Forest Ecology and Management 585 (2025) 122621

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Mechanical site preparation and use of non-invasive cover crops influences early-successional forest vegetation composition of a reclaimed airstrip in the Boreal Forest

Nicholas Harper [a], Amanda L. Schoonmaker [a,*], Andrés G. Rolhauser [a], Mark Baah-Acheamfour [a], Ann Smreciu [b], Erin C. Fraser-Reid [a]

[a] Centre for Boreal Research, Northern Alberta Institute of Technology, 8102 99 Avenue, Peace River, AB T8S1R2, Canada
[b] Wild Rose Consulting Inc, 15109 77 Avenue NW, Edmonton, AB T5R 3B5, Canada

ARTICLE INFO

Keywords:
Arrested succession
Forest succession
Land reclamation
Non-invasive cover crop
Soil decompaction
Surface ruggedness

ABSTRACT

Rebuilding native forest ecosystems after industrial disturbance is key to sustainable resource development. However, self-sustaining forests do not always result from current reclamation practices, mostly due to grass-driven arrested succession. Here we assessed the interactive effects of soil treatment and cover cropping on forest succession in a recently reclaimed airstrip in western Canada. Three surface soil treatment techniques were applied in five block replicates following asphalt removal, soil decompaction, site recontouring and topsoil placement with dozers: no surface treatment (smooth), discing with agricultural disc harrows (disc), or plowing with a RipPlow™ (plow). Within each soil treatment, subplots were then either seeded with *Secale cereale* (fall rye), a non-invasive annual grass, or left without a cover crop. In the first 5 years after treatment, soil treatment had a much greater impact on the vegetation than cover cropping. Plowing favored tree growth while both plowing and discing treatments supported natural regeneration of seed-banking shrub species and native forb cover when compared to the smooth treatment. The smooth treatment favored grass species (mostly non-native), presumably by allowing them to spread horizontally though it also encouraged higher rates of establishment of wind-dispersed *Salix* species. In general, the discing soil treatment had intermediate effects on tree growth and vegetation community composition. *Secale cereale* suppressed non-native weeds during the early stages and disappeared towards the end of the experiment, without hindering the establishment of desirable woody species. We conclude that increasing soil surface variability through the plow treatment tested in the present investigation, and potentially aided by the addition of a non-invasive cover crop, represent a combination of reclamation strategies to promote forest development in heavily disturbed industrial sites.

1. Introduction

The boreal forest, constituting 33 % of the world's forest cover, holds significant ecological importance. These forests are rich in biodiversity, serve as critical habitat for birds and other wildlife, and contribute to essential global functions such as carbon sequestration, air purification, and water filtration. Canada is home to over one quarter of the world's boreal forests, and this forest type comprises 75 % of Canada's forests and woodlands (Natural Resources Canada, 2020). Many communities across northern Canada rely on these forests for the values and products they provide, including employment with forestry, oil, gas, and mineral extraction companies, subsistence from hunting, trapping, and gathering (Johnson and Miyanishi, 2012; Brandt et al., 2013), clean water sources, and the ability to take part in forest-based recreational, spiritual, or cultural activities. Disturbing the forest landscape to access these resources is a necessary part of development, but restoring these lands to a condition similar to that which existed pre-disturbance – typically a self-sustaining native forest ecosystem – is equally important from both regulatory and social perspectives. The extraction of non-renewable resources commonly leads to soil compaction, which, if untreated, negatively impacts tree growth by hindering root development and reducing soil permeability (Cambi et al., 2014; Wronski and Murphy, 1994). As a result, soil decompaction treatments such as soil ripping or tilling are often the first step in the post-disturbance land

* Corresponding author.
E-mail address: aschoonmaker@nait.ca (A.L. Schoonmaker).

https://doi.org/10.1016/j.foreco.2025.122621
Received 20 January 2025; Received in revised form 2 March 2025; Accepted 3 March 2025
Available online 12 March 2025

reclamation process. Following decompaction, traditional soil handling includes recontouring to integrate the site with the surrounding landscape and the surface placement of stockpiled subsoil and topsoil, often achieving a "smooth" soil condition (Environment and Sustainable Resource Development, 2013). Given the importance of soil properties in vegetation recovery, understanding how reclamation practices affect soil characteristics is crucial for improving reclamation outcomes.

In Alberta, as in many other regions, restoring industrially disturbed forested land after soil decompaction and topsoil placement is focused on two main challenges: the establishment of native woody vegetation and the effective management of invasive weeds (Environment and Sustainable Resource Development, 2013). The typical reclamation practice of soil ripping followed by smooth surface soil placement has been shown to limit surface heterogeneity and increase bulk density, therefore limiting tree establishment and growth (Schott et al., 2014; McConkey et al., 2012). Intensive mechanical site preparation approaches, such as deep ripping, offer an alternative by creating rough surfaces and diverse microsites, alleviating decompaction, and fostering natural regeneration and early establishment of woody species (Blackwell et al., 2016). Furthermore, the deep cavities and voids created by intensive site preparation can contribute to the continued decompaction of soils for years following treatment due to freeze-thaw cycles (McNabb and Startsev, 2022; McNabb, 1994). While these studies illustrate positive effects for individual species, the broader impacts of different mechanical site preparation tools on plant community composition, diversity, and the establishment of multiple woody species in land reclamation remains poorly understood.

Typical weed management for reclamation currently relies heavily on the application of chemical herbicides. However, the widespread use of these chemicals faces opposition from the public in some areas due to their environmental impacts, which is leading some reclamation practitioners to explore alternative methods to manage invasive weeds. Cover crops can be helpful tools in weed management because they occupy space and outcompete weeds and may also improve the micro habitat for woody plant establishment (Macdonald et al., 2015). However, grass cover crops can have serious drawbacks when aggressive and persistent species are selected and applied at too high of application rates (Franklin et al., 2012). In fact, historical utilization of perennial non-native grass as cover crops has likely contributed to a state of arrested succession in many legacy industrial well sites throughout northern Alberta (Lupardus et al., 2019; Baah-Acheamfour et al., 2022). Arrested succession is the long-term stagnation of ecosystem recovery, preventing progression beyond an early seral stage. It is therefore critical to have a deep understanding of species characteristics to select an appropriate cover crop for the desired forest plant community (Macdonald et al., 2015; Snively, 2014). Short-lived annual cover crops may be preferred since they would only occupy the soil surface during the first year of the successional process, when sites are most vulnerable to plant invasions. However, there is currently limited information regarding both the efficacy of these short-lived cover crops as well as the longer-term influence they may have in shaping the native forest plant community in land reclamation sites.

In the present investigation the interactive role of two alternative reclamation practices, to support forest recovery after severe industrial disturbances were compared. More specifically, we assessed the impact of cover cropping in combination with a range of mechanical soil treatment intensities on a severely disturbed site, a decommissioned airstrip in northern Alberta, using a 5-year survey. We compare three mechanical soil treatments with varying levels of soil disturbance: (1) plowing, which creates deep furrows and significant surface variability; (2) discing, which provides moderate disturbance by breaking up the soil surface; and (3) a smooth treatment, which results in minimal surface variation and represents standard reclamation practices. These treatments will be evaluated with respect to their ability to support establishment and growth of native forest vegetation. In this study we addressed the following questions: (1) How does the type of mechanical site preparation affect the establishment of woody species? We hypothesized that treatments which maximize decompaction will support increased growth of tree and shrub species. (2) How does mechanical site preparation affect the establishment of spontaneous desirable (native shrubs and trees) and undesirable (non-native grasses) vegetation? We hypothesize that mechanical treatments which result in greater surface variability will correspond with increased diversity of plant species, both desirable and undesirable. (3) How does fall rye (*Secale cereale*), an annual grass cover crop, influence the establishment of desirable species? H3: We hypothesized that while the cover crop may initially suppress desirable species due to competition. H4: However, due to the short-life cycle of this species, these effects will be reduced over time (i.e., by the end of our study).

2. Methods

2.1. Study site description and operational reclamation activities

This study was conducted on a decommissioned airstrip located approximately 30 km northeast of Peace River, Alberta (lat. 56° 23.792′ N, long. 116 52.887 W). The airstrip was an 18-ha area that was stripped, graded, and paved in the 1980s and was regularly used to fly in personnel of Canadian Natural Resources Ltd. (CNRL). The area is within the dry mixed-wood sub-region of the boreal forest natural region of Alberta (Natural Regions Committee, 2006). The mean (30-yr) annual precipitation was 386 mm at the time of the study (ECCC, 2015). The daily average temperature is −14.9 °C in January and 16.3 °C in July (ECCC, n.d.). Dark Gray Chernozemic soils (Soil Classification Working Group, 1998) were dominant in the area with undulating glacial till and hummocky uplands. The remnant forests surrounding the airstrip are dominated by two tree species, *Populus tremuloides* Michx. (trembling aspen) and *Picea glauca* Moench Voss (white spruce), with some *Populus balsamifera* L. (balsam poplar), and *Betula papyrifera* Marsh (paper birch). The natural forest understory vegetation contained a diverse array of shrubs with the most common including *Symphoricarpos albus* L. (snowberry), *Rubus idaeus* L. (common raspberry), *Rosa acicularis* Lindl. (prickly rose), *Shepherdia canadensis* L. (Canada buffaloberry), *Viburnum edule* Michx. Raf. (low-bush cranberry) and *Salix spp*. L. (willows) intermixed with a variety of herbaceous species some of which included: *Elymus innovatus* Beal. (hairy wild rye), *Cornus canadensis* L. (bunchberry), *Eurybia conspicua* Nesom (showy aster), *Symphyotrichum ciliolatum* Love & Love (Lindley's Aster), *Solidago altissima* L. (goldenrod) and *Chamaenerion angustifolium* L. Scopoli (fireweed).

In 2012, decommissioning and reclamation activities were initiated with the removal of the airstrip and asphalt. Reconstruction of the landform was initiated in June 2014 and completed in July 2014 where the entire site was regraded to align with the surrounding landscape. As the soil underlying the asphalt was severely compacted, significant effort was put into alleviating site-wide compaction prior to placement of topsoil. The entire upland area was first deep ripped with straight ripper shanks attached to a dozer in the north-south and east-west directions. Following this, a pair of deep ripping plows (RipPlows™, McNabb et al., 2012; McNabb and Startsev, 2022) were employed in lapping passes in the north-south direction to provide more extensive soil decompaction. Finally, the soil surface was disced with a tractor and then lightly bladed with a dozer to create a smooth soil surface prior to topsoil placement. Stockpiled topsoil (forest floor and A horizon), which had been conserved during site construction in the 1970s, was trucked from an adjacent location, dumped in piles and spread with a dozer blade to a target placement depth of 10–15 cm.

2.2. Experimental design

The research was situated within a 6-ha section of the reclaimed airstrip footprint where 15 replicate soil treatment strips were divided into five blocks across this area with 3 strips located within each block where each soil treatment strip was approximately 35 × 125 m in size (Fig. 1). The experiment employed a split-plot design, with mechanical soil treatment deployed at the plot level (strip) and cover crop at split-plot level. Soil treatments, which were implemented following the operational reclamation activities described previously, included: (i) Smooth, this was the baseline or control condition where no further mechanical treatments were implemented beyond topsoil placement with dozers. (ii) Disc, where the surface topsoil was disced with a tractor-pulled agriculture disc attachment in late July 2014. This created a rougher soil surface compared with the baseline condition, but less extreme than in the plow treatment. (iii) Plow – in November 2014, following freezing of the upper 7–15 cm of soil, a dozer with two Rip-Plow™ attachments was employed using lapping passes to create a highly heterogeneous soil surface. This treatment resulted in the roughest soil surface relative to the Disc and Smooth treatments.

Each of the 125 m x 35 m soil treatment strips were further subdivided into equal-sized (25 ×35 m) cover crop subplots (Fig. 1b). Originally these subplots contained five unique seeding treatments representing native forbs and grasses as well as a short-term non-native grass, *Secale cereale* (hand-seeded in April 2015 at a rate of 25 kg ha^{-1}). However, the native vegetation did not emerge to a sufficient degree to be detectable above background levels (Supplemental Information, Table S1, Figure S1). More importantly, it was not influential in shifting the vegetation community due to low rates of emergence, therefore the cover cropping treatment level was simplified to represent two levels: no cover crop treatment or *Secale cereale* treatment. In each soil treatment strip, cover crop treatment subplots were randomly assigned where three received no treatment and two received the cover crop treatment (Fig. 1b provides an example though randomization was unique to individual soil treatment strips).

The entire experimental area was planted with several native tree and shrub species at the following densities: four tree species *Pinus banksiana* (jack pine) at 500 stems ha^{-1}, *Picea glauca* at 1000 stems ha^{-1}, *Populus balsamifera* unrooted stem cuttings [0.5–1.0 cm diameter x 50 cm length] at 500 stems ha^{-1}, *Populus tremuloides* at 1200 stems ha^{-1} and four shrub species *Alnus alnobetula* Ehrhark K Kock (green alder) at 200 stems ha^{-1}, *Cornus sericea* L. (red-osier dogwood) at 250 stems ha^{-1}, *Salix bebbiana.* (Bebb's willow) at 500 stems ha^{-1}, and *Shepherdia canadensis* at 50 stems ha^{-1}, were planted in each treatment combination in May of 2015 with the exception of *Picea glauca* which was summer planted in early August 2015. The target densities varied according to species type but remained constant for each species across the experimental site; the total effective density of trees and shrubs was 4200 stems ha^{-1}. All seedlings had been produced at a commercial nursery in the region with seed from local provenances; spring planted seedlings were grown in 2014 and overwintered in cold-storage prior to planting while summer planted seedlings were grown in 2015 and hot-lifted prior to planting.

2.3. Vegetation surveys

Vegetation surveys were conducted annually from late July through early August for five growing seasons (2015–2019). Within each 25 m x 35 m cover crop sub-plot, vegetation was assessed at seven points, five points along a transect running from the southeast to the northwest corner, and two additional points on each side of the midpoint (randomly selected by tossing a quadrat into the general area) (Fig. 1b). While this was the general approach taken to surveys, we would like to highlight that individual point locations were not marked, therefore somewhat different survey point locations were assessed each year. Functionally, there was a minimum distance of 7 m between individual survey point centers.

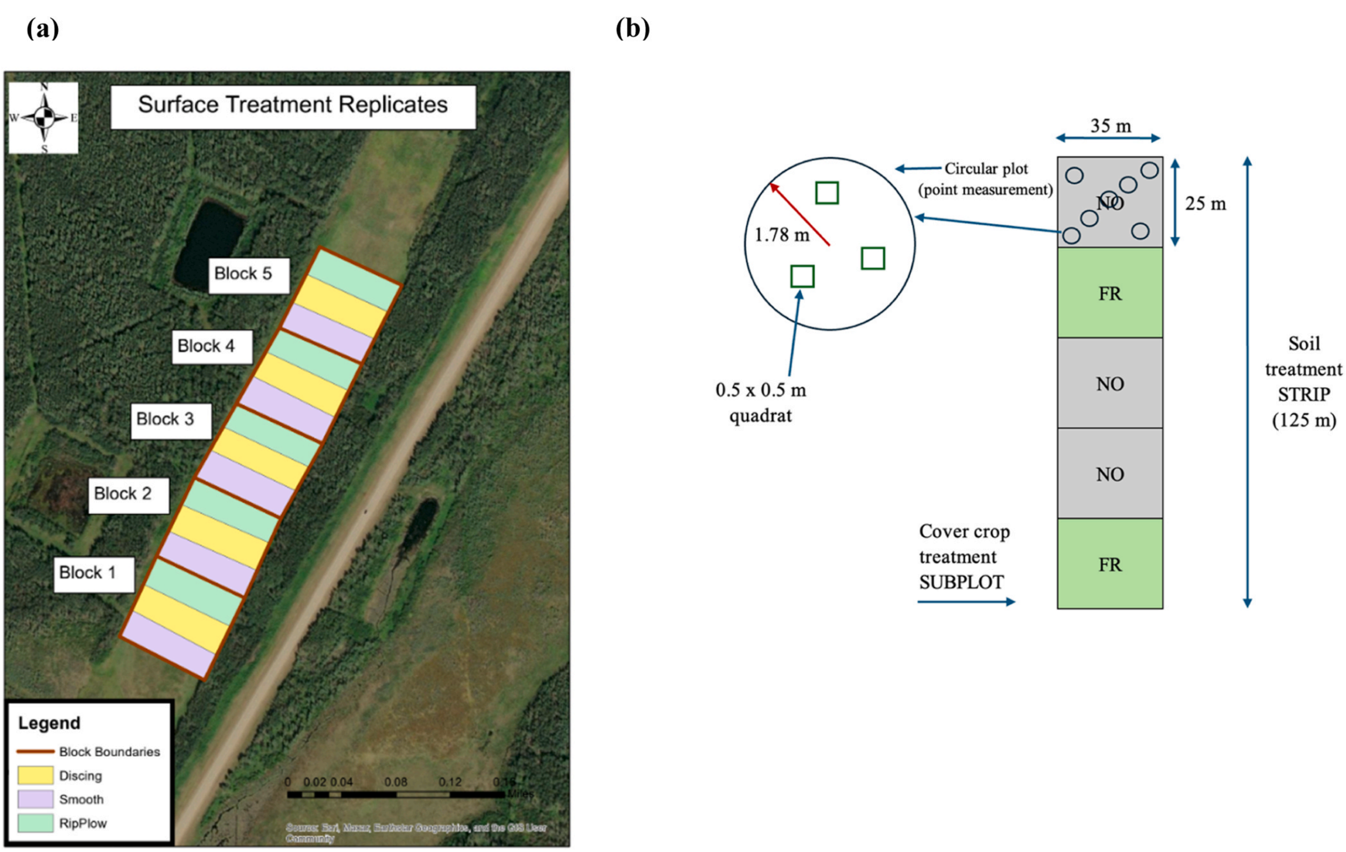

Fig. 1. (a) Aerial view of the airstrip study site, with differing colours representing block replicates with individual soil treatment strips. (b) diagrammatic example of experimental units and measurement units within a single soil treatment strip where FR = fall rye and No = no cover crop. Note this diagram is not to scale and is intended for illustration purposes only. Sampling points were conducted within 1.78 m radius circular plots (10 m^2).

At each survey point, a 1.78 m radius circular plot (10 m^2) was delineated and all tree and shrub species tallied. The height of the tallest individual of each tree and shrub species were recorded from year 2 to 5 in each plot. Lastly, three 0.5 m x 0.5 m quadrats were randomly thrown at each plot (Fig. 1b) where all vascular plant species observed within the quadrat were recorded with a visual estimate of the % of ground area covered by each species < 1.5 m in height. As this was relatively new reclamation, there was limited development of bryophytes and lichens at this early stage of succession therefore we did not assess these groups at that time.

2.4. Soil sampling and ground surface characterization

Both soil surface elevations and soil bulk density were collected across the study site to capture environmental differences amongst soil treatments and across time. Soils were sampled in the first and fifth growing seasons (2015 and 2019) for mean and maximum soil bulk density in five soil pits (one per cover crop plot) along the diagonal of each replicate soil treatment strip. Soil samples were collected from three depths in the mineral soil (0–5, 10–15, and 25–30 cm), by inserting three metal rings of 106 cm^3 into the ground. Soil samples were oven-dried at 105 ºC to constant mass and weighed. The bulk density of the soil was then calculated by dividing dry weight by metal ring volume.

In the first and third years of the investigation (2015 and 2017), surface elevation estimates were taken in each of the 15 soil treatment strips at 0.75 m intervals in a diagonal line from southeast to northwest with a Spectra precision laser (Model LL300, Spectra Precision, Dayton, OH). The difference in elevation between adjacent measurements was utilized to develop an estimate of surface ruggedness. This is a simple, linearized version of the Terrain Ruggedness Index developed for large-scale land surface analyses, which is calculated from gridded elevation maps (Riley et al., 1999).

2.5. Statistical analyses

Data was analyzed using R statistical software (R Core Team, 2024). Generalized linear mixed-effects models (GLMM) were employed and fitted using the function glmmTMB in the R package glmmTMB (Brooks et al., 2017). The distribution utilized for each response was modified based on the structure and best fit solution for each model. Total vegetation cover was fit with a Gamma distribution, relative cover (proportion of total vegetation cover by group) was fitted with an ordered beta regression (*ordbeta*, Kubinec, 2022) to allow inclusion of [0, 1] in the proportion, stem counts were fitted with a generalized Poisson distribution (Consul and Famoye, 1992) except where overdispersion was present in which case a negative binomial distribution was utilized (*nbinom2*, quadratic parameterization from Hardin and Hilbe, 2018), tree and shrub heights and site elevations were fitted with a Gamma distribution and soil bulk density with a gaussian distribution.

Fixed effects in these models included the year of measurement, cover crop treatment and soil treatment, all of them as categorical variables. The structure of random effects was hierarchical as cover crop treatment subplots (25 ×35 m) were spatially nested within soil treatment strips, and these were nested within replicate blocks. For vegetation responses (counts, heights, cover / relative cover), a model selection approach was employed to reduce the complexity of a model that could potentially include 3-way interactions between year X cover crop treatment X soil treatment. For this process, a 3-way interaction model was fit to the data and the function *dredge* was utilized to generate a list of all possible model combinations (R package MuMIn, Barton, 2024). For the present study, we utilized the model that contained at least one fixed effect and resulted in the lowest AICc; the final models that were derived from this process are presented in Table 1. For surface elevations, a two-way factorial model including year X soil treatment. Random effects for this model were the replicate blocks. Soil bulk density was evaluated with a 3-factor model that included year X soil treatment X soil depth with nested random effects that included soil sampling pit, within a soil treatment strip, within a replicate block.

Table 1
Summary of final best-fit models utilized for tree and shrub stem counts, heights and vegetation cover and relative abundance. In some cases, to meet assumptions, a dispersion parameter was added to allow for unequal variance by factor level.

Response parameter	Dispersion Parameter	Final model
Stem count		
Conifers	Year	y ~ year + soil treatment
Deciduous trees	Year	y ~ year
Shrubs	Year X Soil treatment	y ~ year X soil treatment
White spruce	Year	y ~ year X soil treatment
Alder	-	y ~ soil treatment
Lodgepole pine	-	y ~ year + soil treatment + cover crop
Balsam poplar	-	y ~ year + cover crop
Aspen	Year	y ~ year
Raspberry	Year	y ~ year X soil treatment
Willows	Year X Soil treatment	y ~ year X soil treatment
Heights		
White spruce	Year X Soil treatment	y ~ year X soil treatment
Alder	-	y ~ year
Lodgepole pine	Year	y ~ year X soil treatment
Balsam poplar	-	y ~ year
Aspen	Year	y ~ year X soil treatment + year X cover crop treatment + soil X cover crop treatment
Raspberry	Year X Soil treatment	y ~ year + soil treatment
Willows	Year	y ~ year X soil treatment + cover crop treatment
Total plant cover and Relative cover		
Total cover	Year X Soil treatment	y ~ year X soil treatment
Grasses	-	y ~ year X soil treatment + year X cover crop treatment
Native forbs	Year	y ~ year X soil treatment
Woody species	Year	y ~ year + soil treatment
Non-native forbs	Year X Cover crop treatment	y ~ year X cover crop treatment

To better fit the data, vegetation cover and relative abundance variables were averaged to a single value per 25 m x 35 m subplot (i.e., averaging over 21 quadrat-based measurements). For tree and shrub heights, we took the average of a single cover crop level (fall rye vs no cover crop) per soil treatment strip replicate to better meet model assumptions. For surface elevations we averaged up to a single value per soil treatment strip. Model assumptions were assessed with diagnostic plots of fitted and residual values and histogram of residuals of the DHARMa package (Hartig, 2022). In some instances, models were refitted to allow for unequal variance by fixed-effects factors to better meet model assumptions (Table 1 summarizes models where this occurred, *dispformula*). When significant ($\alpha<0.05$) effects were detected in linear models, treatments were separated with post-hoc Sidak pairwise comparisons using the emmeans function (Lenth, 2022). Graphical presentation of results was focused on fixed effects with significant effects.

Multivariate techniques were used to examine the relationships between plant-group composition and treatments. For this, we classified species into nine groups: native forbs, nonnative forbs, native grasses, nonnative grasses, sedges, horsetails, tall shrubs (alders and willows), small shrubs (all remaining shrubs), and trees. Data across plant groups were transformed using Hellinger standardization (i.e. the square root of relative abundance), a widely applied method for community composition data that reduces the influence of highly abundant species while maintaining ecological relationships (Borcard et al., 2018). Differences in plant-group composition among years and among treatments in the final year (2019) were visualized using Principal Coordinates Analysis (PCoA) based on Bray-Curtis dissimilarity. PCoA was chosen over Non-metric Multidimensional Scaling (NMDS), which is often recommended in ecological applications (Borcard et al., 2018) because, among other properties, it provides an explicit measure of variance explained by each axis, facilitating interpretation (although NMDS yielded quantitatively similar results). PCoA was implemented using the function capscale in the R package vegan (Oksanen et al., 2024). Function capscale can handle non-Euclidean distances, such as Bray-Curtis, and rescales eigenvalues to ensure they are non-negative, an important feature for accurately calculating the proportion of variance explained by each axis. To examine treatment effects on plant-group composition within the final year (2019), Permutational Multivariate Analysis of Variance (PERMANOVA) was performed based on Bray-Curtis dissimilarity. Soil treatment, cover crop treatment, and their interaction were included as predictors. The analysis was conducted using the function adonis2 in the R package vegan. The permutation structure (99,999 permutations) accounted for the hierarchical nature of the experimental design by restricting permutations within blocks (for soil treatments) and plots (for cover crop treatments). These restrictions were implemented using the function how in the R package permute (Simpson, 2022). Finally, pairwise PERMANOVA comparisons were conducted to identify significant differences between levels of factors showing significant effects in the main PERMANOVA. To control for multiple comparisons, *p*-values were adjusted using the Benjamini-Hochberg procedure, and *R*-squared values were extracted to quantify effect sizes.

3. Results

3.1. Soil responses

Mean bulk density was strongly dependent on both year and depth of measurement, and to a lesser degree on the interaction between soil treatment and depth (Table 2). Specifically, mean bulk density increased with depth and decreased from years 1–5, while the interaction meant that the plow treatment decreased bulk density only at the intermediate depth, between 10 and 15 cm (Table 3a). In general, soil surface ruggedness (change in elevation) was higher in the plow treatment than in the disc treatment, and higher in the disc treatment than in the smooth treatment (Table 3b), while the interaction meant that year differences were only seen in the plow treatment, where the elevational difference in year 1 was 10.5 cm but dropped to 7.3 cm in year 3 (Table 3b).

Table 2
Analysis of variance table for mean bulk density in a three-factor mixed effects statistical model output where factor 1 was year of measurements (year), factor 2 was surface soil treatment and factor 3 was soil depth. Elevation differences were evaluated as a two-factor mixed effects statistical model output where factor 1 was year of measurements (year) and factor 2 was surface soil treatment.

Response	Parameter	Degrees of freedom	F-value	p-value
Mean bulk density	year	1	34.5045	< 0.0001
	soil treatment	2	1.0237	0.5993
	depth class	2	166.9478	< 0.0001
	year X soil treatment	2	0.4473	0.7995
	year X depth class	2	4.0494	0.1320
	soil treatment X depth class	4	10.3491	0.0349
	year X soil treatment X depth class	4	5.1214	0.2750
Elevation differences	year	1	8.7721	0.0030
	soil treatment	2	554.1942	< 0.0001
	year X soil treatment	2	19.1543	< 0.0001

Table 3
Mean bulk density (a) and surface variation (b) as a function of surface soil treatment (smooth = no treatment, plow = surface plowed with a RipPlow™ attached to D7, and disc = surface disced with an agriculture disc attached to a tractor). Values in brackets represent the 95 % confidence interval on the mean. For bulk density, post-hoc comparisons were conducted between soil treatments within a soil depth. Different letters between treatment means indicate a significant effect at $p < 0.05$ (n = 5 for soil placement).

(a) Bulk density

Response	Bulk density (g cm^{-3})		
Year 1	1.23a (1.20–1.26)		
Year 5	1.37b (1.34–1.41)		
Soil depth interval:	**0–5 cm**	**10–15 cm**	**25–30 cm**
Smooth	1.19a (1.14–1.24)	1.35e (1.30–1.41)	1.40 f (1.34–1.45)
Disc	1.20a (1.15–1.25)	1.29de (1.24–1.34)	1.42 f (1.37–1.48)
Plow	1.19a (1.14–1.24)	1.26d (1.21–1.32)	1.40 f (1.35–1.46)

(b) Elevational differences

Soil treatment	Year	Elevation difference (cm)
Smooth	1	2.4a (2.1–2.8)
	3	2.4a (2.1–2.7)
Disc	1	4.0b (3.5–4.5)
	3	3.6b (3.1–4.0)
Plow	1	10.5d (9.4–11.6)
	3	7.3c (6.5–8.2)

3.2. Understory community responses

Total vegetation cover was significantly dependent on the interaction between year of measurement and soil treatment while the cover crop treatment was not influential (Table 4). Within year of assessment, total cover was similar among soil treatments for years 1–2 and 5 but decreased in the plow treatment in year 3 and increased significantly in the disc treatment in year 4 relative to the other treatments (Fig. 2a).

The relative abundance of non-native forbs generally decreased with time (Fig. 2b), though it was also dependent on the year by cover-crop interaction that was confined to the first year of the study (Table 3, Fig. 2b). In this case, relative abundance of non-native forbs significantly

Table 4
Analysis of deviance table for total vegetation cover and relative abundance (proportion of total cover by vegetation group). All models were fitted using an ordered beta regression distribution with a logit-link function except for total cover which was fit with a Gamma distribution and log function.

Response parameter	Factor level	Chi-square value	Degrees of freedom	p-value
Total	Year	42.4797	4	< 0.0001
	Soil treatment	7.0616	2	0.0293
	Year X Soil treatment	28.5984	8	0.0004
Grasses	Year	276.2137	4	< 0.0001
	Soil treatment	0.6203	1	0.4309
	CC treatment	19.5002	2	< 0.0001
	Year X Soil treatment	63.25	4	< 0.0001
	Year X CC treatment	29.2177	8	0.0003
Native forbs	Year	95.0761	4	< 0.0001
	Soil treatment	3.8999	2	0.1423
	Year X Soil treatment	18.765	8	0.0162
Woody species	Year	158.206	4	< 0.0001
	Soil treatment	18.386	2	0.0001
Non-native forbs	Year	433.6435	4	< 0.0001
	CC treatment	0.5004	1	0.4793
	Year X CC treatment	31.466	4	< 0.0001

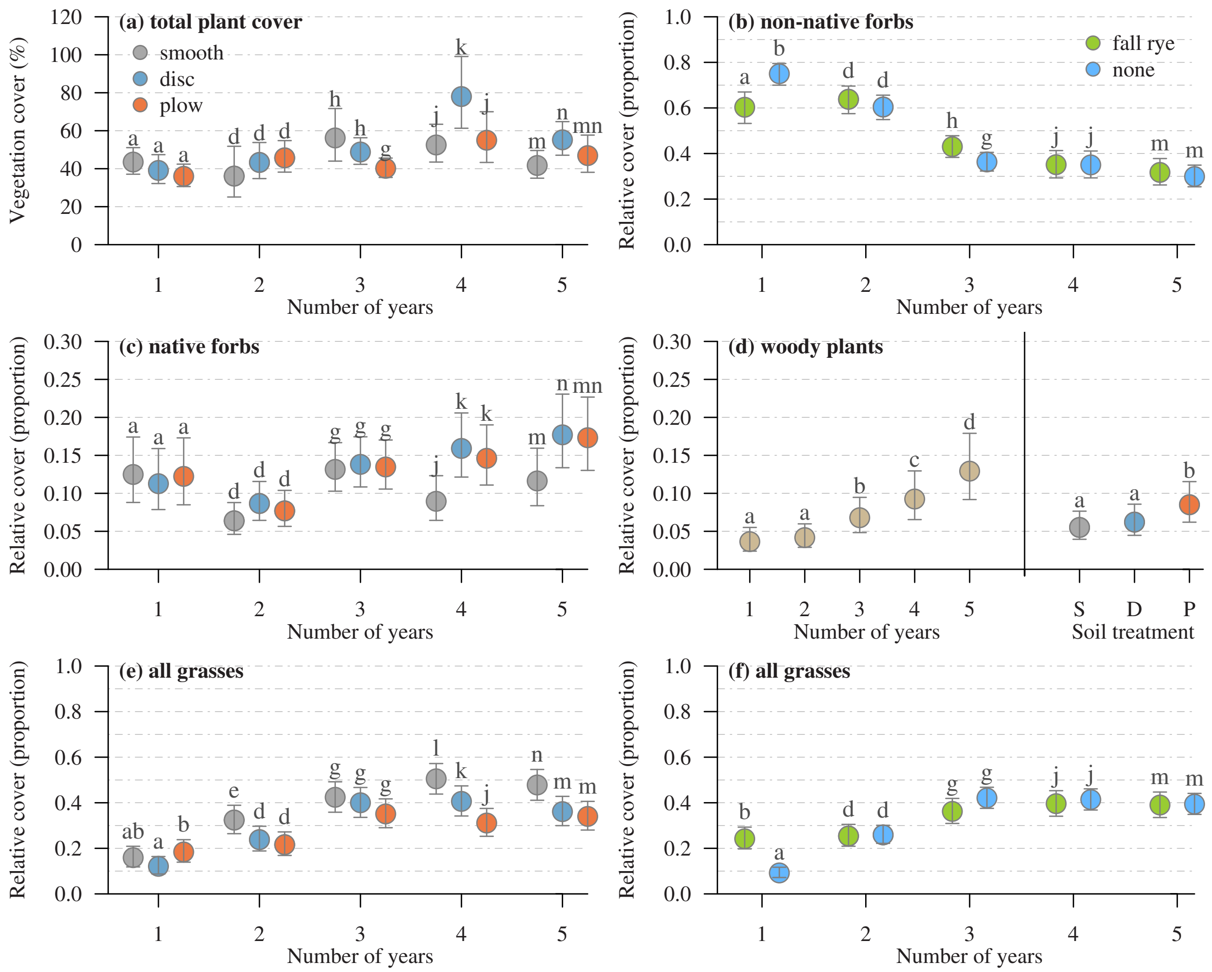

Fig. 2. Mean (a) total cover (%) and (b-f) relative abundance (proportion of total cover) for understory plant classes grouped by statistically significant factor levels. Soil treatments included: smooth (S) = no treatment, plow (P) = surface plowed with a RipPlow™ attached to D7 and disc (D) = surface disced with an agriculture disc attached to a tractor. Cover crop treatment included broadcast of fall rye (FR) or no cover crop (No). Values are estimated marginal means with error bars representing 95 % confidence intervals on the mean. Different letters between treatment means *within the same year of measurement* indicate a significant effect at p < 0.05 (n = 5 replicate blocks). Different letters between treatment means *within the same year of measurement* indicate a significant effect at α < 0.05.

higher in the absence of cover cropping relative to the treatment that included fall rye (Fig. 2b). The abundance of native forbs also interacted with year and soil treatment (Table 3) as there was no effective difference among soil treatments in years 1–3, but between years 4 and 5 both disc and plow maintained higher relative abundances of native forbs compared with the smooth treatment (Fig. 2c). Woody plant cover increased over time (Table 3, Fig. 2d) and was significantly higher in the plow treatment relative to smooth and disc (Fig. 2d). Grass relative abundance depended on both year by soil treatment and year by cover-crop interactions (Table 3), though in general grass abundance increased over time (Fig. 2e-f). Differences between soil treatments were smaller in year 1, but larger in years 4–5, where the smooth treatment averaged ~0.5 while the other treatments ranged from 0.3 to 0.4 (Fig. 2e). Conversely, differences were larger between cover-crop treatments in year 1 with relative abundance of grasses in the fall rye treatment averaging 0.25 compared with 0.10 in no-cover crop; in subsequent years, however, there was no distinction among cover crop treatments (Fig. 2f).

Overall, the composition of vegetation groups changed over time, with the most notable changes occurring between years two (2016) and three (2017), where the groups separate along the first PCoA, and between years four (2018) and five (2019), where they separate along the second PCoA (Fig. 3a). When analysing the effect of experimental treatments, we found a significant effect of soil treatment (Table 5a). The smooth treatment was significantly different from the plow treatment, while the disc treatment overlapped with the other two (Table 5b, Fig. 3b). Trees, medium-low shrubs and native forbs were most characteristic of the plow treatment, while non-native grasses were more abundant in the smooth soil treatment (Fig. 4b).

3.3. Woody plant responses

The stem density of both conifer species together (*Picea glauca* and *Pinus banksiana*) was highest in year 1 and lowest in year 3 with some improvement in overall stem counts by year 5, likely due to improved visibility of these species as they became taller (Table 6, Fig. 4a). The plow soil treatment also resulted in significantly higher conifer stem counts at 0.80 overall compared with only 0.58 in the smooth treatment across all measurement years (Table 5, Fig. 4a). For *Picea glauca* the significant interaction between soil treatment and measurement year was driven by higher observed stem counts in year 4 for the plow treatment compared with smooth and disc treatment as stem counts were otherwise similar amongst soil treatments in other years (Table 6, Fig. 4c). *Pinus banksiana* stem counts were significantly higher in the plow treatment compared to smooth and disc treatments across years (Table 6, Fig. 4e). Stem counts of *Pinus banksiana* followed the same overall pattern observed in conifers as a whole with highest counts in year 1, dropping to lowest levels in year 2–3 and then recovering

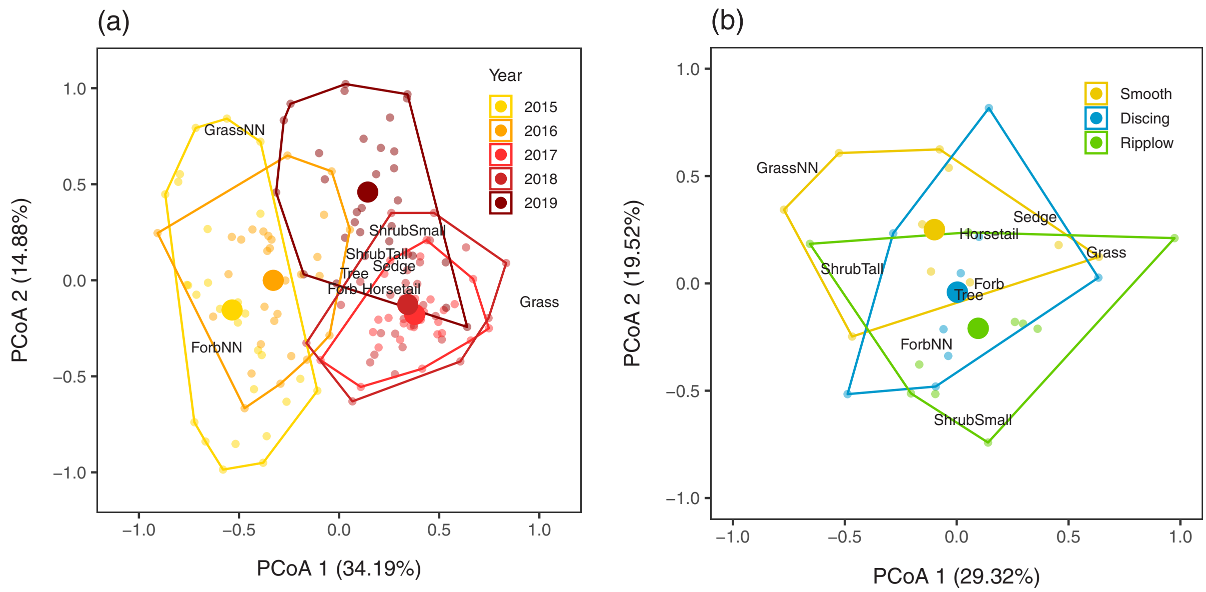

Fig. 3. Principal Coordinates Analysis (PCoA, aka Multidimensional scaling) of plant groups across five years (a) and in year the last year, 2019 (b), based on abundance data transformed by the Hellinger method and the Bray-Curtis distance. Matrix dimensions were 9 by 150 and 9 by 30 respectively for panels (a) and (b). Individual points (partially transparent dots) represent averages calculated at the level of the combination between site preparation and cover crop treatments, i.e. averaging across subplots to get one value for each treatment combination within each block. Centroids (i.e., the average position for a given group of points) are shown as large dots. Nonnative plant groups show NN after their names (e.g., GrassNN, as opposed to native grasses, Grass).

Table 5
Permanova results of year-5 (2019) for the effects of soil and cover crop treatments on the multivariate abundance of 9 plant groups, as in Fig. 3b (a). Cover data were transformed using the Hellinger method, and distances were measured using the Bray-Curtis method. Table b contains pairwise comparisons (corrected by the Benjamini & Hochberg method) between soil treatment treatments; *p* values of soil treatment are above the diagonal.

(a)

Factor	**DF**	**SS**	R^2	***F* value**	***p* value**
Soil treatment	2	0.073	0.12	1.70	0.048
Cover crop	1	0.007	0.01	0.31	0.836
Soil treatment X Cover crop	2	0.038	0.06	0.87	0.302
Residual	24	0.517	0.82		
Total	29	0.635	1		

(b)

	Smooth	Disc	Plow
Smooth	NA	0.08	0.13
Disc	0.119	NA	0.04
Plow	0.013	0.443	NA

somewhat by year 5 (Fig. 4e).

There were no significant responses among deciduous trees with 1.0–1.2 stems per 10 m^2 plot observed annually (Table 6, Fig. 4b). For *Populus balsamifera* and *Populus tremuloides* there was a significant effect due to year of measurement (Table 6) with Populus *tremuloides* stem counts increasing slightly by year 5 (Fig. 4d) and *Populus balsamifera* counts decreasing slightly over time (Fig. 4f). *Populus balsamifera* stem counts were slightly higher in the absence of a cover crop at 0.18 compared with 0.12 in the fall rye treatment (Fig. 4f).

The density of shrubs depended on interacting effects of year and soil treatment, where shrub counts generally increased over time with both plow and disc treatments supporting higher stem counts by year 5 compared with the smooth treatment (Table 6, Fig. 4g). In particular, stem counts of *Rubus idaeus* drove much of this interaction as it was also dependent on interaction of year by soil treatment (Table 6, Fig. 4h). While *Salix* spp. stem counts also responded to the interaction of year and soil treatment, it was in the opposite direction as that observed for *Rubus idaeus* where both smooth and disc treatments showed significantly higher stem counts in year 5 compared with plow treatment (Table 6, Fig. 4i). *Alnus* spp. stem counts showed no change through years of assessment (not shown) or soil treatment (Table 6, Fig. 4a).

Plowing resulted in the highest year-five height for *Picea glauca*, *Pinus banksiana*, *Populus tremuloides* and *Salix* spp., followed by discing and smooth (Fig. 5) and all species measured grew taller over time (Table 7, Fig. 5). *Populus tremuloides* height was also influenced by a two-way interaction between cover crop and soil treatment (Table 7) as this species was taller without a cover crop in the plow treatment, despite having similar growth between cover crop treatments in the smooth and disc treatments (Fig. 5d).

4. Discussion

Our results provide valuable insights into the efficacy of restoration practices aimed at promoting native species while controlling undesirable weeds. Plowing limited graminoid dominance and favoured the density and growth of trees and shrubs, while graminoid dominance was highest in the smooth treatment. *Salix* species, however, responded most prominently in the smooth treatment. Mechanical site preparation significantly influenced surface elevation, while its effects on bulk density were only pronounced at the intermediary 10–15 cm depth range. The choice of cover crop affected vegetation outcomes, with *Secale cereale* providing initial relief in weed pressure, and no long-term woody growth drawbacks.

4.1. Q1 How does the type of mechanical soil treatment affect establishment of woody species?

Relating to planted tree and shrubs species, the most consistently observed effect of the mechanical soil treatments was the general increase in height growth over time, particularly in the plow treatment. While soil bulk density generally decreased over time, reflecting recovery processes, we did observe a slight decline in bulk density primarily at intermediate depths in the plow treatment. However, this effect was modest though coupled with the growth responses these findings support that mechanical interventions can alleviate soil compaction, although the effect may vary by depth (Batey, 2009).

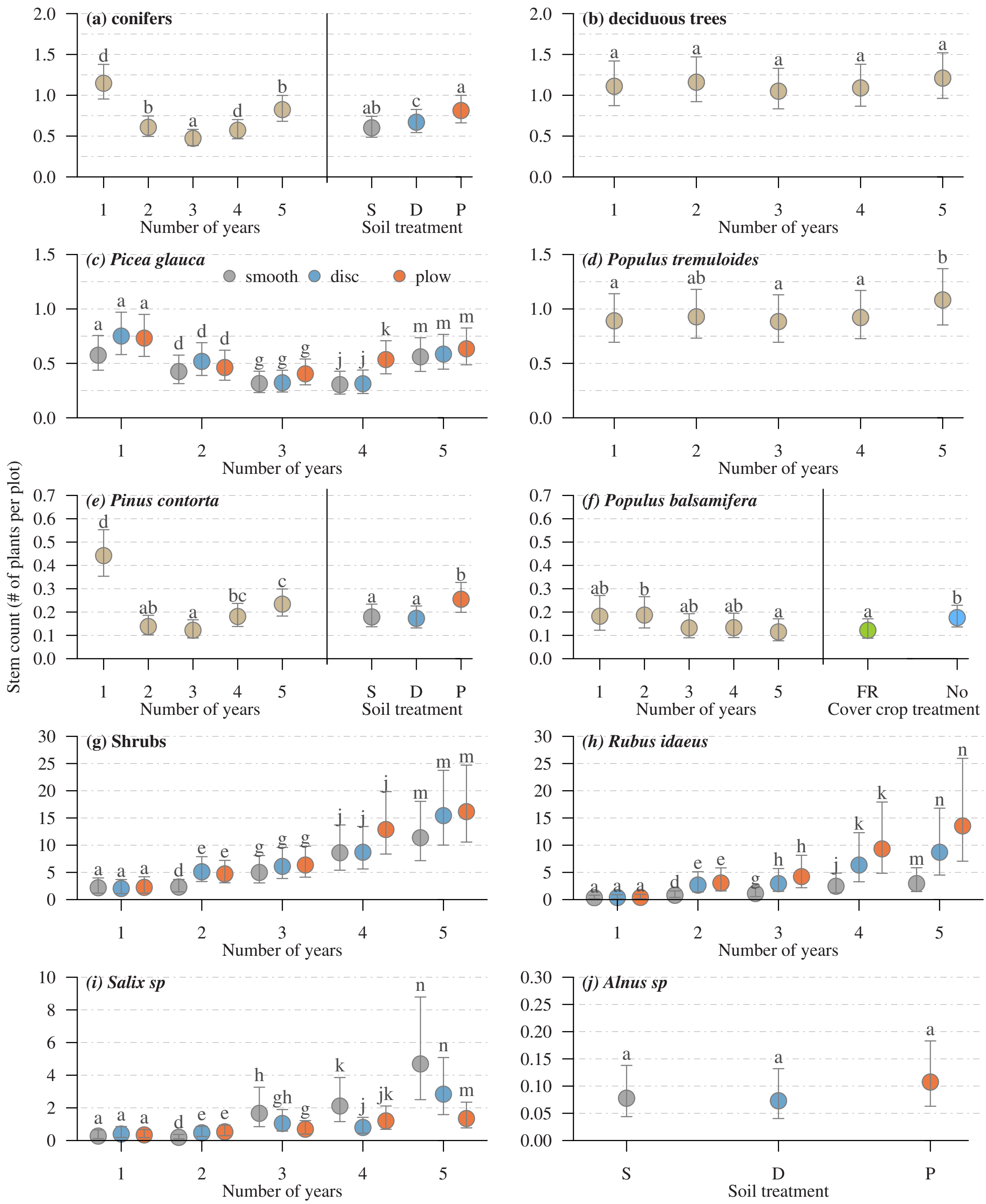

Fig. 4. Mean stem counts per 10 m^2 circular plot for tree and shrub groups as well as individual species grouped by statistically significant factor levels. Soil treatments included: smooth (S) = no treatment, plow (P) = surface plowed with a RipPlow™ attached to D7 and disc (D) = surface disced with an agriculture disc attached to a tractor. Cover crop treatment included broadcast of fall rye (FR) or no cover crop (No). Values are estimated marginal means with error bars representing 95 % confidence intervals on the mean. Different letters between treatment means *within the same year of measurement* indicate a significant effect at $p < 0.05$ (n = 5 replicate blocks). Multiplying the stem count by 1000 equates to a density estimate in stems per hectare.

Deeper mechanical interventions may be required to improve soil structure more uniformly across different depths. While not observed for deciduous tree species, both conifers and shrubs also increased their stem counts in the mechanical soil treatments. The reasons behind these stem count increases, however, likely differs for each group. For the conifers it is possible that they were responding directly to the improved soil physical structure (improved survival) while the shrub group, which largely reflected *Rubus idaeus*, may have responded to the mechanical scarification effect directly, thereby stimulating seed emergence within the soil seed bank. These results partially support our hypothesis that plowing would create the most elevation change and decrease bulk density the most out of the three treatments. However, contrary to our

Table 6
Analysis of deviance table for stem counts. All models were fitted using a Generalized Poisson distribution with a log-link function except for deciduous trees, *Populus balsamifera* and *Salix* spp. which were fitted using a negative binomial.

Response parameter	Factor level	Chi-square value	Degrees of freedom	p-value
Conifers	Year	222.0148	4	< 0.0001
	Soil treatment	8.5244	2	0.0141
Deciduous trees	Year	7.1642	4	0.1275
Shrubs	Year	5.0517	2	0.0800
	Soil treatment	624.399	4	< 0.0001
	Year X Soil treatment	28.9368	8	0.0003
White spruce	Year	104.5463	4	< 0.0001
	Soil treatment	5.1377	2	0.0766
	Year X Soil treatment	16.4115	8	0.0369
Alder	Soil treatment	1.9665	2	0.3741
Lodgepole pine	Soil treatment	8.5319	2	0.0140
	Year	150.3225	4	< 0.0001
	Cover crop treatment	1.9386	1	0.1638
Balsam poplar	Year	11.8713	4	0.0183
	Cover crop treatment	3.9937	1	0.0457
Aspen	Year	14.687	4	0.0054
Raspberry	Soil treatment	15.744	2	0.0004
	Year	594.483	4	0.0000
	Year X Soil treatment	26.125	8	0.0010
Willows	Soil treatment	3.0874	2	0.2136
	Year	314.1636	4	< 0.0001
	Year X Soil treatment	97.2973	8	< 0.0001

expectations, bulk density differences were limited to the 10–15 cm depth, and there were no significant differences in bulk density or surface elevation between discing and smooth treatments despite some clear growth and plant stem count benefits associated with the disc treatment.

4.2. Q2 How does mechanical site preparation affect the establishment of spontaneous desirable (native shrubs and trees) and undesirable (non-native grasses) vegetation?

Increased surface variation, where soil microtopography would have created a range of surface moisture conditions, likely reduced the competitive advantage of non-native grasses, which prefer more uniform surfaces (Gilland and McCarthy, 2013). We hypothesize that the plow treatment's rough terrain may have physically limited the spread of these grasses, as the barriers created by the surface heterogeneity hindered the lateral expansion of rhizomatous or stoloniferous species (Johnston, 2019). This negative influence of soil surface roughness on grass responses has also been observed by others (Frouz et al., 2018). Furthermore, the increased relative abundance of native forbs and woody species in the plow and disc treatments highlights the benefits of surface heterogeneity in promoting desirable understory vegetation. Likely by creating varied microenvironments, these treatments supported a higher diversity of native species, which is crucial for successful forest restoration. These findings partially support our hypothesis that greater surface variability corresponds with increased plant diversity, as diversity increased primarily among native species, while the response of undesirable species was more variable.

4.3. Q3 How does fall rye (Secale cereale), an annual grass cover crop, influence the establishment of desirable species?

In the first year, *Secale cereale* effectively suppressed non-native forbs, reducing potential competition from this group of plants. This early suppression of undesirable vegetation may provide a window of opportunity for native species to establish without facing intense competition, although *Secale cereale* could have become a competitor on its own. While *Secale cereale* provided short-term weed suppression, it did not appear to interfere with the long-term recovery of desirable species. By the end of the study period, differences between the cover-crop and control treatments had diminished, suggesting that the effects were largely temporary and beneficial for early-stage vegetation dynamics. This supported our fourth hypothesis that any negative effects on desirable species would be negligible by the end of our study. Other boreal reclamation trials have also shown a lack of negative interactions between native vegetation cover and cover cropping, citing an initial decrease in the ingress of only non-native understory vegetation (Macdonald et al., 2015) which is consistent with the decline in the relative abundance of non-native forbs, in year 1 only, within the cover crop treatment. The ability of the cover crop to suppress weeds without hindering native species establishment makes it a valuable tool in restoration projects. The competitive effects of *Secale cereale* facilitates the exclusion of pioneer weed species (Silva and Bagavathiannan, 2023) which may otherwise have persisted for 2–3 years. After the annual cover crop expires following the first growing season, native herbaceous and woody species are able to establish with minimal weed pressure in year 2 onwards. The limited negative effect associated with fall rye (slight reductions in stem counts of *Populus balsamifera* and modest height reductions in the plow treatment with *P. tremuloides*) were restricted to the fastest-growing tree species which were more likely to encounter fall rye plants in the first growing season as their roots explored the soil profile. We suggest that slower growing conifers and shrubs and seed-based emergence of other shrubs likely encountered fall rye plants less frequently due to their smaller initial size and growth strategies.

4.4. Temporal dynamics

The temporal trends observed for grass and forb species suggest that vegetation dynamics are highly dynamic and may shift as the site undergoes successional processes. Initial rates of mortality in conifers, as expressed by the sharp declines in stem densities from year 1 to year 2 with some 'recovery' observed in year 5 for *Picea glauca* suggests that site factors place significant pressure on these species. Competing vegetation experiment-wide was high, particularly in years 2–3 when ruderal vegetation (non-native forbs and grasses) was highly abundant. The challenges associated with grass competition, specifically, are well known in boreal reforestation, and this competition was likely a contributing cause to mortality in both *Picea glauca* and *Pinus banksiana* (Lieffers et al., 1993; Bell et al., 2011; Hangs and Knight, 2011). The plow treatment resulted in significantly higher stem counts relative to the smooth treatment, which highlights the opportunity of reclamation practices in supporting tree species establishment in highly disturbed sites.

Density of native shrubs increased with time, particularly in plow-treated plots, further emphasizing the benefits of increased surface ruggedness. Native shrubs such as *Rubus idaeus* and *Salix spp.* showed opposite responses to soil treatments, with *Rubus idaeus* (animal- and gravity-dispersed) being favored by plowing, and *Salix spp.* (wind-dispersed) by the smooth treatment. The additional surface mechanical disturbance created by plowing and discing may have promoted the germination of *Rubus idaeus* seeds stored in the seed bank through mechanical scarification (Pergolotti et al., 2023), while the higher surface heterogeneity, with more extreme microsites (drier upper parts of the furrows vs. excess moisture in the bottom of furrows) may have been more challenging for wind-dispersed seeds to find appropriate microsites for germination and establishment (Johnston, 2019). These findings support our first hypothesis that increased decompaction would promote greater tree and shrub growth, though species-specific responses were observed, with *Salix spp.* favouring smooth treatments for

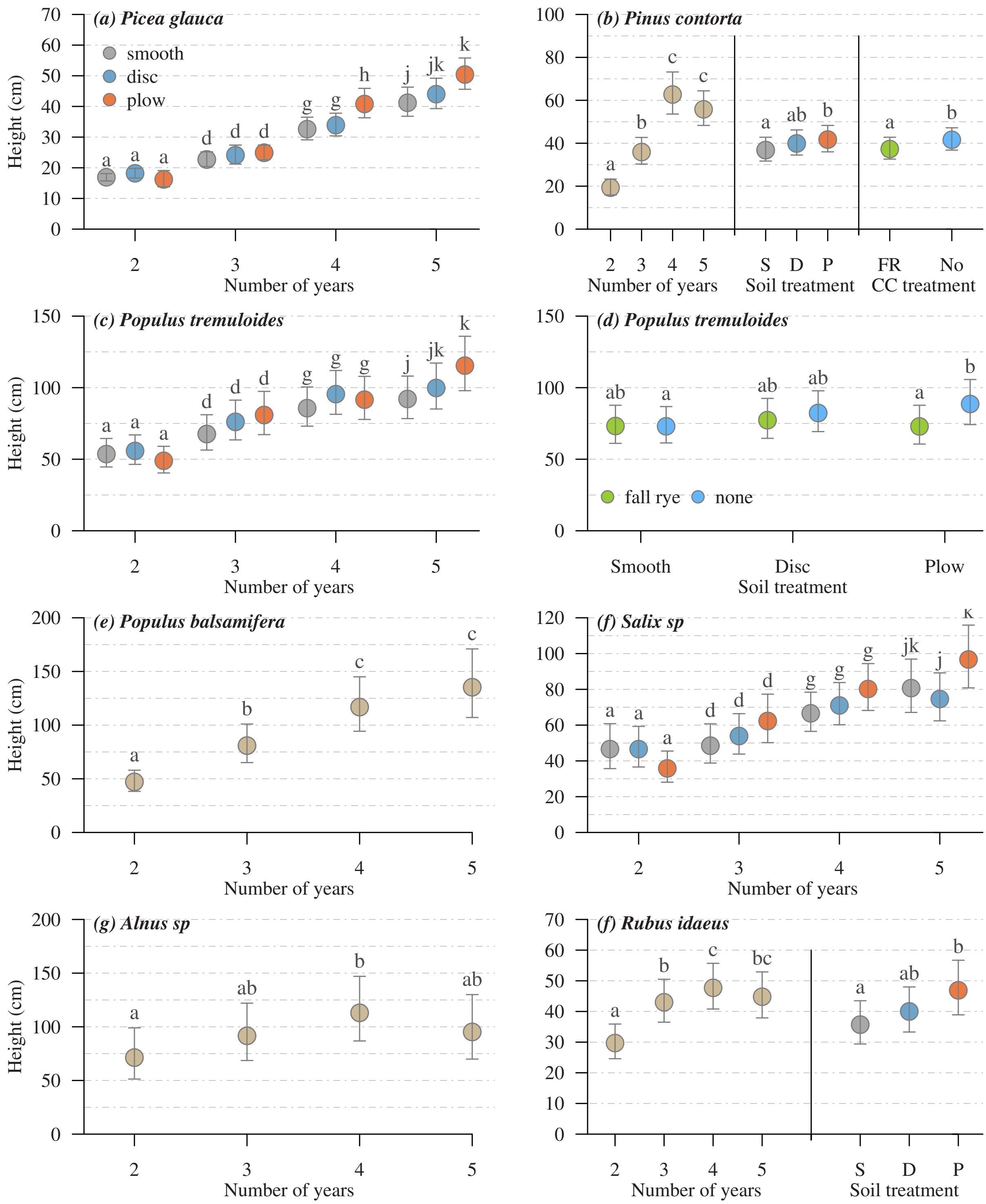

Fig. 5. Mean height of tree and shrub species grouped by statistically significant factor levels. Soil treatments included: smooth (S) = no treatment, plow (P) = surface plowed with a RipPlow™ attached to D7 and disc (D) = surface disced with an agriculture disc attached to a tractor. Cover crop treatment included broadcast of fall rye (FR) or no cover crop (No). Values are estimated marginal means with error bars representing 95 % confidence intervals on the mean. Different letters between treatment means *within the same year of measurement* indicate a significant effect at $p < 0.05$ ($n = 5$ replicate blocks).

establishement (stem counts) and the plow treatment for growth. The mixed-findings relating to *Rubus idaeus* and *Salix* stem counts both support and refute our second hypothesis.

4.5. Management implications

Our findings suggest that plowing, which created surface micro topographical variation, is a highly effective strategy for promoting the establishment of native woody species and shrubs on severely disturbed sites. This treatment enhanced microhabitat diversity, improved soil moisture retention, and suppressed non-native grasses, contributing to the initial stages of forest restoration. The fact that the disc treatment tended to show intermediate responses between the plow and smooth treatments, further supports the assertion that much of the benefit was

Table 7
Analysis of deviance table for tree or shrub height. All models were fitted using a Gamma distribution with a log-link function.

Response parameter	Factor level	Chi-square value	Degrees of freedom	p-value
White spruce	Soil treatment	13.419	2	0.0012
	Year	968.139	3	< 0.0001
	Year X Soil treatment	12.562	6	0.0505
Alder	Year	9.3813	3	0.0246
Lodgepole pine	Soil treatment	5.6275	2	0.0600
	Cover crop treatment	6.1085	1	0.0135
	Year	336.7288	3	< 0.0001
Balsam poplar	Year	142.91	3	< 0.0001
Aspen	Year	341.9045	3	< 0.0001
	Soil treatment	5.7935	2	0.0552
	Cover crop treatment	4.2086	1	0.0402
	Year X Soil treatment	18.1405	6	0.0059
	Year X Cover crop treatment	4.8009	3	0.1870
	Cover crop X Soil treatment	6.2164	2	0.0447
Raspberry	Year	75.1065	3	0.0000
	Soil treatment	9.3609	2	0.0093
Willows	Year	154.159	3	0.0000
	Soil treatment	3.5168	2	0.1723
	Cover crop treatment	0.11	1	0.7401
	Year X Soil treatment	18.2442	6	0.0057

due to the surface variation imposed by these treatments with stronger responses associated with increased intensity of mechanical treatment. These results highlight the potential of intensive mechanical treatments to accelerate vegetation recovery in challenging environments, such as decommissioned airstrips, where soil compaction and uniformity would otherwise impede restoration efforts. Given that non-native grasses pose a significant threat to forest succession (Lupardus et al., 2019; Baah-Acheamfour et al., 2022), deep plowing and other intensive mechanical interventions could provide land managers with an effective tool to combat grass-driven arrested succession.

The use of *Secale cereale* as a cover crop proved beneficial for weed suppression during the early stages of restoration, without negatively affecting the establishment of native species. However, annual species such as *Secale cereale* that do not show further establishment from seed (unlike other annual weeds) should be viewed as a temporary measure rather than a long-term solution. Using a native species for cover cropping could further reduce the risk of non-native cover crops establishing long-term. Future restoration projects may benefit from integrating *Secale cereale* or similar cover crops with other management practices, such as selective herbicide application or manual weeding, to maintain control over non-native species without compromising the establishment of native vegetation. Furthermore, effects of cover cropping were smaller in effect size compared to mechanical site preparation, which continues to exert a strong influence in shaping overstory and understory vegetation at this site. This suggests the best use-case for cover cropping may be reserved for those sites where non-native, weedy species are of greatest concern and where other considerations warrant a more aggressive, initial effort in reducing the abundances of these species. Cases may include adjacency to sensitive ecological areas, agricultural land-uses or other recreational areas where weedy species may represent an ongoing concern.

5. Conclusion

This study underscores the potential for targeted restoration strategies to overcome the persistent barriers to ecosystem recovery in northern Alberta's industrially disturbed sites. By demonstrating that mechanical site preparation, particularly plowing to create surface microtopography, fosters native tree establishment while limiting non-native grass encroachment, we offer practical guidance for improving reclamation outcomes. The successful use of *Secale cereale* as a temporary cover crop further illustrates how early-stage weed suppression can be achieved without compromising long-term forest development. These findings hold valuable implications for land managers and policymakers striving for sustainable forest management. Future research should explore how these interventions perform over longer time scales and in diverse ecosystems, helping refine best practices for restoring ecological integrity in industrially disturbed forest landscapes.

Ethics approval and consent to participate

Not applicable

Funding

This study was funded by an NSERC Industrial Chair Research Grant for Colleges (472065-14 & 472065-19) as well as with financial and in-kind support from Shell Canada Limited, and Canadian Natural.

Author contribution

ALS, AS, and EFR conceived and designed the research; ALS and MBA performed the experiment; ALS and AGR analyzed the data; NH, MBA, AGR, and ALS wrote and edited the manuscript; AS and EFR, edited and provided feedback on the manuscript. ALS contributed funding acquisition, project administration and supervision of junior staff.

CRediT authorship contribution statement

Schoonmaker Amanda L.: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Harper Nicholas:** Writing – review & editing, Writing – original draft. **Baah-Acheamfour Mark:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Rolhauser Andrés G.:** Writing – review & editing, Writing – original draft. **Smreciu Ann:** Writing – review & editing, Conceptualization. **Fraser-Reid Erin C.:** Writing – review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We are grateful to NAIT's field staff and student research assistants involved in this project for carrying out the data collection, and experiment establishment. A special thank-you to Trevor Floreani and Jeremy Dostie, both of whom spent significant time working in the field during the initial setup of the study and to Trish Hiley, Jessica Hudson and Molly Bannister who spent multiple years monitoring this study. Thank-you to the many other student research assistants that have supported the measurements and got their hands dirty on this project over the years.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2025.122621.

Data availability

Data will be made available on request.

References

Baah-Acheamfour, M., Dewey, M., Fraser, E.C., Schreiber, S.G., Schoonmaker, A., 2022. Assessing ecological recovery of reclaimed well sites: a case study from Alberta, Canada. Front. For. Glob. Change 5, 859246. https://doi.org/10.3389/ffgc.2022.849246.

Barton, K., 2024. _MuMIn: Multi-model inference_. R package version 1.48.4. ⟨https://CRAN.R-project.org/package=MuMIn⟩.

Batey, T., 2009. Soil compaction and soil management – a review. Soil Use Manag. 25 (4), 335–345. https://doi.org/10.1111/j.1475-2743.2009.00236.x.

Bell, F.W., Ter-Mikaelian, M., Wagner, R.G., 2011. Relative competitiveness of nine early-successional boreal forest species associated with planted jack pine and black spruce seedlings. Can. J. For. Res. 30 (5), 790–800. DOI:10.1139/x00-004.

Blackwell, P., Isbister, B., Riethmuller, G., Barrett-Lennard, E., Hall, D., Lemon, J., Hagan, J., Ward, P., 2016. Deeper ripping and topsoil slotting to overcome subsoil compaction and other constraints more economically: way to go. Proc. Grains Res. Update, Sess. 5.

Borcard, D., Gillet, F., Legendre, P., 2018. Numerical ecology with R, second edition. Springer, New York.

Brandt, J.P., Flannigan, M.D., Maynard, D.G., Thompson, I.D., Volney, W.J.A., 2013. An introduction to Canada's boreal zone: ecosystem processes, health, sustainability, and environmental issues. Environ. Rev. 21 (4), 207–226. https://doi.org/10.1139/er-2013-0040.

Brooks, M.E., Kristensen, K., van, Benthem, K.J., Magnusson, A., Berg, C.W., Nielsen, A., Skaug, H.J., Maechler, M., Bolker, B.M., 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. R. J. 9 (2), 378–400.

Cambi, M., Certini, G., Neri, F., Marchi, E., 2014. The impact of heavy traffic on forest soils: a review. For. Ecol. Manag. 338, 124–138. https://doi.org/10.1016/j.foreco.2014.11.022.

Consul, P.C., Famoye, F., 1992. Generalized Poisson regression model. Commun. Stat.: Theory Methods 21, 89–109.

Environment and Climate Change Canada, n.d. Canadian Climate Normals 1981-2010 Station Data: Peace River A. ⟨https://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID= 2770&autofwd= 1⟩.

Environment and Climate Change Canada, 2015. Temperature and precipitation in historical perspective: annual 2015; Environment Canada, Climate Trends and Variations Bulletin, ⟨https://climate.weather.gc.ca/historical_data/search_historic_data_e.html⟩.

Environment and Sustainable Resource Development, 2013. 2010 Reclamation Criteria for Wellsites and Associated Facilities for Cultivated Lands (Updated July 2013). Alberta Government, Edmonton, Alberta. 92 pp.

Franklin, J.A., Zipper, C.E., Burger, J.A., Skousen, J.G., Jacobs, D.F., 2012. Influence of herbaceous ground cover on forest restoration of eastern US coal surface mines. N. For. 43, 905–924.

Frouz, J., Mudrak, O., Reitchmiedova, E., Walmsley, A., Vachova, P., Simackova, H., Albrechtova, J., Moradi, J., Kucera, J., 2018. Rough wave-like heaped overburden promotes establishment of woody vegetation while leveling promotes grasses during unassisted post mining site development. J. Environ. Manag. 205, 50–58.

Gilland, K.E., McCarthy, B.C., 2013. Microtopography influences early successional plant communities on experimental coal surface mine land reclamation. Restor. Ecol. 22 (2), 232–239. https://doi.org/10.1111/rec.12066.

Hangs, R.D., Knight, J.D., 2011. Interspecific competition for nitrogen between early successional species and planted white spruce and jack pine seedlings. Can. J. For. Res. 32 (10), 1813–1821. DOI:10.1139/x02-100.

Hardin, J.W., Hilbe, J.M., 2018. Generalized linear models and extensions, Fourth Edition. StataCorp LLC, Texas, United States of America. ISBN-13: 978-1-59718-226-3.

Hartig, F., 2022. DHARMa: Residual diagnostics for hierarchical (Multi-level / Mixed) regression models. R package version 0.4.6, <⟨https://CRAN.R-project.org/package=DHARMa⟩>

Johnson, E.A., Miyanishi, K., 2012. The boreal forest as a cultural landscape. Ann. N. Y. Acad. Sci. 1249 (1), 151–165. https://doi.org/10.1111/j.1749-6632.2011.06312.x.

Johnston, D.B., 2019. Rough soil surface lessens annual grass invasion in disturbed rangeland. Rangel. Ecol. Manag. 72 (2), 292–300. https://doi.org/10.1016/j.rama.2018.10.010.

Kubinec, R., 2022. Ordered beta regression: a parsimonious, well-fitting model for continuous data with lower and upper bounds. Political Anal. https://doi.org/10.1017/pan.2022.20.

Lenth, R.V., 2022. _emmeans: Estimated marginal means, aka Least-Squares Means_. R package version 1.8.1-1. ⟨https://CRAN.R-project.org/package=emmeans⟩.

Lieffers, V.J., Macdonald, S.E., Hodd, E.H., 1993. Ecology of and control strategies for Calamagrostis canadensis in boreal forest sites. Can. J. For. Res. 23 (10). https://doi.org/10.1139/x93-258.

Lupardus, R.C., McIntosh, A.C.S., Janz, A., Farr, D., 2019. Succession after reclamation: identifying and assessing ecological indicators of forest recovery on reclaimed oil and natural gas well pads. Ecol. Ind., 105515

Macdonald, S.E., Snively, A.E.K., Fair, F.M., Landhausser, S.M., 2015. Early trajectories of forest understory development on reclamation sites: influence of forest floor placement and a cover crop. Restor. Ecol. 23 (5), 698–706.

McConkey, T., Bulmer, C., Sanborn, P., 2012. Effectiveness of five soil reclamation and reforestation techniques on oil and gas well sites in northeastern British Columbia. Can. J. Soil Sci. 92, 165–177.

McNabb, D.H., 1994. Tillage of compacted haul roads and landings in the boreal forests of Alberta, Canada. For. Ecol. Manag. 66 (1-3), 179–194. https://doi.org/10.1016/0378-1127(94)90156-2.

McNabb, D.H., Sobze, J.M., Schoonmaker, A., 2012. Tilling Compacted Soils with RipPlows: A Disturbed Soil Restoration Technique. NAIT Boreal Research Institute: Boreal Reclamation Program. ⟨https://www.cclmportal.ca/sites/default/files/2022-04/Tilling%20Compacted%20Soils%20with%20RipPlows.pdf⟩.

McNabb, D.H., Startsev, A., 2022. Seven-year changes in bulk density following forest harvesting and machine trafficking in Alberta, Canada. Forests 13 (4), 553. https://doi.org/10.3390/f13040553.

Natural Regions Committee, 2006. Natural regions and subregions of Alberta. Compiled by DJ Downing and WW Pettapiece. Government of Alberta Pub. No. T/852. ⟨https://www.albertaparks.ca/media/2942026/nrsrcomplete_may_06.pdf⟩.

Natural Resources Canada, 2020. 8 facts about Canada's boreal forest. Government of Canada. ⟨https://www.nrcan.gc.ca/our-natural-resources/forests/sustainable-forest-management/boreal-forest/8-facts-about-canadas-boreal-forest/17394⟩.

Oksanen, J., Simpson, G., Blanchet, F., Kindt, R., Legendre, P., Minchin, P., O'Hara, R., Solymos, P., Stevens, M., Szoecs, E., Wagner, H., Barbour, M., Bedward, M., Bolker, B., Borcard, D., Carvalho, G., Chirico, M., De Caceres, M., Durand, S., Evangelista, H., FitzJohn, R., Friendly, M., Furneaux, B., Hannigan, G., Hill, M., Lahti, L., McGlinn, D., Ouellette, M., Ribeiro Cunha, E., Smith, T., Stier, A., Ter Braak, C., Weedon, J., 2024. vegan: Community Ecology Package. R package version 2.6-6.1, <⟨https://CRAN.R-project.org/package=vegan⟩> .

Pergolotti, V., Marcellini, M., Contreras, E., Mezzetti, B., Gambardella, M., Capocasa, F., Sabbadini, S., 2023. Standardization of an in vitro seed germination protocol compared to acid scarification and cold stratification methods for different raspberry genotypes. Horticulturae 9 (2), 153. https://doi.org/10.3390/horticulturae9020153.

R Core Team, 2024. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. ⟨https://www.R-project.org⟩.

Riley, S.J., DeGloria, S.D., Elliot, R., 1999. Index that quantifies topographic heterogeneity. Intermt. J. Sci. 5 (1–4), 23–27.

Schott, K.M., Karst, J., Landhäusser, S.M., 2014. The role of microsite conditions in restoring trembling aspen (*Populus tremuloides* Michx) from seed. Restor. Ecol. 22, 292–295.

Silva, G.C., Bagavathiannan, M., 2023. Mechanisms of weed suppression by cereal rye cover crop: a review. Agron. J. 115 (4), 1571–1585. https://doi.org/10.1002/agj2.21347.

Simpson, G., 2022. permute: Functions for Generating Restricted Permutations of Data. R package version 0.9-7, <⟨https://CRAN.R-project.org/package=permute⟩> .

Snively, A.E.K., 2014. Competitive Relationships in Forest Restoration: Impact of Cover Crops and Fertilization on Tree and Understory Development. Department of Renewable Resources, University of Alberta.

Soil Classification Working Group, 1998. National Research Council Canada, Canada. Agriculture, and Agri-Food Canada. Research Branch. The Canadian system of soil classification. NRC Research Press, p. 187.

Wronski, E.B., Murphy, G., 1994. Responses of forest crops to soil compaction. Dev. Agric. Eng. 11, 3.