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Erasing anthropogenic disturbance: Natural revegetation of linear features following wildfire, and the implications for woodland caribou (*Rangifer tarandus caribou*) habitat management.

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ABSTRACT

The federal recovery strategy for woodland caribou identifies wildfires within the last 40 years and anthropogenic disturbance visible at a scale of 1:50,000, including a 500-m buffer, as disturbed. Long-term vegetation recovery on linear features post-fire has not yet been documented. We examined vegetation recovery including stem density and height, hiding cover, and reindeer lichen cover along 40+ year-old legacy linear features in Northern Saskatchewan, in both uplands and lowlands 1–41 years post-fire. We compared these results with burned areas off-lines and unburned lines. On unburned lines in uplands there was minimal recovery, while there was significant recovery of stem count, height and hiding cover on burned lines and burned off-lines. Reindeer lichen cover and thickness remained significantly lower on burned lines and burned off-lines than on unburned lines until the 41-year age group, where there was no longer a significant difference. In lowlands, the stem density and stem height were initially significantly higher on unburned lines than on either burned lines or burned off-lines. After 27–32 years post-fire there was no longer a significant difference in stem densities. Our findings show that fires substantially accelerate natural revegetation and instigate a recovery that is similar on and off disturbance features in both uplands and lowlands. These findings can inform management decisions on restoration planning and calculation of range disturbance metrics. We suggest that the anthropogenic 500-m buffer should be removed post fire, as anthropogenic disturbance is reset, and anthropogenic disturbance should be classified as naturally recovering.

1. Introduction

Woodland caribou (*Rangifer tarandus caribou* (Gmelin, 1788)) are found throughout Canada's boreal forest. Habitat disturbance from human-caused and natural sources, as well as increased predation as a result of habitat alteration, have led to local population declines throughout their distribution (ECCC 2020). The species is listed as Threatened in Canada (COSEWIC 2002) and Vulnerable in Saskatchewan (SKCDC 2023). In Canada, Environment Canada and Climate Change has defined disturbed habitat as lands with i) anthropogenic (human-caused) disturbance visible on Landsat imagery (a series of Earth-imaging satellites) at a scale of 1:50,000, including the area within a 500 m buffer of the anthropogenic disturbance; and/or ii) fire disturbance in the last 40 years, as mapped by each provincial and territorial jurisdiction (without buffer) (ECCC 2020). Although the effect of anthropogenic disturbance likely varies for individual ranges, national level meta-analysis has demonstrated that the application of a 500 m buffer to mapped anthropogenic features best represents the combined effects of increased predation and avoidance of caribou populations across Canada (ECCC 2020).

The Boreal Shield of Saskatchewan (SK1) and the northern portion of the Boreal Plain of Saskatchewan (SK2) are regions where wildfires are extensive and frequent with a fire cycle of 99 years (Acton et al., 1998; Parisien et al., 2004). As such, fire is a major and consistent ecological process in this part of the Canadian Boreal Ecosystem. Wildfires within these regions are permitted to occur with minimal human intervention, primarily because the area has limited commercial forest productivity or human settlement (Kansas et al., 2016). Wildfire remains the dominant ecological disturbance process determining the vegetative landscape in this region (SKMOE 2021).

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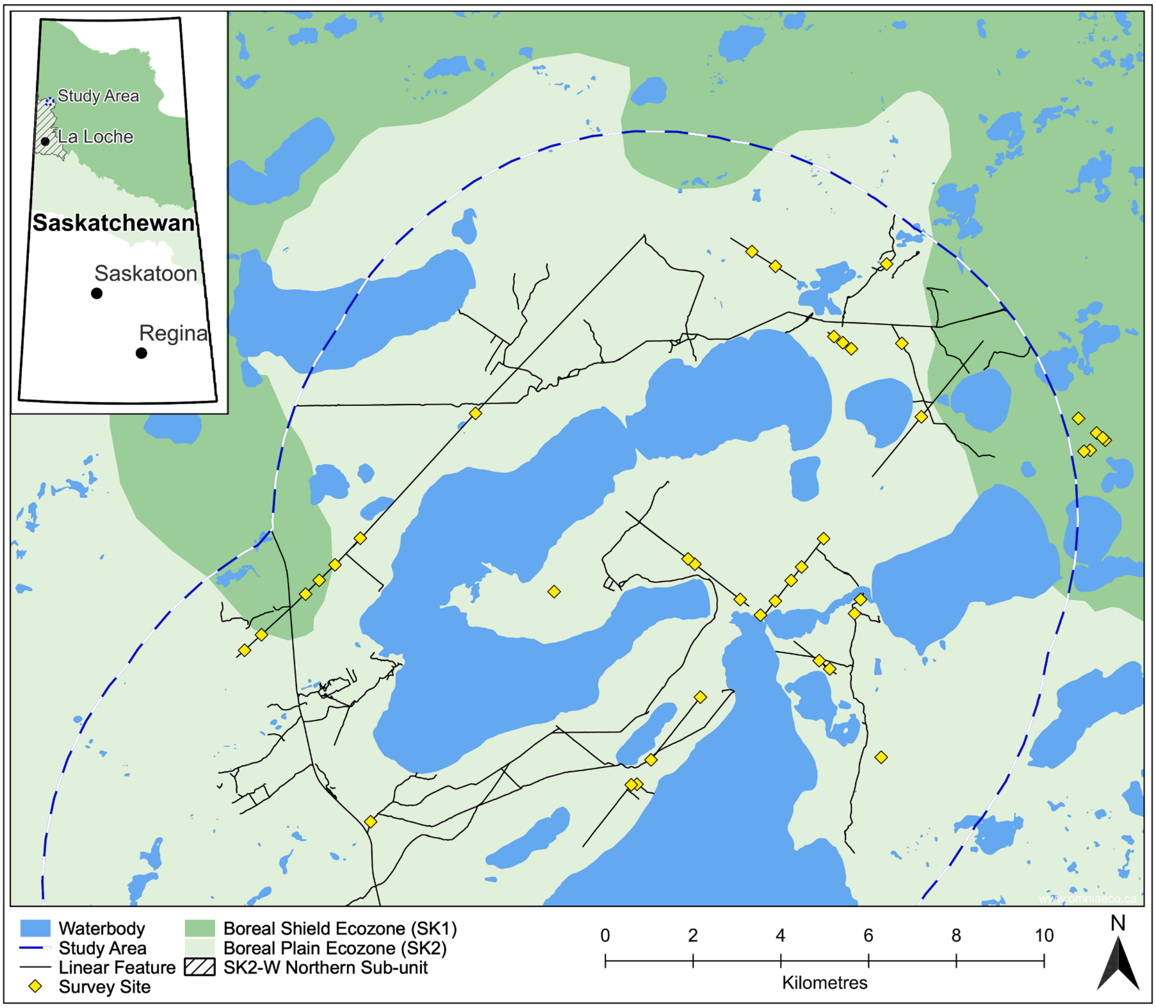


Fig. 1. Location of the study area and survey sites within the Boreal Plain (SK2) and Boreal Shield (SK1) of northern Saskatchewan, Canada. Software used to create the site layout: QGIS 3.24.3. No permissions required. All geographic data are freely available (open).

SK1 currently has 60% disturbed habitat, where fire accounts for 58% and anthropogenic disturbance is 3%[1] (ECCC 2020). SK2 is currently 45% disturbed habitat, where 30% is caused by fire, and 20% is due to anthropogenic disturbance (ECCC 2020). ECCC (2020) has identified a management threshold, to ensure sustainable woodland caribou populations, for SK1 of 40% undisturbed habitat, with no more than 5% of this to be human-caused disturbance. In SK2, the recovery strategy has identified a threshold of 65% undisturbed habitat. Their analysis indicates that the SK2 population is at risk as a result of habitat disturbance that exceeds the target threshold. The management objective for SK2 is to increase to 65% undisturbed habitat over time (ECCC 2020).

There are inherent differences in the nature and magnitude of habitat effects of anthropogenic disturbance compared to natural disturbance on woodland caribou. Industrial disturbance may have both direct effects (habitat loss and/or alteration as well as physical barriers to movement) and indirect effects (changed alternate prey and predator populations and predation/hunting efficiencies). One of the primary concerns with industrial disturbance is increased occurrence, distribution and movement efficiency of predators/hunters as a result of linear features such as roads and legacy seismic lines which predators may use for travel and increased line of sight (Latham et al., 2011; Whittington et al., 2011; Hervieux et al., 2013; Dickie et al., 2022). Recent research by Dickie et al. (2022) has indicated that wolf home ranges are smaller in areas with higher linear feature densities, and that the effect of linear features is disproportionately strong in low-productivity habitats where prey resources are limited, suggesting that linear features provide a greater benefit to wolves in areas where prey are scarcer. This implies that restoring linear features in low-productivity habitat may have a higher impact on wolf predation by simultaneously reducing wolf hunting efficiency and increasing home range size, thereby reducing wolf density.

The relationship between wolf use of linear features and low productivity habitat is critical for northern Saskatchewan. The northern Boreal Plain and Shield Regions of Saskatchewan have been characterized as low productivity ungulate habitat (Dickie et al., 2022). This region has very sparse deer populations, typically limited to the southern portion, and is very much a wolf-bear/caribou-moose predator/prey system (McLoughlin et al., 2016). Therefore, understanding the density, distribution and natural regeneration status of linear features across this region is key to landscape management and restoration or off-setting planning. Reclamation of stagnant linear features has been identified as crucial across all woodland caribou ranges (Dickie et al., 2021), but will be especially critical for SK1 where the mandated critical habitat threshold for anthropogenic disturbance is five percent (ECCC 2020). In addition, this would also represent an improvement of habitat conditions for other species, especially Species at Risk Act (SARA) listed species, across the boreal forest. The re-vegetation status and level of

[1] Areas overlapped by both anthropogenic and natural disturbance are counted once.

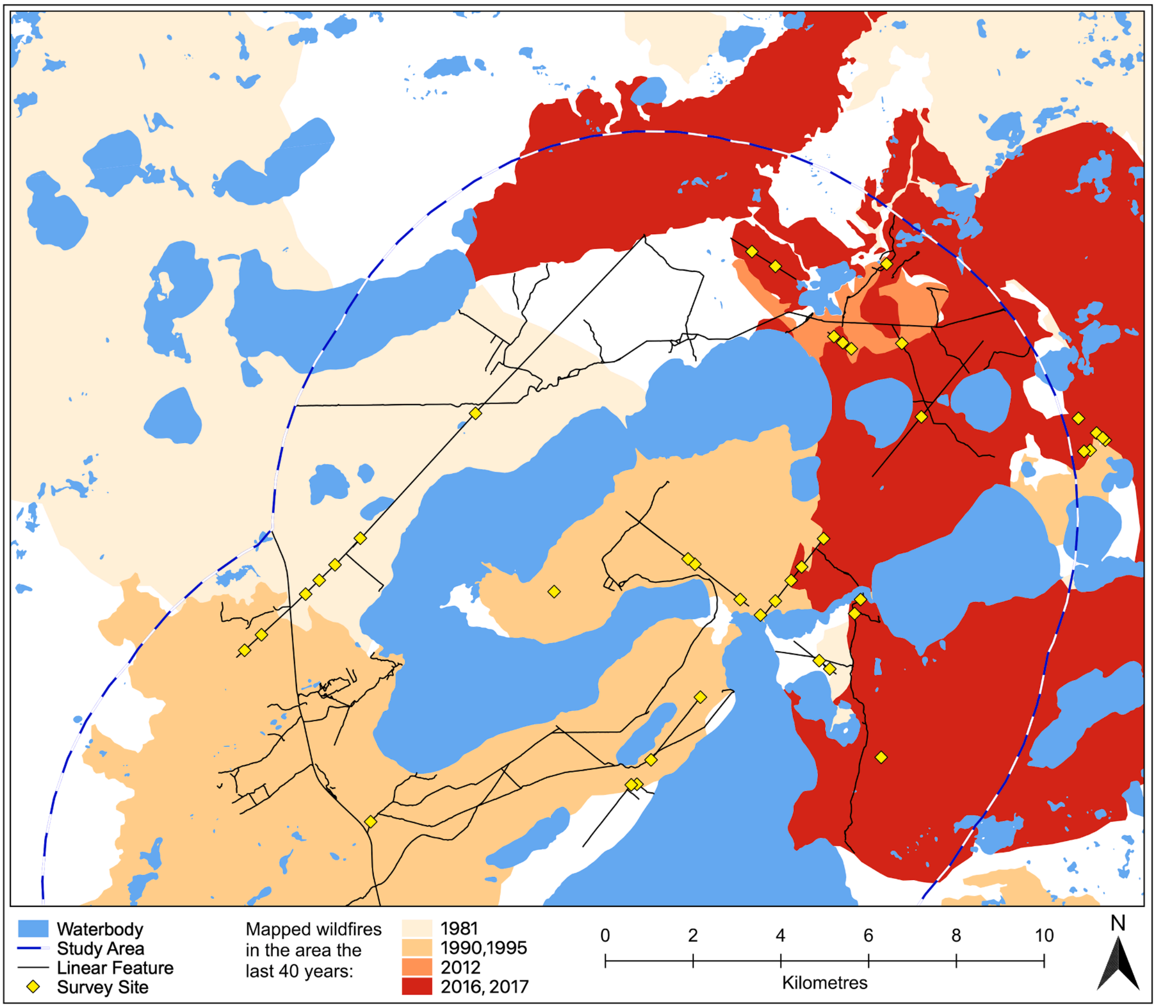


Fig. 2. Wildfires mapped over the last 40 years in the study area within the Boreal Plain (SK2) and Boreal Shield (SK1) of northern Saskatchewan, Canada. Software used to create the site layout: QGIS 3.24.3. No permissions required. All geographic data are freely available (open).

human activity associated with many legacy linear features are currently uncertain (SKMOE 2021). As a result, a program to assess the status, pattern and success of natural regeneration following wildfire could be important because reforestation of linear features can cost as much as $12,500 (CAD) per linear kilometer (Filicetti et al., 2019).

Wildfires are believed to affect woodland caribou populations by reducing cover and biomass of lichen forage (Klein 1982; Dunford et al., 2006; Collins et al., 2011; Barrier and Johnson 2012); as well as increasing snow depth and deadfall, reducing ease of movement and/or forage accessibility (Metsaranta and Mallory 2007). Caribou avoidance of burned areas has been documented in several studies (Schaefer and Pruitt 1991; Fritz et al., 1993; Joly et al., 2003; Dalerum et al., 2007; Konkolics et al., 2021), and woodland caribou are generally not expected to return to burned areas for several decades after fire until lichen forage supply, or other factors, have recovered sufficiently (ECCC 2020).

Based on the studies identified above, ECCC (2020) applied the threshold of 40 years and beyond for when habitat becomes suitable for woodland caribou following wildfire. However, more recent research in areas with high fire and low anthropogenic disturbance indicate fires may not always be detrimental for woodland caribou. Skatter et al. (2017) and Silva et al. (2020) found that woodland caribou within SK1 use and may even prefer some habitats within mapped fire polygons, particularly during calving season, which supports Bergerud's (1974) hypothesis that caribou likely have developed a compatible relationship with fire.

There may, however, be another aspect where fire could have an indirect positive effect on the landscape, and for woodland caribou, in that it has the potential to reset some stagnant anthropogenic disturbance. Previous research in the Boreal Plain of Alberta has demonstrated that natural revegetation does occur on linear features post fire. Filicetti and Nielsen (2018) investigated vegetation recovery on linear features five years post fire in upland jack pine stands and documented two-fold higher stem densities on seismic lines compared to adjacent burned forest. Filicetti and Nielsen (2020) also investigated vegetation recovery in lowlands (bogs, poor fens, rich fens, and poor mesic forests) ranging from one to 22 years post fire and documented denser regeneration on burnt lines versus unburnt lines in sites with a greater proportion of serotinous species (i.e. black spruce in bogs and poor mesic forests). Finally, Filicetti and Nielsen (2022) investigated vegetation recovery in mesic upland forests (aspen and white spruce dominant) ranging from two to 23 years post fire, and documented higher stem densities on lines than in adjacent forests. However, to date, no research has been completed to investigate long term vegetation recovery to document whether the short-term trends documented continue over the long term, 40 years post fire, when habitat is no longer considered disturbed.

In this paper we expand on the work of Filicetti and Nielsen (2018, 2020) by examining natural vegetation recovery along linear features in both upland jack pine forests and black spruce bogs from 1 to 41 years post fire. We investigate the effects of natural wildfire on tree stem density, stem height, visual obstruction (hiding cover), as well as reindeer lichen (*Cladina* spp.) recovery on burned lines versus burned adjacent forest. We then compare these results with vegetation recovery

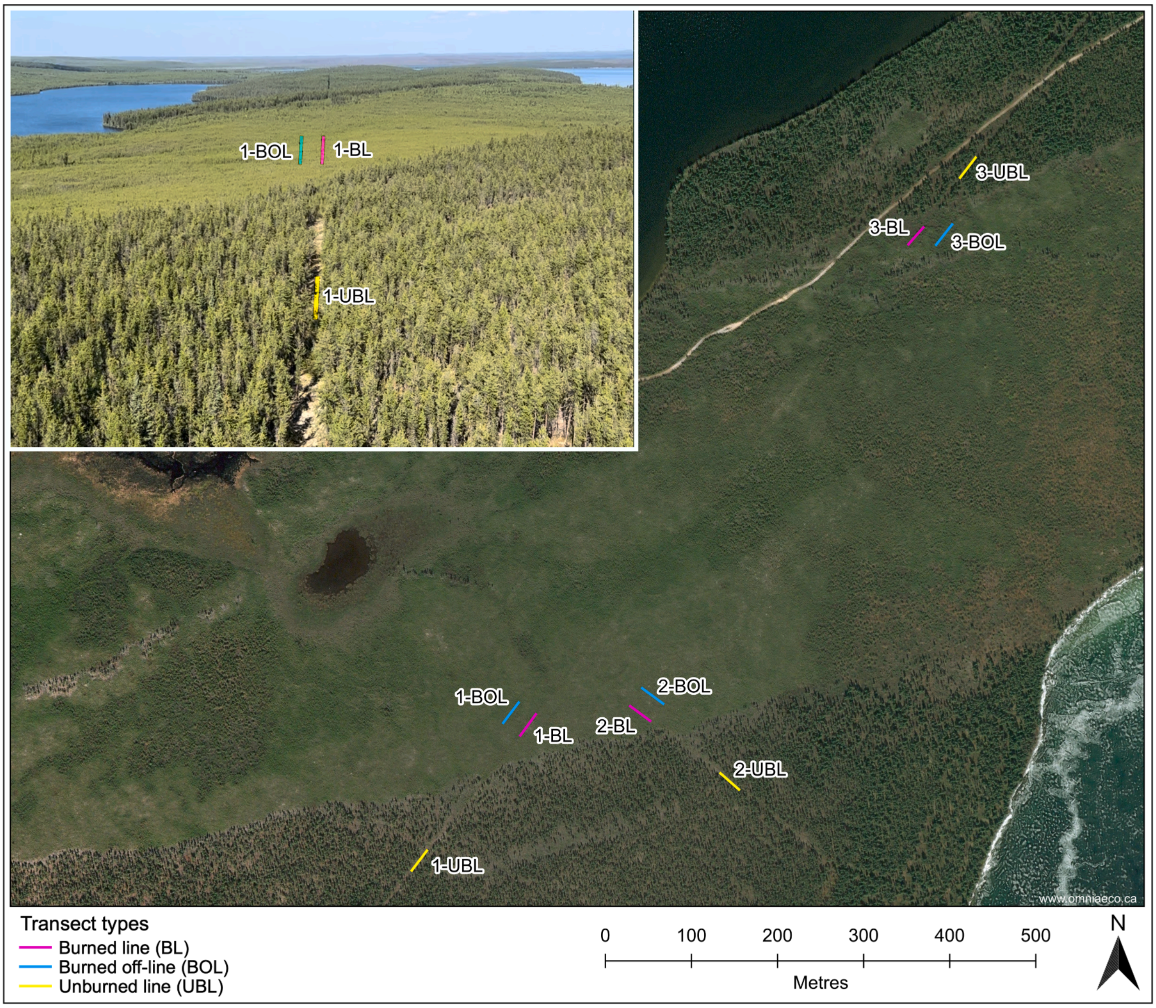


Fig. 3. Layout of the survey sites with triplicate transect lines represented by a transect on the burned line (BL), a transect in adjacent burned forest (burned off-line, BOL); and a transect in an unburned part of the line (UBL). Inset photograph displays an aerial view of site number 1. Image courtesy of Hans G. Skatter. Software used to create the site layout: QGIS 3.24.3. No permissions required.

on unburned lines. Our long-term findings, in a setting closer to that of the Boreal Shield, can be used to contribute knowledge about long term vegetation recovery on seismic lines, inform management decisions on restoration planning and the implication these results may have on calculation of range disturbance metrics.

2. Materials and methods

2.1. Study area

The study area is located in the Firebag Hills landscape area in the northern part of the Boreal Plain Ecozone (SK2), with inclusions of the Boreal Shield Ecozone (SK1) of northern Saskatchewan, in an area provincially identified as SK2 West, Northern sub-unit (ECCC 2020) (Fig. 1). The study area has a fire and anthropogenic disturbance regime closely resembling that of SK1 (SKMOE 2021). The Firebag Hills landscape area is predominantly a gently to strongly rolling morainic plain (Acton et al., 1998). The vegetation in the area is principally short stubby jack pine (*Pinus banksiana* Lamb) with a lichen understory, a reflection of extremely sandy soils and the high frequency of fire (Acton et al., 1998). The tree stands vary between young, extremely dense stands to old, open, park like stands (Carroll and Bliss 1982). This factor also is a consequence of the frequent wildfires in the region which results in the spread of jack pine (Acton et al., 1998). In the absence of fires, this cover type tends to transition toward a black spruce (*Picea mariana* (Mill.) B.S.P.) dominated cover type, which is considered a climax forest condition in the region (McLaughlan et al., 2010). Due to the high frequency of fire disturbance, black spruce forest is a less common cover type that is generally limited to islands, peninsulas, and other areas less prone to wildfire effects.

Ground cover is dominated by reindeer lichens (primarily *Cladina mitis* (Sandst.) Hustich) or feather mosses (primarily *Pleurozium schreberi* (Brid) Mitt.). Ericaceous shrubs such as blueberry (*Vaccinium myrtiloides* Michx.), bog cranberry (*V. vitis-ideae* L.), and Labrador tea (*Ledum groenlandicum*, Oeder) are common in the shrub layer, along with occasional willow (*Salix* spp.) or green alder (*Alnus viridis* Chaix) D.C.) shrubs. Poorly drained lowlands (bogs and poor fens) are characterized by an open canopy of black spruce and, to a lesser extent, tamarack (*Larix laricina* (Du Roi) K. Koch). The understory is largely dominated by ericaceous shrubs, and ground cover is represented by peat (*Sphagnum* spp.) and feather mosses. Tamarack is the dominant tree species in well drained lowlands (rich fens) with an understory dominated by willow species, birch species (*Betula* spp.) and ericaceous shrubs. Uplands comprise approximately 66% of the study area, lowlands (predominantly bogs) comprise approximately 6%, and water bodies approximately 27% (Omnia 2021).

The current linear feature density in the study area is 1.29 km/km^2, and predominantly consist of gravel roads and trails (0.57 km/km^2), and legacy seismic lines (0.72 km/km^2). Narrower linear features (e.g., hand cuts) not visible on Landsat imagery at a scale of 1:50,000 are not included. The legacy lines were cut between 1977 and 1980 (Armitage 2013), which makes these lines 42–45 years old at the time of the study. These lines are straight, 4–6 m wide, and up to 15 km long in the study area. Based on fire mapping provided by the Saskatchewan Ministry of Environment, seven fires have occurred within the study area the last 40 years (since 1982). These fires covered 231 km^2, which equates to 58% of the study area (including water) and 79% of the terrestrial area only (Omnia 2021). The fires were categorized into four age groups describing the number of years since fire, as described in Section 2.3 (Fig. 2).

2.2. Site selection and field methods

A desktop assessment was completed using existing ecosite, fire, anthropogenic and current Google Earth and Bing Imagery mapping compiled for a terrestrial baseline survey completed in area (Omnia 2021). The desktop assessment identified candidate sites in upland and lowland areas along linear features (i.e., legacy seismic lines and trails) that had been completely or partially affected by any of the seven wildfires within the study area. The focus of the field program was on lines that had not experienced human use since creation.

The sites were accessed in the field by foot, by use of all-terrain vehicles (ATV), or by helicopter. Additional sites discovered from the air immediately adjacent to the study area were opportunistically included in the program as well. At each site, an assessment of human use since fire was completed based on evidence of vehicle tracks, compacted vegetation and broken or bent over trees. If evidence of human use was noted, the site would be excluded from the survey. Since some of the linear features in the study area were up to 15 kms long, several survey sites were placed along some lines. Sites on the same line were spaced at least 400 m apart (as per Filicetti and Nielsen 2020), unless in a separate fire polygon (i.e. fire from a different year) and/or a different vegetation type (ecosite) or polygon.

In total, 40 sites were sampled in the summer of 2022 with each site consisting of either triplicate transects (22 sites) or a pair of transects (18 sites) for a total of 102 transects. The triplicate transects were each represented by: (1) a transect on the burned line, (2) a transect in adjacent burned forest (off-line); and (3) a transect on an unburned part of the line in the same ecosite (Fig. 3). As per Filicetti and Nielsen (2018), each site was selected based on the requirement of having uniform stand conditions (i.e., height, density, age). Efforts were also made to ensure adjacent unburned sections of the same line were within the same ecosite. In instances where unburned sections of lines were not available adjacent to the burned transects and within the same ecosite, paired transects on burned line and off-line would be sampled. Burned transects were required to have 100% fire severity (measured by overstory tree mortality), and unburned transects were required to have 0% fire severity (i.e., located far enough from the fire edge to have no effect from fire). Each transect measured 30 m in length and was located in the center of the linear feature. Adjacent paired control transects were located 25 m into the adjacent burned forest running parallel to the linear feature. A coin toss was used to randomize which side of the seismic lines the adjacent forest control transect was located, however, if the control transect interfered with adjacent unburned forest polygons, they were placed on the opposite side. Also, if a transect was located in an area with less than 100% fire severity, it was moved parallel into an area with 100% fire severity (see 3-BOL in Fig. 3, this transect was moved out of a residual patch).

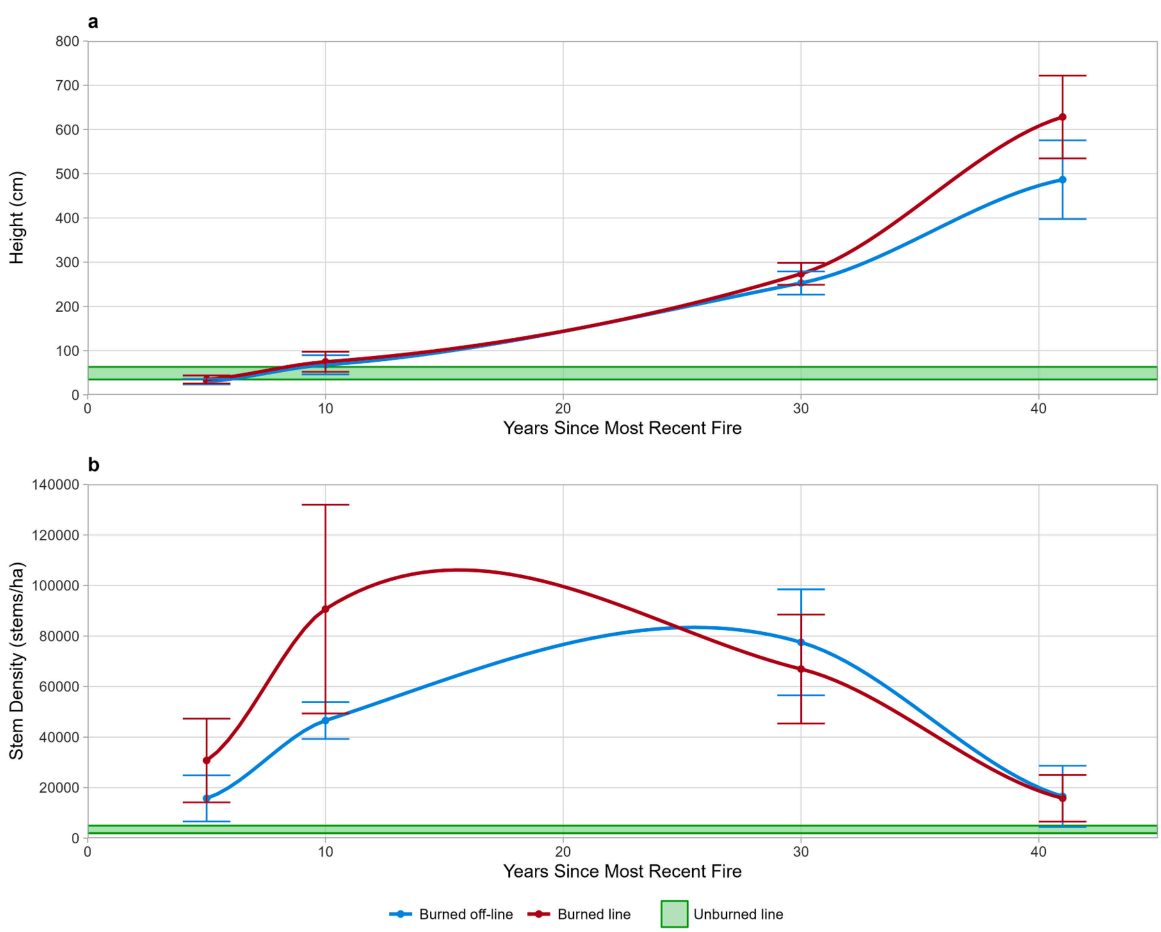


Fig. 4. Stem height (a) and stem density (b) for upland burned off-line, burned line, and unburned line transects against years since the most recent fire. Variation around the means is illustrated by standard error bars. Unburned line data is independent of time and therefore illustrated as a rectangle bounded by standard error.

Tree regeneration (stem count) and forest stand conditions were measured along the transects with regenerating tree species counted within the full 1 m x 30 m quadrat. Stem height, diameter at mid-point, and species were recorded at 3-meter intervals along the transects, totaling 10 samples per transect. To avoid bias, the individual trees closest to the 0 m, 3 m, 6 m, and so on, up to 27 m along the transect where measured. Site-specific information regarding the adjacent unburned forest was collected including ecosite, tree canopy closure and composition, species, diameter at breast height (DBH), age (based on tree cores), and height of key tree species using a Haglöf Vertex 5 (Sweden) hypsometer. Stem counts were not completed in the adjacent unburned forest as this information is well documented by McLaughlan et al. (2010).

Visual obstruction from vegetation (hiding cover) was measured in two directions from the center and along each transect and corresponding reference transect(s) adapting methods by Nudds (1977) as described in Charlebois et al. (2015). A red and white color-coded cloth measuring 2.5 m in height was held upright 15 m from the observer at transect center. The observer viewed the cloth from caribou eye level height (1.8 m above ground). An estimate of the percent obstructed/hidden (by vegetation) was recorded for each 25 cm x 25 cm block which makes up the cloth.

Additional information including reindeer lichen species (*Cladina* spp.) percentage cover and mat thickness was estimated in five 20 cm x 50 cm plots spaced five m apart along the transect.

2.3. Statistical analysis

Data from burned line and burned off-line transects in uplands and lowlands were categorized into four age groups describing the number of years since the most recent fire; 5–6 years, 10 years, 27–32 years, and 41 years. Data from unburned line transects were similarly categorized into the same four age groups based on the age group of the burned line and burned off-line plots in the corresponding triplicate. For unburned line plots in both uplands and lowlands, we tested for any significant difference in stem height, stem density, visual obstruction, lichen cover, and lichen depth between the four age groups. This data was first tested for normality using Shapiro-Wilk's normality tests, and as some data did not conform to the normal distribution ($p < 0.05$), a Kruskall-Wallis H tests where used to test for differences. No significant differences were found between age groups for any variables. Data from unburned line transects were therefore categorized into either 'upland unburned line' or 'lowland unburned line' categories. These two categories describe linear features that have not been disturbed by fire, thus they are not associated with a post-fire age group, but rather act as a time-independent reference for burned line and adjacent burn transects in all age groups.

Patterns in regeneration across time were visualized by plotting the means and standard errors for stem height and stem density (stems per hectare) against the number of years since the most recent fire for both upland and lowland forests. Hiding cover across time was also visualized by comparing the mean and standard error at each height interval for each age group in upland and lowland forests. Upland or lowland unburned line data were included as references on all visualizations. In these visualizations, standard error bars indicate the degree of variability in the data. A formal statistical test for differences in stem height, stem density, hiding cover, and reindeer lichen cover between burned line, burned off-line, and unburned line transects for each forest type and age group was conducted using Dunn's tests. Dunn's tests were used as Shapiro-Wilk's normality tests revealed that some data did not conform to the normal distribution ($p < 0.05$).

Data visualization and statistical analysis was performed using R Statistical Software (v4.1.2; R Core Team, 2022), and the packages ggplot2 (v3.4.0; Wickham, 2016) and ggpubr (v0.4.0; Kassambara, 2020).

Table 1
Dunn's test *p*-values and z-statistics (in parentheses) for stem heights, stem density, and hiding cover for upland and lowland transects at each age group. Hiding cover refers to the average percentage hidden values from 0–250 cm from ground; see Appendix 1 (upland) and Appendix 2 (lowland) for the Dunn's test *p*-values by interval.

	5–6 Years	10 Years	27–32 Years	41 Years
Upland				
Stem Height				
Burned Line – Burned Off-line	0.953 (−0.059)	0.827 (−0.219)	0.809 (−0.241)	0.744 (−0.327)
Burned Line – Unburned Line	0.852 (−0.186)	0.247 (1.158)	< 0.001*** (3.976)	< 0.001*** (3.427)
Burned Off-line – Unburned Line	0.801 (−0.252)	0.379 (0.879)	< 0.001*** (3.836)	0.002** (3.033)
Stem Density				
Burned Line – Burned Off-line	0.527 (−0.633)	0.715 (−0.365)	0.977 (0.028)	0.657 (−0.444)
Burned Line – Unburned Line	0.017* (2.379)	0.004** (2.881)	< 0.001*** (3.826)	0.013* (2.479)
Burned Off-line – Unburned Line	0.094 (1.675)	0.016* (2.416)	< 0.001*** (3.975)	0.052 (1.946)
Hiding Cover				
Burned Line – Burned Off-line	0.560 (0.584)	1.000 (0.000)	0.835 (−0.208)	0.695 (−0.392)
Burned Line – Unburned Line	0.365 (−0.906)	0.031* (2.164)	< 0.001*** (4.280)	< 0.001*** (3.407)
Burned Off-line – Unburned Line	0.786 (−0.271)	0.031* (2.164)	< 0.001*** (4.063)	0.003** (2.948)
Lowland				
Stem Height				
Burned Line – Burned Off-line	0.953 (0.059)	–	0.361 (0.913)	0.898 (0.128)
Burned Line – Unburned Line	0.001** (−3.239)	–	0.852 (0.186)	0.609 (0.511)
Burned Off-line – Unburned Line	0.001** (−3.179)	–	0.192 (1.304)	0.500 (0.675)
Stem Density				
Burned Line – Burned Off-line	0.953 (−0.059)	–	0.091 (−1.690)	0.054 (−1.926)
Burned Line – Unburned Line	0.014* (−2.466)	–	0.008** (2.667)	0.112 (1.588)
Burned Off-line – Unburned Line	0.012* (−2.526)	–	0.551 (0.597)	0.381 (−0.876)
Hiding Cover				
Burned Line – Burned Off-line	0.853 (0.185)	–	0.656 (0.446)	0.696 (0.390)
Burned Line – Unburned Line	0.192 (−1.306)	–	0.346 (0.943)	0.369 (0.897)
Burned Off-line – Unburned Line	0.260 (−1.126)	–	0.145 (1.458)	0.171 (1.368)

* Significant below the 0.05 probability level.
** Significant below the 0.01 probability level.
*** Significant below the 0.001 probability level.

3. Results

3.1. Upland regeneration dynamics

3.1.1. Stems/ha and stem height

On the unburned lines, there has been minimal vegetation recovery, both in terms of stem density and height, since time of cutting (40+ years) (Fig. 4). Stem density on burned lines and burned off-line transects initially rapidly increased, before decreasing between the 10 year and 27–32 year time groups (Fig. 4). This pattern of regeneration and thinning occurred more quickly on burned line transects, where the stem density was significantly greater than on the unburned line transects by the 5–6 year group. Stem density remained significantly greater on the burned line transects than on the unburned line transects in all of the older age groups (Fig. 4, Table 1). In comparison, stem density on the burned off-line transect was not significantly greater than the unburned line transect until the 10 year age group. Stem density remained significantly greater on burned off-line transects than on unburned line

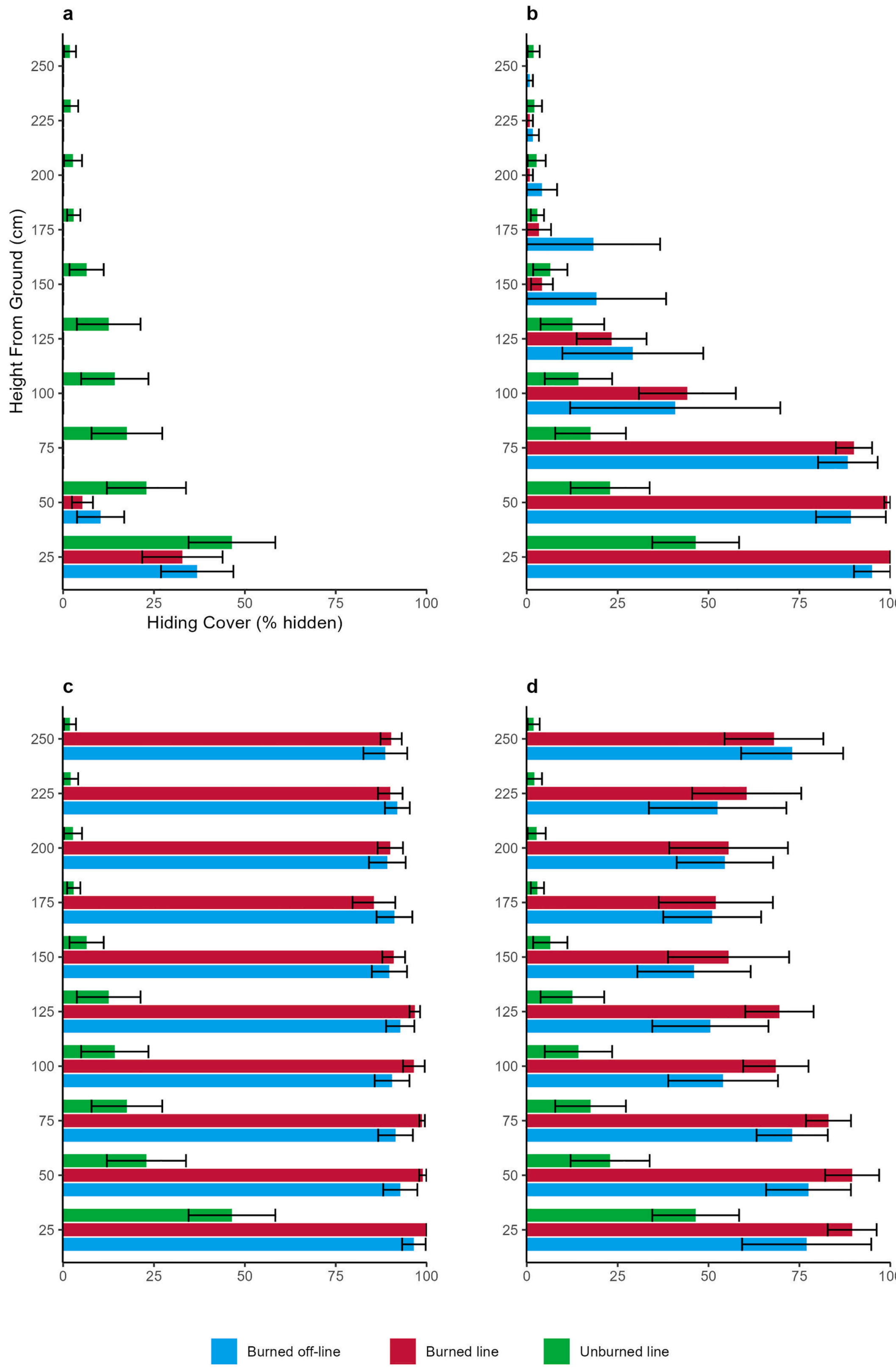


Fig. 5. Mean and standard error (error bars) showing hiding cover for upland burned off-line, burned line, and unburned line transects at age groups 5–6 years (a), 10 years (b), 27–32 years (c), and 41 years (d).

transects in the 27–32 year age group, but was no longer a significantly different by the 41 year age group. There was no significant difference in stem density between burned line and burned off-line transects in any age group (Table 1).

Stem height consistently increased on burned line and burned off-line transects across time (Fig. 4). In age groups 5–6 and 10 years, the average stem height on these transects was not significantly different compared to the average stem height on the unburned line transect,

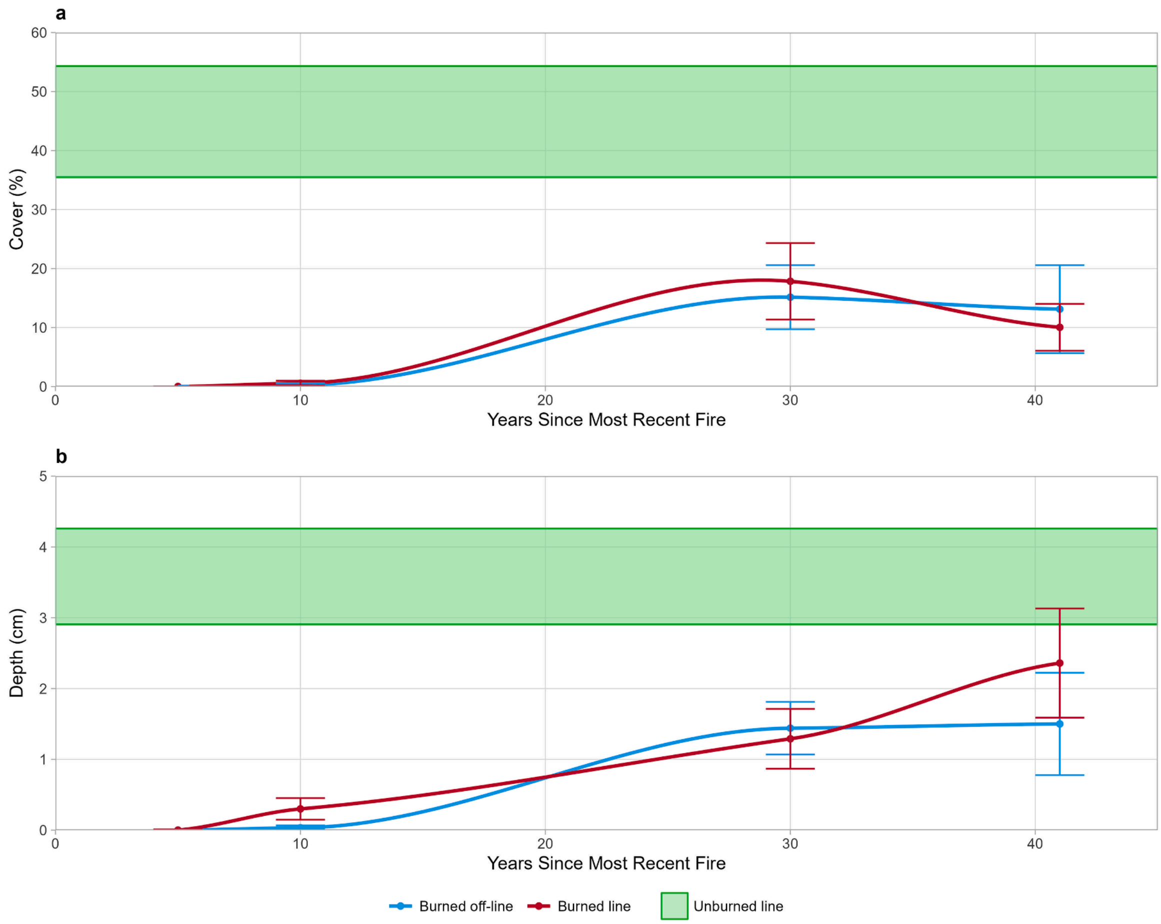


Fig. 6. Reindeer lichen (*Cladina* spp.) percentage cover (a) and mat thickness (b) for upland burned off-line, burned line, and unburned line transects against years since the most recent fire. Variation around the means is illustrated by standard error bars. Unburned line data is independent of time and therefore illustrated as a rectangle bounded by standard error.

however, by the 27–32 and 41 year age groups, stem height was significantly greater on burned line and burned off-line transects. There was no significant difference in stem height between burned line and burned off-line transects in any age group (Table 1).

3.1.2. Visual obstruction

In the first age group, 5–6 years, there was no significant difference in hiding cover between burned line, burned off-line, and unburned line transects (Fig 5. Table 1). In the following two age groups, 10 years and 27–32 years, hiding cover progressively increased on the burned line and burned off-line transects, and was significantly higher than hiding cover on unburned line transects. Hiding cover decreased on burned line and burned off-line transects by the 41 year age group, but remained significantly higher than on the unburned line transect. There was no significant difference in hiding cover between burned line and burned off-line transects in any age group or any height-from-ground interval (Appendix 1).

3.1.3. Reindeer lichen cover and mat thickness

The average cover and mat thickness of reindeer lichen was relatively high on the unburned lines at 45% ± 9% and 3.6 ± 0.7 cm (Fig. 6). No reindeer lichen was observed on either burned line of burned off-line plots in the 5–6 years group. Reindeer lichen cover and thickness remained significantly lower on burned line and burned off-line plots than on unburned line plots until the 41-year age group, where no significant difference was found between all plots for both lichen cover and thickness (Fig. 6, Table 2). The exception to this is in the 10-year age group, where there was no significant difference in lichen depth between the burned line and unburned line plots. There was no significant difference in either reindeer lichen cover or thickness between burned line and burned off-line in any age group (Fig. 6, Table 2).

3.2. Lowland regeneration dynamics

3.2.1. Stems/ha and stem height

On the unburned lines, there is limited vegetation recovery since time of cutting (40+ years), however the stem density is about five times higher in the lowlands compared to the uplands. The average stems per hectare was 20,481 ± 2692, with an average height of 58 ± 13 cm. Stem density and stem height was initially significantly higher on unburned line transects than on either burned line or burned off-line transects (Fig. 7). By the 27–32 year age group and into the 41 year age group, there was no longer a significant difference in stem density between the three transects, with the exception of stem density being significantly higher on burned line transects than on unburned line transects in the 27–32 year age group. There was no significant difference in stem density between burned line and burned off-line transects in any age group (Table 1).

3.2.2. Visual obstruction

In all age groups, there was no significant difference in hiding cover between burned line, burned off-line, and unburned line transects (Fig. 8, Table 1). Furthermore, there was no height- from-ground interval where a significant difference in hiding cover occurred between these transects (Appendix 2).

Table 2
Dunn's test *p*-values and z-statistic (in parentheses) for *Cladina* spp. depth and ground cover for upland and lowland plots at each age group**.

	5–6 Years	10 Years	27–32 Years	41 Years
Upland				
Lichen Depth				
Burned Line – Burned Off-line	1.00 (0.000)	0.422 (−0.804)	0.762 (0.303)	0.558 (−0.586)
Burned Line – Unburned Line	< 0.001*** (−3.678)	0.163 (−1.393)	0.012* (−2.520)	0.263 (−1.118)
Burned Off-line – Unburned Line	< 0.001*** (−3.678)	0.016* (−2.418)	0.028* (−2.198)	0.068 (−1.823)
Lichen Proportion				
Burned Line – Burned Off-line	1.00 (0.000)	0.610 (−0.510)	0.991 (0.012)	0.963 (0.047)
Burned Line – Unburned Line	< 0.001*** (−3.676)	0.100 (−1.644)	0.042* (−2.034)	0.086 (−1.718)
Burned Off-line – Unburned Line	< 0.001*** (−3.676)	0.022* (−2.295)	0.043* (−2.021)	0.097 (−1.662)
Lowland				
Lichen Depth				
Burned Line – Burned Off-line	0.965 (0.044)	–	0.847 (0.193)	0.661 (0.439)
Burned Line – Unburned Line	0.255 (−1.139)	–	0.288 (1.062)	0.992 (−0.010)
Burned Off-line – Unburned Line	0.273 (−1.095)	–	0.194 (1.298)	0.581 (0.551)
Lichen Proportion				
Burned Line – Burned Off-line	0.965 (0.044)	–	0.847 (0.193)	0.770 (0.293)
Burned Line – Unburned Line	0.255 (−1.139)	–	0.288 (1.062)	0.827 (0.218)
Burned Off-line – Unburned Line	0.273 (−1.095)	–	0.194 (1.298)	0.553 (0.593)

* Significant below the 0.05 probability level.
** Significant below the 0.01 probability level.
*** Significant below the 0.001 probability level.

3.2.3. Reindeer lichen cover and mat thickness

The average cover and mat thickness of reindeer lichen was very low on the unburned lines (Fig. 9). No significant difference between reindeer lichen cover or mat thickness was found between the three transect locations for any age group (Fig. 9, Table 2).

4. Discussion

Our results document natural regeneration on linear features following wildfire, in the SK2 West, Northern sub-unit. The SK2 sub-unit of Saskatchewan is an area with natural wildfire disturbance with minimal fire suppression (Government of Saskatchewan 2021). These findings provide novel information about long term vegetation recovery on legacy exploration lines and lend support to informed management decisions on woodland caribou habitat restoration planning in the region. The outcomes of our study align with recent discoveries made by Filicetti and Nielsen (2018 and 2020) on short-term vegetation recovery on legacy linear features after fires. Our research demonstrates that the early post fire regeneration documented in these studies in fact does persist over a span of 40+ years. This time span corresponds to the length of time, post fire, where ECCC (2020) considers post fire areas to no longer be disturbed and thus provide critical habitat to woodland caribou.

4.1. Upland regeneration dynamics

In the absence of fire, we noted minimal recovery of trees and shrubs even after more than 40 years since the establishment of the line. This highlights the long-term impacts and raises questions about the potential factors inhibiting natural regeneration. On the contrary, when a wildfire occurred, there was a noticeable and rapid increase in stem counts and heights of trees and shrubs, which highlights the role of fire as a catalyst for ecological recovery. Of particular note, there were no significant differences observed in stem counts, heights, and hiding cover between the burned line and the burned off-line in any age category post-fire.

These results demonstrates that post wildfire vegetation establishment is similar in burned forest areas and burned legacy linear features across all sites, revealing that the past disturbance regimes did not alter the potential for forest re-establishment. Jackpine was the dominant species in the uplands. This species is well adapted to pyric ecosystems, producing serotinous cones that open immediately following wildfire (Burns and Honkala 1990). The large number of seeds released germinate in the same year, establishing extensive, even-aged, pure stands on upland sand/gravel substrates (Yarranton and Yarranton 1975; Kenkel 1988).

As Filicetti and Nielsen (2018) documented, we also observed trends toward higher stem densities on burned lines versus burned off-lines. This observation was however only noted in the younger age groups, up to 10 years post fire, and was not statistically significant. As the forest matured, the stem counts evened out on and off-line, as the overall density decreased with age. The lower stem-counts in the oldest age group demonstrate that natural self-thinning is occurring as the forest matures as discussed by Kenkel (1988).

The finding that lichen cover and mat thickness was higher for unburned lines than for burned lines and burned off-lines in all age categories, was not unexpected as these lines may have been left undisturbed since creation, or for some time. This may also be due to the method that was used for cutting the lines in the late 1970s. From the 1950s until the 1990s, seismic lines were created by bulldozers that removed all trees and shrubs along with varying amounts of organics, topsoil and subsoil (Lee and Boutin, 2006). Even with the use of this technique, it is likely that some low level ground vegetation, including lichens, were left intact, and unlike areas affected by wildfires, the establishment phase was not always necessary.

4.2. Lowland regeneration dynamics

Our findings demonstrate differences in recovery between uplands and lowlands, as the unburned lines in lowlands had natural recovery stem densities that were five times higher than uplands. This result indicates that some natural recovery is occurring in these areas in the absence of fire, which implies that, given sufficient time, the lowlands will slowly revegetate. We did find, however, that in the 27–32 years post fire age group, stem densities were no longer different from unburned lines, indicating that fires can speed up the revegetation process by at least 8–13 years, but possibly sooner.

Generally, both stem counts and hiding cover was much lower in the lowlands than in the uplands post fire, which is likely a result of the difference in tree species regenerating characteristics and because black spruce were most abundant in lowlands compared to jack pine in the uplands. Black spruce does not have serotinous cones and relies on being

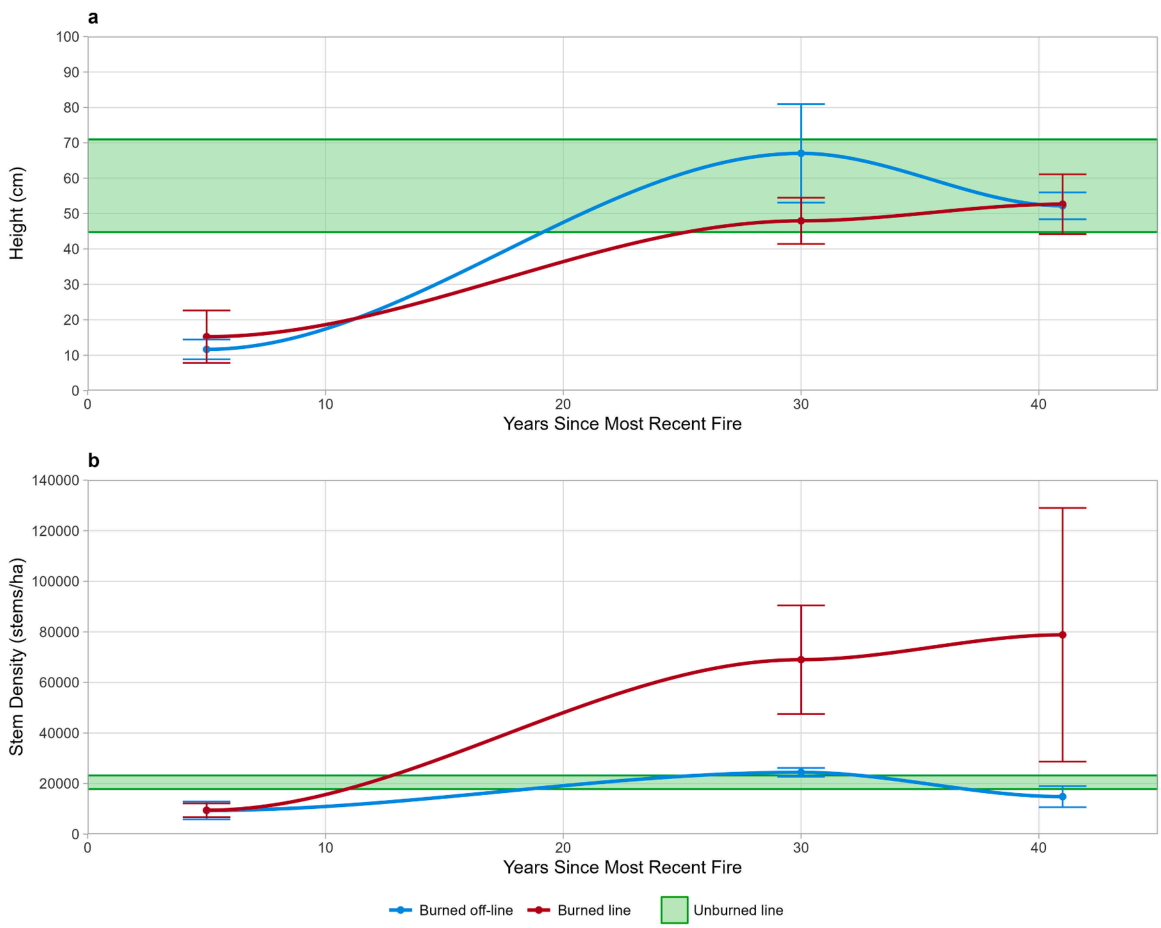


Fig. 7. Stem height (a) and stem density (b) for lowland burned off-line, burned line, and unburned line transects against years since the most recent fire. Variation around the means is illustrated by standard error bars. Unburned line data is independent of time and therefore illustrated as a rectangle bounded by standard error. No lowland transects in the 10 year age group were sampled.

self-replaced via seedling establishment from aerial seedbanks (Greene and Johnson 1999; Johnstone et al., 2010)

Lichen cover in lowlands sites is low and patchy overall and it is not surprising that no significant differences in lichen cover were observed.

5. Conclusions and management implications

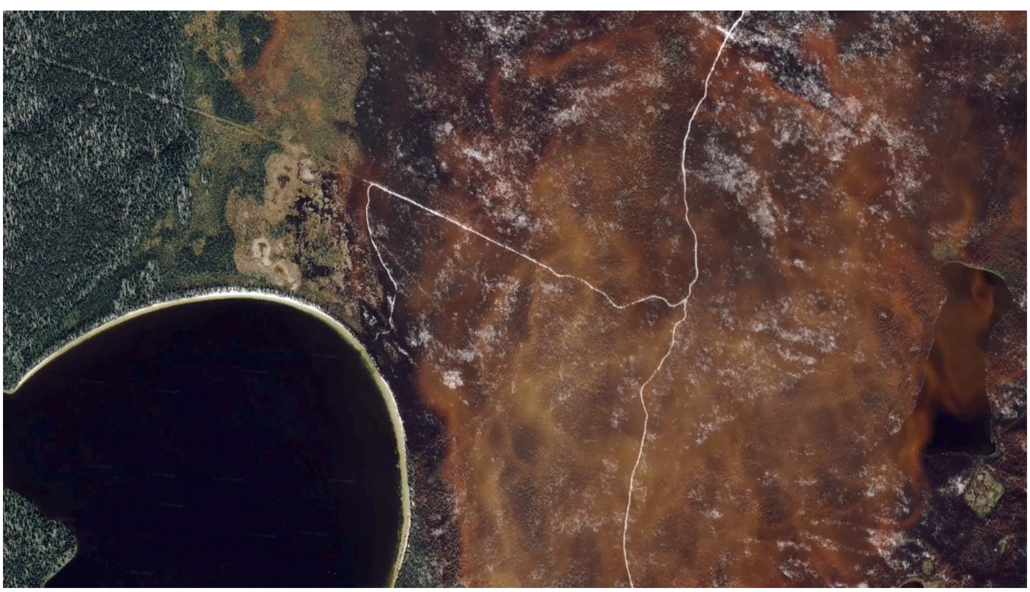
The potential management implications of these findings, as they pertain to woodland caribou habitat management in particular, are important for three reasons. First, we suggest that post fire, the currently applied 500 m buffer for anthropogenic disturbance, including linear features such as trails and legacy seismic lines, should be removed from the burned portion of the line. Following fire, given the extent and degree of natural regeneration, the legacy feature should be treated as natural disturbance. Once this area reaches 40 years of age, the entire area should be considered undisturbed.

Second, the current methods of restoration/reforestation of seismic lines are expensive (averaging $12,500 per km), with uncertainty of which seismic lines need treatments, if any, resulting in inefficiencies in restoration actions (Filicetti et al., 2019). As our results have demonstrated, because there is some recovery in the lowlands, the best use of resources would be in uplands rather than lowlands.

Finally, ECCC (2020) has outlined specific goals to reduce the current level of anthropogenic disturbance across all woodland caribou ranges in Canada. Given the extent of the current linear footprint across Canada, the cost of restoring these lines and how efficient wildfires are in terms of resetting the disturbance, some type of prescribed burn might be more efficient both in terms of cost and revegetation success. As an example, an estimated 150,000 km of legacy seismic lines across Alberta will require some type of intervention to be on a trajectory to full recovery (Anderson 2018). Using Filicetti et al. (2019) cost per km calculation, this would cost approximately $1.9 billion (CAD) to achieve with current conventional restoration methods.

Our findings will assist in boreal caribou habitat management in Saskatchewan and across Canada. First, we can use these natural regeneration results in conjunction with up to date fire mapping and legacy anthropogenic disturbance to more accurately calculate the current levels of critical woodland caribou habitat across woodland caribou ranges. Second, using the study results and up to date fire and baseline ecological land classification mapping (e.g., upland vs. lowland) we can rank or prioritize areas for the application of restoration/revegetation efforts. Third, for industry and project planning purposes, these same map layers can be used to minimize future impacts or align project related footprint to areas where impacts already exist and are not likely to recover.

We have created a short video highlighting our findings. Filmed in 2022, the video features a flyover above one of the legacy seismic lines in the study area cut in the late 1970′s across both upland and lowland areas. Over the years, portions of this line have been impacted by wildfires ranging from five to 32 years ago (Video 1).



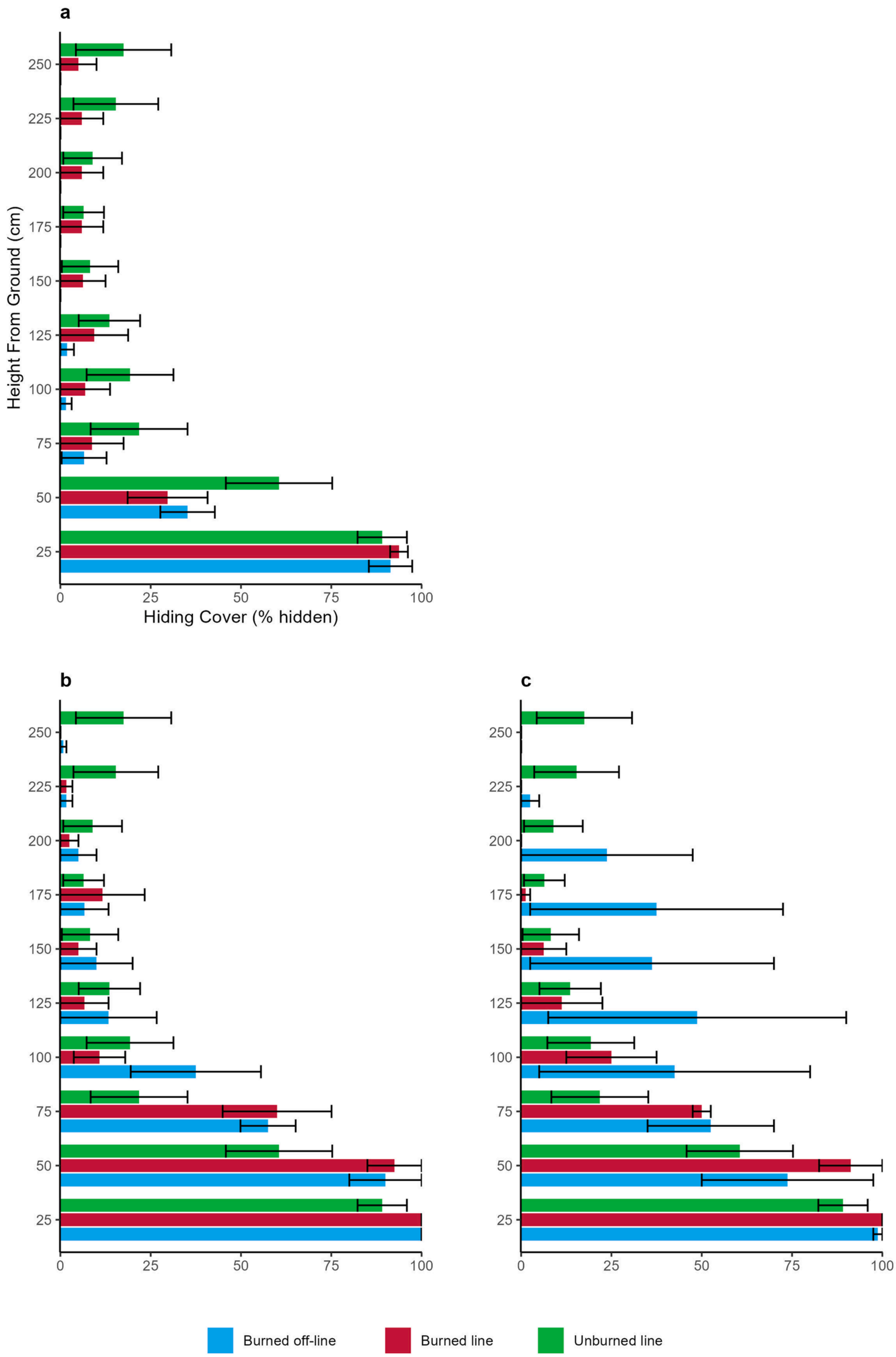


Fig. 8. Mean and standard error (error bars) showing hiding cover for lowland burned off-line, burned line, and unburned line transects at age groups 5–6 years (a), 27–32 years (b), and 41 years (c). No lowland transects in the 10 year age group were sampled.

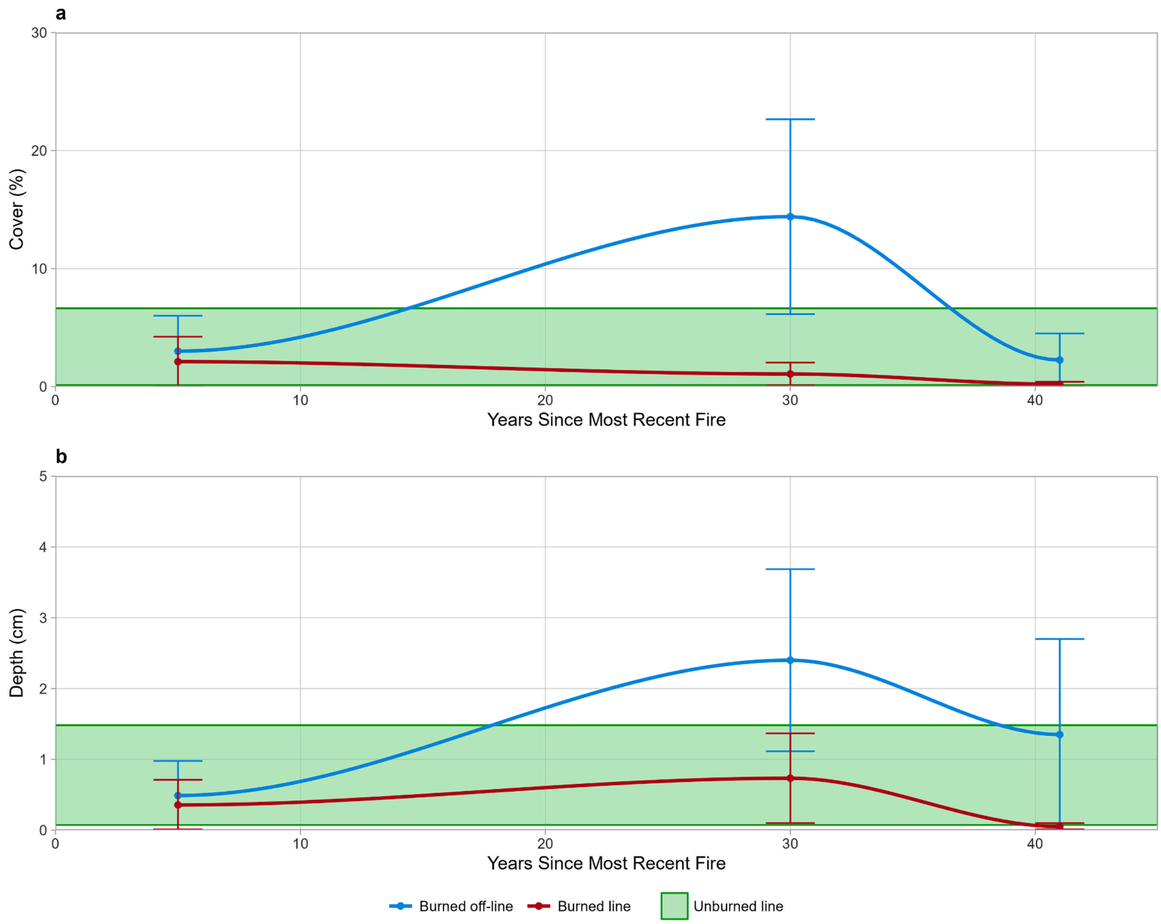


Fig. 9. Reindeer lichen (*Cladina* spp.) percentage cover (a) and mat thickness (b) for upland burned off-line, burned line, and unburned line transects against years since the most recent fire. Variation around the means is illustrated by standard error bars. Unburned line data is independent of time and therefore illustrated as a rectangle bounded by standard error. No lowland transects in the 10-year age group were sampled.

CRediT authorship contribution statement

H.G. Skatter: Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **M.L. Charlebois:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **S. Coats:** Writing – original draft, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Hans Skatter and Michael Charlebois reports financial support was provided by NexGen Energy. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2024.100539.

Appendices

Appendix 1

Dunn's test *p*-values for hiding cover for upland transects at each interval and age group.

	5–6 Year	10 Years	27–32 Years	41 Years
250 cm				
Burned Line – Burned Off-line	1.00	0.32	0.59	0.88
Burned Off-line – Unburned Line	0.16	0.56	<0.001	<0.001
Burned Line – Unburned Line	0.16	0.49	<0.001	<0.001
225 cm				
Burned Line – Burned Off-line	1.000	0.906	0.714	0.835
Burned Off-line – Unburned Line	0.334	0.333	<0.001	0.002
Burned Line – Unburned Line	0.334	0.413	<0.001	<0.001
200 cm				
Burned Line – Burned Off-line	1.000	0.875	0.981	0.919
Burned Off-line – Unburned Line	0.164	0.517	<0.001	0.001
Burned Line – Unburned Line	0.164	0.654	<0.001	0.002
175 cm				
Burned Line – Burned Off-line	1.000	0.772	0.846	0.960
Burned Off-line – Unburned Line	0.083	0.582	<0.001	0.001
Burned Line – Unburned Line	0.083	0.854	<0.001	0.002
150 cm				
Burned Line – Burned Off-line	1.000	0.772	0.846	0.960
Burned Off-line – Unburned Line	0.083	0.582	<0.001	0.001
Burned Line – Unburned Line	0.083	0.854	<0.001	0.002
125 cm				
Burned Line – Burned Off-line	1.000	0.936	0.697	0.727
Burned Off-line – Unburned Line	0.041	0.051	<0.001	0.016
Burned Line – Unburned Line	0.041	0.065	<0.001	0.005
100 cm				
Burned Line – Burned Off-line	1.000	0.938	0.407	0.588
Burned Off-line – Unburned Line	0.009	0.083	<0.001	0.036
Burned Line – Unburned Line	0.009	0.067	<0.001	0.006
75 cm				
Burned Line – Burned Off-line	1.000	0.907	0.473	0.787
Burned Off-line – Unburned Line	0.009	0.035	0.001	0.020
Burned Line – Unburned Line	0.009	0.024	0.000	0.008
50 cm				
Burned Line – Burned Off-line	0.785	0.670	0.655	0.624
Burned Off-line – Unburned Line	0.265	0.049	<0.001	0.035
Burned Line – Unburned Line	0.415	0.012	<0.001	0.007
25 cm				
Burned Line – Burned Off-line	0.637	0.688	0.499	0.747
Burned Off-line – Unburned Line	0.942	0.099	0.003	0.196
Burned Line – Unburned Line	0.556	0.031	<0.001	0.093

Appendix 2

Dunn's test *p*-values for hiding cover for lowland transects at each interval and age group.

	5–6 Year	10 Years	27–32 Years	41 Years
250 cm				
Burned Line – Burned Off-line	0.469	–	0.436	1.000
Burned Off-line – Unburned Line	0.110	–	0.933	0.381
Burned Line – Unburned Line	0.369	–	0.314	0.381
225 cm				
Burned Line – Burned Off-line	0.469	–	1.000	0.388
Burned Off-line – Unburned Line	0.110	–	0.888	0.798
Burned Line – Unburned Line	0.369	–	0.888	0.412
200 cm				
Burned Line – Burned Off-line	0.469	–	0.898	0.292
Burned Off-line – Unburned Line	0.110	–	0.829	0.573
Burned Line – Unburned Line	0.369	–	0.948	0.452
175 cm				
Burned Line – Burned Off-line	0.431	–	0.898	0.216
Burned Off-line – Unburned Line	0.126	–	0.948	0.097
Burned Line – Unburned Line	0.442	–	0.829	0.906
150 cm				
Burned Line – Burned Off-line	0.469	–	0.898	0.323
Burned Off-line – Unburned Line	0.110	–	0.829	0.081
Burned Line – Unburned Line	0.369	–	0.948	0.607
125 cm				
Burned Line – Burned Off-line	0.878	–	0.811	0.343
Burned Off-line – Unburned Line	0.171	–	0.904	0.226
Burned Line – Unburned Line	0.222	–	0.686	0.978

(*continued on next page*)

Appendix 2 (*continued*)

	5–6 Year	10 Years	27–32 Years	41 Years
100 cm				
Burned Line – Burned Off-line	0.878	–	0.456	1.000
Burned Off-line – Unburned Line	0.125	–	0.169	0.364
Burned Line – Unburned Line	0.166	–	0.621	0.364
75 cm				
Burned Line – Burned Off-line	0.728	–	0.833	1.000
Burned Off-line – Unburned Line	0.078	–	0.136	0.138
Burned Line – Unburned Line	0.036	–	0.082	0.138
50 cm				
Burned Line – Burned Off-line	0.630	–	0.871	0.406
Burned Off-line – Unburned Line	0.216	–	0.205	0.767
Burned Line – Unburned Line	0.089	–	0.144	0.183
25 cm				
Burned Line – Burned Off-line	0.510	–	1.000	0.410
Burned Off-line – Unburned Line	0.803	–	0.091	0.769
Burned Line – Unburned Line	0.376	–	0.091	0.186

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