cultivation in the province of Alberta, Canada. University of Toronto Press, Toronto, Ontario, Canada
Mummey DL, Stahl PD, Buyer JS (2002) Soil microbiological properties 20 years after surface mine reclamation: spatial analysis of reclaimed and undisturbed sites. Soil Biology and Biochemistry 34:1717–1725
Öder P, Heilmann-Clausen J, Christensen M, Aule E, van Dort KW, Pikavera A, et al. (2006) Diversity of dead wood inhabiting fungi and bryophytes in semi-natural beech forests in Europe. Biological Conservation 131:58–71
Oksanen J, Blanchet FG, Friendly M, Kindt R, Legendre P, McGlinn D, et al. (2017) Vegan: community ecology package. R package version 2.5–6. https://cran.r-project.org/web/packages/vegan/index.html (accessed 16 Oct 2020)
Pinno BD, Das Gupta S (2018) Coarse woody debris as a land reclamation amendment at an oil sands mining operation in boreal Alberta, Canada. Sustainability 10:1640
Pinno BD, Hawkes VC (2015) Temporal trends of ecosystem development on different site types in reclaimed boreal forests. Forests 6:2109–2124
R Core Team (2020) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www. Rproject.org/
Rowland SM, Prescott CE, GreySton SJ, Quideau SA, Bradford G (2009) Recru-
ating a functioning forest soil in reclaimed oil sands in northern Alberta: an approach for measuring success in ecological restoration. Journal of Envi-
rmental Quality 38:1580–1590
Shaughnessy BE (2010) Natural recovery of upland boreal Forest vegetation on a hummocky peat-marl mix substrate in the Athabasca oil sands region, Alberta. MSc Thesis, University of Alberta, Edmonton, Alberta, Canada
Tropek R, Hejda M, Kadlec T, Spitzer L (2013) Local and landscape factors affect-
ing communities of plants and diurnal Lepidoptera in black coal spoil heaps: implications for restoration management. Ecological Engineering 57:252–260
USDA Forest Service (2021) Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sci-
ences Laboratory. https://www.fs.fed.us/database/feis/plants/bryophyte/polyum/all.html (accessed 16 Mar 2021)
Vinge T, Pyper M (2012) Managing woody materials on industrial sites: meeting economic, ecological and forest health goals through a collaborative approach. Alberta School of Forest Science and Management, Edmonton, Alberta, Canada
Wells JM, Boddy L (1990) Woody decay, and phosphorus and fungal biomass allocation, in mycelial cord systems. New Phytology 116:285–295

Supporting Information
The following information may be found in the online version of this article:
Table S1. Plant species by soil cover and woody debris types (presence + absence – asterisk (*) non-native species.
Figure S1. Mean woody plant density in (A) forest floor-mineral mix (FFM) and (B) peat-mineral mix (PMM) by woody debris size class.

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