

TAILORED RESTORATION RESPONSE: PREDICTIONS AND GUIDELINES FOR WETLAND RENEWAL

RESEARCH ARTICLE

Soil mounding as a restoration approach of seismic lines in boreal peatlands: implications on microtopography

Jaime Pinzon^{1,2} , Anna Dabros¹, Philip Hoffman¹

Seismic lines—narrow and straight corridors from which overstory has been removed to allow access for oil and gas exploration—are a major human footprint in the boreal forest of western Canada. With slow to minimal recovery of tree cover along these corridors, seismic lines have become a persistent landscape feature affecting connectivity and habitat quality in forested ecosystems, particularly in wetland areas. Soil mounding is a common ground preparation treatment widely applied along seismic lines, with the expectation that it will enhance tree seedling establishment and improve the return of tree cover to disturbed areas. However, much is still unknown about environmental responses following treatment application. In this study, we compared the ground microtopography in treated and untreated seismic lines, as well as the relative elevation between treated and untreated seismic lines with their adjacent treed peatland. The ground elevation in both treated and untreated sites was significantly lower on seismic lines relative to their adjacent treed peatland, with a greater elevation difference in treated areas. Likewise, ground microtopography was orders of magnitude higher along treated areas compared to the natural variation in the adjacent treed peatland. Given the important changes in relative elevation and topography following treatment application, our results suggest the potential for eventual treatment success may be more unpredictable than expected; this may have critical consequences for other ecological properties beyond the restoration goal of tree establishment and return of tree cover.

Key words: boreal wetlands, ground preparation, oil and gas exploration, peatland restoration, topography along seismic lines

Implications for Practice

- The lower ground surface along seismic lines relative to the adjacent undisturbed treed peatlands has important implications for habitat conditions that contribute to the delayed natural return of tree cover.
- Soil mounding, a treatment aimed to facilitate the return of tree cover to seismic lines by raising the substrate away from the water table, introduces a much greater topographic heterogeneity than the natural variation in the adjacent undisturbed peatland, which may cause important long-term changes in environmental conditions.
- The large density of mounds and their corresponding pits, often constructed in a systematic pattern, may contribute to the creation of an unnatural topographic pattern along linear disturbances, which in turn may reduce the restoration effectiveness of such treatment.

Boutin 2006; Schneider et al. 2010), which are narrow linear corridors where trees and shrubs had been cut for access of equipment and personnel to map underground bitumen deposits. Although return of tree cover was expected to occur along seismic lines, it has been well documented that many lines fail to develop tree cover naturally, particularly in treed peatlands (Van Rensen et al. 2015; Dabros et al. 2018). The linear footprint associated to seismic lines often remains on the landscape several decades following construction (Lee & Boutin 2006), even after wildfire (Barber et al. 2021; Pinzon et al. 2021).

This delay in tree recovery may be due to the loss of ground microtopography typically found in treed peatlands. Depth of water table and vegetation have been identified as important elements in the formation of peatland ground microtopography

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¹Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 5320 - 122 Street, Edmonton, AB T6H 3S5, Canada

²Address correspondence to J. Pinzon, email jaime.pinzon@nrcan.gc.ca

Introduction

Seismic exploration for oil and gas has left an extensive network of linear disturbances across the boreal region of northern Alberta (Canada) (Chen et al. 2017). Much of that linear footprint has resulted from the construction of seismic lines (Lee &

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(Belyea & Clymo 2001; Frolking et al. 2010) that result in a variety of microforms (hummocks, lawns, hollows, and pools) (Belyea & Clymo 2001; Nungesser 2003; Belyea & Baird 2006) and influence overall peatland dynamics (Yu et al. 2001; Malhotra et al. 2016). The hummock-hollow continuum shapes the distribution and composition of biota across peatland ecosystems (Vitt et al. 1995; Bubier et al. 2006; Andersen et al. 2011), and influences carbon accumulation and emissions (Bubier et al. 1995; Christensen et al. 2003; Lai 2009). Its importance is such that modeling this continuum is of relevance (Moore et al. 2019; Graham et al. 2020). Thus, disturbances in peatlands alter the feedback among these parameters, leading to important changes to ecosystem functions and processes.

The construction of seismic lines across wetlands has been shown to contribute to the simplification of ground microtopography (Lee & Boutin 2006; Stevenson et al. 2019), which has important implications for the return of tree cover to disturbed areas. The effects of such footprint on several ecological properties are well documented. For instance, growing conditions along seismic lines are different to those in the adjacent forest due to soil compaction and higher soil moisture (Braverman & Quinton 2016; Davidson et al. 2020). These in turn influence other properties, such as permafrost thaw (Braverman & Quinton 2016) and methane emissions (Strack et al. 2019). Such effects on abiotic factors further affect biotic factors, including the species composition of plants (Finnegan et al. 2018a; Dabros et al. 2022) and invertebrates (Riva et al. 2020; Pinzon et al. 2021), as well as wildlife movement (Tigner et al. 2014; DeMars & Boutin 2018; Finnegan et al. 2018b). Over the last decades, the construction of seismic lines has become an increasingly growing ecological issue due to their impact on the endangered woodland Caribou (*Rangifer tarandus caribou*) (Dyer et al. 2001; Government of Canada 2002; Thomas & Gray 2002), as seismic lines lead to increased habitat loss (Wasser et al. 2011; Nagy-Reis et al. 2021) and increased interaction with predators and other ungulates (James & Stuart-Smith 2000; Latham et al. 2011a, 2011b).

The mitigation of the linear footprint associated to the oil and gas exploration through the application of mechanical treatments that aim to restore tree cover along seismic lines has become an active area of research, with widespread implementation underway within the province of Alberta (Filicetti et al. 2019; Echiverri et al. 2020; Kleinke et al. 2022). Soil mounding is a mechanical site preparation technique commonly used in forestry as a silvicultural application that has been shown to enhance tree seedling establishment by creating favorable growing conditions (e.g., soil temperature and moisture), and by reducing competition with other ground and understory vegetation (Sutton 1993; Takyi & Hillman 2000; Pyper et al. 2014). It has been suggested that this ground preparation technique can emulate the natural pit and mound microtopography resulting from tree fall (Londo & Mroz 2001). Mounds introduce topographic heterogeneity and enhance seedling survival by raising the substrate above the shallow water table, typical of peatlands. In forestry applications, mounds are traditionally created using an excavator to dig into the ground and carefully invert the soil over the ground surface adjacent to the resulting pit. This technique, however, has been adapted for application in wetlands by using a tracking excavator

equipped with a backhoe. Mounds in peatlands, however, commonly result in the surface layer (acrotelm) being buried under deeper decomposing peat (catotelm; Ingram 1978; Clymo 1984), with alternative mounding techniques proposed to address this issue (Kleinke et al. 2022; Schmidt et al. 2022). Mounding has become one of the most commonly applied ground preparation treatments to date in Alberta (Filicetti et al. 2019) for the restoration goal of aiding the return of tree cover along seismic lines.

Despite the benefits of mounding when used as a silvicultural approach (Sutton 1993; Caners et al. 2019), particularly in the context of improving seedling establishment in areas disturbed by oil and gas exploration activities (Filicetti et al. 2019), ongoing research is being focused to better understand the impacts of this treatment on site conditions and other ecological properties in peatlands (e.g., Echiverri et al. 2020; Murray et al. 2021; Schmidt et al. 2022). Nonetheless, the application of this treatment may have important implications for the successful recovery of peatlands disturbed by oil and gas development. Given these important knowledge gaps, the general aim of this study is to contribute to the growing baseline information around the applicability of soil mounding in the context of peatland restoration and describe changes in microtopography and relative elevation of the ground in treated seismic lines, using the undisturbed adjacent peatland and untreated seismic lines as reference. We expect this new information will contribute to filling operational knowledge gaps and to informing restoration practitioners.

Methods

Study Area

We carried out this study at a peatland complex located approximately 30 km south of the hamlet of Conklin (Alberta, Canada; 55°22'20.38"N, 111°9'52.78"W) in the vicinity of the Canadian Natural Resources Ltd. (CNRL) Kirby South in situ SAGD Plant, within the Athabasca oil sands (Fig. 1). We selected 10 sites within a 2.3 km by 1.5 km area in wooded moderate-rich fens (based on vegetation composition). The overstory in this area is dominated by black spruce (*Picea mariana*) and tamarack (*Larix laricina*). Black spruce/tamarack seedlings and several shrub species, including bog birch (*Betula pumila*), Labrador tea (*Rhododendron groenlandicum*) and several willow species (*Salix* spp.) characterize the understory. In addition, three-leaved false Salomon's seal (*Maianthemum trifolium*), bog rosemary (*Andromeda polifolia*), small cranberry (*Vaccinium oxycoccos*), various sedge species (*Carex* spp.), water horsetail (*Equisetum fluviale*), marsh cinquefoil (*Comarum palustre*), and bog buckbean (*Menyanthes trifoliata*) dominate the herbaceous layer. Common nonvascular species include red-stemmed feather moss (*Pleurozium schreberi*), bog haircap (*Polytrichum strictum*), bog groove-moss (*Aulacomnium palustre*), woolly feathermoss (*Tomenthypnum nitens*), and peat mosses (*Sphagnum angustifolium* and *Sphagnum warnstorffii*).

Experimental Design and Data Collection

The 10 sites were disturbed by the presence of a seismic line constructed around 2000. Seismic lines at five of these sites were

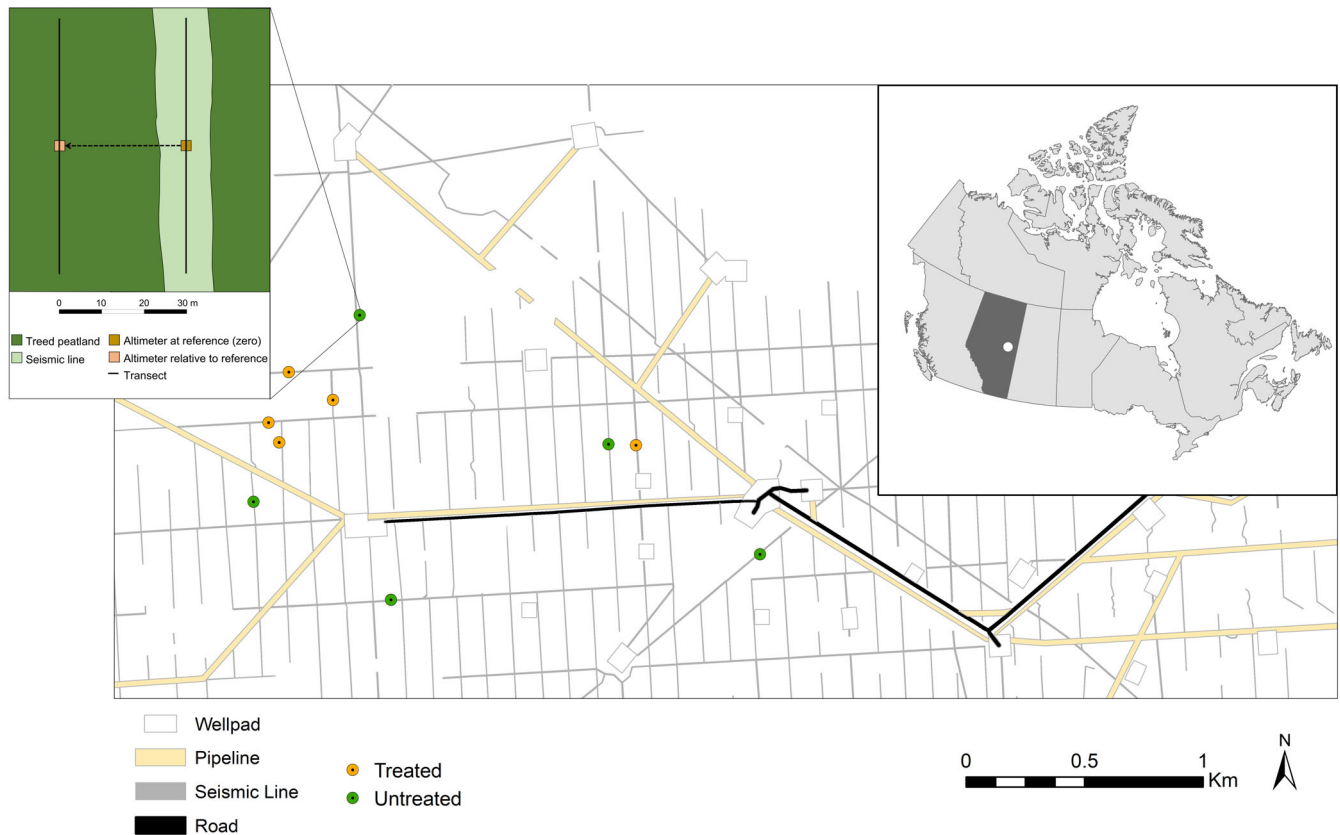


Figure 1. Locations of untreated (green) and treated (orange) seismic lines within a boreal peatland in NE Alberta, Canada. The inset map shows the location of the study area (white dot) in the province and the inset diagram describes the transect setup.

mounded in 2015 (Fig. 2), while the lines at the remaining five sites were untreated and used as a reference control. Selected seismic lines were 6–8 m wide. Site selection was based on GIS layers provided by the Regional Industry Caribou Collaboration group (RICC; <https://www.cosia.ca/initiatives/land/projects/regional-industry-caribou-collaboration>) and the Alberta Biodiversity Monitoring Institute Boreal Wetland Probability Map (Hird et al. 2017) to narrow down sites with similar predicted wetness conditions. At each site, we installed two parallel 60 m long transects: one along the center of the seismic line and the other in the adjacent treed peatland, 30 m from the seismic line transect (Fig. 1).

We measured the relative elevation of the ground surface along the two transects using a Zip Level Pro-2000 High Precision Altimeter (Technidea Corporation, U.S.A.). To accomplish this, we first placed the altimeter at the 30 m mark of the seismic line transect and used this point as the reference level (zero) for all other measurements within each site. The point for the reference level was always chosen to be at the ground level above any standing water. We measured the elevation (positive or negative) relative to the reference every 0.5 m along the seismic line in both directions (Fig. 2). Then, we measured the elevation 30 m into the adjacent treed peatland relative to the reference level, perpendicularly from the seismic line transect, so we could move the altimeter to this point, and again, measured the elevation at 0.5-m intervals in each direction along the treed peatland transect

relative to the initial reference level on the seismic line transect (Fig. 1). To estimate the ground elevation when the transect intersected a pool of water, we measured the relative elevation at the water surface with the altimeter and added the depth of the pool, which was measured with a measuring tape. This protocol yielded 121 observations along each transect, with a total of 242 measurements at each site and 2,420 measurements overall. Although observations at each site are relative to each other, measurements were independent among sites, and thus, correspond to replicate observations at either treated or untreated conditions ($n = 5$). At the treated sites, we also recorded the relative elevation at the base and top of five mounds along the seismic line transect, using the high precision altimeter, to calculate mound height.

Data Analyses

Mound Characteristics. Using the observations of relative elevation taken at the base and top of selected mounds at each treated site, we calculated the height of each mound from the difference between the top and base measurements and used these values to estimate the height loss since mound creation, using the targeted height of 80 cm when the treatment was applied. Since we did not have the actual initial mound height, we acknowledge that the estimated height loss presented here is not accurate and measured with much error; however, not only it is the best

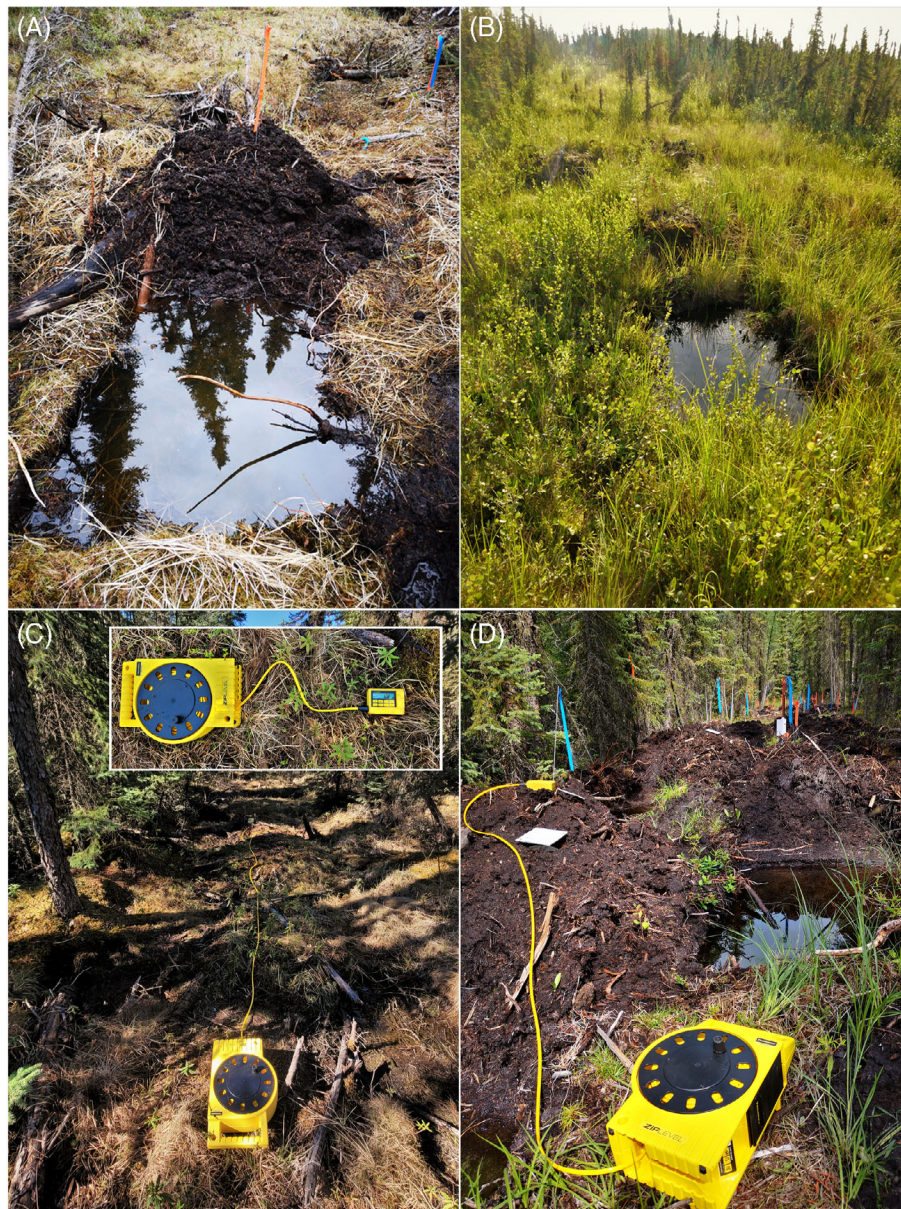


Figure 2. Example of mounds and their associated pits on a seismic line, and the collection of relative ground elevation. (A) Recently created mound (from a different study site); (B) 4-year-old mound (at Kirby site). As a reference, pits are about 90 cm (A) and 75 cm (B) wide, while mounds are about 40 cm (A) and 35 cm (B) high; (C) setup of the high precision altimeter to record relative ground elevations at Kirby site (large yellow box is set at the zero-reference level, while small box measures the ground elevation relative to the reference point; inset picture shows a detailed view of the setup); (D) use of altimeter to measure mound height (from a different study site as in A). Pictures taken by J.P.

estimate available at this site, it also provides a rough approximation of mound height loss that is relevant to address longer-term treatment effectiveness. Furthermore, using the description of how these sites were mounded, as provided by Filicetti et al. (2019), we provide a very rough estimate of mound density and area covered by mound pits at each of our treated sites.

Elevation. We compared the relative elevation between Habitats (Treed peatland vs. Seismic line) for untreated and treated

sites separately using General Linear Mixed Models, as transects within sites and observations within transects were not independent. We used site as a random effect and an autoregressive correlation structure of first order (AR1) for observations within transects to account for the lack of independence among observations. The model for treated sites included in addition a constant variance structure to account for the greater variability in relative elevation introduced by the treatment application. Given that observations within each site are relative to each other, direct elevation comparisons between treated and

untreated lines are meaningless. To address this comparison, we obtained the mean relative elevation for each transect and then computed the difference between each treed peatland and seismic line transect pair. From the resulting differences we compared treated and untreated sites using a General Linear Model with a constant variance structure to account for heterogeneous variances between transects. Although we did not measure the distance to the water table, the pits of the mounds were consistently filled with water almost to the edge. Thus, we used the reference (zero) level of the seismic line, which was always above any standing water, to compute the percentage of points along each transect above such level to estimate the proportion of points along the transects at each site above the water table. This estimation was then compared between Habitats and between treated and untreated areas using a Generalized Linear Mixed Model, with beta distribution (appropriate for proportional data) and site as a random effect. We took a similar approach to estimate the percentage of points along each seismic line transect above the mean elevation of the corresponding adjacent treed peatland. This estimation, however, focuses on evaluating the proportion of points potentially suitable for tree establishment along the seismic line transect. This estimation was compared between treated and untreated areas, also using a Generalized Linear Model with a beta distribution.

Topography. We compared the terrain heterogeneity between Habitats (Treed peatland vs. Seismic line), and between Sites (Treated vs. Untreated), using two methods: estimation of Terrain Ruggedness Index (TRI) and calculation of coefficient of variation (CV). We followed the procedure proposed by Riley et al. (1999) to compute TRI values. This method was developed to estimate terrain heterogeneity from raster data, in which the squared differences in elevation between the focal cell and the eight adjacent cells are summed and then the square root applied to obtain the TRI value, with the procedure repeated for every cell in the raster. Since our data were collected along linear transects, we modified the calculation of TRI by computing instead the difference in relative elevation between the focal distance and two distances (1 m) in each direction. Resulting TRI values were then analyzed using General Linear Mixed Model. Since the calculation of TRI is independent for each transect, the interaction between Site and Habitat is meaningful, thus we used a single model for these comparisons. The model assumed observations to be nested by transect and transects nested within sites as a random effect and a constant variance structure was included to account for heterogeneous variances between transects. We calculated CV (standard deviation/mean $\times 100$) of observations at each Site by Habitat combination.

We carried out all analyses using R 3.6.3 (R Core Team 2020). Both General Linear Mixed Models and General Linear Models were fit using the *nlme* package (Pinheiro et al. 2021). Generalized Linear Mixed Models and Generalized Linear Models were fit using the *glmmTMB* (Brooks et al. 2017) and *betareg* (Cribari-Neto & Zeileis 2010) packages, respectively. Post hoc comparisons were estimated using least squares means using the *emmeans* package (Lenth 2021).

Results

Mound Characteristics

As of August 2019, mound height was quite variable, ranging from 24.4 to 43.4 cm (mean \pm standard deviation: $34.4 \text{ cm} \pm 5.16$). Thus, from the targeted original height of 80 cm when created in 2015, mounds seemed to have settled considerably, with an estimated height loss of 36.6–55.6 cm, which corresponds to an average height loss of 57.0%. Mounds were created at 3 m intervals in a 1–2 checkered pattern; thus, within each of our 60 m transects, we estimated 31–32 mounds and as many pits (516–533 mounds/km). Mound length and width were targeted to 1 and 0.75 m, respectively; thus, the area of each pit at the surface level could be estimated to be at least 0.75 m^2 , which corresponds to approximately $23.3\text{--}24.0 \text{ m}^2$ of the 60 m transect (scaled to $387.5\text{--}400.0 \text{ m}^2$ for every kilometer treated). It should be noted that these values are rough estimates based on the targeted mound size and not actual measurements taken in the field.

Elevation

Relative ground elevation was significantly different between the seismic line and the adjacent treed peatland in both untreated ($F_{[1,4]} = 37.03$, $p = 0.004$) and treated ($F_{[1,4]} = 25.57$, $p = 0.007$) sites. On average, seismic lines in untreated areas (Fig. 3A) were 11.4 cm lower than the adjacent treed peatland (mean relative elevation \pm standard error: Treed peatland = $20.4 \text{ cm} \pm 2.65$; Seismic line: $9.0 \text{ cm} \pm 2.65$). Despite treatment application, seismic lines in treated areas remained lower than the adjacent treed peatland (Fig. 3B), but the difference was much greater than on untreated areas, with an average change of 21.4 cm (Treed peatland = $23.9 \text{ cm} \pm 2.72$; Seismic line: $2.5 \text{ cm} \pm 3.25$). The mean elevation difference (Fig. 4) between the adjacent treed peatland and seismic line transects was on average 10.1 cm greater in treated areas ($21.5 \text{ cm} \pm 2.53$) compared to untreated areas ($11.4 \text{ cm} \pm 1.85$); however, this difference was marginally significant ($F_{[1,8]} = 4.31$, $p = 0.072$).

The proportion of points above the reference (zero) level was only significantly different between habitats ($z = -5.422$, $p < 0.001$), but not between untreated and treated sites. Thus, the proportion of points above the reference value was consistently higher in the treed peatland (Untreated sites = 0.97 ± 0.016 ; Treated sites = 0.98 ± 0.011) compared to the seismic line (Untreated sites = 0.79 ± 0.061 ; Treated sites = 0.67 ± 0.077), reflecting a similar pattern to that observed from the relative elevation results described above.

Contrary to the expectations given treatment application, the proportion of points along seismic line transects above the mean elevation of the corresponding adjacent peatland was not significantly different between treated and untreated areas ($z = 0.632$, $p = 0.527$). In fact, the proportion was on average lower in treated areas (0.12 ± 0.043) compared to untreated areas (0.16 ± 0.049). Although these results seem contradictory, given the fact that the total number of points per transect is fixed, these reflect the greater number of points that are measured at lower elevations due to the pits created by the treatment application.

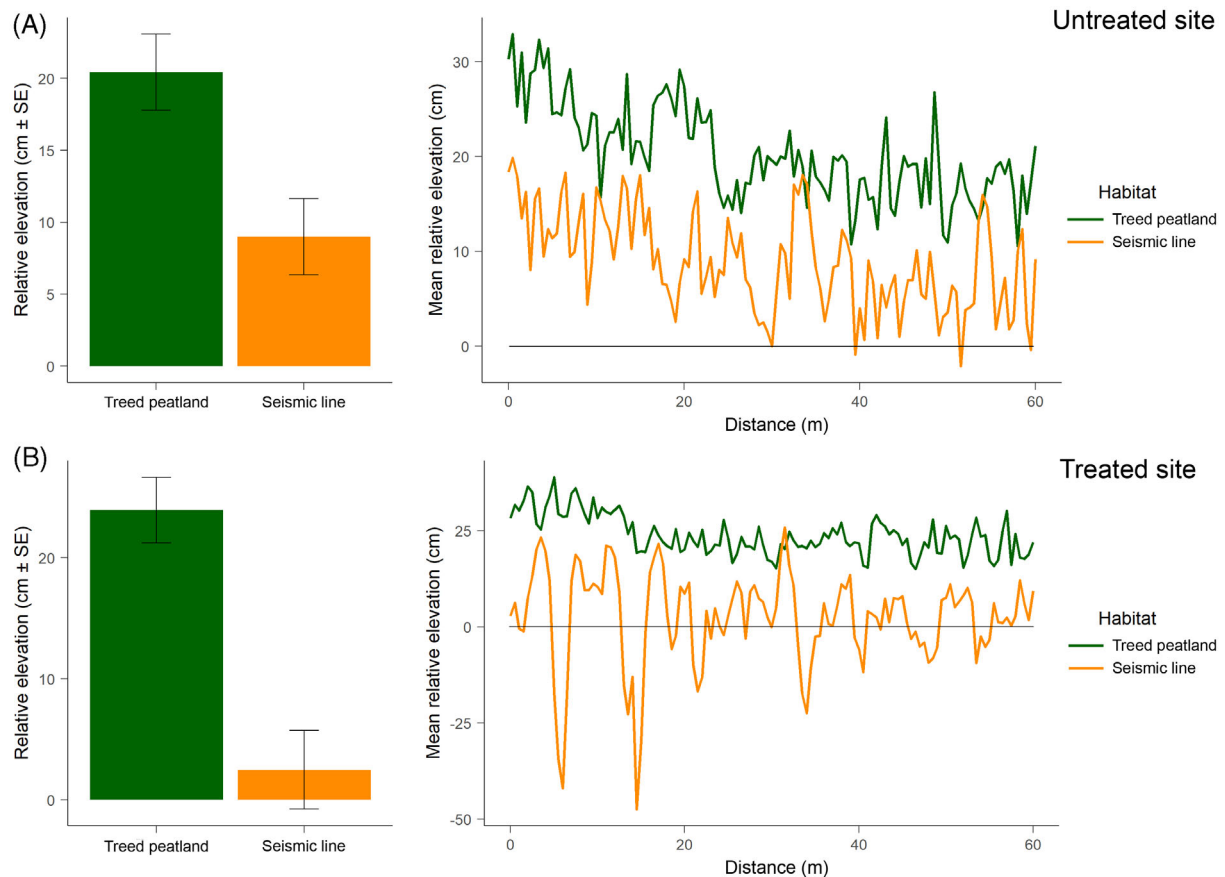


Figure 3. Relative ground elevation between seismic lines and their adjacent undisturbed treed peatland (error bars denote \pm SE). (A) Untreated sites; (B) treated (mounded) sites. Plots on the right represent mean relative elevation profiles along the 60 m transect in both treed peatland and seismic line habitats.

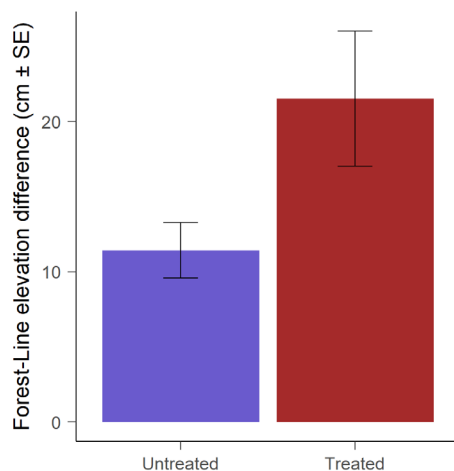


Figure 4. Relative elevation difference between seismic lines and their adjacent undisturbed treed peatland in untreated and treated (mounded) sites (error bars denote \pm SE).

Topography

Values of TRI were significantly different between Sites ($F_{[1,8]} = 12.82$, $p = 0.007$), Habitats ($F_{[1,8]} = 8.70$, $p = 0.019$), and their interaction ($F_{[1,8]} = 8.12$, $p = 0.022$; Fig. 5A). Although

topographic heterogeneity was slightly larger in untreated seismic lines ($18.5 \text{ cm} \pm 2.16$) compared to the adjacent treed peatland ($16.4 \text{ cm} \pm 2.13$), this difference was not significant ($t_{[8]} = -0.68$, $p = 0.519$). In treated areas, however, TRI was significantly different ($t_{[8]} = -4.05$, $p = 0.004$), with seismic lines ($37.7 \text{ cm} \pm 3.44$) showing on average a higher terrain ruggedness value (16.4 cm higher) than the treed peatland ($21.2 \text{ cm} \pm 2.23$). While no significant differences in terrain heterogeneity were detected in treed peatland transects between treated and untreated sites, as expected ($t_{[8]} = 1.87$, $p = 0.099$), TRI was on average 20 cm higher in treated seismic lines compared to untreated seismic lines ($t_{[8]} = 3.49$, $p = 0.008$). The variation in relative elevation, as measured by the coefficient of variation, is consistent with the terrain ruggedness results (Fig. 5B). While the variation in treed peatland sites was consistently lower regardless on whether the area was adjacent to a treated or an untreated seismic line ($CV_{\text{treated}} = 21.7\%$; $CV_{\text{untreated}} = 24.6\%$), this variation was higher in untreated lines ($CV = 58.2\%$), and orders of magnitude higher in treated lines ($CV = 522.4\%$).

Discussion

We describe patterns in ground microtopography and elevation associated to the construction of seismic lines in one peatland

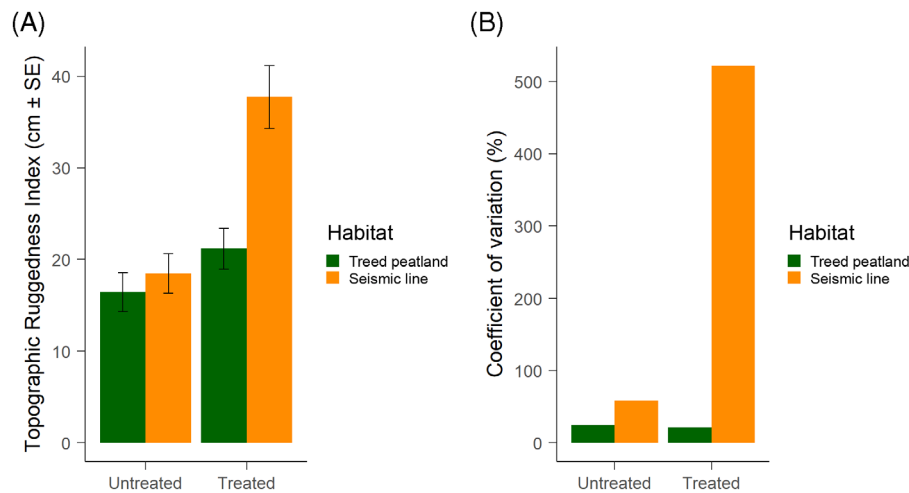


Figure 5. Topography along seismic lines and their adjacent undisturbed treed peatland in untreated and treated (mounded) sites. (A) Topographic ruggedness index (TRI; error bars denote \pm SE); (B) coefficient of variation (CV).

area of NE Alberta, and provide additional evidence on how ground topography is altered when ground preparation treatments (in this case, soil mounding) are applied for the purpose of facilitating the restoration of these disturbed sites. To our knowledge, no information about relative ground elevation and topography has been reported on mounded seismic lines, and thus, results presented here are perhaps the first evidence about these properties on treated areas. Our results contribute not only to the current knowledge in the context of effects of seismic line construction on microtopography and relative elevation, but also provide new information on these aspects following the application of mounding treatments.

Untreated Seismic Lines

Previous research has demonstrated some of the negative effects the construction of seismic lines has on various habitat conditions. Besides the evident disturbance created by vegetation removal, the peat profile is affected by the heavy machinery employed for construction and later use for exploration, resulting in significant ground compaction (McNabb et al. 2001; Cambi et al. 2015; Davidson et al. 2020) and reduction in topographic complexity (Lovitt et al. 2018; Stevenson et al. 2019; Filicetti & Nielsen 2020). Although conventional seismic lines were normally constructed and used during the winter when the ground is frozen, reducing to some extent ground disturbance, it was clearly not fully avoided. Studies have shown that the ground on seismic lines is usually lower (1.2–8.4 cm) than the ground of the adjacent treed peatland (Lovitt et al. 2018; Stevenson et al. 2019; Dabros et al. 2022). Our results are consistent with these observations, as we also detected a lower relative elevation of the ground along seismic lines. The ground depression along untreated seismic lines in our study area, however, was higher (11.2 cm) than reported elsewhere, demonstrating in part the large site-to-site variability in ground compaction across the Alberta oil sands.

Ground compaction, and the resulting difference in relative elevation, has ecological implications, as it leads to important changes in surface hydrology, especially in ecosystems where water table is relatively shallow, such as peatlands (Braverman & Quinton 2016; Volik et al. 2020). The observed higher ground moisture levels along the lines (Lovitt et al. 2018; Davidson et al. 2020; Pinzon et al. 2021) are exacerbated by the reduction of water uptake due to tree removal (Vitt et al. 1975). Changes in ground moisture, together with higher soil compaction (Lee & Boutin 2006; Davidson et al. 2020), in turn have a direct influence on the ability of tree seedlings to survive and establish (Lee & Boutin 2006; Caners & Lieffers 2014). They also affect species composition of the vegetation in the understory along these linear features (Revel et al. 1984; Van Rensen et al. 2015; Finnegan et al. 2018a), explaining in part the minimal return of tree cover on most seismic lines and their subsequent prevalence on the landscape, even several decades following construction (Lee & Boutin 2006).

As noted above, previous research has shown the simplification of topography along seismic lines compared to the adjacent treed peatland. For instance, Stevenson et al. (2019) showed an average reduction of microtopographic complexity along seismic lines in different ecosites by 20%, with a greater and significant reduction of about 50% in bogs, and a relatively lower but not significant reduction in poor fens (about 7%) or rich fens (about 18%). However, our observations based on ruggedness (TRI) and coefficient of variation values, show a different and opposite pattern. Terrain ruggedness was slightly higher, although not significantly different, along untreated seismic lines compared to the adjacent peatland, suggesting that topographic relief was only marginally affected by the presence of the seismic line. However, the variability in relative elevation was twice as high along the untreated seismic lines than in the adjacent treed peatland. We believe these differences may be attributed to local site conditions, as Stevenson et al. (2019) included several sites in different ecosites across a much larger

area than we did in our study. Although we did not evaluate line use (either by humans or wildlife), the presence of trails along the seismic lines was considerable, with the transect crossing the trail at several points, likely influencing the observed variability in microtopography. Furthermore, it is possible that transects in the adjacent undisturbed peatland crossed over areas with a higher density of lawns than hummock-hollows, reflecting a lower terrain ruggedness; however, our data are insufficient to test this conjecture.

Treated Seismic Lines

Mounding programs often report the targeted height of mounds at creation, which is quite variable. For instance, at oil sands exploration pads in Alberta, Liefers et al. (2017) reported mound heights of 8.9–39.6 cm, Caners et al. (2019) reported heights of 20.6–40.8, and Murray et al. (2021) reported a targeted height of 60 cm. Likewise, on seismic lines, mound heights ranged from 20 cm (Schmidt et al. 2022) to 40–60 cm (Pinzon et al. unpublished data) and 80 cm as part of this study (Filicetti et al. 2019). About 4 years after sites in our study area were treated, when we took the measurements reported here, mounds were still visible but were much reduced in height due to settlement, apparently having lost about half of their targeted initial height. These patterns might have important implications to changes in microtopography over time along treated seismic lines, and the long-term effectiveness of mounds for seedling establishment. Nonetheless, compared to the adjacent peatland, the relative elevation along treated lines was much lower than along untreated lines. This observation may seem contradictory given the very nature and goal of treatment application by the creation of raised surfaces; however, as the construction of each mound leaves behind a pit at least as deep as the original mound height, the ground surface necessarily drops, affecting the reported average elevation, as well as the relative proportion of points above the mean adjacent peatland. In peatlands, soil mounding is specifically used to increase surface topography and improve growing conditions for establishment and survival of tree seedlings (Sutton 1993), which has been empirically demonstrated (Liefers et al. 2017; Filicetti et al. 2019), and therefore is not targeted to mitigate the difference in relative elevation between compacted seismic lines and their adjacent peatland. However, our results suggest that not only does mounding fail to reduce the difference in relative elevation between treated seismic lines and the adjacent peatland, but it may even exacerbate that difference, with untreated lines and their adjacent peatland more similar in relative elevation than treated lines and their adjacent peatland. This can lead to further changes to the hydrology of the peatland and may have important effects on the species composition and biodiversity of treated areas.

Topographic simplification has been identified as one of the causes for reduced return of tree cover along seismic lines (Lee & Boutin 2006; Filicetti & Nielsen 2020) and drilling pads (Caners & Liefers 2014; Liefers et al. 2017). Thus, the application of mechanical treatments that increase topography is expected to aid in the survival and establishment of both planted tree seedlings and natural tree seedling regeneration, as is the

case with soil mounding, through the creation of the raised surface of the mound. However, the topographic heterogeneity introduced by the mounds and their pits, as revealed by our results, was undoubtedly much greater than the natural range of topographic variability observed in the undisturbed peatland, not to mention the large density of water pools systematically and linearly distributed along treated areas. These conditions, therefore, may have relevant consequences for other ecological properties, such as hydrological fluxes within the peatland (Braverman & Quinton 2016) and greater methane emissions due to the increased density of water pools (Hamilton et al. 1994; Moore et al. 1994). With mound settlement, it is expected that the observed heterogeneity would be reduced, but even at the still undetermined point in time in which mounds will no longer be distinguishable, the presence of the pits may still be noticeable due to slow infilling. Due to the shallow water table characteristic of peatlands, these pits are commonly filled with water preventing the creation of new peat as well as reducing the surface available for the re-establishment and growth of vegetation (roughly estimated here as about 400 m² per kilometer of seismic line) over large areas, as mounding programs normally apply the treatment over several kilometers of seismic lines. Thus, the persistence of these pits on the landscape will probably be much longer than that of the mounds, having a long-lasting and unnatural effect on both relative elevation and microtopography along seismic lines (and not to mention other ecological properties, such as the hydrology of the peatland), with the potential of maintaining a different linear footprint than that of the original untreated seismic lines, even if tree cover is eventually restored.

It is widely recognized that the extensive linear footprint associated to the exploration of oil and gas in Alberta is an important environmental issue that needs to be addressed for the maintenance and conservation of the different ecosystems, such as wetlands, that occur across the boreal forest. The slow or minimal recovery of tree cover on seismic lines documented in the growing scientific literature has made evident the need for intervention to mitigate such footprint and to restore disturbed areas. Thus, the purpose of this study is not to criticize the use of mounding as a mechanical treatment aimed to improve habitat conditions along linear features, or even suggest that mounding should not be considered as part of the restoration toolbox currently used in Alberta, particularly in peatlands. On the contrary, our objective is to provide baseline evidence that can be used to fill knowledge gaps associated to the application of silvicultural treatments that have been proven under different environmental conditions (i.e., mounding in upland habitats), with the expectation that this new information can be used to adapt and modify current practices and improve their application. The observations presented here are based on measurements taken within a relatively small peatland area within the Alberta oil sands. However, given the very nature of the application of mounding treatments, it is reasonable to expect similar elevation and microtopography responses at other peatland sites where this treatment has been used.

Many of the human intervention approaches in Alberta currently applied on linear disturbances, generally labeled as

restoration treatments, were originally designed from a functional point of view, with some of them being implemented from silvicultural methods used in forestry. That is, with the main objective of reducing wildlife (and human) use of linear corridors, and with the expectation that by doing so, not only predatory interactions on Caribou would diminish, but also the return of tree cover would be enhanced. Although treatment application in this context may be effective for dealing with some of the many issues Caribou are facing, restoration programs need and should have a much broader ecological focus, in which treatments do not impose potentially negative effects on other nontarget properties of the ecosystem or generate a much greater human footprint than the one being addressed. Thus, more research is needed to better understand the ecological responses to soil mounding on peatlands, and to describe and evaluate the advantages and disadvantages of using this treatment. For instance, very little is known about the overall rate of mound settlement (here we provide an approximation), how settlement changes with different soil textures and compositions and how settlement influences topography along treated areas, with subsequent effects on tree seedling survival, establishment and growth. Furthermore, as mound size is usually determined by site wetness, more research is needed to understand the footprint associated to the creation of pits of variable size and depth. Site to site variability has important implications for restoration programs, as it may limit the generalization of treatment application across geographical areas, suggesting perhaps a more site-specific approach when implementing specific treatments for the purpose of mitigating linear footprints. Thus, long-term monitoring programs of treated areas are crucial to provide essential information on whether treatment application has been effective and therefore on whether successful restoration has been achieved.

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