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A data compilation and synthesis of the impacts of seismic surveys on surface soil properties in boreal Alberta, Canada

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Abstract

Linear clearings of vegetation to perform geophysical surveys, called seismic lines, are created for oil and gas exploration in boreal Canada and often persist on the landscape for decades after disturbance. Therefore, an assessment of environmental conditions on seismic lines is needed to inform restoration efforts. This study aimed to compile surface soil properties (upper 5–15 cm; dry bulk density, organic matter content, organic matter bulk density, volumetric water content, and water content by mass) on and off seismic lines across upland, transitional, and peatland ecosystems in northern Alberta, Canada (N=1,638). Soil properties differ between seismic line and reference samples, especially on older 'conventional' lines. Changes included higher dry bulk density, lower organic matter content, and elimination of microtopographic variability. Changes in dry bulk density can, in part, be explained by a reduction in organic matter content, but altered carbon cycling and/or compaction are also important. Restoration techniques such as inverted mounding create an entirely distinct soil condition, with higher mean bulk densities and lower organic matter contents than both on and off seismic lines. Therefore, an assessment of microtopographic recovery should be conducted before prescribing restoration treatments to limit further degradation of soil structure.

Keywords

boreal, forest, peatlands, seismic lines, soil

1. Introduction

Resource exploration across Canada's boreal and subarctic regions has resulted in the creation of a network of seismic lines across the landscape. Seismic lines are linear clearings where trees and other surface vegetation are removed to accommodate the equipment and field crews needed to perform geophysical surveys of the subsurface (Dabros *et al.*, 2018). Seismic lines are estimated to comprise 46% of human-made linear features across boreal Canada, which also include roads, pipelines, and powerlines (Lee and Boutin, 2006; Pasher *et al.*, 2013). Further, in some regions, such as the Oil Sands regions of Alberta, seismic lines have average linear densities of 2 km km^{-2} and can be over 40 km km^{-2} (Figure 1; Lee and Boutin, 2006; Pasher *et al.*, 2013; Dabros *et al.*, 2018; ABMI, 2019; Echiverri *et al.*, 2020). These linear features also often persist on the landscape, with tree recovery frequently limited even decades after line establishment (Lee and Boutin, 2006; Dabros *et al.*, 2022). Their persistence causes a wide variety of ecosystem changes, including habitat fragmentation, species population shifts and altered movement, potential greenhouse gas emission increases, and altered hydrological, fire, and successional patterns (e.g., Lee and Boutin, 2006; Filicetti and Nielsen, 2018; Finnegan *et al.*, 2018; Lovitt *et al.*, 2018; Abib *et al.*, 2019; Davidson *et al.*, 2020; Deane *et al.*, 2020; Nagy-Reis *et al.*, 2021; Dabros *et al.*, 2022; Schmidt *et al.*, 2022; Weiland *et al.*, 2023). The high density of lines across northern Alberta, however, means that assessments of seismic line recovery trajectories are needed to prioritize restoration efforts.

Assessing the recovery trajectory of seismic lines in comparison to reference conditions requires evaluating all abiotic and biotic aspects that contribute to ecosystem function. One such factor is soil properties, as they are associated with water and biogeochemical cycling that affect vegetation growth and are altered when seismic lines are created. This alteration comes from the machinery used to clear the vegetation, where soil compression, soil removal, and microtopographic simplification can occur (Filicetti and Nielsen, 2018; Stevenson *et al.*, 2019; Davidson *et al.*, 2020; Filicetti and Nielsen, 2022). Compaction and removal of surface soils increases surface soil bulk density and causes pore spaces to be smaller and less connected (Rezanezhad *et al.*, 2016; Davidson *et al.*, 2020; Filicetti and Nielsen, 2022). In peatlands, where water tables are close to the surface, reduction in pore space and connectivity results in higher soil water content, reduced saturated hydraulic conductivity, local ponding, and overland water flow (Emers *et al.*, 1995; Williams *et al.*, 2013; Davidson *et al.*, 2020; Weiland, 2024). The removal of trees also reduces water loss through transpiration and can also raise surface temperatures and therefore increase evaporative losses (Kettridge *et al.*, 2013; Abib *et al.*, 2019). Surface disturbance can also lead to soil organic matter loss, either through direct removal or by enhancing mineralization post-disturbance via soil mixing and aeration (Mallik and Hu, 1997). Changes to the bulk density and water content of soils with seismic line creation also lead to shifts in vegetation assemblages, which alters the quantity and decomposability of litter inputs (Davidson *et al.*, 2020; Dabros and Higgins, 2023).

The degree of alteration to the soil surface following seismic line creation depends on when the seismic line was created, as practices have changed over the last few decades (Dabros *et al.*, 2018). Older ‘conventional’ seismic lines for oil and gas exploration were typically created with bulldozers and were made wide to accommodate large machinery and vehicles (5 to 10 m; prior to the 1990s; Dabros *et al.*, 2018). When bulldozed, the surface was flattened and roots and surface soils were removed (Dabros *et al.*, 2018). With technological advances and pressures to reduce tree loss and environmental impacts, ‘low impact’ seismic lines were eventually created, with bulldozers replaced by mulchers with shoes to reduce soil compaction. Further, the creation of seismic lines was limited to the winter season when the ground was frozen to limit soil compaction and removal (Filicetti *et al.*, 2023). These lines were also typically narrower, and 3D seismic lines in the early 2000s were made even smaller (2 to 4 m; Dabros *et al.*, 2018; Filicetti *et al.*, 2023).

Following seismic line creation, soil properties are also impacted by additional disturbances and restoration treatments. Additional disturbances include wildfire and forest harvesting, which both alter soil properties and, in some cases, delay ecosystem recovery (e.g., Filicetti and Nielsen, 2018; Deane *et al.*, 2020; Filicetti and Nielsen, 2022; Van Dongen *et al.*, 2023). Restoration treatments include many traditional silviculture treatments such as mounding, plowing, and scraping the soil surface to create height and loosen soil, both of which promote seedling establishment and growth (Natural Resources Canada, 2019). In peatlands, a common restoration technique is inverted mounding, where mounds are created by lifting peat from the surface with a bulldozer and inverting it on the line (Filicetti *et al.*, 2019; Kleinke *et al.*, 2022; Pinzon *et al.*, 2023). In this process, the peat profile is inverted, and older, more decomposed peat that was originally protected from oxic decomposition below the water table is now re-exposed and vegetation is buried beneath the mound (Kleinke *et al.*, 2022). Depending on the local peat depths, underlying mineral soils can also be exposed and mixed into the peat profile (Filicetti *et al.*, 2019; Kleinke *et al.*, 2022). In contrast to mineral soils, where mounding has been successful for promoting tree growth post-harvesting by raising the microsite above the water table and increasing nutrient availability, drainage, and soil temperature at the rooting zone (Hjelm *et al.*, 2019), in peatlands these treatments have not always promoted tree growth, with mounds prone to slumping and causing soil conditions to remain wet (Filicetti *et al.*, 2019; Fliesser, 2023; Pinzon *et al.*, 2023; Shellian *et al.*, 2024). Therefore, treatments that do not invert the profile have been proposed as alternatives (Kleinke *et al.*, 2022; Schmidt *et al.*, 2022; Fliesser, 2023). However, restoration treatments all re-disturb the soil profile to some extent and could lead to carbon losses, suggesting that restoration planning should include an assessment of whether the local environmental conditions, including soil hydrophysical properties, are conducive to treatment success and/or if treatment is needed (Pinzon *et al.*, 2023).

Due to the variation in the severity of impacts on soil properties associated with seismic line creation within different ecosystems, along with further impacts from additional disturbances and restoration treatments, sampling across a variety of ecosystem and disturbance types is needed to determine indicators of recovery and understand the predominant drivers of soil property shifts. Therefore, this project aimed to collect new data and compile previously published and unpublished data on five major soil properties at both reference and on-line localities across northern Alberta: (i) dry bulk density, (ii) organic matter content, (iii) organic matter bulk density, (iv) volumetric water content, and (v) water content by mass. This study: (1) establishes a surface soil sample database for seismic lines across northern Alberta that will provide baseline information on soil property changes with this disturbance type, (2) investigates the predominant drivers of soil property changes for different ecosystems on untreated and treated seismic lines, and (3) identifies data gaps for understanding soil property changes to inform future research goals.

2. Methods

2.1. Study Area

Samples were collected within the Boreal Plains Ecozone of Canada, which is characterized by a fully-humid snow climate with cool summers (Dfc in the Köppen-Geiger Climate Classification; Figure 1; Ecological Stratification Working Group, 1995; Kottek *et al.*, 2006). Mean annual air temperature ranges from 4°C in the south to -2°C in the north (1981-2010; Ireson *et al.*, 2015). Highest mean air temperatures occur in July (15 to 20 °C) and lowest mean air temperatures are in January (-10 to -22 °C; 1981-2010; Ireson *et al.*, 2015). Total annual precipitation ranges from 430 to 640 mm (1981-2010; Ireson *et al.*, 2015). Snow accounts for 21 to 40% of the total annual precipitation (1981-2010; Ireson *et al.*, 2015).

The Boreal Forest and Foothills Natural Regions of Alberta are situated within the Boreal Plains Ecozone of Canada and make up a combined 68% of the province (Figure 1; National Regions Committee, 2006). These regions are characterized by a mixture of upland forest and wetlands (National Regions Committee, 2006). Upland forests in the Boreal Forest Natural Region are composed of predominantly *Populus tremuloides* and shift to mixedwood forests of *P. tremuloides, P. balsamifera*, and *Picea glauca* moving northward. The Foothills Natural region is distinguished from the Boreal Forest Natural region by the presence of *Pinus contorta* within its mixedwood forest stands, and generally grades from mixedwood to coniferous moving northward (National Regions Committee, 2006). Stands of *Pinus banksiana* are also common on xeric, sandy soils in the Boreal Forest Natural region. Wetland areas are mainly fens, bogs, and swamps that transition from shrubby to treed moving northward, with *Picea mariana* and *Larix laricina* being the dominant species. Transitional areas between upland

and wetland regions are generally swamps to upland forests where *Picea mariana* and *Rhododendron groenlandicum* dominate and there is patchy bryophyte cover (Alberta Environment and Sustainable Resource Development, 2015; Willoughby *et al.*, 2019). Soils are generally luvisols and brunisols in upland and gleysols and mesisols in wetland areas (National Regions Committee, 2006; Ireson *et al.*, 2015).

2.2. Soil Property Literature Data Compilation

The database is comprised of 1,638 surface samples from 662 plots and 51 locations from samples analyzed for this study (N=195) and previously analyzed samples from published and unpublished studies (N=1,443; Table 1 and S1 and Supplementary Data File). The depth of the surface samples compiled ranged from 5 to 15 cm. Locations are defined in this study as samples that are within a 5 km radius of each other. Location groups were determined using the density-based spatial clustering of applications with noise (DBSCAN) algorithm in QGIS with a minimum cluster size of 1 and a maximum distance of 5 km (QGIS Development Team, 2020). The dataset includes samples from peatland (53%), transitional (22%) and upland (25%) sites. Data compiled included dry bulk density, organic matter content, volumetric water content, and water content by mass. When both dry bulk density and organic matter content were analyzed on the same sample, organic matter bulk density was calculated by multiplying the organic matter proportion by the dry bulk density. Samples were classified into ecosite and ecosystem type, sampling area (on or off the seismic line), and microtopographic position (high, low, intermediate, or no microtopography; see Tables S1 and S2). All classifications were based on field observations. With microtopographic position, a high point includes both hummocks or mounds and a low point includes hollows and pits. Additional disturbances such as wildfire, forest harvesting, and restoration treatments, were also noted when applicable. Samples taken on seismic lines were categorized by seismic line type (low impact or conventional), treatment status (untreated, treated), and treatment type (intact or inverted profile; see Tables S1 and S2). Samples taken adjacent to seismic lines are also referred to as reference samples in this study.

2.3. Soil Property Determination

New soil samples (0-10 cm) were collected in the summers of 2022 and 2023 (N=195; June-August; Table 1) and were sampled using a metal cylinder of known volume. The sample was carefully extracted using a serrated knife to cut through small roots while minimizing soil compaction. Soil sample volumes ranged from 284 to 880 cm^3. Samples were frozen post-sampling in the field and shipped to the University of Waterloo, where they remained frozen until analysis. The 10 cm sample included the litter, folic, humic (LFH) layer in the upland samples and the living and poorly decomposed mosses in the peatland and transitional samples.

To determine dry bulk density (g cm^{-3}) and water content (%), samples were weighed before and after drying at 60 °C for 48 hours or until a consistent dry weight was measured. Dry bulk density was then calculated as the dry weight divided by the original field volume. Water content was calculated by volume and by weight. Volumetric water content was calculated as the ratio of water mass to dry mass multiplied by the dry bulk density. Water content by mass was calculated as the water weight in the sample divided by the total sample weight. We expect high variability in water content as samples are collected on different days. However, because reference and seismic line samples were generally collected at the same time, we expect a trend is possible to detect.

Organic matter content (%) was determined using the loss-on-ignition method (after Heiri *et al.*, 2001). Samples were ignited at 550 °C for 4 hours and organic matter content was calculated as the weight of sample lost divided by the dry sample weight. Sample amounts differed between organic and mineral samples (≥30% and <30% organic matter content, respectively; Soil Classification Working Group, 1998), where 1 g and 10 g were ignited, respectively. Organic matter bulk density (g OM cm^{-3}) was calculated by multiplying the dry bulk density by the proportion organic matter in the sample.

2.4. Statistical Analysis

Differences between groups were determined using type III ANOVA tests on linear mixed effects (LME) model results to account for uneven and clustered sampling in the soil property database (Pinheiro and Bates, 2000). Ecosites were grouped into ecosystem type (peatland, transitional, upland) for this analysis to have a sufficient sample size in each of the tested groups (i.e., N≥30; Tables S2 and S3). For all soil properties, two LME models were fit. The first used position (on or off the seismic line) and ecosystem type (peatland, transitional, and upland) and their interaction as fixed factors (Table S4). Treated seismic line samples were not included in this model. The exclusion of these samples was because are no samples from upland sites that have been treated (Table S3). The second used microtopography (high or low point) and seismic line category (conventional, low impact, reference, and treated inverted profile) and their interaction as fixed factors (Table S5). The second model did not include upland samples, as these sites were not sampled for microtopography and few samples were taken on low impact seismic lines, especially for organic matter and water content (N=0-4; Table S3). A model was also fit on the upland samples using position and additional disturbance as fixed factors to test their influence on dry bulk density (Table S6). Only upland samples had harvest or wildfire as additional disturbances in the dataset, and dry bulk density was the only soil property with sufficient samples in the database to perform this analysis (≥ 30 samples per subcategory; Table S3). We grouped the additional disturbances of wildfire and forest harvest activities together as both are expected to increase bulk density at the soil surface, with forest harvest activities impacting the seismic line through machinery and harvest slash addition, and wildfires through combustion (e.g., Bock and Van Rees, 2002a; Filicetti and Nielsen, 2018). Both the plot and location were used as random factors in all LME models. The assumptions of homogeneity of variance and normality of residuals were inspected visually using residuals versus fitted value plots for each model. Some soil property values were transformed prior to analysis to meet model assumptions (i.e., dry bulk density, organic matter content, and organic matter bulk density). Transformations for each soil property are listed in Tables S4, S5 and S6. Linear mixed effects models were fit using the ‘lmer’ function from the lme4 package and type III tests were performed using the ‘Anova’ function from the car package in R (Bates *et al.*, 2015; Fox and Weisberg, 2019; R Core Team, 2024). Significant differences between groups were determined via Tukey tests on the least square means from the LME model using the ‘emmeans’ function of the emmeans package in R (Lenth, 2024).

The relationship between dry bulk density and organic matter content was assessed by curve fitting using the ‘nls’ function in R (R Core Team, 2024). The following exponential relationship was fit based on previous studies by Grigal *et al.* (1989) and Hossain *et al.* (2015):

(1)
$$DBD = a * e^{\frac{-OM}{b}} + c$$

where DBD is dry bulk density, OM is organic matter content, and a, b, and c are constants. Ecosystem type and position on or off the seismic lines were added as factors iteratively and models were tested for whether they improved model fit using a type I ANOVA test in R (R Core Team, 2024). Factors for site type and position were included in the final form of the relationship with the following equation:

$$DBD = (a + d * line + f * type) * e^{\frac{-OM}{b}} + c \qquad (2)$$

where line has a value of 0 for off and 1 for on the seismic line, type has a value of 0 for peatland/transitional and 1 for upland samples, and d and f are constants. Peatland and transitional samples were grouped together as they are predominantly organic soils and had similar organic matter bulk densities.

3. Results

3.1. Surface Soil Properties and Untreated Seismic Lines

Surface average dry bulk density was higher on untreated seismic lines compared to adjacent reference areas, but there was only strong evidence for this difference in upland samples (Figure 2A, Tables 2 and S4). In peatland and transitional samples, the type of seismic line influenced microtopographic differences. Conventional seismic lines had higher and indistinguishable dry bulk densities between hummocks and hollows, while low impact seismic lines and reference samples had distinct microtopographic differences and were not different from each other (Figure 2B, Tables 3 and S5).

Organic matter content in surface soil samples was highest in peatland and lowest in upland samples (Figure 3A, Tables 2 and S4). Lower organic matter content on seismic lines had the strongest evidence in transitional samples, and both peatland and upland samples had limited evidence for changes in surface soils (Figure 3A, Tables 2 and S4). Organic matter content of hummocks on conventional seismic lines in peatland and transitional samples were not distinguishable from hollows from that line type (Figure 3B, Tables 3 and S5). Low impact seismic lines had a similar pattern to reference samples, with distinct microtopographic differences, where organic matter content was higher in hummocks (Figure 3B).

Organic matter bulk density was controlled by ecosystem type, where peatland and transitional samples had similar and lower organic matter bulk density compared to upland samples (Figure 4A, Tables 2 and S4). In peatland and transitional samples, differences between microtopographic features were impacted by seismic line category, where hollows had a higher organic matter bulk density than hummocks for untreated and reference samples, apart from untreated conventional lines that had limited evidence for differences between hummocks and hollows (Figure 4B, Tables 3 and S5).

High variability in volumetric water content, which is expected with variable temporal patterns, meant there was limited evidence for differences between ecosystem types and seismic line versus reference samples, but volumetric water content was generally higher on seismic lines (Figure 5A, Tables 2 and S4). When samples are split by seismic line category for transitional and peatland ecosystems, hummocks on conventional seismic lines were not distinguishable from hollows on the same line type (Figure 5B, Tables 3 and S5). Low impact seismic line samples, did, however, have distinguishable differences between microtopographic features, with hollows being wetter, and were similar to reference locations (Figure 5B, Tables 3 and S5).

Water content by mass was highest in peatland and lowest in upland samples (Figure 6A, Tables 2 and S4). Untreated and reference samples were only different in upland sites, where seismic lines had higher values (Figure 6A, Tables 3,and S4). Water content by mass was also not different between microtopographic features in both untreated and reference samples in peatland and transitional samples (Figure 6B, Tables 3 and S5).

3.2. Impacts on Soil Properties with Treatments and Additional Disturbances

Inverted mounding treatments, designed to increase microtopographic variability on seismic lines in peatland and transitional ecosystems, result in different soil properties than both untreated seismic line and reference samples (Figures 2–6). Mounds on treated seismic lines had the highest dry bulk density on average, with values over three times higher than both untreated and reference samples (Figure 2B, Tables 3 and S5). Mounds also had a higher bulk density than their corresponding pits, which reverses the pattern of higher bulk density between high and low points observed in low impact and reference samples (Figure 2B and Table 3). Mean organic matter content in both the mounds and pits was lower by 9 to 18% on average compared to untreated seismic line and reference samples, and mounds and pits were not distinct from each other (Figure 3B and Table 3). Average organic matter bulk density on the mounds was also highest compared to untreated and reference hummocks, and pits were significantly higher and distinct from all hollows except those on conventional seismic lines (Figure 4B and Table 3). Volumetric water content of mounds was comparable to that of both seismic line and reference hummocks, while pits had the highest average volumetric water content across all categories and were distinct from reference sites (Figure 5B and Table 3). Water content by mass in mounds was significantly reduced compared to all other categories (Figure 6B and Table 3). The relative abundance of samples categorized as mineral soil (<30% organic matter) was higher in areas subjected to inverted mounding, particularly in transitional sites (Figure 7A). An increase in the relative number of samples that were considered mineral soil was not seen in intact profile treatments, which, although not included in the statistical analysis due to a low sample number and only being sampled in peatlands (Table S3), had a similar proportion of samples that have organic matter content that is >30% to reference samples (Figure 7A).

Additional disturbances in upland ecosystems, such as forest harvesting and wildfire, had limited evidence for further contributing to altering dry bulk density in soils (Figure 7B, Tables 4 and S6). Instead, being on the seismic line was the only factor that had a significant effect (Figure 7B, Tables 4 and S6). Further, both forest harvesting and wildfire values had a similar range of dry bulk densities (Figure 7B). Higher, but not significant mean bulk densities were recorded on the seismic lines that also had an additional disturbance (Figure 7B and Table 4).

3.3. Relationship of Dry Bulk Density and Organic Matter in Surface Soils

Dry bulk density increased exponentially with decreasing organic matter content in all surface samples (Figure 8 and Table S7). The inclusion of ecosystem type explains additional variability within the relationship, where transitional and peatland sites had a reduced dry bulk density increase for a given decrease in organic matter content (Figure 8 and Tables S7 and S8). Although the addition of position within the model on its own did not significantly improve model fit (i.e., on and off the seismic line), it did improve the model when included with ecosystem type, where both upland and transitional/peatland sites had a greater bulk density increase at a given organic matter content on seismic lines compared to reference ecosystems (Figure 8 and Tables S7 and S8).

4. Discussion

4.1. Ecosystem Type Critical in Characterizing Altered Soil Properties on Seismic Lines

Ecosystem type was an important factor in explaining the differences in soil properties between untreated seismic line and reference samples, where the presence of mineral matter in the upper 15 cm of the soil profile had a strong influence on whether changes in soil properties were discernible (Figures 2 and 8). Average thickness of the organic matter-rich LFH layer in boreal Alberta ranges from 3 to 14 cm across the various upland and transitional forest ecosite types (Willoughby *et al.*, 2019) and LFH and mineral soil components typically have a large difference in bulk densities (e.g., 0.08 g cm^{-3} vs. 1.33 g cm^{-3} respectively in boreal mixedwood forests; Bock and Van Rees, 2002a). Therefore, small changes to LFH thickness would significantly alter sample bulk density through an increased mineral soil content alone (Grigal *et al.*, 1989; Weiland, 2024; Figures 2 and 8). In peatland and transitional swamp sites, where organic soil layers are typically much greater than 15 cm depth (e.g., range 8 to 757 cm and average 242 cm depth in boreal Alberta; N=64, Zoltai *et al.*, 2000), changes in bulk density in response to changes in mineral matter content are not as likely.

While shifts in dry bulk density can be partially explained by changing the relative amount of mineral matter content in the sample (Figure 8), seismic lines in all ecosystem types still tend to have higher densities at a given organic matter content, suggesting other factors influence surface soil properties, such as compression, altered extent of decomposition, and vegetation composition shifts. In upland samples, previous studies have shown that when the LFH and mineral layer are separated for analysis, the bulk density of the mineral layer is not significantly different between seismic line and reference samples, and instead, LFH thickness is decreased (Van Dongen *et al.*, 2023). If the mineral soil layer does not significantly change in terms of bulk density, then the dry bulk density of the LFH layer would need to be higher to explain the observed changes in total sample bulk density. This could be a result of soil compression (Tan *et al.*, 2005), removal of the less dense litter and fermented portions of the LFH (Lee *et al.*, 2002), or enhanced decomposition through increases in soil temperature post-tree removal (Schmidt *et al.*, 1996). Whether changes in dry bulk density are present or absent in the mineral soil layer are likely dependent on water content, as wetter sites are more prone to significant compression (McNabb and Startsev, 2022). In transitional and peatland samples, a similar pattern is seen, but dry bulk density is much lower for a given organic matter content in reference samples compared to on seismic lines (Figure 8). Organic soil horizons in transitional sites, which are typically gleysols or mesisols (Soil Classification Working Group, 1998; Willoughby *et al.*, 2019), have a much lower organic matter bulk density than LFH layers in mineral soils and are more similar to that of surface peatland samples (Figure 4; 0.08 g cm^{-3} LFH layer of gleysols; Shaw *et al.*, 2005), with more recalcitrant organic matter inputs, such as *Sphagnum* mosses and wetter conditions that inhibit aerobic decomposition (e.g., Moore *et al.*, 2007; Turetsky *et al.*, 2008). Therefore, we would expect a lower total sample dry bulk density in both of these ecosystem types.

Microtopography in transitional and peatland sites is also important to consider when evaluating impacts of seismic lines in these ecosystems, as discernible changes in soil properties depended on sample position (Figures 2–6). Hummocks in reference areas generally have a lower bulk density, higher organic matter content, lower organic matter bulk density, and lower volumetric water content than hollows, which has been demonstrated in other peatland studies (Figure 6; e.g., Thompson and Waddington, 2013). Lower bulk densities and higher organic matter content in surface peat on hummocks can be attributed to the greater resistance to decay of *Sphagnum* species found in hummocks compared to hollow species (Turetsky *et al.*, 2008). Resistance to decay also means that surface peats in hummocks have a lower organic matter bulk density (Loisel *et al.*, 2014). Higher volumetric water contents are also related to peat decomposability, as less fibric peat has reduced pore space connectivity and higher water retention (Rezanezhad *et al.*, 2016). These general trends are not always consistent on a plot-by-plot basis, as climate, vegetation composition, and local hydrological conditions can alter these relationships (Branham and Strack, 2014). For conventional seismic lines, both hummock and hollow soil properties tended to be indistinct from reference hollow samples, suggesting that in this seismic line type, where generally a greater amount of soil disturbance has occurred, simplification of microtopography remains (Figures 2–6). This observation is supported by elevation surveys of the soil surface on seismic lines in the region (Stevenson *et al.*, 2019). This contrasts with low impact seismic lines, where soil properties have a distinct microtopography and were generally not different than the reference samples (Figures 2–6). Other studies have also shown that microtopographic recovery tends to occur quickly on low impact seismic lines, and therefore changes in practices have indeed sped up recovery (Echiverri *et al.*, 2020; Filicetti *et al.*, 2023). Depending on the site, however, absolute elevation shifts and changes to water table positions means that hydrological conditions may still not be conducive to tree growth (Lovitt *et al.*, 2018; Pinzon *et al.*, 2023; Weiland, 2024). A longer microtopographic recovery time in conventional lines may also be due to ecohydrological feedbacks, where exposure of more decomposed peat with higher bulk densities and compression causes locally wetter conditions, which causes a shift towards hollow plant species that are less resistant to decay and have lower primary production and litter inputs, and therefore continue to have higher bulk densities that promote higher water retention (Belyea and Clymo, 2001; Rezanezhad *et al.*, 2016). Therefore, not until sufficient peat accumulation and the redevelopment of high points on the surface occurs will there be high points for trees to grow successfully and promote recovery (Belyea and Clymo, 2001).

Patterns of water content by volume and mass differed between ecosystem types, likely due to differences in larger scale hydrological shifts following disturbance (Figures 5–6 and Table 2). Peatland and transitional samples had significantly higher volumetric water content in seismic line hummocks on conventional lines compared to reference areas, which due to the proximity to the water table, would be more prone to increases in water content than drier microsites (Emers *et al.*, 1995; Williams *et al.*, 2013; Davidson *et al.*, 2020). In upland samples, significantly lower water content by mass on seismic lines suggests that porosity has decreased, and therefore less water is retained in the mineral soil profile (Table 2; Tan *et al.*, 2005). In contrast, there was no significant difference in water content by mass in peatlands, even when split by microtopography (Figure 6). Minimal changes to water content by mass are likely due to the surface being made of living and poorly decomposed *Sphagnum* mosses, and so water mass represents not only water in pore spaces, but also secondary porosity in the living vegetation. Further, *Sphagnum* mosses can mitigate water loss through capillary rise, and so water contents would remain high, even in hummocks that are further from the water table (McCarter and Price, 2014). Overall, we generally observed a larger impact of seismic line disturbance on hydrological conditions at wetter sites, thus leading to even wetter conditions as the result of disturbance.

4.2. Additional Disturbances and Restoration Further Alter Soil Properties

Seismic lines treated with inverted mounding generally have higher dry bulk density, lower water content by mass, and lower organic matter contents compared to both untreated seismic lines and reference samples, due to the process of inverting the soil during mounding and resulting in the exposure of older, more decomposed peat and mineral soil, as demonstrated in previous studies (Figures 2–3 and Table 3; Davidson *et al.*, 2020; Kleinke *et al.*, 2022; Fliesser, 2023). Distinct soil properties from both untreated seismic lines and reference samples have also been shown to promote different vegetation assemblages post-treatment (Goud *et al.*, 2024), including the intended increased seedling establishment and growth, but also a reduction in bryophyte and shrub cover (Echiverri *et al.*, 2020; Shellian *et al.*, 2024). Success of seedling establishment likely depends on the ability of the mound to provide ideal soil conditions in the rooting zone, as high water content and low mound height following erosion and slumping in highly humified peat can lead to reduced seedling survival (Lieffers *et al.*, 2017; Fliesser, 2023; Shellian *et al.*, 2024). Although inverted mounds can lead to short-term success in seedling establishment, bryophytes have been shown not to recover, due to the disconnection of the top of the mound from the water table that limits the ability to bring water to the surface through capillary rise (Echiverri *et al.*, 2020). Since the recovery of bryophytes is linked to successfully re-establishing peat accumulation and microtopography (e.g., Pouliot *et al.*, 2011), continued monitoring of treatments is needed to determine if they lead to faster recovery of overall ecosystem function, especially when microtopographic gradients in low-impact seismic lines have been shown to be recovering both in terms of their soil properties (this study; Filicetti *et al.*, 2023; Pinzon *et al.*, 2023) and bryophyte and shrub cover (Echiverri *et al.*, 2020). Further, the pits created as a result of inverted mounding are deep and often filled with water, which limits vegetation growth, hinders natural microtopographic recovery, and these pits may persist for much longer than the mounds (Pinzon *et al.*, 2023). Therefore, careful consideration of what types of sites would benefit from this type of treatment is critical for long-term restoration success.

Seismic lines in upland areas that had additional disturbances such as forest harvesting and wildfire had the highest dry bulk density of the surface soils, but additional disturbances did not have as significant of a role in altering soil properties compared to the initial seismic line creation (Figure 7 and Table 4). Forest harvesting initially increases the thickness of the LFH layer, as harvest slash is added to the ground surface (Bock and Van Rees, 2002a). However, shifts to nutrient-rich litter with the establishment of different understory plant communities and increases in decomposition with nutrient leaching post-harvest have been shown to decrease LFH thickness over time (Pennock and van Kessel, 1997; Bock and Van Rees, 2002a; Lee *et al.*, 2002). Therefore, depending on timing of harvesting and sampling, we would expect a large range in surface bulk densities due to changing LFH thicknesses. Wildfire has been shown to lead to more rapid tree growth on seismic lines in both xeric and mesic upland areas compared to the adjacent forest, so although initially the LFH is removed via combustion, tree recovery could lead to more rapid accumulation of litter post-fire through increased biomass inputs (Chen *et al.*, 2017; Filicetti and Nielsen, 2018; 2022). Additionally, increased soil bulk density on seismic lines in peatlands can increase soil smouldering potential compared to adjacent natural areas, which could contribute to differences in soils on seismic lines disturbed by wildfire, depending on how it counteracts the effects of increased moisture (Pinzon *et al.*, 2021; Weiland *et al.*, 2023). Decreases in enzymatic activity and slow fungal community recovery post-fire also slows decomposition and allows for more rapid recovery of LFH thickness post-fire (e.g., Köster *et al.*, 2014; Köster *et al.*, 2015). Therefore, timing of sampling post-wildfire in both reference and seismic line samples would also impact the effect size.

4.3. Database Representativeness

Overall, peatland and transitional samples are better represented than upland samples in the database, having more samples analyzed for the various soil properties incorporated in this study (Tables 2–4). Peatlands and transitional to upland coniferous sites account for 13% and 25% of the Boreal Plains Ecozone respectively (ABMI, 2013; Government of Alberta, 2018; DeLancey *et al.*, 2020; ABMI, 2021; Table S9) and samples from these ecosystems were 75% of the database (N=1,232). Samples included replicates within plots to record microtopographic variability, however, and when compared on the plot scale, peatland and transitional sites combined were comparable to upland sites (N=293 plots vs. N=361 plots on and off seismic lines combined for peatland/transitional and upland samples respectively; Table S3). Fens, which are the dominant peatland type in the region (91% of the peatland ecosite area; DeLancey *et al.*, 2020; ABMI, 2021), also accounted for the majority of the samples (N=814). The peatland samples are also clustered into 15 locations, with three locations (Kirby South, Lidea Pilot, and

Brazeau) accounting for 66% of the peatland samples (Table 1). Therefore, future sampling efforts in other locations within the Boreal Plains Ecozone would help to improve representativeness in the dataset. More sampling of intact profile mounding treatments, as these are implemented, would also allow for comparisons to more traditional inverted profile treatments, as samples currently only come from one location and are limited for each intact profile type (i.e., inline mounding, hummock transfer, and rip and lift; Brazeau; N=48 total; Table S3). The peatland and transitional samples also have a high number of measurements for each of the soil properties, with missing data ranging from 8–30% for a given soil property (Table S3).

In contrast, all upland samples had dry bulk density measurements (N=406), but datasets for the other soil properties are much smaller, with organic matter content and organic matter bulk density having the lowest number of samples (N=65; 83% of the samples missing data; Table S3). Samples were also mainly from conventional seismic lines, and so analysis of line type was not feasible in this study (i.e., N=0 for organic matter content and organic matter bulk density and N=4 for volumetric water content and water content by mass for low-impact seismic lines; Figures 3-6). Upland samples had a wider distribution of samples across the study region when compared to peatland and transitional samples, with 33 locations each having generally less than 5% of the samples, except for Tiger Sands, which accounted for 26% of the samples (Table 1). Further, samples generally represented the distribution of the upland ecosite types, where deciduous upland forests have the highest number of samples (N=301) and areal coverage in the Boreal Plains (36% of forested area; ABMI, 2013; Table S9). Therefore, more upland samples with measurements of soil properties, especially on low-impact seismic lines, would make the dataset more representative of the study area.

4.4. Future Directions

Although this database provides surface soil sample information across various ecosites within northern Alberta, the samples are restricted to the upper 5 to 15 cm of the profile and may not necessarily capture the full extent of soil property changes from disturbance, especially in deeper organic soils. However, differences in soil properties at depths greater than 50 cm on seismic lines are minimal (Kleinke *et al.*, 2022; Weiland, 2024). Additionally, in peatland and transitional areas, new moss growth and peat accumulation may comprise a large portion of the soil sample, as rates of vertical accumulation of new peat have been shown to be 0.32 to 0.64 cm yr^{-1} for rich fens in the region (Vitt *et al.*, 2009). These vertical accumulation rates for rich fens suggest that the upper 10 cm of the soil profile would be all new moss growth by 32 years post-disturbance, which is within the range of the earliest conventional seismic lines (Dabros *et al.*, 2018). Although not necessarily important for answering questions about surface processes, site assessment for other costs, such as determining carbon loss, changes in fuel properties for wildfires, and changes to groundwater flow would benefit from analyzing deeper peat layers to capture the disturbance layer (e.g., Deane *et al.*, 2020; Kleinke *et al.*, 2022; Weiland *et al.*, 2023; Weiland, 2024). In upland samples, most disturbance to the carbon storage in the forest floor has been shown to occur in the upper 20–30 cm of the mineral soil, and the LFH layer is the most prone to disturbance (Lim *et al.*, 2018; Filicetti and Nielsen, 2022). Therefore, in the samples where the entire LFH is captured, estimates of soil organic carbon loss and recovery would likely be captured.

This study demonstrates that loss of organic matter in soils with disturbance can explain some of the variation in dry bulk density in seismic line soils (Figure 8); however, understanding the relative roles of soil removal, changing decomposability post-disturbance, and compression in also changing the organic matter content of soils remains a challenge (e.g., Tan *et al.*, 2005; Davidson *et al.*, 2020). In upland samples, future work should separate LFH and mineral soil and determine bulk density and organic matter content on each component to determine carbon loss and relative compression (e.g., Lee *et al.*, 2002). Other geochemical analyses, such as elemental concentrations in the soil (e.g., C, N, P, K, and Ca) would also help to determine post-disturbance processes such as enhanced mineralization with nutrient release and transport (e.g., Simard *et al.*, 2001; Hynes and Germida, 2013) and reduction in nutrient availability and poor aeration limiting mineralization in compressed soils (e.g., Tan *et al.*, 2005). In peatland samples, age-depth modelling to determine hiatuses and accumulation post disturbance would also help to distinguish between these different factors (e.g., Magnan *et al.*, 2020).

Long term monitoring of soil properties would also help to determine the relative roles of post-disturbance processes on resulting values. In upland samples this could include measuring LFH thickness and density over time to determine an accumulation rate and predict the return of soil organic matter to pre-disturbance conditions, either at one site or in a chrono sequence (e.g., Shrestha and Chen, 2010). Soil samples from other restoration techniques used in upland areas, such as disc trenching, plowing, scalping, and scarification would also be a benefit to the database and would help to determine their impacts to soil properties on seismic lines specifically (Schmidt *et al.*, 1996; Bock and Van Rees, 2002b). In peatlands, previous studies have shown that mounds can degrade over time or if degradation does not occur, makes microtopography exaggerated (Lieffers *et al.*, 2017; Pinzon *et al.*, 2023). Therefore, continued monitoring of their impacts post-restoration would help to inform future restoration planning efforts, as the mounds compiled in this study are < 11 years post-restoration. Finally, water contents in soils at the surface can vary widely across seasonal and interannual scales, and therefore long-term monitoring across multiple sites and a more strictly paired sample design would both improve our understanding of changes in hydrological conditions with seismic line creation and subsequent recovery (Weiland *et al.*, 2023; Weiland, 2024).

5. Conclusion

Surface soil properties on seismic lines are significantly different from reference samples, especially on older conventional seismic lines, where disturbance is still evident even after over 20 years since the initial disturbance. These changes can in part be explained by the loss of organic matter in the soil, which increases the dry bulk density. Even accounting for organic matter loss, seismic lines still have higher dry bulk densities for a given organic matter content, suggesting that other factors, such as enhanced decomposition, compression, and changes to litter inputs are also needed to explain differences to reference samples. Soil properties in peatland and transitional samples on conventional lines are not distinguishable by microtopography, suggesting that the simplification of the seismic line surface has also remained post-disturbance. In low impact seismic lines, however, microtopographic patterns of soil properties are similar to reference values, suggesting a more rapid recovery. Since microtopography appears to recover on low impact seismic lines, inverted mounding may not be necessary, and recovery of site conditions should be scrutinized prior to implementation. Seismic lines with additional disturbances in upland areas have the highest bulk densities, but the role of these disturbances on surface soil properties on seismic lines appears to have less of an impact than seismic line creation itself, likely due to post-disturbance processes. Overall, this database provides baseline information on seismic line soil properties, and through this synthesis, we were able to show the role of organic matter loss in altering surface soil properties, both of which are important for restoration and reclamation work, including closure certification applications across Alberta (Alberta Energy Regulator, 2024). Future work should focus on sampling underrepresented areas, focusing on upland sample organic matter and water contents. Further, deeper soil profiles, assessment of the LFH and mineral layers separately, and investigating changes in peat accumulation rates in organic soils will help to determine the relative roles of compression, decomposition, and carbon loss in altering soil properties on seismic lines. Long term monitoring of surface soil properties will also help to determine rates of change through time, which can be used to estimate recovery trajectories for both treated and untreated seismic lines.

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8. Data Availability Statement

Data analyzed during this study are provided in full within the published article and its supplementary materials.

9. Competing Interests Statement

The authors declare no competing interests.

10. Author Contribution Statement

MAD: Conceptualization, Investigation, Formal Analysis, Project administration, Visualization, Data Curation, Writing – Original Draft, Writing – Review and Editing

MS: Conceptualization, Supervision, Funding Acquisition, Resources, Writing – Review and Editing

SJD, PJD, AF SK, PK, KK, SEN, MAS, NT, JMW, LW, SW: Investigation, Writing – Review and Editing

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12. Tables

Table 1: Summary of surface soil sample locations and their sources included in this study from northern Alberta, Canada. On and off in the plot counts refers to plots that are on or off a seismic line. Locations are clustered sample points that are with 5 km of each other. Latitude and longitude values are averages of the sample coordinates for each reference and location combination.

Reference	**Location**	**Samples**	**Plots**		**Latitude** (°N)	**Longitude** (°W)
			On	**Off**		
Davidson *et al.* (2020)	Kirby South	110	10	10	55.37	111.157
	Tiger Sands A	59	5	5	56.427	111.107
	Tiger Sands B	88	7	8	56.329	111.581
Deane *et al.* (2020)	Wabasca A	2	1	1	55.711	113.577
	Wabasca B	2	1	1	55.918	113.680
	Wabasca C	4	2	2	56.013	114.024
	Wabasca D	4	2	2	55.793	113.403
Filicetti and Nielsen (2022)	Behan	6	3	3	55.286	111.330
	Chard A	32	16	16	55.803	110.646
	Chard B	4	2	2	55.818	110.801
	Conklin	4	2	2	55.630	111.154
	Gregoire Lake A	14	7	7	56.517	111.262
	Gregoire Lake B	2	1	1	55.733	112.487
	Greyling Creek	2	1	1	56.388	111.504
	Hanging Stone	16	8	8	56.425	111.283
	Ings Island	16	8	8	57.248	111.661
	Janvier A	2	1	1	55.934	110.659
	Janvier B	8	4	4	55.888	110.766
	Leismer B	6	3	3	55.742	110.918
	Mariana Lake A	10	5	5	55.727	112.109
	Mariana Lake B	12	6	6	55.804	112.185
	Mariana Lake C	10	5	5	55.722	112.304
	Mariana Lake D	2	1	1	56.000	111.998
	Mariana Lake E	2	1	1	55.886	112.143
	McClelland Lake A	4	2	2	57.512	111.457
	McClelland Lake B	18	9	9	57.546	111.159
	NW Fort McMurray	2	1	1	56.787	111.757
	Saprae Creek	4	2	2	56.648	111.11
	Surmont B	24	12	12	56.166	110.867
	Tiger Sands A	10	5	5	56.424	111.034
	Tiger Sands B	82	41	41	56.260	111.595
	West Fort McKay	4	2	2	57.180	111.674

Hillson (unpublished)	Lidea Pilot	262	59	13	55.052	110.480
Kleinke (unpublished)	Lidea Pilot	96	8	8	55.051	110.473
	West Clyde	60	8	2	55.080	111.194
	South Clyde	96	16	0	55.289	111.194
Kleinke *et al.* (2022)	Brazeau	16	3	1	52.889	115.549
	South Clyde	18	2	1	55.080	111.194
Korsah (unpublished)	Carmon Creek	23	4	4	56.362	116.796
	Harmon Valley	13	2	2	56.202	116.934
	IPAD	12	2	2	56.398	116.898
Schmidt (unpublished)	Brazeau	111	8	2	52.889	115.556
Van Dongen *et al.* (2023)	Manning	24	4	4	57.390	118.381
Ketcheson (unpublished)	Foster Creek	15	2	1	55.329	110.256
	Lidea Pilot	6	1	0	55.055	110.483
Weiland (2024)	Kirby South	72	9	13	55.367	111.136
	Maqua	54	9	9	56.367	111.297
Subtotal		1443	313	239	-	-
New Samples (this study)	Avenir	8	2	2	55.057	112.086
	Conklin Road North	4	2	2	55.105	111.960
	Conklin Road South	4	2	2	55.059	111.991
	East Athabasca	5	2	2	57.113	111.419
	East Fort McKay	4	1	0	57.114	111.317
	Greyling Creek	8	4	4	56.388	111.439
	Kirby South	62	18	7	55.365	111.168
	Leismer A	12	6	6	55.801	111.334
	Lidea Pilot	24	8	4	55.05	110.474
	Maqua	12	1	1	56.371	111.29
	Philomena	8	1	1	55.223	111.316
	Poplar	6	3	3	56.939	111.699
	South Fort McKay	6	1	1	56.886	111.964
	Surmont A	6	1	1	56.181	111.041
	Tiger Sands A	16	8	8	56.386	111.054
	Tiger Sands B	4	2	2	56.359	111.573
	Timberlea	6	1	1	56.766	111.485
Subtotal		195	63	47	-	-
TOTAL		1638	376	286	-	-

Table 2: Least square means and standard error (SE) of surface soil properties (dry bulk density, organic matter content, organic matter bulk density, volumetric water content, water content by mass) for each ecosystem type for untreated seismic lines (ON) and adjacent reference samples (OFF).

	OFF					**ON**				
A. Dry Bulk Density (g cm^{-3})										
Ecosystem	**Mean**	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
Peatland	0.041	0.005	213	65	14	0.043	0.005	309	87	12
Transitional	0.061	0.007	122	33	9	0.082	0.009	144	33	10
Upland	0.377	0.034	187	181	32	0.524	0.047	195	180	32
B. Organic Matter Content (%)										
Ecosystem	**Mean**	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
Peatland	92.63	0.98	158	46	9	91.41	1.10	252	71	8
Transitional	92.00	1.12	116	27	6	86.35	1.86	121	27	7
Upland	36.75	10.81	31	30	9	31.11	11.62	34	30	9
C. Organic Matter Bulk Density (g OM cm^{-3})										
Ecosystem	**Mean**	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
Peatland	0.036	0.004	140	46	9	0.033	0.004	232	69	8
Transitional	0.042	0.005	101	24	6	0.042	0.005	108	25	7
Upland	0.078	0.012	31	30	9	0.081	0.012	34	30	9
D. Volumetric Water Content (%)										
Ecosystem	**Mean**	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
Peatland	29.6	4.6	184	55	9	31.3	4.6	297	78	7
Transitional	29.7	4.8	120	31	8	35.3	4.9	142	31	9
Upland	32.8	5.3	41	35	11	37.7	5.3	49	34	11
E. Water Content by Mass (%)										
Ecosystem	**Mean**	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
Peatland	73.9	3.9	184	55	9	76.5	3.9	297	78	7
Transitional	71.0	4.0	120	31	8	68.2	4.0	142	31	9
Upland	52.0	4.2	41	35	11	44.0	4.2	49	34	11

Table 3: Least square means and standard error (SE) of surface soil properties (dry bulk density, organic matter content, organic matter bulk density, volumetric water content, water content by mass) for each seismic line category for hummocks/mounds (HIGH) and hollows/pits (LOW) in transitional and peatland samples.

	HIGH (Hummocks/Mounds)					**LOW (Hollows/Pits)**				
A. Dry Bulk Density (g cm^{-3})										
Category	**Mean**	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
Conventional	0.055	0.010	86	31	11	0.073	0.014	53	24	10
Low Impact	0.024	0.004	149	78	4	0.049	0.008	130	73	4
Reference	0.032	0.005	174	87	15	0.049	0.008	125	71	15
Treated Inverted	0.165	0.028	159	61	6	0.107	0.018	153	59	6
B. Organic Matter Content (%)										
Category	**Mean**	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
Conventional	91.02	1.85	57	26	11	90.01	2.05	62	26	11
Low Impact	92.53	1.48	111	70	4	89.05	2.17	111	68	4
Reference	94.55	1.01	123	67	14	90.98	1.67	115	69	14
Treated Inverted	77.13	4.50	129	54	5	80.45	3.84	131	54	5
C. Organic Matter Bulk Density (g OM cm^{-3})										
Category	**Mean**	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
Conventional	0.038	0.006	47	22	9	0.051	0.008	50	22	10
Low Impact	0.025	0.004	110	70	4	0.045	0.007	111	68	4
Reference	0.032	0.004	112	64	14	0.048	0.007	103	66	14
Treated Inverted	0.087	0.012	129	54	5	0.067	0.009	131	54	5
D. Volumetric Water Content (%)										
Category	**Mean**	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
Conventional	44.3	5.5	85	30	10	52.8	5.7	48	21	9
Low Impact	25.9	5.2	149	78	4	47.8	5.2	130	73	4
Reference	29.9	4.8	158	83	14	40.4	4.9	118	69	14
Treated Inverted	36.1	5.1	152	60	6	57.8	5.1	147	58	6
E. Water Content by Mass (%)										
Category	**Mean**	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
Conventional	83.2	3.5	85	30	10	81.4	3.7	48	21	9
Low Impact	86.6	3.3	149	78	4	87.9	3.3	130	73	4
Reference	83.6	3	158	83	14	84.1	3.1	118	69	14
Treated Inverted	61.7	3.3	152	60	6	77.2	3.3	147	58	6

Table 4: Least square means and standard error (SE) of dry bulk density (g cm^{-3}) for untreated seismic lines (ON) and reference samples (OFF) and additional disturbances (fire and forest harvesting).

Additional Disturbance	**OFF**					**ON**				
	Mean	**SE**	**N**	**Plots**	**Locations**	**Mean**	**SE**	**N**	**Plots**	**Locations**
No	0.440	0.047	94	88	25	0.620	0.047	101	87	25
Yes	0.522	0.049	93	93	18	0.706	0.049	94	93	18

13. Figures

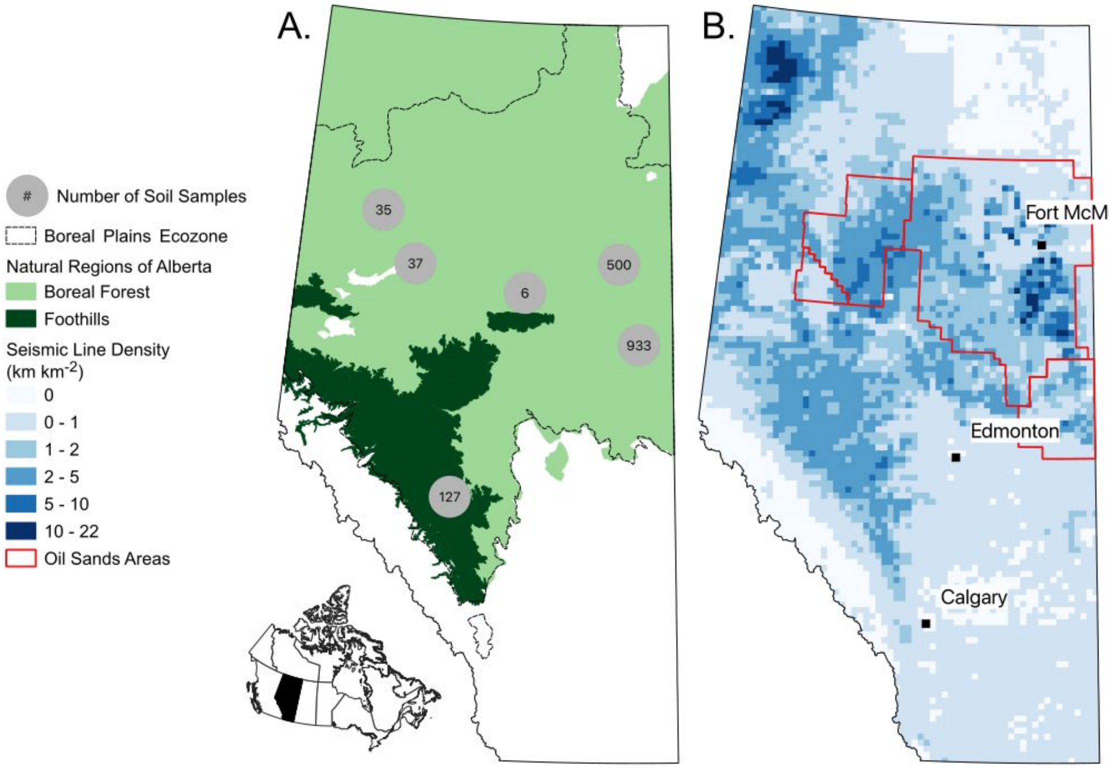

Figure 1: Map of surface soil sampling points included in this study, showing (**A**) the Boreal Plains Ecozone (Ecological Stratification Working Group, 1995) and Natural Regions of Alberta (National Regions Committee, 2006) and (**B**) seismic line density. Seismic line density derived from the Human Footprint Index using a 10 × 10 km grid (ABMI, 2019). Inset map shows the location of Alberta within Canada. Map was created using QGIS software (WGS84 and UTM Zones 11 and 12; QGIS Development Team, 2020).

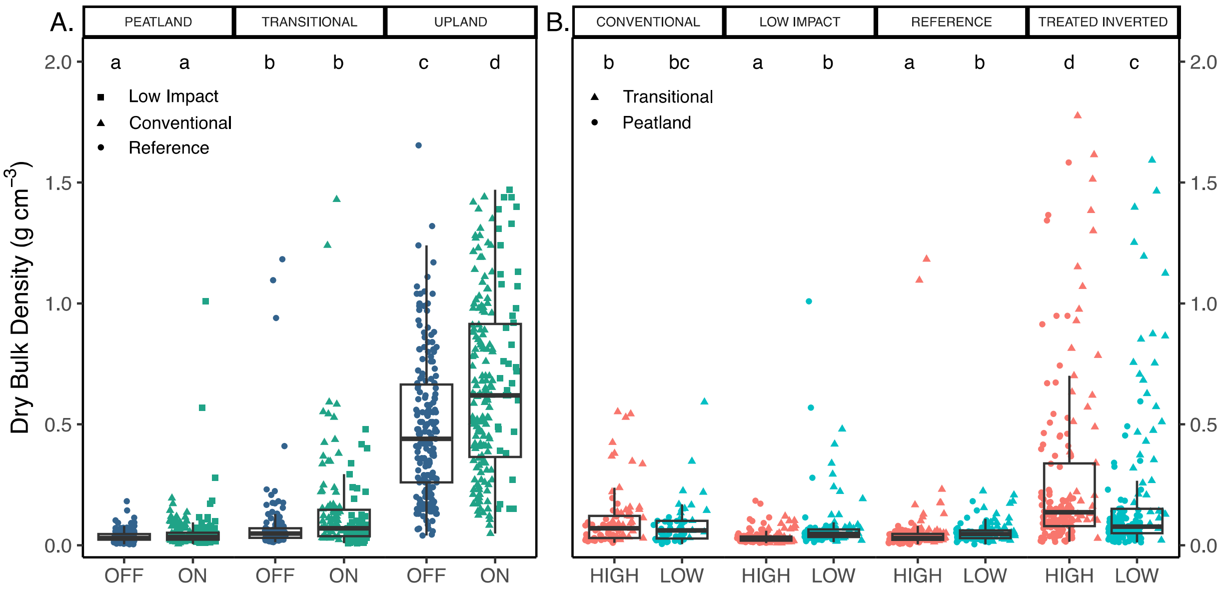

Figure 2: Dry bulk density of surface soil samples taken on and off untreated seismic lines in northern Alberta, Canada. Boxplots show the median as a solid horizontal line, the box is the interquartile range, and the whiskers bound the minimum and maximum values that are within 1.5 times the interquartile range. **A.** Samples sorted by their ecosystem type and their relative position, either on the seismic line (ON) or off the seismic line at an adjacent reference location (OFF). Shape of points indicate seismic line type. **B.** Peatland and transitional samples sorted by their microtopographic position, either a high point (hummock or mound; HIGH) or a low point (hollow or pit; LOW) and seismic line type, including sites that were treated with the inverted mounding technique. Shape of points indicate ecosystem type.

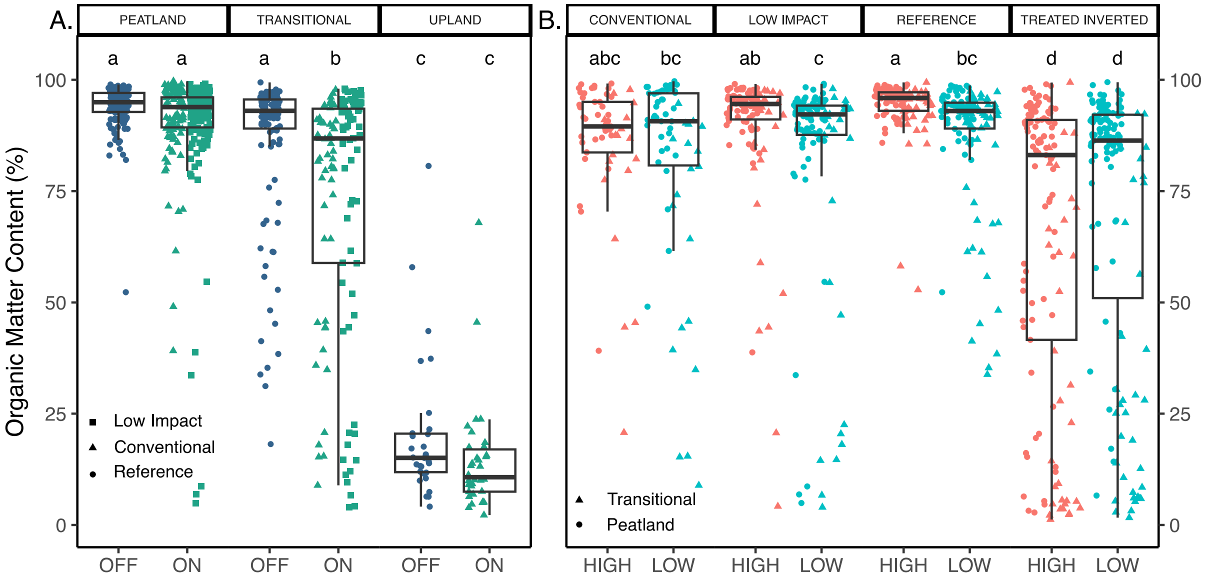

Figure 3: Organic matter content of surface soil samples taken on and off untreated seismic lines in northern Alberta, Canada. Boxplots show the median as a solid horizontal line, the box is the interquartile range, and the whiskers bound the minimum and maximum values that are within 1.5 times the interquartile range. **A.** Samples sorted by ecosystem type and their relative position, either on the seismic line (ON) or off the seismic line at an adjacent reference location (OFF). Shape of points indicate seismic line type. **B.** Peatland and transitional samples sorted by their microtopographic position, either a high point (hummock or mound; HIGH) or a low point (hollow or pit; LOW) and seismic line type, including sites that were treated with the inverted mounding technique. Shape of points indicate ecosystem type.

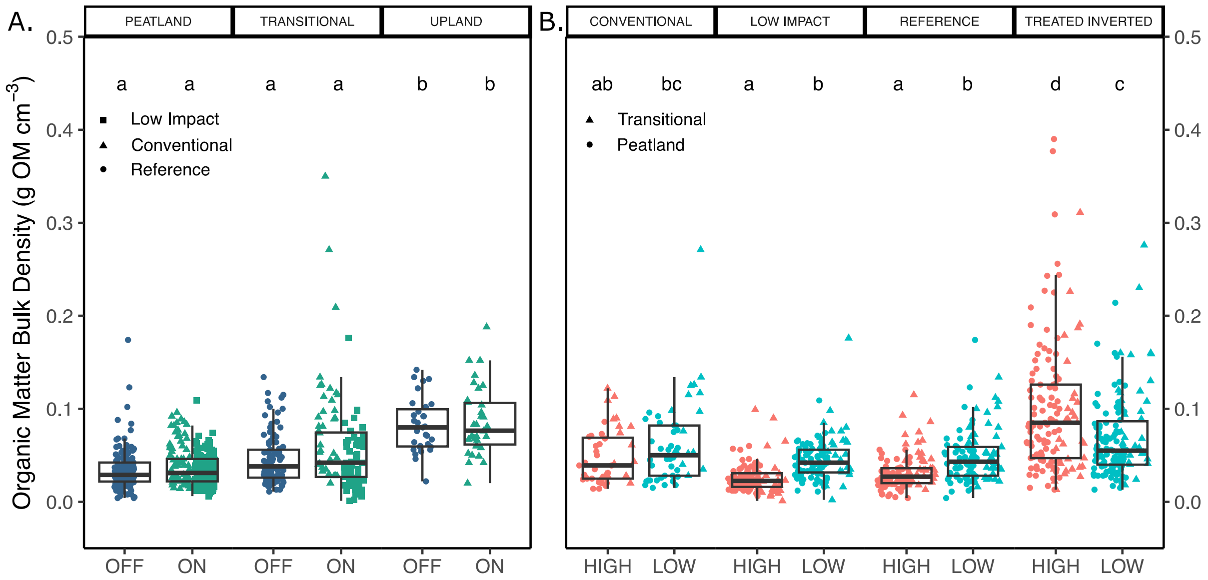

Figure 4: Organic matter bulk density of surface soil samples taken on and off untreated seismic lines in northern Alberta, Canada. Boxplots show the median as a solid horizontal line, the box is the interquartile range, and the whiskers bound the minimum and maximum values that are within 1.5 times the interquartile range. **A.** Samples sorted by ecosystem type and their relative position, either on the seismic line (ON) or off the seismic line at an adjacent reference location (OFF). Shape of points indicate seismic line type. **B.** Peatland and transitional samples sorted by their microtopographic position, either a high point (hummock or mound; HIGH) or a low point (hollow or pit; LOW) and seismic line type, including sites that were treated with the inverted mounding technique. Shape of points indicate ecosystem type.

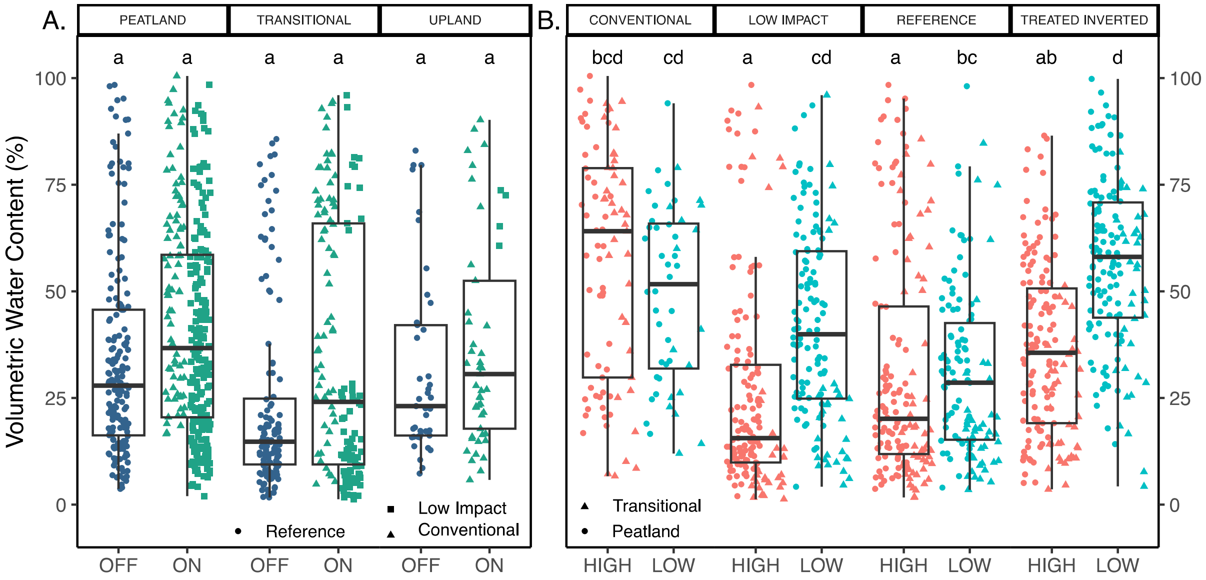

Figure 5: Volumetric water content of surface soil samples taken on and off untreated seismic lines in northern Alberta, Canada. Boxplots show the median as a solid horizontal line, the box is the interquartile range, and the whiskers bound the minimum and maximum values that are within 1.5 times the interquartile range. **A.** Samples sorted by ecosystem type and their relative position, either on the seismic line (ON) or off the seismic line at an adjacent reference location (OFF). Shape of points indicate seismic line type. **B.** Peatland and transitional samples sorted by their microtopographic position, either a high point (hummock or mound; HIGH) or a low point (hollow or pit; LOW) and seismic line type, including sites that were treated with the inverted mounding technique. Shape of points indicate ecosystem type.

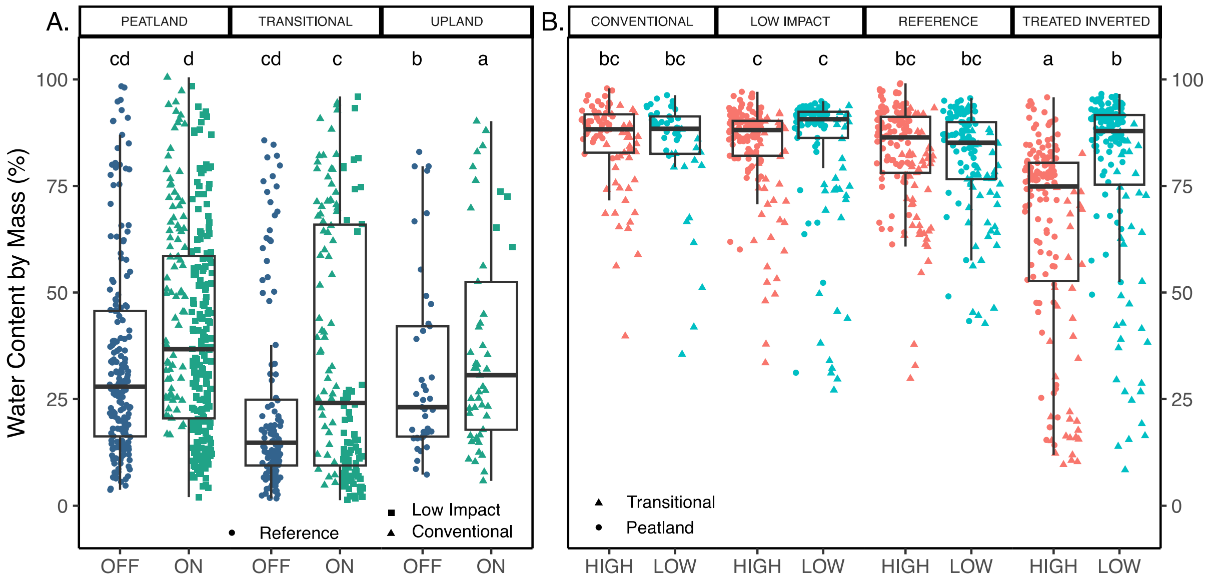

Figure 6: Water content by mass of surface soil samples taken on and off untreated seismic lines in northern Alberta, Canada. Boxplots show the median as a solid horizontal line, the box is the interquartile range, and the whiskers bound the minimum and maximum values that are within 1.5 times the interquartile range. **A.** Samples sorted by ecosystem type and their relative position, either on the seismic line (ON) or off the seismic line at an adjacent reference location (OFF). Shape of points indicate seismic line type. **B.** Peatland and transitional samples sorted by their microtopographic position, either a high point (hummock or mound; HIGH) or a low point (hollow or pit; LOW) and seismic line type, including sites that were treated with the inverted mounding technique. Shape of points indicate ecosystem type.

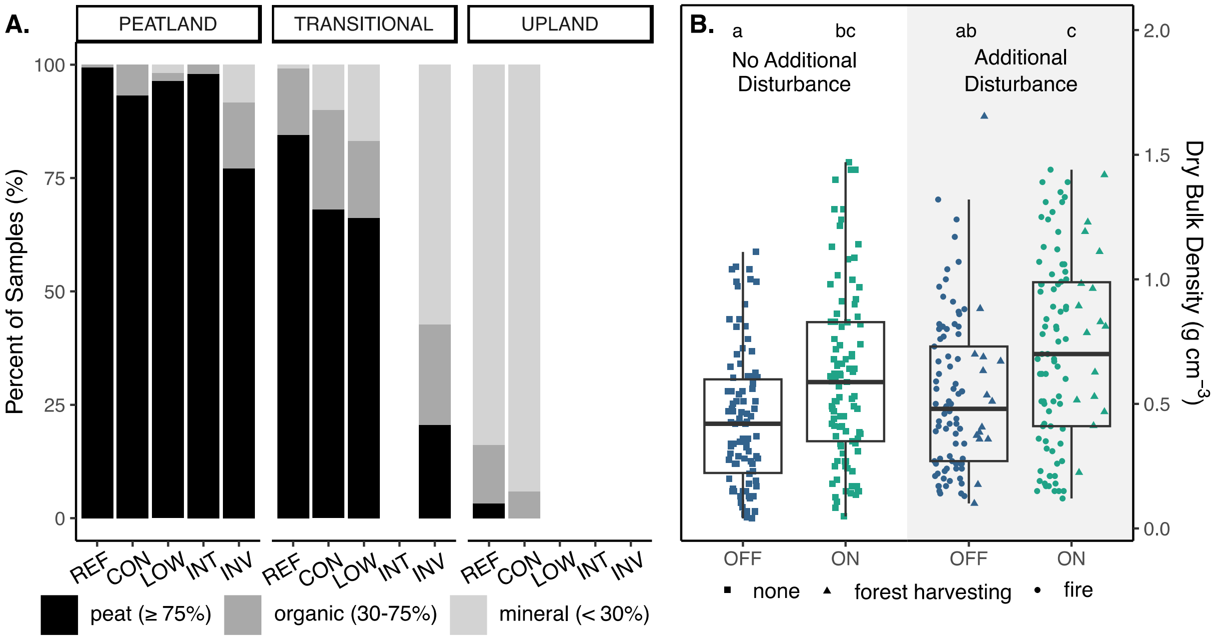

Figure 7: A. Percentage of samples in each seismic line category that are considered peat (>75% organic matter content; Loisel *et al.*, 2014), organic (30-75% organic matter content; Soil Classification Working Group, 1998), or mineral (<30% organic matter content; Soil Classification Working Group, 1998). REF: reference, CON: conventional seismic line, LOW: low impact seismic line INT: treated seismic line, intact profile, INV: treated seismic line, inverted profile**.** Note that no bar means that there were no samples that had organic matter content measured in that category. **B.** Dry bulk density of surface soil samples from uplands taken on and off untreated seismic lines in northern Alberta, Canada. Samples sorted by their relative position, either on the seismic line (ON) or off the seismic line at a reference location (OFF) and whether an additional disturbance has occurred at the site (forest harvesting or fire). Shape of points indicates disturbance type. Boxplots show the median as a solid horizontal line, the box is the interquartile range, and the whiskers bound the minimum and maximum values that are within 1.5 times the interquartile range.

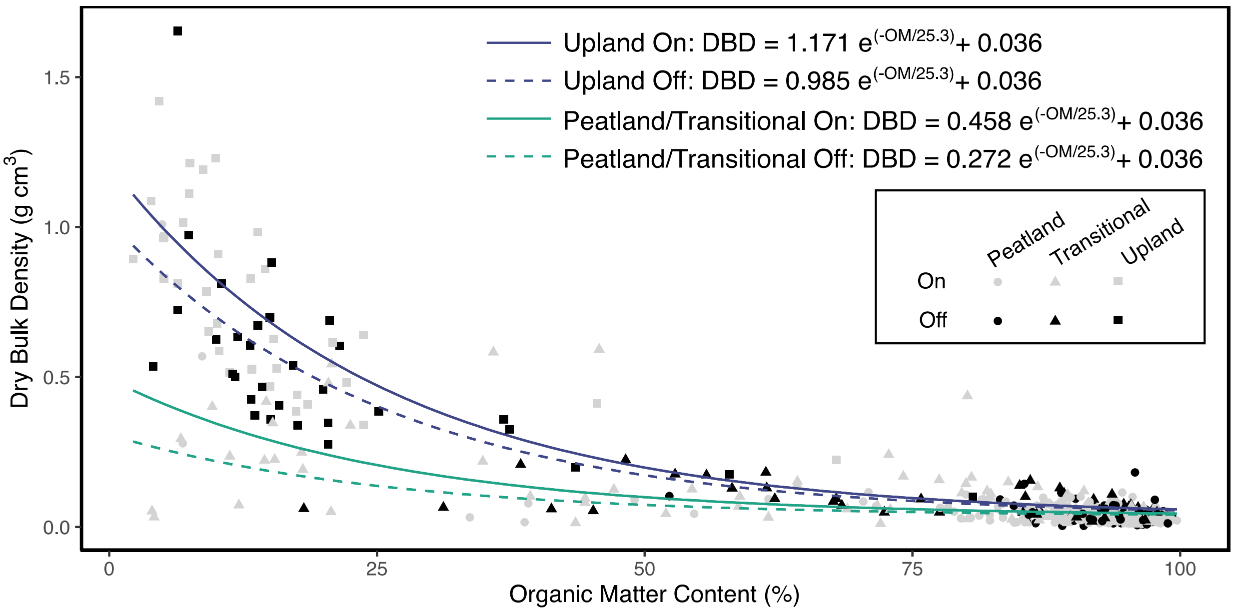

Figure 8: Relationship between organic matter content and dry bulk density in surface soil samples in peatland/transitional and upland ecosystems on and off untreated seismic lines in northern Alberta, Canada.