

**Hydroclimatic influence of seismic line disturbances based on field measurements
and modelling across Alberta, Canada**

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Unlike the traditional thesis format, this submission has been compiled as a collection of written scholarly work (manuscripts). Four independent manuscripts to be submitted for publication are presented as chapters 2, 3, 4, and 5 of this thesis. As a result, repeated information may be included.

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Abstract

Geologic exploration for petroleum has resulted in a dense network of seismic lines—linear clearings—across the boreal forest, yet their effects on hydrometeorological conditions remain understudied. With a focus on peatland ecosystems, this study used a combination of field-based measurements and hydrological modelling (CoupModel) to investigate the impact of seismic lines on wintertime hydrometeorological conditions, summertime evapotranspiration (ET), and the annual water balance for study sites in Alberta, Canada. Winter assessments revealed that photosynthetically active radiation (PAR) was 1.8 times higher on seismic lines than in the adjacent forest understory, with greater negative net radiation (i.e., high outgoing radiation for the ground surface) also observed. Wind speeds on seismic lines during the unfrozen period were significantly elevated, 8 times higher at an east-west site and 7 times higher at a north-south site, compared to the adjacent undisturbed peatlands. Soil temperatures remained above freezing for seven days longer on the lines, suggesting thermal insulation effects caused by the deeper snowpack observed on the seismic lines. Snowpack dynamics captured by time-lapse photography across upland and peatland sites showed a 5 cm higher maximum snow depth on seismic lines, and a 3 cm greater average snow depth, though the latter was not statistically significant. Snow depth declined more rapidly on seismic lines, but with maximum depth reached five days later, snow-free conditions occurred one day later despite an ablation duration five days shorter than in undisturbed areas. Actual ET (AET) from the ground layer on seismic lines in peatlands was 59% and 14% higher than adjacent areas based on lysimeter and chamber measurements, respectively. Soil temperature, PAR, and plant composition were key drivers of chamber-based AET, while lysimeter-based AET was mainly influenced by PAR and wind speed. Potential ET (PET) was 51% higher on seismic lines, raising the Priestley-Taylor coefficient (α) from 0.61 to 0.73. While not directly measured, tree transpiration estimates from the literature were applied, which revealed

that seismic line AET still surpassed that of adjacent areas with an intact tree cover by 31%. Comparing 1-D simulations for on and off seismic line conditions for peatlands from a process-based hydrological model (CoupModel) supported field-based findings, indicating higher soil moisture, temperature, and shallower groundwater depths on seismic lines. The simulated AET was 6% higher on the lines, largely driven by moss evaporation, which compensated for lost canopy transpiration. Despite higher ET, increased precipitation that reaches the ground surface and lateral flow led to 5 mm more water storage on seismic lines. Model sensitivity analysis revealed that an increase in soil compaction substantially elevated runoff, drainage, soil moisture, and storage. The seismic line had a greater difference in conditions from offline areas when peatland canopy LAI was greater; the undisturbed condition with higher LAI resulted in higher transpiration, and cooler soils. Overall, the findings illustrated that seismic line clearing results in measurable local changes in hydrological conditions; future research should explore the impact of seismic lines on the catchment scale to better understand the cumulative impact of these disturbances on hydrological processes in boreal ecosystems.

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List of Abbreviations

Abbreviation	Definition
ADE	Audet Lake
AET	Actual Evapotranspiration
CC	Carmon Creek
CHR	Christian Lake
DOY	Day of Year
ET	Evapotranspiration
GWD	Ground Water Depth
HV	Harmon Valley
IP	Peace River
KS	Kirby Site
LAI	Leaf Area Index
MS	Maqua Site
NR	Net Radiation
Offline	Adjacent natural area
Online	Seismic line
PAR	Photosynthetically Active Radiation
PET	Potential Evapotranspiration
PT	Priestley and Taylor
RH	Relative Humidity
SWE	Snow Water Equivalent
Ta	Air Temperature
Tc	chamber temperature
Ts	Soil Temperature
VPD	Vapor Pressure Deficit
VWC	Volumetric Water Content
WS	Wind Speed
WS-D	Wind Speed Direction
α	Coefficient of Evaporability

Chapter 1.

Literature Review

1.1. Introduction and problem context

Geologic exploration for petroleum resources has created a network of linear clearings known as seismic lines. These anthropogenic disturbances were created for geologic mapping of oil reserves, primarily in the Alberta Oil Sands Region (AOSR), altering ecosystems by fragmenting forest cover (Weiland et al., 2023; Dabros et al., 2018) and can contribute to anthropogenic climate change by increasing greenhouse gas emissions (Strack et al., 2019). It has been reported that 46% of all linear features across the Canadian boreal ecosystem are seismic lines (Pasher et al., 2013). It has been estimated that the total length of seismic lines is five times the length of roads and rail lines (Pattison et al., 2016); however, this disturbance has a lower impact compared to surface mining, which fully removes ecosystem components such as soils and vegetation (Jordaan, 2012). In 2021, seismic lines accounted for 57.7% of linear disturbances in the province of Alberta with an average density of 1.5 km per km² (ABMI, 2023). The vast majority of abandoned lines are in the western boreal region and are often characterized by poor natural recolonization of the vegetative cover and slow recovery of trees, especially in peatlands (van Rensen et al., 2015). Seismic line operation results in soil compaction and a reduction in microtopography (Stevenson et al., 2019), which also affects carbon cycling and water supply (Strack et al., 2019; Weiland et al., 2023). Although the width of conventional seismic lines has reduced from 10 m to lower impact approaches since the mid-1990s, with a line width of less than 5 m, the high density of narrow lines has enhanced the area subject to edge effects and subsequently their total footprint (Dabros et al., 2017). The impact of seismic lines on physical and chemical soil properties (Dabros et al.,

2017), microclimatic conditions (Pohlman et al., 2007; Franklin et al., 2021), water table position (Lovitt et al., 2018), carbon dynamics (Schmidt et al., 2022), ground layer plant community composition (Deane et al., 2020; Goud et al., 2024), wildlife behavior (Wilson, 2011), wildfire (Deane et al., 2020; Weiland et al., 2023), and permafrost degradation (Williams et al., 2013) has been investigated in several studies. The common finding of most studies is that the impact of seismic lines on ecosystem function varies over time and strongly depends on the abiotic and biotic conditions of the study area (Dabros et al., 2019; Davidson et al., 2021; Kleinke et al., 2022).

Studies on the effect of seismic lines on local to regional hydrology are scarce. Previous research has investigated the impact of seismic lines and/or linear disturbances on some pertinent variables such as moisture and temperature of the soil (Dabros et al., 2017), light/solar radiation (Pohlman et al. 2007; William and Quinton, 2013), bulk density and volumetric water content of the soil (Davidson et al., 2021; Davies et al., 2025), air temperature and vapor pressure deficit (Franklin et al., 2021; Haag and Bliss, 1974; Pohlman et al., 2007), wind speed (Burton, 2002; Weiland et al., 2023), snow water equivalent (Weiland et al., 2024), groundwater table (Weiland et al., 2024), and hydraulic conductivity (Weiland et al., 2024). Nevertheless, many unanswered questions regarding seismic line implications for hydrological variables and the various components of the water balance remain including effects on actual evapotranspiration, snowpack properties, the cumulative effect of changes in water balance on discharge at the catchment scale, and variation in local response caused by the width, orientation and edge effects of the disturbance. Further, most previous studies have focused on the summertime period, resulting in limited knowledge about the implications of seismic lines on wintertime meteorological and hydrological conditions. Therefore, the goal of this thesis is to further our understanding of the effect of seismic line disturbance on local water balance, with a focus on peatland ecosystems.

1.2. Literature review and conceptual framework

1.2.1. Water balance components affected by seismic lines

More than 20% of the Canadian boreal forest consists of peatlands (Tarnocai et al., 2000), which play a key role in shaping hydrological conditions at high latitudes. These ecosystems are hydrologically more complex than mineral wetlands and are considered more difficult to construct (Price et al., 2003; Petrone et al., 2008; Devito et al., 2012). Their hydrological connection to upland areas further complicates restoration efforts. During wet years, peatlands receive water from surrounding uplands, whereas in dry years, they supply water to nearby upland forests (Ferone and Devito, 2004). The persistently wet conditions in peatlands are maintained by intricate feedback mechanisms, primarily influenced by soil properties and vegetation (Waddington et al., 2015). Previous research has shown that in forested and afforested peatlands, trees and shrubs significantly affect peatland hydrology by reducing surface moisture through transpiration and interception (van Seters and Price, 2001), while also providing shade that lowers evaporative demand on the moss surface (Thompson, 2012).

In the Western Boreal Plain, peatland hydrology is further complicated by significant annual and decadal climate variability (Devito et al., 2012) and limited excess water availability during most years (Devito et al., 2012; Marshall et al., 1999). In this region, the close synchronization of precipitation and evapotranspiration creates a hydrologic regime dominated by vertical water fluxes. However, variation in soil depth, geology, and, to a lesser extent, topography also drives important lateral water redistribution, which is critical to peatland function (Van der Ploeg et al., 2012). As a result, the water balance of these peatlands is highly vulnerable to disturbances that may alter patterns of precipitation and actual evapotranspiration (AET).

The water balance can be expressed according to Equation 1 (Devito et al., 2012):

$$\Delta S = P - ET + \Delta R + \Delta GW \quad (1)$$

Where ΔS is change in storage, P is precipitation, ET is evapotranspiration (evaporation + transpiration), ΔR is changes of input and output of runoff, ΔGW is variation of input and output of groundwater.

The following sections will discuss the impact of seismic lines on water balance each component.

1.2.1.1. Precipitation

In general, the loss of canopy cover on seismic lines is expected to reduce interception and thus increase precipitation at the ground surface (Dabros et al., 2019; Kettridge et al., 2013). This pattern likely varies in space and time due to differences in canopy type and cover across the western boreal region and differential effects of seismic line disturbances on snow and rain.

1.2.1.1.1. Snow

Snow is known as an integral driver of water balance and influences the partitioning of energy availability, specifically in cold regions (Tsui, 2022). As seismic line disturbances result in the removal of canopy cover, interception of snow will be reduced, increasing snow accumulation on the seismic line. Pomeroy et al. (2012) revealed that the removal of 60% canopy cover will induce a 45% increase in snowpack. An increase of 16% and 21% in snow water equivalent (SWE) following 40% and 50% tree removal has been detected by Woods et al. (2006) and Troendle and King (1987), respectively. Further, Hojatimalekshah et al. (2021) observed higher snow depth in open areas than under the canopy. Snowpack in open areas may also be affected by sublimation losses and wind redistribution. Pomeroy et al. (2012) pointed out that 10% to 45% of seasonal snowfall is lost due to the sublimation of intercepted snow in the forests of western Canada, which confirms the importance of sublimation in snow distribution. Although there are some opposite findings regarding snow dynamics on clear-cuts into the forest, this discrepancy can be attributed

to the fact that snow properties mainly depend on geographical locations, type, and age of disturbance. For instance, in the studies of Onuchin (2015), Onuchin et al. (2017), and Ketcheson et al. (2012) a decrease in SWE after harvesting due to sublimation has been reported. It is also reported that high wind speed in open areas increases blowing snow fluxes and sublimation losses (Pomeroy and Gray, 1994), which reduces snow depth (Dharmadasa et al., 2024). Overall, Troendle and Meiman (1984), Troendle and King (1985), and Wheeler (1987) have found that intercepted snow after forest harvesting has a higher significance than the redistribution of snow by wind. According to field measurements from seismic lines, the open area created by seismic lines reduced snowfall interception and has been shown to enhance snow accumulation, with higher SWE observed on a small sample of seismic lines in the east-west direction compared to the adjacent ecosystem (Weiland et al., 2024).

Regarding ablation, since the energy required for evaporation and sublimation from snowpack is much higher than melting, ablation dominates evaporation (Winkler et al., 2010). Clear-cutting has been shown to increase snow ablation rates up to 100% more than undisturbed forests (Toews and Gluns, 1986; Berris and Harr 1987; Spittlehouse and Winkler, 2004). An integrative review comparing snow properties in forested and open sites across Canada and Europe indicated that the forest canopy controls 57% of snow accumulation and 72% of snow ablation (Varhola et al., 2010).

Despite greater ablation rates, thicker snowpack on seismic lines might also result in longer-lasting snow cover on linear disturbances, which function as a snow catchment basin (Haag and Bliss, 1974). In several studies, it has been observed that snow lasts longer in the open sites than in the forest (Dickerson-Lange et al., 2017; Lundquist et al., 2013); however, Sun et al. (2022) found that this discrepancy depends on the canopy density. The study of Hojatimalekshah et al. (2021) revealed that there is a significant relationship between vegetation structure and sub-canopy

snow depth in under-the-canopy regions, while snow depth in open areas is highly controlled by solar radiation and elevation. Extended duration of snow accumulation delays plant phenology and subsequently causes a shortened growing season (Dabros, 2008; Bjorkman et al., 2015). Further, it has been reported that high snow depth increases microbial biomass carbon and bacterial diversities, influencing winter carbon cycling in wetlands (Wang et al., 2020).

1.2.1.1.2. Rainfall

Similar to snow, rainfall is a major driver of water balance and may affect energy balance indirectly. Cutting trees leads to a greater proportion of rain reaching the ground due to the absence of interception (Abib et al., 2019; Thompson et al., 2014). Additionally, enhanced rainfall caused by tree removal can lead to a reduction in the GWD in the snow melting and storm period, even several years after disturbance (Adams et al., 1991; Dhakal and Sidle, 2003). An increase in rainfall on the seismic lines should follow the same pattern as snow; however, its magnitude depends on the type of forest cover and its density (Winkler et al., 2010). For example, due to the fact that black spruce trees have a narrow structure and often open canopy, their loss might have less impact on rainfall interception than other tree species (Brown et al., 2010). In support of this idea, rainfall interception losses in a Scots pine stand were reduced by 7%, while the basal area decreased by 47% (Knoche, 2005).

1.2.1.2. Evapotranspiration (ET)

ET is an integral part of water balance in peatlands and typically represents the greatest portion of water loss (Scarlett et al., 2017; Sonnentag et al., 2010; Petrone et al., 2004; Runkle et al., 2014). Additionally, ET is one of the more complicated hydrological processes to predict as it is affected by biotic and abiotic components (Warren et al., 2018). The impact of seismic lines on ET depends on the type of climate and ecosystem, and the age of fragmentation. For instance, without water limitation, there is a linear relationship between ET and loss of canopy; however, in an area with

a water deficit, it might be nonlinear (Hibbert, 1983). In terms of age, the study of Putuhena and Cordery (2000) depicted that ET will decline in the first years following harvesting and then will go up with growing vegetation. Amiro et al. (2006) and Liu et al. (2005) found that removing vegetation will decrease transpiration and evaporation from interception; however, it accelerates the evaporation from the soil surface. Canopy clearing can increase available radiation at the surface and Van Huizen and Petrone (2020) confirmed the key role of radiation on ET. Spittlehouse and Black (1982), and Knoche (2005) detected, increased evaporation from soil and transpiration from understory vegetation (particularly in old-cleared areas) caused by canopy opening, and this might offset, at least partially, the reduction in transpiration from trees. However, Wei et al. (2022) observed that the decrease in transpiration was substantially higher than the increase in evaporation. This finding seems reasonable in forests; however, in peatlands, it might be the opposite due to the open canopy. A recent study by Kononovs et al. (2024) applied a hydrological modelling approach that predicted up to a 33% reduction in simulated evapotranspiration rates on seismic lines as compared to the adjacent area in both a lowland and an upland site.

In peatlands, high availability of moisture may affect patterns of ET following seismic line disturbance. Soil compaction results in higher bulk density of near-surface soil, which in turn enhances soil moisture content and thermal conductivity (Braverman and Quinton, 2016). Price et al. (2010) and McCarter and Price (2013) have revealed a pivotal role of soil moisture in controlling ET. High thermal conductivity also amplifies the thawing of frozen water within the soil profile in spring, increasing ice melting. High available moisture due to melted ice and high bulk density leads to greater evaporation (van Huizen and Petrone, 2020). Overall, observed shifts in ET in response to seismic line disturbance will depend on changes in driving variables, including

available radiation, vapour pressure deficit, wind speed, and plant community, as described in the following sections.

1.2.1.2.1. Net Radiation (R_n) and Air Temperature (T_a)

The removal of trees will allow greater shortwave radiation to reach the surface. Higher light intensity on seismic lines compared to the adjacent area has been indicated in the studies of Stern et al. (2018) and Franklin et al. (2021). William and Quinton (2013) revealed an increase in incoming radiation on the linear disturbance compared to the undisturbed vicinity. It is worth noting that the impact of the seismic lines on radiation is strongly associated with the orientation and width (Franklin et al., 2021; Pomeroy et al., 2012; Stern et al., 2018; Revel et al., 1984). Most studies have pointed out that in northern latitudes, south-facing fragmentations receive more radiation (Franklin et al., 2021; Pomeroy et al., 2012). Although high radiation and greater tree regeneration in the east-west direction have been reported by Stern et al. (2018) and van Rensen et al. (2015), respectively, these conflicting results might be attributed to topography condition, the accuracy of modelling, and collected data time (Olson and Rupper, 2019). From the aspect of water balance, R_n provides the required energy for the evaporation of wet soil and transpiration of vegetation. The impact of R_n on vegetation composition has been reported by Echiverri et al. (2022), subsequently altering energy partitioning (Carey, 2008).

Due to the high R_n on the lines, a large amount of energy will be distributed as latent heat, hampering the increase in T_a (Haag and Bliss, 1978). Franklin et al. (2021) pointed out the necessity of the study of diurnal and nocturnal T_a patterns. Their survey indicated that diurnal T_a on the seismic lines was higher than the undisturbed forest, whereas this pattern was inverse during the night. This finding might be related to higher R_n during the day than at night due to greater outgoing longwave radiation from the ground surface at nighttime due to the lack of canopy. Franklin et al (2021) also observed that orientation played a role in temperature patterns where T_a

on north-south seismic lines during the day and night was greater than the east-west line. An increase in T_a on the seismic lines has also been reported by Dabros et al. (2019), which is consistent with the report of Ghuman and Lal (1987) from cleared areas.

1.2.1.2.2. Relative Humidity (RH) or Vapor Pressure Deficit (VPD)

RH or VPD is considered a factor that controls ET and, as such, ultimately affects the water balance (Carey, 2008). Although Scarlett et al. (2017) stated that VPD does not control the ET in the sub-humid region, in some studies, the role of VPD on ET has been reported (Kucera, 1954; Admiral et al., 2006; Admiral and Lafleur, 2007). The importance of VPD on ET is most significant in vascular plant-rich peatlands, where stomatal conductance is directly controlled by VPD (Phillips et al., 2016). Lower RH on the seismic lines than intact forests owing to high R_n and T_a has been observed (Ghuman and Lal, 1986). Similarly, Ketcheson et al. (2012) reported high RH in a forested peatland compared to adjacent cutover, tree-free areas. In the study of Franklin et al. (2021), RH was lower in the seismic lines than in the adjacent area by 3.8%. A decrease in RH or an increase in VPD might increase ET (Wu et al., 2016; Williams and Quinton, 2013); however, the extent of the increase depends on other weather variables.

1.2.1.2.3. Wind Speed (WS)

WS plays an important role in controlling ET (Carey, 2008). Increasing wind velocity is one of the impacts of the seismic lines that has been observed in several studies (Dabros et al., 2017; Dabros et al., 2019; Stern et al., 2018). Given the subsidence of the ground surface in the seismic lines (Petrone et al., 2008), there is a thicker boundary layer in the center than in the adjacent area, which can result in a visible gradient of temperature, wind velocity, and other variables in the height (Haag and Bliss, 1987). Similar to other weather variables, WS is also affected by orientation (Damschen et al., 2014), so the study of Stern et al. (2018) illustrated that north-south seismic lines had higher WS compared to an east-west orientation. WS can also drive other

components related to water balance, such as soil moisture. Stern et al. (2018) and Legates et al. (2011) observed that high WS can gradually reduce soil moisture on seismic lines.

1.2.1.2.4. Soil Moisture

Seismic lines influence soil moisture by compaction and compression of soil and removal of vegetation. Compaction can alter the structure of soil by decreasing effective porosity and subsequently increasing water retention (Arnup, 2000). High soil moisture content on the line is a key obstacle in recovering woody vegetation (van Rensen et al., 2015), particularly in lowlands (Lee and Boutin, 2006). Weiland et al. (2023) demonstrated that the compression of organic soils on seismic lines increases the soil moisture content in the peat, resulting in less susceptibility of seismic lines to wildfire propagation compared to the natural area. The investigation of Kononovs et al. (2024) indicated that the variation of soil water content and temperature on the line depends on a complex combination of factors and is highly site-specific. In some studies, it has been stated that high soil moisture on seismic lines alters growing conditions on the line compared to those off the line (Braverman & Quinton 2016; Davidson et al., 2020).

Cutting trees can also raise soil moisture by reducing water intake by the root system (Dabros et al., 2017). Spittlehouse (2006) connected an increase in soil moisture following harvesting to a lower evaporation rate and reduced interception losses. Carey (2008) found that surface conductance is regulated by soil moisture and then drives the ET. Moreover, withdrawing the upper peat layer will lower GWD, contributing to increased soil moisture. Given that, soil moisture on seismic lines would be higher than in undisturbed forests, enhancing surface conductance for evaporation.

1.2.1.2.5. Vegetation Cover

Cutting trees on seismic lines will reduce leaf area index (LAI) and transpiration; however, surface conductance will increase owing to an increase in soil moisture (Dabros et al., 2017). High

moisture in parallel with high light intensity might be desirable for some species, such as graminoids, which hinders tree regeneration (Davidson et al., 2021). It has been reported that GWD drives plant community composition in peatlands (Goud et al., 2018). Since one of the implications of seismic line creation is a shift in GWD towards wetter conditions, alteration of plant community composition can be inferred. For instance, Sphagnum mosses are favoured by wet conditions compared to feather moss (Kangas et al., 2014). The study of Kettridge et al. (2017) revealed that sphagnum moss has higher subcanopy ET than feather moss. Thus, shifts in plant cover can result in shifts in ET. Therefore, it can be inferred that ground cover change induced by seismic lines will alter water balance as the ET strongly depends on the type of species (Admiral and Lafleur, 2007).

1.2.1.3. Runoff and Lateral Groundwater Flow

Once a peatland reaches saturation, the excess water is released as surface runoff (Holden and Burt, 2003). However, in the area with seasonal water deficit ($ET > P$) and dominant vertical flow (i.e., peatlands in sub-humid climate), runoff is a minor component of water balance (Thompson et al., 2014; Devito et al., 2005). Nonetheless, antecedent moisture contents have a significant impact on surface water flow, with potential for runoff under wet conditions when soil storage is full (Ketcheson and Price, 2016; Wells et al., 2017). Wu et al. (2010) reported that ET was the main component of water loss in a dry period, whereas runoff would be the dominant component in water loss in the wet period. Regarding seismic lines, high precipitation with greater antecedent soil moisture on compacted soil might increase the possibility of surface and near-surface runoff (Hetherington, 1987; Monteith et al., 2006; Biagi et al., 2021), especially right after cutting trees (MacDonald et al., 2003).

In terms of uplands, it has been reported that runoff is likely to occur; however, in Alberta's subhumid climate, it plays a minor role in the water balance due to the high ET (Volik et al., 2020). Ireson et al. (2015) observed the dominant role of aspect on runoff compared to soil moisture and soil texture. Comparing the effect of peatlands and forestlands on runoff indicated that peatlands act as a source of runoff compared to forestlands (Hokanson et al., 2020). Keim et al. (2006) found that high rainfall intensity on the compacted soil combined with high soil moisture following clear-cutting enhances the probability of runoff (Luce and Cundy 1994), and this could occur on seismic lines, particularly in uplands.

1.2.1.4. Storage changes

Differences between water inputs and outputs result in a change in storage, reflected in varying GWD and soil moisture. The water storage capacity of peat is related to specific yield, defined as the volume of water gained or released from storage for a unit length change in the GWD (Freeze and Cherry, 1979). Low specific yield means the GWD response to a rain event will be relatively large and flashy, whereas high specific yield results in a GWD response to a rain event that will be comparatively subdued and protracted (Schut and Westbrook, 2022). Differences in net storage in response to seismic line disturbance will depend on the balance between shifts in water inputs and outputs. Most researchers have pointed out that the reduction of intercepted precipitation and transpiration following clear-cutting will decrease GWD (Winkler et al., 2010; Rex and Dube, 2006). On the other hand, low infiltration induced by soil compaction on seismic lines may limit groundwater recharge, although increases in the recharge following harvesting have been reported (Bent, 2001). Therefore, it can be inferred that the interpretation of GWD fluctuation on seismic lines is implicit and depends on various factors, particularly soil and vegetation properties. The study of Liu et al. (2023) highlighted the impact of the bulk density of soil on water storage in peatlands, while Lapen et al. (2000) pointed out the important role of GWD in governing water

storage, especially on fens. It has also been reported that the wetlands connected to the seismic line have a lower water storage capacity, leading to overflow of water into the seismic line (Hamilton, 2020). Wetter condition on seismic line indicates a higher water storage compared to undisturbed peatlands (Kononovs et al., 2025). Nevertheless, understanding the water storage on seismic lines requires long-term monitoring of all relevant components. Most of the previous studies on water storage on seismic lines are based only on the growing season (Hamilton, 2020; Braverman and Quinton, 2016). Accordingly, the change in water storage in peatland disturbed by seismic lines are poorly understood.

1.2.2. Modelling water balance affected by seismic lines

Peatland hydrology is complicated due to the variability of peat properties and complexity of peat profiles, with sharp transitions between the poorly decomposed top peat with large air-filled porosity and the more compact and more decomposed peat below (Holden, 2009; Weber et al., 2017). Furthermore, high heterogeneity of peat properties among different peatlands or different zones of the same profile can complicate the study of the hydrological process of peatlands (Mezbahuddin et al., 2016). Due to the complexity of peatland hydrology, any change can generate multiple responses and uncertain feedback. For instance, the study of Waddington et al. (2015) highlighted the complexity of hydrological feedbacks in peatlands to GWD variations. Furthermore, any natural and anthropogenic disturbances can adversely influence the ecosystem and have further implications (Gallego-Sala et al., 2018). Accordingly, hydrological models complement field observations for a better understanding of peatland hydrology.

Hydrological modelling is mainly based on a simplification of the actual hydrological process (Moges et al., 2020), which results from restrictions in data and knowledge, errors in measurements, and interactive processes at different scales (Gupta et al., 2006). A major

improvement to hydrological models in peatlands might be their increased capability to recognize the fact that various types of peatlands behave hydrologically in different ways (Whitfield et al., 2009). For this purpose, a combination of targeted field measurements and a physical-based model has been recommended in some studies (Pomeroy et al., 2007; Wang et al., 2021). However, Moges et al. (2020) suggested that the complexity of physical-based models with a large number of required parameters might lead to high uncertainty on large scales. Chen et al. (2017) in supporting the finding of Moges et al. (2020) found that physical-based models depend on detailed knowledge of hydrometeorological data.

From the aspects of scale, small-scale models, focused on localized areas, have been noted for their ability to capture fine local variations and heterogeneities, as well as being more sensitive to disturbances. In contrast, large-scale models focused on regional water resources offer a broader perspective, providing a more comprehensive view and describing average properties (Mozafari et al., 2023; Lawrence et al., 2019). Although there are a variety of hydrological models in peatlands, such as MODFLOW (Kelbe et al., 2016), SIMGRO (Querner et al., 2010), PHIM (Brooks and Kreft, 1989), and WBalMo (Dietrich et al., 2008), most of them have not been tested in peatlands that are affected by seismic lines. Due to the complexity of hydrological conditions under seismic line disturbances, the modelling technique can contribute to answering several questions that remained in previous investigations. The closest application of process-based modelling to seismic line studies in peatland was by Williams and Quinton (2013). However, their research focused on incoming radiation along a seismic line and not the hydrological component. Therefore, testing a process-based model like CoupModel (Jansson, 2012; He et al., 2021) could be useful to understand the effects of seismic line on peatland hydrology. This coupled one-dimensional mass and energy model includes detailed soil physics, hydrology, photosynthesis, and

ecosystem respiration and can simulate water fluxes in peatlands (He et al., 2016). A one-dimensional model allows for easy adjustments to represent changes in vegetation and soil caused by seismic lines, enabling the assessment of potential water balance responses and key sensitive parameters for future studies—without the added complexity of large-scale modelling. CoupModel has been applied to simulate carbon flux from a peatland disturbed by extraction (He et al., 2023a) and to study the impact of water level variations on carbon dynamics in a continental bog (He et al., 2023b). As a consequence, this model has been tested in Canadian peatlands and seems to be an accepted and robust model for this zone; however, it has not been used to investigate water balance from a peatland disturbed by a seismic line.

1.3. Research objectives and hypotheses

Altogether, slow recovery rates of trees and the colonization of lines by invasive species necessitate the study of the hydrological variables impacted by seismic lines as these may be important drivers of plant community composition (Echiverri et al., 2022). Although wet conditions and high light intensity on seismic lines have been reported in most studies, previous studies were generally only associated with growing season conditions and warm months, while we continue to lack knowledge of the effect of seismic lines on environmental variables in cold months during the non-growing season. Moreover, peatland's function as a water store or source plays a pivotal role in the hydrological condition of catchments in the western boreal forest. However, seismic line operation might alter hydrological components due to the lack of intercepted precipitation, high wind speed and incoming radiation, and soil compaction (Davidson et al., 2019; Franklin et al., 2021). Therefore, understanding the water balance components affected

by seismic lines on the local scale will provide insight into the potential hydrological responses to seismic line disturbances on the catchment scale.

Therefore, the overall objective of this thesis is to provide insights into the impact of seismic lines on hydrological processes based on field measurements and modelling techniques across Alberta with a focus on peatlands. Accordingly, the main objectives of this thesis are:

- 1) To determine the influence of seismic lines on hydroclimatic variables in non-growing seasons (i.e., wintertime), including snowpack characteristics (Chapters 2 and 3).
- 2) To evaluate the impact of seismic lines on actual and potential evapotranspiration in peatlands (Chapter 4).
- 3) To quantify the extent to which water balance components in peatlands are affected by seismic lines using a modelling approach (Chapter 5).

Chapter 2.

An initial assessment of winter microclimatic conditions in response to seismic line disturbance in a forested peatland

2.1. Abstract

Linear disturbances are widespread in the boreal region of Alberta, Canada. Despite their ubiquitous nature, little is known about their influence on over-winter meteorological conditions and if and how they alter the snowpack and soil temperature profiles through altered energy and water balances in the wintertime. The presence of seismic lines could affect hydrological processes in both the wintertime and warm months. This will then affect plant communities and carbon cycling on these disturbances. Thus, understanding the effect of seismic lines on meteorological conditions during cold weather conditions will be important to better understand how they alter ecosystem function. Accordingly, this study aims to assess the effect of two seismic lines with different orientations created for petroleum resource exploration on energy and meteorological variables by comparing them to the near surface conditions in the adjacent wooded peatland area from October 2022 to April 2023. We observed 1.8 times higher photon flux density of photosynthetically active radiation on the linear disturbances than in the understory of the undisturbed locations and a greater negative net radiation on the seismic lines compared to that observed off the lines. Furthermore, the average wind speed during the unfrozen period on the seismic lines were eight times higher at the east-west oriented site and seven times higher at the south-north oriented site than the adjacent wooded peatland. Together, these changes resulted in a denser snowpack on the seismic line and overall higher snow water equivalent in the pre-melt snowpack. This provided insulation for the soil and soil temperature on the lines stayed above freezing seven days longer at the east-west oriented site and 10 days longer at the south-north oriented site in the upper 15 cm, which would result in more microbial activity and potential higher over-winter carbon releases. The average soil temperature on two seismic lines was warmer than the undisturbed adjacent area. Together these changes likely alter ecosystem functions including water balance and carbon cycling which necessitates future research monitoring these variables in both growing and non-growing seasons.

Keywords: Net Radiation, Soil Moisture, Wind Speed, Soil Temperature, Peatland, Seismic Line

2.2. Introduction

Geologic exploration for petroleum resources has created a network of linear clearings known as seismic lines in Alberta, Canada. These anthropogenic disturbances alter ecosystems by fragmenting forest cover (Weiland et al., 2023, Dabros et al., 2018) and can contribute to anthropogenic climate change by increasing greenhouse gas emissions (Strack et al., 2019). Once the initial seismic survey has been completed, these lines are often abandoned and left to recolonize with vegetation naturally (Dabros et al., 2019). The vast majority of abandoned lines are in the boreal region and are often characterized by poor natural recolonization of the vegetative cover and slow recovery of trees, especially in peatlands (van Rensen et al., 2015). Where seismic lines cross peatlands, there can be soil compaction and a reduction in microtopography (Stevenson et al. 2019), which also affects carbon cycling and water supply (Strack et al., 2019; Weiland et al., 2023). Although the width of conventional seismic lines has reduced from 10 m to a line width of less than 5 m to minimize the impact of the line on fragmentation since the mid-1990s, the high density of narrow lines has enhanced the area subject to edge effects and subsequently their footprints (Dabros et al., 2017). The impact of seismic lines on physical and chemical soil properties (Dabros et al., 2017), microclimatic conditions (Pohlman et al., 2007), hydrology (Lovitt et al., 2018), carbon dynamics (Schmidt et al., 2022), ground cover composition (Deane et al., 2020), wildlife behavior (Wilson, 2011), wildfire (Deane et al., 2020, Weiland et al., 2023), and permafrost degradation (Williams et al., 2013) has been investigated in several studies. The common finding of most studies is that the impact of seismic lines on ecosystem function varies over time and strongly depends on the abiotic and biotic conditions of the study area (Dabros et al., 2019, Davidson et al., 2021, Kleinke et al., 2022).

Slow recovery rates of trees and the colonization of invasive species on seismic lines necessitate the study of the environmental variables impacted by seismic lines to discover drivers of recovery trajectory of the plant community (Echiverri et al., 2022). Previous research has investigated the effect of seismic lines and/or linear disturbances on some pertinent components such as soil moisture and temperature by Dabros et al. (2017) which has been reported to be higher on the seismic line than in the adjacent undisturbed area. Greater light and solar radiation have been revealed in the study of Pohlman et al. (2007) and William and Quinton (2013), respectively. Soil compaction during operation of seismic lines results in high bulk density and volumetric water

content of the soil (Davidson et al., 2021). Creating an open area by seismic line leads to higher air temperature and vapor pressure deficit, which has been reported previously (Franklin et al., 2021; Haag and Bliss, 1974; Pohlman et al., 2007). Moreover, one of the most visible implications of seismic line creation is high wind speed (Burton, 2002, Weiland et al., 2023). Additionally, previous studies have revealed the impact of the structure of seismic lines, particularly orientation, on microclimatic conditions (Franklin et al., 2021; Stern et al., 2018), taxonomic and functional composition (Dabros et al., 2022), and regeneration of forest vegetation (van Rensen et al., 2015). Accordingly, it has been reported that line orientation plays a role in light availability, influencing biotic and abiotic conditions (Hegels, 2023). Although the impact of seismic lines on the ecosystem has been reported in most studies, previous studies were associated with growing season conditions and warm months, so we continue to lack knowledge on the effect of seismic lines on environmental variables in cold months during the non-growing season. Undoubtedly, there is a different interaction among hydroclimatic variables in winter that is less known. For example, snow depth is a controlling factor on the depth of freezing, where the low thermal conductivity of snow, combined with deep snowpacks, provides an insulating layer for the ground, drastically reducing the freezing rate (Van Huizen and Petrone, 2020).

On seismic lines where the tree canopy has been removed with minimal natural regrowth, reduced snowfall interception likely enhances snow accumulation, especially considering the reduction or elimination of the subsequent sublimation of snowfall intercepted in the tree canopy of adjacent natural ecosystems. It has been reported that sublimation of intercepted snow can be up to 40% of annual snowpacks (Pomeroy et al., 1998). Most importantly, frozen soil layers are controlled by weather conditions in cold months and in turn insulate underlying soil structures (William et al., 2013, Quinton et al., 2009). Moreover, these frozen layers are particularly vulnerable to any disturbance and the implication of any disruption will eventually influence the energy balance (Williams and Quinton, 2013) and carbon cycling (Strack et al., 2018). Further, wintertime processes may affect summer soil moisture, and this is known to drive carbon cycling in peatlands (Swails et al., 2022). Snow cover insulates the soil and, hence, protects it against extreme temperature fluctuations during the winter, which influences growing season length. Additionally, at high latitudes, it has been reported that winter flux rates tend to be an important fraction of the annual carbon balance (Schädel et al., 2018). Therefore, to better understand the

full impact of seismic lines on ecosystem function and the potential drivers that limit tree recovery, a better understanding of changes in wintertime conditions is needed.

This study aims to assess the influence of seismic lines on hydroclimatic variables including air temperature, relative humidity, wind speed, net radiation, photosynthetically active radiation, end of season snowpack, and soil temperature in a boreal wooded peatland during cold months (October to April). The main research objectives were to: 1) compare microclimatic variables (i.e., net radiation, air temperature, relative humidity and wind speed) on two seismic lines to those within the undisturbed adjacent wooded peatland, 2) quantify differences in snowpack depth and density and soil temperature on seismic lines compared to the adjacent forested peatland, and 3) to evaluate the impact of the structure of seismic lines including orientation and width on these hydroclimatic variables. These findings will provide insights into the hydroclimatic responses to seismic line disturbance in the non-growing season that in turn drives winter hydrological processes with potential impact into growing season ecosystem function, for example by affecting runoff pathways and early growing season carbon dynamics.

2.3. Study Site and Methods

The study area sits atop the Stony Mountain Boreal upland landform (56° 22' 14.2968" N, 111° 17' 22.92" W, at 632 m above sea level) ~40 km south of Fort McMurray, Alberta (Figure 2-1). This region is situated in the Western Boreal Plains ecoregion, which has a cold and sub-humid climate where most of the annual precipitation falls as rain (342 mm) with the majority delivered during May to August and the remainder falls as snow (114 mm of water equivalent) (Biagi et al., 2021). The mean annual daily air temperature is 0.7 ± 1.2 °C with maximum typically occurring in July when daily air temperatures average 16.8 ± 1.1 °C (Environment and Climate Change Canada, 2020).

At the study area, we instrumented two seismic lines. One seismic line is 8 m wide and oriented east-west within a moderate-rich fen peatland (herein referred to as the Maqua Line; Figure 2-2). The overstory in this area is mainly black spruce (*Picea mariana*) with an Ericaceous shrub layer (dominated by *Rhododendron groenlandicum*/Labrador tea) and common nonvascular species including red-stemmed feather moss and *Sphagnum* species. We conducted a tree survey on July 22-24, 2023 (Table S1, Appendix A) considering two plots on the seismic lines and two plots on each side of the undisturbed area, at least 10 m from the edge of the seismic line, where

each plot was 100 m². According to the findings, the density of trees on the seismic line at the Maqua site is 5550 stems per hectare with mostly short trees (<1.4 m). In contrast, the undisturbed peatland has a tree density of 11650 and 13600 stems per hectare on the north and south side of the seismic line, respectively. The second line is oriented north-south and intersects a moderate-rich fen peatland (herein referred to as the Tamarack Line). Though the line was cut in 1998, no tree cover has been re-established. The line is 7 m wide and at the study location is covered with graminoids. The surrounding natural area is a mixed wood forest dominated by black spruce and tamarack trees (average height ~ 5 m) alongside some *Betula pumila* (dwarf birch). The tree density in the stand directly adjacent to the study location is 25,000 stems per hectare and has a basal area of 119.8 m² per hectare.

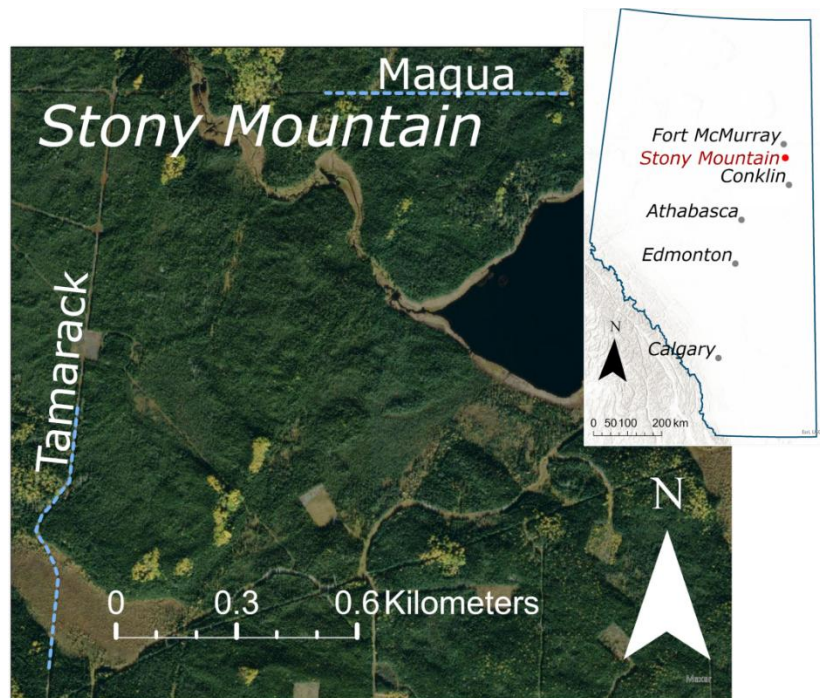


Figure 2-1 The study area is located 40 km south of Fort McMurray, Alberta, Canada.

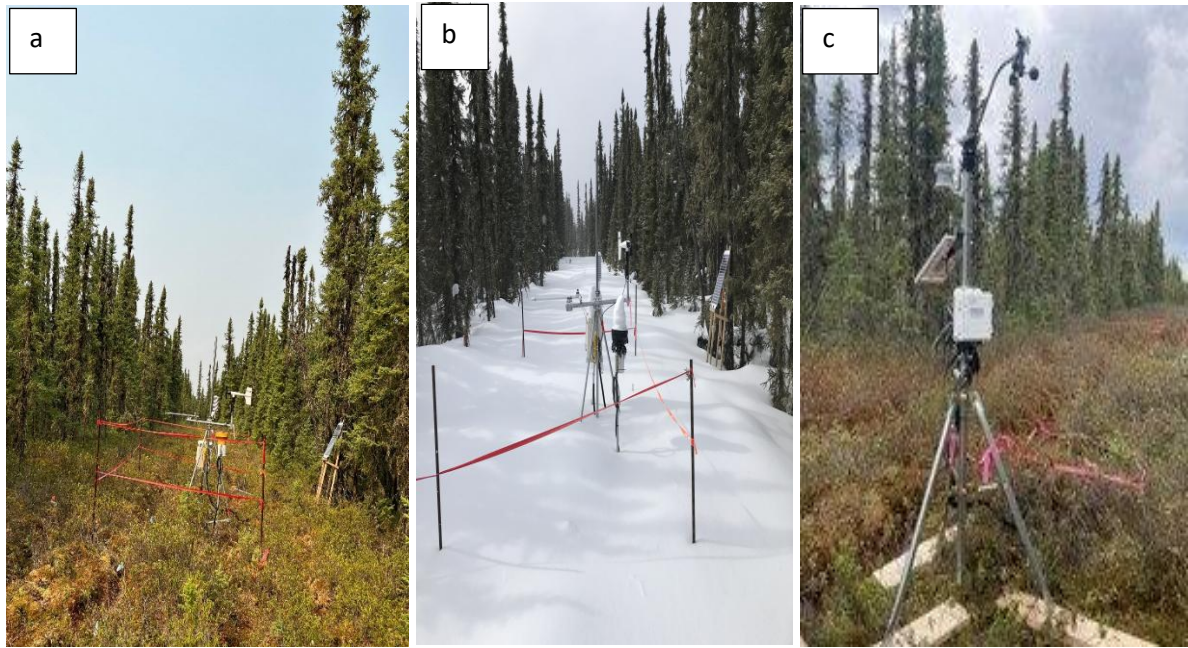


Figure 2-2 The Maqua seismic line (east-west direction) and meteorological station, Fort McMurray, Alberta, May 13, 2023 (a), and March 20, 2023 (b), and the Tamarack seismic line (north-south direction) and meteorological station (c)

Snow surveys were completed at the Maqua site on March 15, 21, 24, 31, and April 2, 2022 and on March 12, 2023 (Figure 2-10). Measurements including depth and density of snow were carried out from on the line and each side of off the line (i.e. North and South side).

In autumn 2023, two meteorological stations were established in each study location; one located in the centre of the seismic line, and the other 20–25 m into the adjacent undisturbed ecosystem. At the Maqua line, each of the meteorological stations recorded net radiation (NR LITE2, Campbell Scientific, USA), air temperature and relative humidity (HMP155A, Campbell Scientific, USA), wind speed and direction (05103-10-L, Campbell Scientific, USA), rainfall (TE525M, Campbell Scientific, USA), Photosynthetically Active Radiation (PAR, Campbell Scientific, USA) at a height of 1.5 m above ground. See Table S2 (Appendix A) for instrument-specific precision details. Soil temperature was measured at depths of 5, 10, and 15 cm using copper-constantan thermocouples. Campbell Scientific CR1000 data loggers measured the variables every minute and then averaged and recorded them every 30 minutes. The recorded 30-minute interval data were later converted to an hourly time scale on Python 3 (ipykernel). As the adjacent natural ecosystem has an average tree height of 5 m, the meteorological station off the

seismic line measured conditions below the tree canopy, representing conditions most likely to affect ground layer vegetation, establishing seedlings, and soil organic matter cycling. Therefore, differences between seismic line (herein referred to as “online”) and adjacent wooded peatland (herein referred to as “offline”) conditions represent changes to the understory and soil layer related to the loss of tree cover on the seismic line.

At the Tamarack site, two Hobo U30 USB (Hobo, 2020) meteorological stations were deployed in paired locations on the Tamarack seismic line and 25 m into the adjacent stand, with instrumentation installed at a height of 1.5 m above the ground. These stations recorded 15 minute data averaged hourly for wind speed and direction (Onset S-WCF-M003, Davis Instruments Corporation, Hayward, CA, USA), air temperature and relative humidity (Onset S-THC-M002, Onset HOBO Data Loggers, Pocasset, MA, USA), precipitation (Onset S-RGF-M002, Davis Instruments Corporation, Hayward, CA, USA), and soil temperature (Onset S-TMB-M006, Onset HOBO Data Loggers, Pocasset, MA, USA; 2 depths; 5 cm and 25 cm). Accordingly, the Tamarack site lacks PAR and NR values during the study period.

We assessed data quality via visual inspection of the time series of all data to assess if the values measured were within reasonable ranges and based on this retained all data. Moreover, there were no gaps in the dataset. Data were tested for normality using the Kolmogorov-Smirnov test (Table 2-1). This test is used to examine the null hypothesis that a set of data comes from a normal distribution (Massey, 1951). We reject the null hypothesis if $p < 0.05$. Since distribution of all variables is not normal except Ta in both on and off lines at the Maqua site (Table 2-1), the Mann-Whitney U test used to compare medians for variables with non-normal distribution (Mann and Whitney, 1947). In contrast, T-Test was exploited for Ta at the Maqua site.

We also explored diurnal patterns to assess changes in variables and their timing between on the line and understory offline. All statistical analyses were done on SPSS V21. Wind rose diagrams were drawn in Python 3 (ipykernel) library in the environment of Jupyter to identify the impact of the seismic line on wind speed and direction.

2.4. Results

The winter months, October 2022 to April 2023 in the Fort McMurray region were similar to average temperature and precipitation conditions in the past few decades. According to data collected at the Fort McMurray A station over the study period, mean temperature was -7.4 °C and

there was 121 mm of precipitation with 20 cm snow on the ground. Average of 25 year recorded data (1998-2022) for the same period were air temperature of -7.9 °C, 137 mm precipitation with 19 cm snow on the ground and (Environment and Climate Change Canada, 2023).

Table 2-1 The results of Kolmogorov-Smirnov (K-S) test to examine normality of data distribution.

		PARavg ($\mu\text{mol m}^{-2}\text{s}^{-1}$)		NR (W/m^{-2})		Ta (°C)		Ts (°C)		RH (%)		WS (m s^{-1})		WS-D (degree)	
		M.	T.	M.	T.	M.	T.	M.	T.	M.	T.	M.	T.	M.	T.
Offline	K-S	6.89	--	5.82	--	0.52	2.24	5.49	18.83	2.93	13.37	6.03	33.57	2.40	12.65
	Sig.	0.00	--	0.00	--	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Online	K-S	6.45	--	4.01	--	0.50	1.93	7.00	24.36	2.85	13.45	3.05	15.162	1.461	7.43
	Sig.	0.00	--	0.00	--	0.96	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00

Table 2-2 The monthly average and standard deviation (std) of each variable measured at the centre of the seismic line (referred to as Online) and in the adjacent wooded peatland (referred to as Offline) with average air temperature (Ta), relative humidity (RH), average wind speed (WS), average net radiation (NR), the direction of wind speed (WS-D), average photosynthetically active radiation (PAR), average soil temperature from 5-15 cm depth (Ts) at Maqua site (M) and from 5-25 cm at Tamarack site (T) from October 1, 2022 and April 30, 2023

			PARavg ($\mu\text{mol m}^{-2}\text{s}^{-1}$)		NR (W/m^2)		Ta ($^{\circ}\text{C}$)		Ts ($^{\circ}\text{C}$)		RH (%)		WS (m s^{-1})		WS-D (degree)	
			M.	T.	M.	T.	M.	T.	M.	T.	M.	T.	M.	T.	M.	T.
Overall	Offline	avg	41.1	--	0.1*	--	-8.2	-8.1	0.0**	0.6**	74.8	80.6	0.04**	0.07**	190.0**	158.9**
		std	147.6	--	28.2	--	12.1	2.3	2.4	0.0	18.1	4.3	0.08	0.03	110.3	3.12
	Online	avg	113.7	--	-10.0	--	-8.4	-8.1	0.5	1.5	73.9	79.1	0.36	0.53	178.2	143.2
		std	262.6	--	82.8	--	12.2	2.6	2.1	0.0	18.2	5.4	0.41	0.15	91.9	4.42
October	Offline	avg	38.2	--	-4.1*	--	4.7	4.9	4.2	4.6**	68.7	70.2	0.07**	0.18**	221.5*	144.2**
		std	63.8	--	9.3	--	3.1	3.1	0.4	0.2	10.6	9.3	0.04	0.08	11.3	4.79
	Online	avg	115.4	--	-6.5	--	4.7	4.9	4.3	6.1	68.2	70.0	0.50	0.61	211.7	130.4
		std	167.8	--	43.5	--	3.1	3.3	0.2	0.2	10.5	10.1	0.18	0.19	12.7	8.07
November	Offline	avg	6.6	--	-4.1**	--	-9.8	-9.2	-0.6**	0.9**	83.2**	85.5	0.02**	0.07**	247.2**	139.0**
		std	6.8	--	1.7	--	1.4	1.4	0.1	0.0	0.9	1.0	0.00	0.02	20.7	4.23
	Online	avg	20.3	--	-12.2	--	-9.8	-9.3	0.1	1.6	80.8	84.5	0.39	0.42	173.3	115.4
		std	25.1	--	3.2	--	1.4	1.6	0.0	0.0	1.2	2.5	0.07	0.06	18.0	6.56
December	Offline	avg	5.0	--	-3.1**	--	-19.7	-19.4	-1.6**	-0.2**	80.8	88.4**	0.01**	0.01**	178.0**	181.3**
		std	4.8	--	2.5	--	1.0	1.1	0.0	0.0	0.6	0.2	0.00	0.00	13.5	1.48
	Online	avg	11.4	--	-7.3	--	-20.1	-19.6	-0.7	0.7	80.7	86.9	0.26	0.44	150.1	149.4
		std	13.8	--	5.4	--	1.1	1.2	0.0	0.0	0.3	0.49	0.03	0.04	17.6	6.31
January	Offline	avg	10.9	--	-2.8**	--	-10.1	-9.6	-1.0**	-0.3**	88.6**	92.9	0.00**	0.05**	90.0**	136.8*
		std	12.1	--	2.3	--	1.1	1.1	0.0	0.0	0.4	0.29	0.00	0.01	4.1	4.03
	Online	avg	14.1	--	-7.2	--	-10.1	-9.8	-0.5	0.6	87.8	92.0	0.33	0.39	157.8	130.0
		std	16.9	--	6.1	--	1.1	1.3	0.0	0.0	0.3	0.98	0.06	0.06	14.6	9.68
February	Offline	avg	7.7	--	-5.0**	--	-14.3	-14.0	-1.5**	-0.5**	80.4**	85.1	0.01**	0.07**	171.1**	137.6**
		std	8.3	--	5.2	--	2.2	2.3	0.0	0.0	1.8	2.22	0.00	0.02	13.4	5.58
	Online	avg	38.4	--	-15.2	--	-14.5	-14.1	-0.6	0.5	78.4	83.3	0.40	0.46	198.2	129.0
		std	52.2	--	13.0	--	2.3	2.6	0.0	0.0	2.9	3.8	0.12	0.14	14.5	7.75
March	Offline	avg	38.2	--	-6.2**	--	-10.6	-11.0	-1.4**	-0.6**	71.9	76.7	0.03**	0.04**	195.0**	173.7
		std	57.1	--	4.5	--	4.0	4.1	0.0	0.0	8.5	7.3	0.03	0.04	12.3	5.45
	Online	avg	147.6	--	-7.6	--	-11.0	-11.0	-0.5	0.5	72.0	74.3	0.28	0.59	178.3	164.2

April	Offline	std	221.1	--	12.4	4.2	4.5	0.1	0.0	9.9	9.39	0.19	0.26	19.7	16.2
		avg	100.4	--	8.0*	2.2	1.8	-0.1	0.2**	61.5	65.3	0.09**	0.11**	223.8**	200.0**
	Online	std	188.8	--	32.1	3.9	3.7	0.2	0.0	13.0	11.2	0.07	0.08	22.5	8.75
		avg	257.3	--	-2.0	2.0	2.1	-0.0	0.6	61.9	62.4	0.38	0.83	194.9	183.9
		std	385.7	--	55.1	4.0	3.9	0.1	0.0	13.2	12.6	0.20	0.38	11.6	20.1

** . Mean difference is significant at the 0.01 level (2-tailed).

* . Mean difference is significant at the 0.05 level (2-tailed).

--- not assessed due to lack of measurement.

2.4.1. Incoming photosynthetically active radiation (PAR) and net radiation (NR)

Monthly average daytime PAR on the Maqua line ranged from $11.4 \mu\text{mol m}^{-2} \text{s}^{-1}$ in December to $257.3 \mu\text{mol m}^{-2} \text{s}^{-1}$ in April, which were more than double that of the PAR measured offline ($5.0 \mu\text{mol m}^{-2} \text{s}^{-1}$ in December and $100.4 \mu\text{mol m}^{-2} \text{s}^{-1}$ in April), with low values both on and off the line from November to January linked to short daylight hours and shallow sun angles (Table 2-2). The highest PAR values occurred in April when the days within the study period were the longest and the sun angles were the highest. Moreover, the wide margin between on the line and off the line is more visible between 9 h and 19 h (local time) in all measurement months (Figure 2-3). Periods of higher and lower PAR at the offline location over the day that disrupt expected diurnal patterns are also linked to sporadic shading by the sparse tree canopy. The difference between PAR offline and online is non-significant in all months (Table 2-2).

In terms of peak PAR during the day, which is more available to plants, there is a one-hour time lag between offline and in October (i.e., maximum PAR is reached offline one hour before online), a 4-hour time lag in March, and a 3-hour time lag in April (Figure 2-3). In all other months studied, the peak PAR is approximately synchronous online and offline. As can be seen from the figure, there are multiple peaks for PAR values off the line. These observations might be related to the placement of the sensor off the line and the impact of tree shading. For example, a tree might block the sun, temporarily reducing PAR.

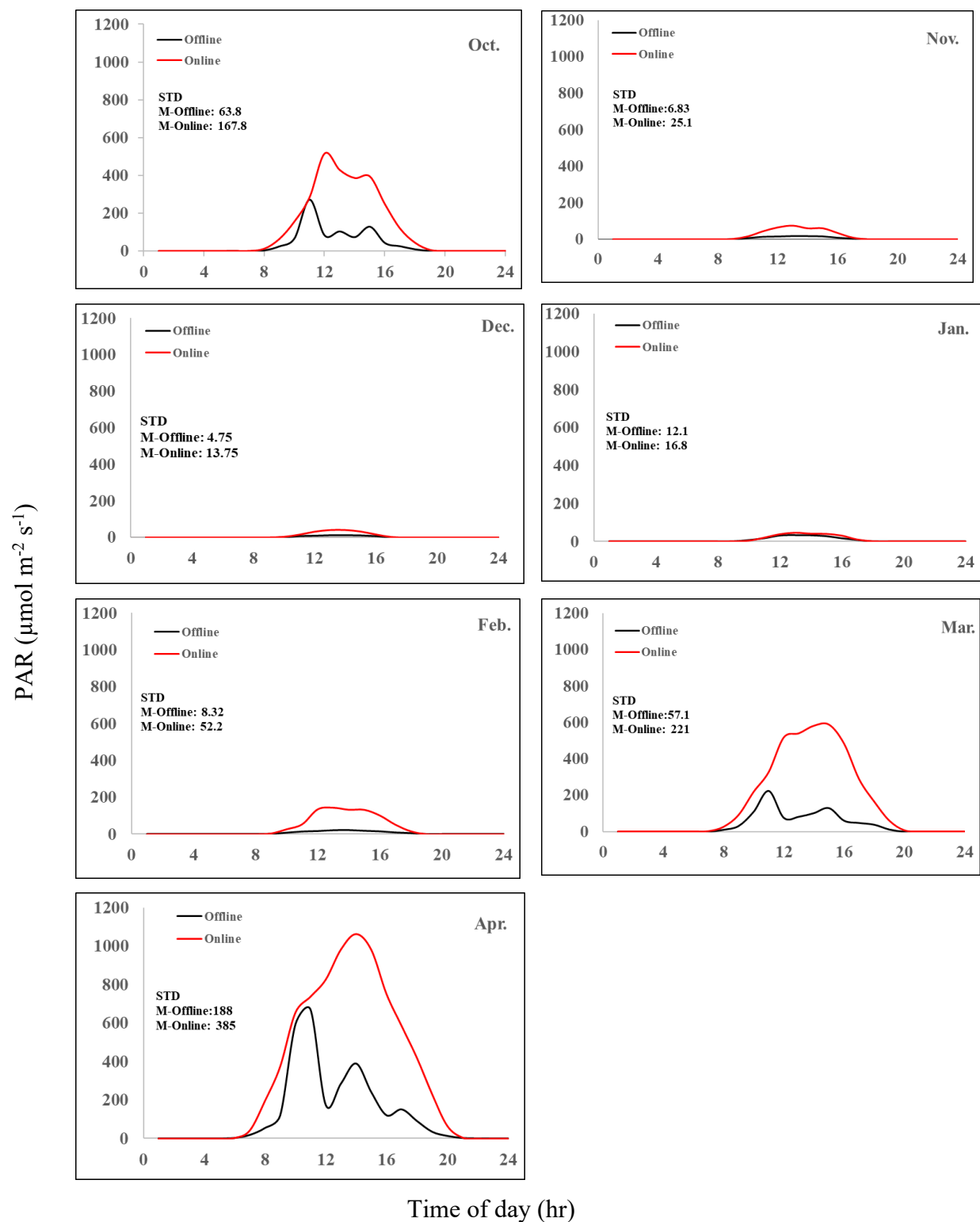


Figure 2-3 The average hourly photon flux density of photosynthetically active radiation (PAR) for each month plotted by local time of day from October 2022 to April 2023 at the Maqua site (M). STD is standard deviation

The diurnal pattern of net radiation (NR) varied between the Maqua online location and within the adjacent wooded peatland understory off the line, and among the months (Figure 2-4). In October, both on and off the line locations had negative NR at night but with greater net emissions on the seismic line. During the day, NR shifted to positive values earlier offline but had higher peaks online. Between November and February, NR was closer to zero throughout the day and night at both locations, moving to negative NR around midday with greater emission from the online location. By March and April, longer days and greater incoming solar radiation were linked with a shift to some positive NR values during the day online in March and at both on and offline locations in April (Figure 2-4). A large negative NR was observed in the morning online, shifting to a positive NR in the afternoon and evening (i.e., 12 h and 15 h). In contrast, positive NR was observed offline between 9 h and 20 h in April. Differences in mean NR between the online (0.1 W m^{-2}) and offline (-10.0 W m^{-2}) locations are statistically significant in all months (Table 2-2). The multiple peaks of NR on the line might be related to synoptic-scale effects (e.g., extended periods of cloudy conditions). Further, because the radiation from the forest wall has affected the radiation measured on the line this may also lead to a shift in the timing of the peaks.

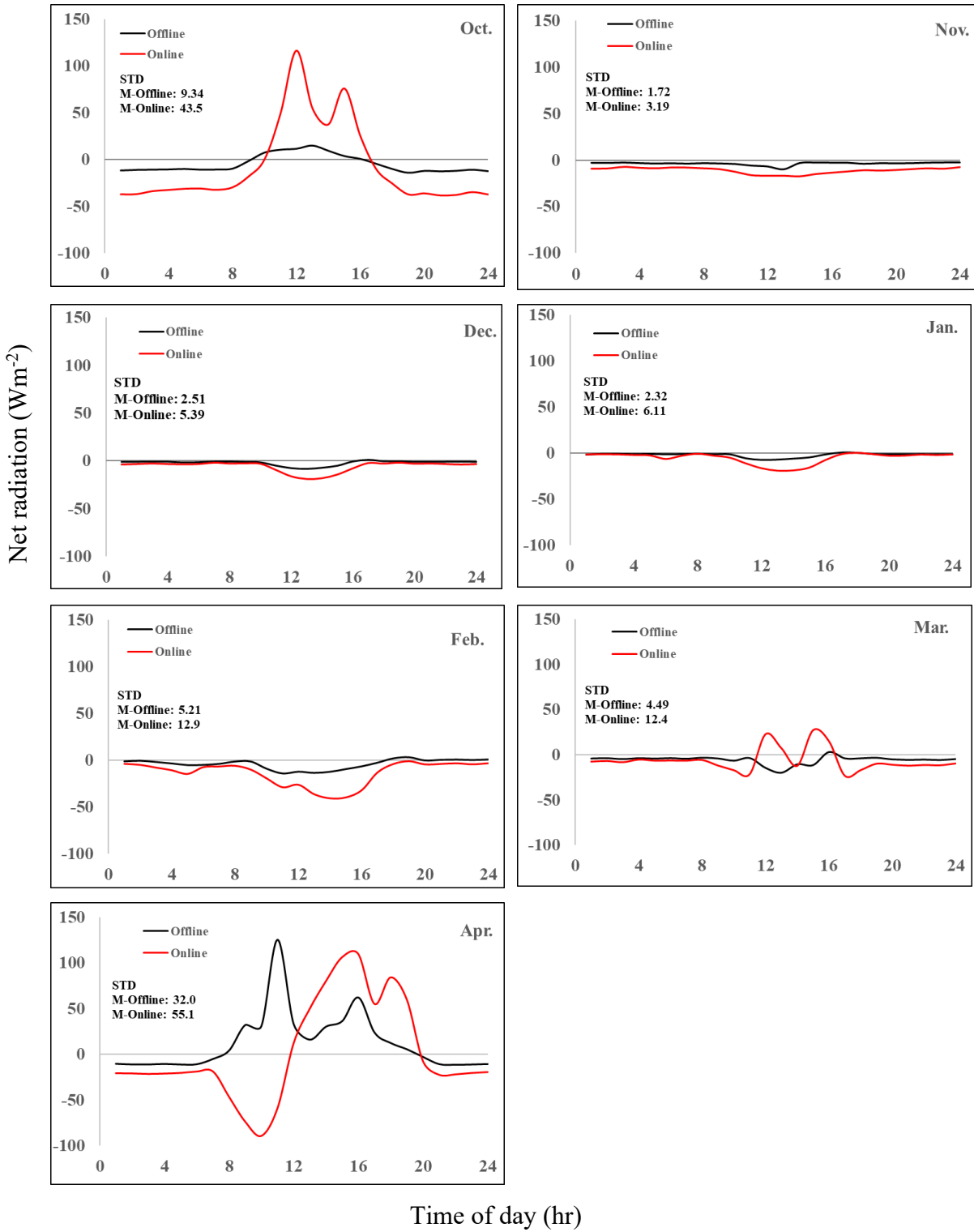


Figure 2-4 The average hourly net radiation for each month plotted by local time of day October 2022 to April 2023 at the Maqua site (M). STD is standard deviation

2.4.2. Air (Ta) and relative humidity

At the Maqua site, the diurnal (i.e., 24-hour) pattern of air temperature is similar between on and offline locations in all measured months (Figure 2-5). The Ta decreases during nighttime in both locations; however, the Ta offline is slightly higher than online in all months (-6.7 °C compared to -6.9 °C). There is no significant difference between Ta online and offline in any month (Table 2-2) with greatest differences in Ta in March and April when online temperatures are 3 and 9 % lower than offline, respectively. In April, there is a one-hour time lag between the peak Ta online and offline. It is noticeable that, due to this lag, Ta on the line is very slightly higher than offline following the peak Ta at the offline location.

Although the average Ta at the Tamarack is slightly higher than at the Maqua (-8.1 °C compared to -9.2 °C off the line; -8.1 °C compared to -8.4 °C on the line), the pattern of Ta is similar at both sites. The highest difference between Ta in both sites is observed at the maximum Ta which is visible in all months. As at the Maqua site, the difference between Ta on the line and off the line is non-significant at the Tamarack site.

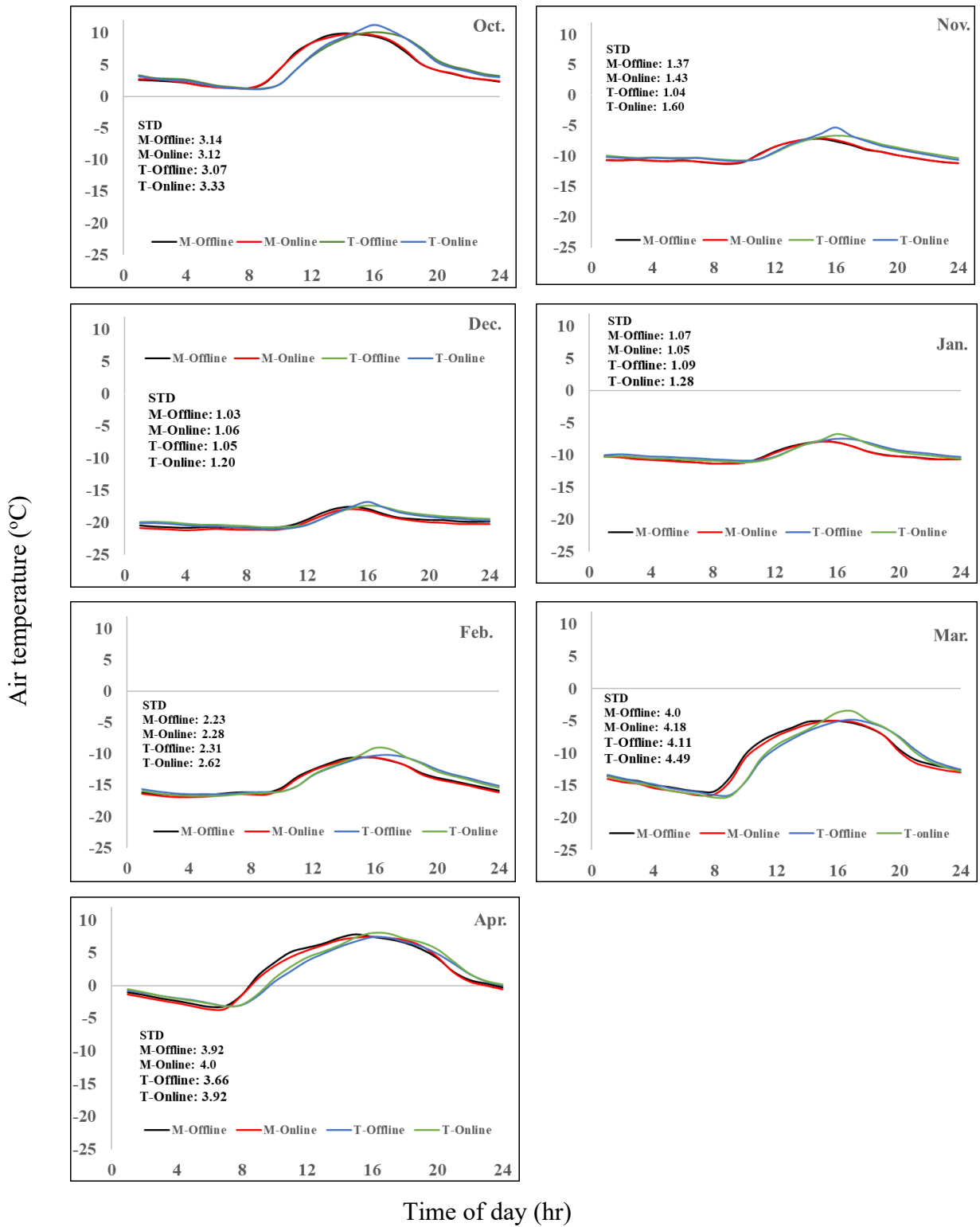


Figure 2-5 The average hourly air temperature for each month plotted by local time of day from October 2022 to April 2023 at the Maqua site (M) and the Tamarack site (T). STD is standard deviation.

Although the impact of the seismic line on relative humidity were significant only in November, January, and February (Table 2-2), differences were still apparent between online and offline measurement locations in other months (Figure 2-6). At Maqua, the RH drops in the afternoon in October, March, and April at both on and off line measurement locations. This pattern is muted in November and February and absent in December and January. Although the pattern is similar at on and offline locations, in general, RH remains about 1% higher offline during the afternoon decline. Based on the measurements, the diurnal variability of RH varies in different months, particularly in November, December, January, and February, which causes a distinguishable difference between RH on the line and off the line. In other words, in these months, off the line had higher humidity compared to on the line by approximately 2.5%. Furthermore, this difference is more visible in the daytime than nighttime. In contrast, in October, March, and April, diurnal variability of relative humidity on the line is similar to off the line.

RH at Tamarack is lower than that at Maqua both on and off lines, although this difference is significant only in December. However, this difference on the line is slightly higher than off the line (80.6 % compared to 74.8 % on the line vs. 79.1 % compared to 73.9 % off the line). The diurnal pattern of RH is similar in both sites.

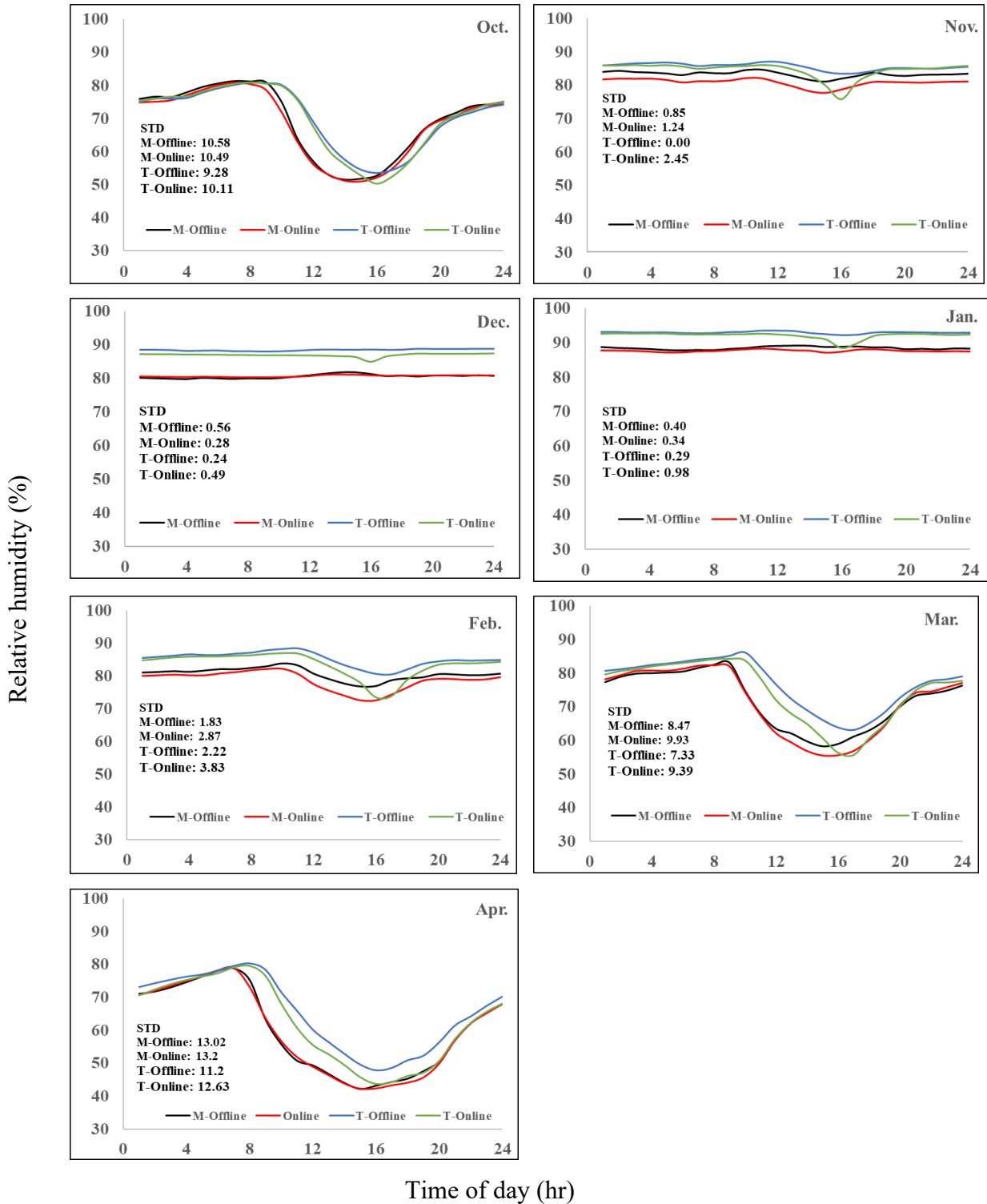


Figure 2-6 The average hourly relative humidity for each month from October 2022 to April 2023 at the Maqua site (M) and the Tamarack site (T). STD is standard deviation.

2.4.3. Wind Speed and direction

Wind speed on the line is significantly higher than off the line at both sites (Table 2-2). The average wind speed at Tamarack (0.3 m s^{-1}) is higher than that at Maqua (0.2 m s^{-1}). The difference in maximum wind speed between on and offline at Tamarack is greater than that at Maqua site as well (0.46 m s^{-1} vs. 0.32 m s^{-1}). The diurnal fluctuation of wind speed on the line was visible in all months (Figure 2-7); however, it was absent in the offline location in November, December, January, and February. Furthermore, the greatest difference between wind speed online and offline occurs in the daytime in all months. Wind direction at Maqua was mostly from the southwest, with the highest wind speeds on the line from the west (Figure 2-8). In contrast, at Tamarack, dominant wind speed gusts occurred from the southeast.

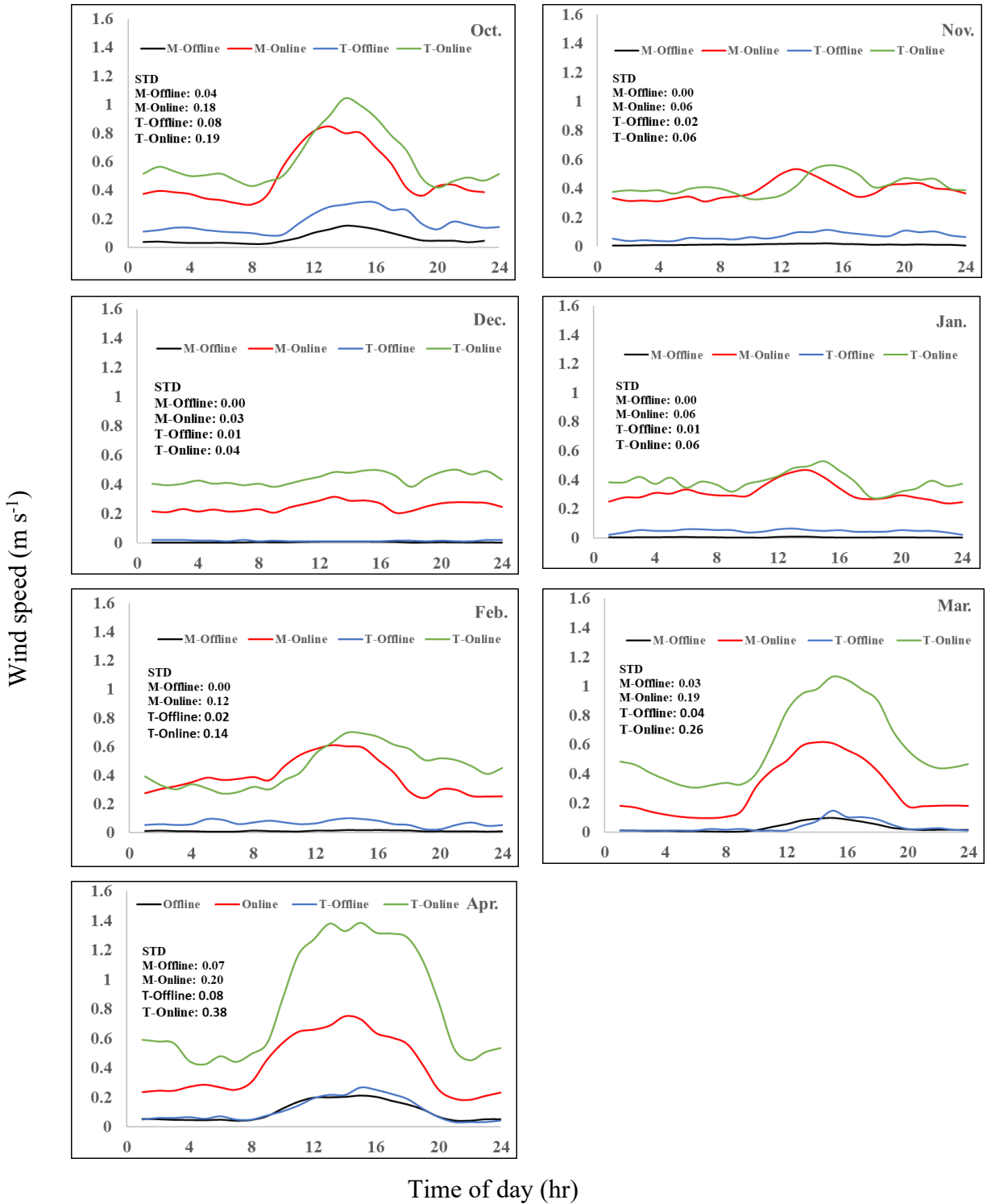


Figure 2-7 Average hourly wind speed during each month measured at 1.5 m above the ground at seismic line and adjacent wooded peatland locations at the Maqua site (M) and the Tamarack site (T). STD is standard deviation

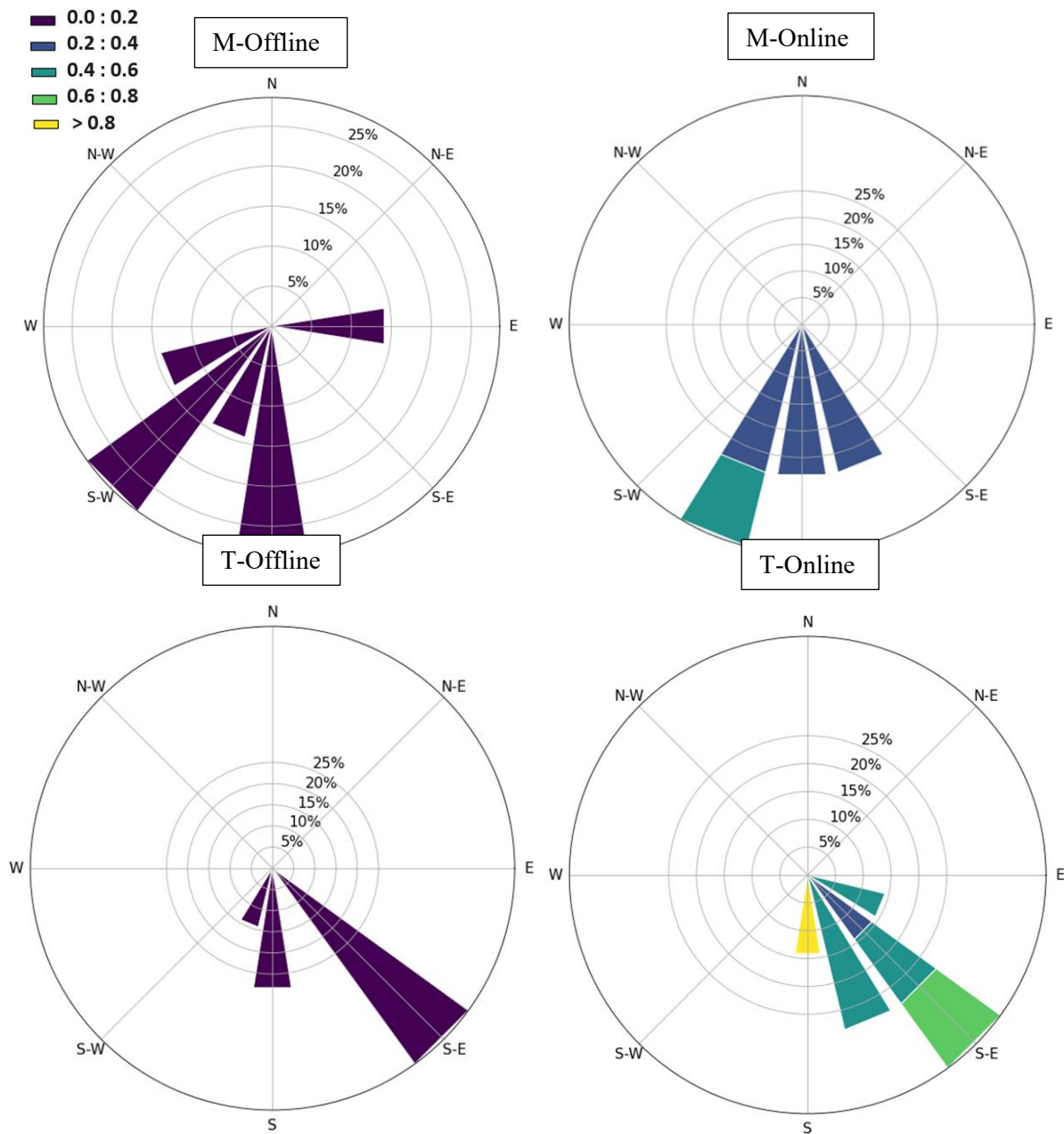


Figure 2-8 Average monthly wind speed ($m s^{-1}$) and direction for the period October to April at Maqua site (M) and Tamarack site (T). Note the difference in scale in the legend for offline and online locations.

2.4.4. Snowpack characteristics

The results of snow survey at the Maqua site indicated that end of season snow depth on the seismic line was higher than off the line, with the latter aligning with the period in which meteorological conditions and soil temperatures were measured (Figure 2-9). Considering density, snow density on the line exceeds off the line by 9% based on both years' measurements.

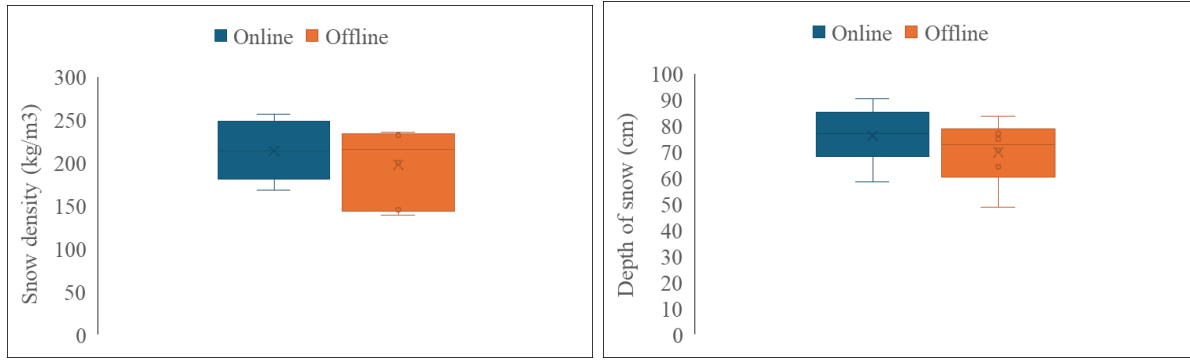


Figure 2-9 Snow density (left) and depth (right) measurements at the Maqua site in 2022 and 2023, STD is standard deviation

2.4.5. Soil temperature

The diurnal pattern of Ts is different between the seismic line and the adjacent understory offline locations (Figure S1-Appendix A). Due to the importance of soil temperature in cold months for microbial activity and subsequently carbon cycling, a whole time series dataset was used to visualize the timing of freezing and warming conditions over the study period (Figure 2-10). At the Maqua site soil temperature drops steeply in October both on and off the line. Following large cooling events (i.e., reducing soil temperature), the offline location has similar Ts at 5, 10 and 15 cm, while diurnal signal at depth is more apparent on the line. Freezing conditions ($T_s < 0^\circ\text{C}$) at 5, 10 and 15 cm occur 5, 3 and 10 days earlier off the line than on the line. Between November and April, soil temperatures are generally higher on the line than off the line by on average 0.7°C , which is statistically different (Table 2-2). Soils at both locations warm rapidly in April, with temperatures rising above freezing on April 30 for on the line and April off the line for all depths, respectively. Moreover, there is a wide margin between the Ts in different depths in the undisturbed location particularly in the daytime compared to the disturbed line. By April, the Ts goes up in both locations; however, it is more visible at shallow depth. That is, the Ts-5 in the offline location peaks at 7.7°C compared to 2.2°C in the online location, both at 14 h.

At the Tamarack site, average Ts at 5 cm on the line is 3°C warmer than that off the line (i.e., -1.27°C to -4.38°C) throughout the entire measurement period. The Ts trends with depth illustrate that the pattern of vertical gradient of Ts has reversed on December 27th. Before that time, Ts in the deeper soil layer (i.e., 25 cm) is higher than in the shallow layer. However, at the end of December, the Ts at 5 cm is greater than the Ts at 25 cm. Freezing conditions off the line at 5 cm occur 10 days earlier than on the line. Contrary to Ts at 5 cm, Ts at 25 cm off the line is warmer than on the line, resulting in earlier freezing conditions on the line than off the line.

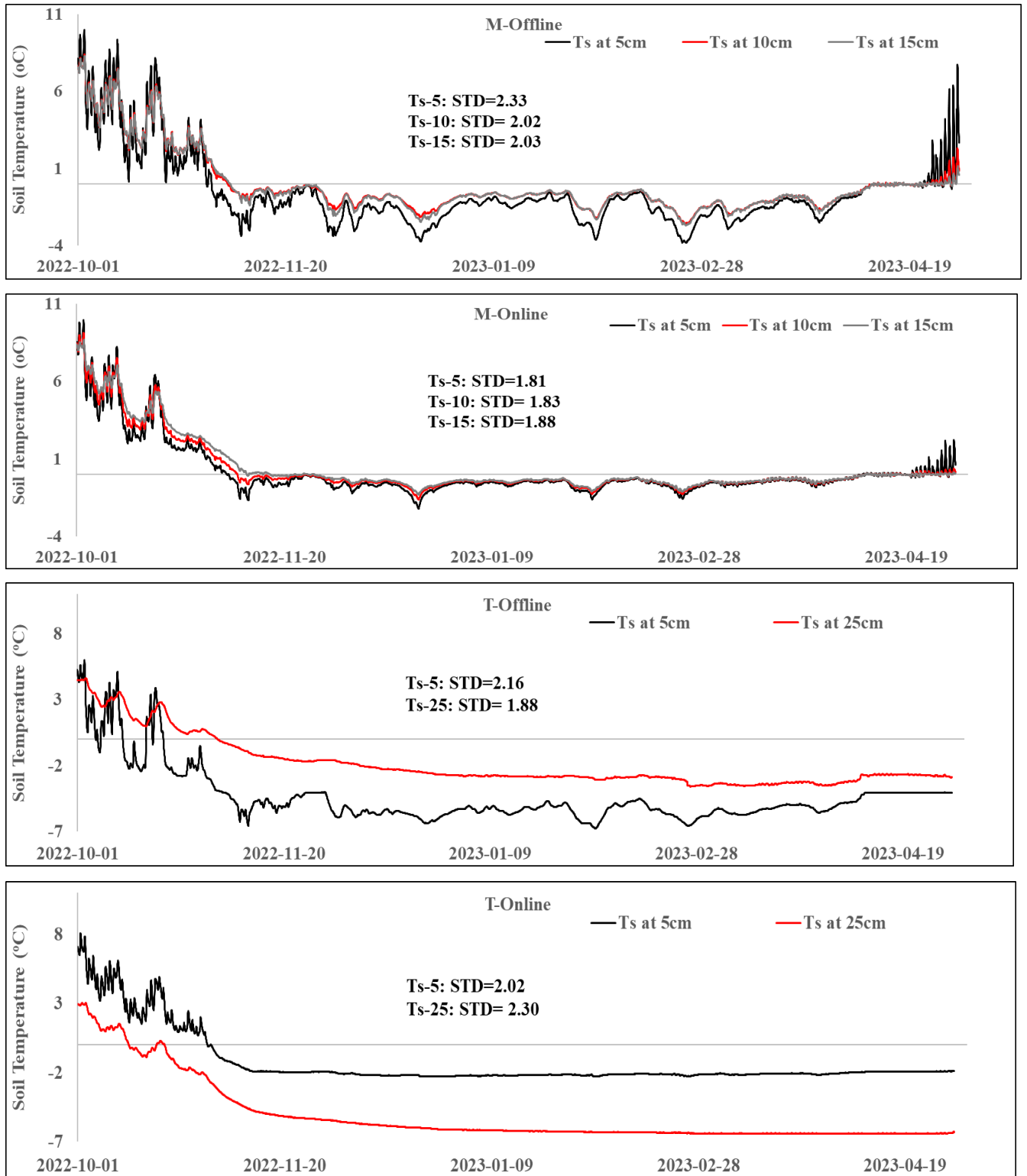


Figure 2-9 The hourly seasonal time series of soil temperature on the seismic line and adjacent wooded peatland (offline) from October 2022 to April 2023 at the Maqua site oriented east-west (M) in and the Tamarack site oriented north-south (T). STD is standard deviation.

To better understand the seasonal pattern of soil temperature variation, the snow on the ground data of the Fort McMurray station was used (ACIS, 2024). Based on the recorded data, the depth of snow increased from December 12th to mid-March (Figure 2-11). Thus, it is likely that the study sites had snow on the ground throughout January, February and March, providing insulation to soils over this period.

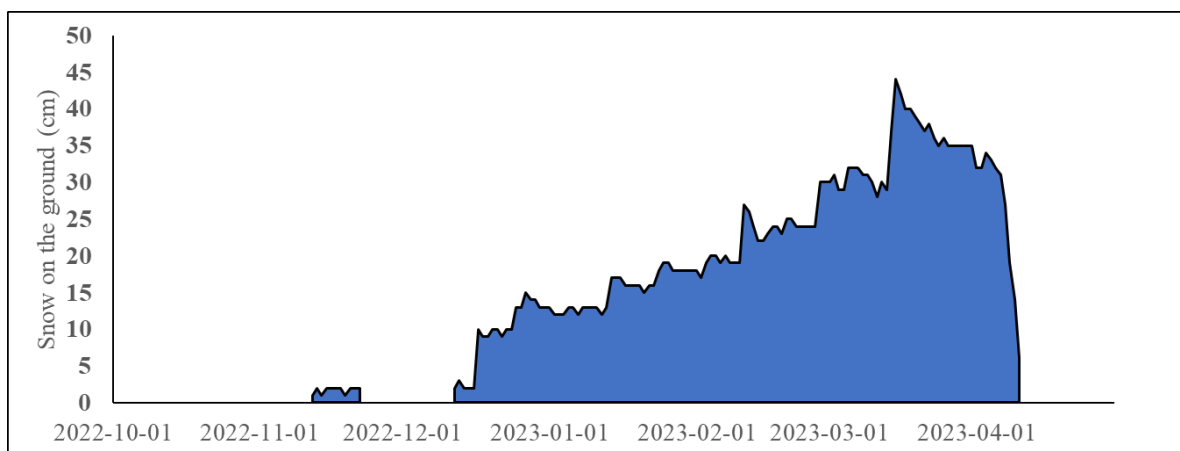


Figure 2-10 The snow on the ground from October 2022 to April 2023 at the Fort McMurray station.

2.5. Discussion

In this study we show that seismic lines have an impact on meteorological variables in the cold months of the non-growing season (October – April), similar to that previously reported for the summer months (Franklin et al. 2021). We measured conditions below the canopy of the adjacent wooded offline location, thus measuring changes in understory meteorological conditions and soil temperature and moisture that result from the loss of the canopy cover on the seismic line in this forested peatland. Although seismic line disturbance is most prominent in the western boreal forest, these disturbances are also present across other boreal and subarctic regions (Strack et al., 2019). Further, changes to forest canopy cover in peatland can occur in response to other disturbances including forest harvesting (Leppä et al., 2020), permafrost thaw (Dearborn et al., 2020) and wildfire (Ackley et al., 2021); therefore, our findings provide first insights into the magnitude of changes in winter meteorological conditions that may arise in these cases. Overall, we observed that removing the canopy on the lines resulted in greater incoming radiation and higher wind speeds likely enhanced along the seismic line by the linear nature of the disturbance. Together these contributed to greater snow depth and density on the line that insulated the soil and

resulted in significantly warmer soil temperatures and reduction in the frozen period. This change has important implications for ecosystem functioning, e.g., likely resulting in greater overwinter microbial activity that will enhance organic matter decomposition and carbon emissions.

2.5.1. Seismic line effects on wintertime energy balance

The loss of canopy cover on the seismic line resulted in more radiation reaching the surface (Figure 2-4). William and Quinton (2013) revealed an increase in incoming radiation on a linear disturbance compared to the undisturbed vicinity. Similarly, in the present study the average PAR on the seismic line was 1.8 times higher than within the adjacent forest (Figure 2-3). The higher PAR on seismic lines compared to the adjacent area has also been reported by Stern et al. (2018) who measured a 2-fold increase and Franklin et al. (2021) with 3.8 times increase on the line. The disparity among findings is mostly related to differences in the width or orientation of seismic lines. Based on results from previous studies it can be inferred that Tamarack with the north-south orientation likely received higher light intensity compared to Maqua with the east-west orientation (Franklin et al., 2021). The lack of observed tree regrowth at the Tamarack site suggests that other site factors, such as wet conditions, likely limit recovery.

Net radiation is the primary driver of the energy balance that regulates evapotranspiration rates, surface moisture content, soil temperature, and plant growth (Revel et al., 1984). The pattern of NR measured indicates that over winter, there is greater negative net radiation at night on the line (Figure 2-4) that is likely due to greater long-wave emission as there is no tree canopy to block it (Abib et al., 2019). Most importantly, the diurnal patterns of NR are different between the period of snow melt (March and April) and other cold months. Tree coverage in the undisturbed forest can control NR distribution by blocking incoming radiation in melting months. For example, Ketcheson et al. (2012) reported NR in a forested peatland was an order of magnitude less than an open area. According to the current findings, it is seen that the distribution of NR in disturbed areas in cold months does not necessarily follow the same pattern as the growing season. One of the reasons might be associated with snow coverage on the ground, which in turn reflects radiation received on the seismic line due to its high albedo. The NR patterns in November, December, January, and February (snowy months) support this idea. To investigate the role of snow on NR, the pattern of recorded snow on the ground in the study area (Figure 2-11), and the measured snow depths on March 12th at the site can be used (Figure 2-9). The real measurement of snow dynamics

at the Maqua site demonstrated that snow depth was 20% deeper on the seismic line than in the adjacent wooded peatland. Moreover, high density of snow on the seismic line (Figure 2-9) increased snow water equivalent. The presence of snow, without overstory trees above the snowpack, will affect the albedo, the NR emission, which, along with snow insulating the ground, will influence soil temperature on the line.

The impact of the seismic line on NR is strongly associated with the orientation and width of the line (Franklin et al., 2021, Pomeroy et al., 2012, Stern et al., 2018, Revel et al., 1984). Most studies have highlighted that in northern latitudes, south-facing canopy fragmentations receive more radiation (Franklin et al., 2021, Pomeroy et al., 2012). Accordingly, the findings of this study might vary if repeated on seismic lines with different orientation (i.e., north-south), widths, and age or restoration status (i.e., with good or moderate vegetation regrowth). Since the average NR was negative on the seismic line and Ta slightly cooler than in the adjacent forest at the east-west line at the Maqua site, this indicates that the greater incoming solar radiation during the day did not compensate for reflection and long wave radiation emission. Given the north-south orientation of the Tamarack line, we would expect greater incoming solar radiation and the Ta results support this hypothesis. The peak temperature at the Tamarack site was higher than that at the Maqua site. Moreover, difference in Ta between on and off the line at the Tamarack is minimal at only 0.29 °C, and smaller than that measured at the Maqua. Franklin et al. (2021) also showed similar findings based on summertime measurements. Their study revealed that the south-north receives more NR than the east-west line which results in high Ta. Nevertheless, overall we observed no significant difference for Ta and RH between on and offline locations, as has been observed in other studies where peatland canopy has been lost (e.g., Ackley et al. 2021).

2.5.2. Effects of seismic lines on wintertime wind conditions

Undoubtedly, clearing trees along seismic lines will affect the wind velocity; however, the magnitude of change plays a pivotal role in energy balance through controls on turbulent fluxes (sensible and latent heat flux) (Carey, 2008). From the aspect of wind properties, there was a significantly higher wind speed (WS) on the line than off the line in all months, regardless of the orientation of seismic lines (Table 2-2). The highest and lowest differences occurred in October and December, respectively. The 8 m width of the seismic line at the Maqua site and 7 m width at Tamarack site likely contribute to the large increase in wind speed on the line, which in turn will

have an effect on the distribution of near-surface soil moisture and temperature. Similar results have been reported on older seismic lines by Stern et al. (2018) with the same width. High wind speed on the seismic line will influence snow distribution as well. For instance, wind redistributes fresh and fluffy snow and in turn increases the density of the snowpack (Weiland et al., 2024; Figure 2-9). The high density of snow enhances the duration of snow cover on the ground, altering soil temperature patterns, ground ice development and persistence and subsequently affects microbial activities and carbon cycling (Rafat et al., 2022, Lafleur et al., 2003). Furthermore, a rise in wind speed will increase seed dispersal in autumn which in turn contributes to the growth of invasive species and shifts in vegetation communities (Farwig et al., 2006, Bacles et al., 2006). Diurnal variability of wind speed indicated that there was a diurnal variability of wind speed; however, wind speed seems to be consistent in the understory at the offline location, especially in colder months such as November, December, January, and February. From the aspect of orientation, the center of the south-north site has 0.17 m s^{-1} higher wind speed than the east-west site which is consistent with the study of Stern et al. (2018).

Overall, higher wind speeds may enhance ventilation and remove energy from the site, potentially offsetting the additional energy input from increased shortwave radiation due to canopy loss. This could also counterbalance the insulating effect of a slightly deeper snowpack along the vegetation lines.

2.5.3. Response of snowpack and soil temperature to altered meteorological conditions

The loss of canopy from the seismic line influences greater redistribution of snow by wind and altered radiation dynamics. High windspeed results in high snowpack density which has been reported by Ackley et al. (2021). Lack of tree canopy on the line causes uniform snow cover compared with off the line which in turn affects the distribution of incoming radiation and snowpack albedo. The snowpack albedo also controls energy balance and pattern of ground thaw, affecting soil temperature. Changes in available radiation (Figure 2-4) and snowpack depth also affected soil temperature so that the T_s is on average higher on the line compared to the adjacent undisturbed forest in these cold months (Table 2-2, Figure 2-10). Soil temperature is a significant driver of heterotrophic microbial activity in peatlands (Melaku et al., 2020). The soil freezing and thawing cycle also influences carbon dioxide emissions (Hao, 2015, Rafat et al., 2022). On the seismic line, the soil temperature regime indicates that the average temperature in most of the cold

months is higher on than off the line (Figure 2-10). This result is most likely due to higher snow depth on the line (Figure 2-9). Greater snow depth and density illustrates that snow remains on the ground for a longer period. This more persistent snow insulates the ground and blocks cold air temperatures from moving into the soil (Iwata et al., 2010). The difference in soil temperature between on and offline locations might also be associated with tree canopy and the effect of root zones on the soil structure and porosity, which subsequently controls soil temperature (Onwuka and Mang, 2018).

Due to warmer soils on the seismic line, the underlying finding was that the freezing period of Ts at 5, 10 and 15 cm in undisturbed was 178, 174, and 174 days compared to 175, 173, 165 days on the seismic line at Maqua site (Figure 2-10). At the Tamarack site, freezing conditions at 5 cm off the line occur 10 days earlier than on the line. The more extensive change to the frozen period at Tamarack compared to the Maqua site may indicate that orientation plays a role either through controls on incoming radiation, snowpack conditions, or both. Further studies of snow accumulation and ablation, alongside soil temperature monitoring at a series of seismic lines that vary in width and orientation are needed to advance our understanding of the effect of seismic lines on winter soil thermal regimes. Nonetheless, across both our study locations, the online site stays above freezing for longer at depth which in turn would result in more microbial activity and potentially greater overwinter carbon losses (Swails et al., 2022), although direct measurement of this is still required. In contrast, the growing season on the seismic line is longer than off the line. It has been reported that a longer growing season results in larger gross primary productivity and subsequently influences the ecosystem carbon balance (Rafat et al., 2022).

2.6. Conclusions

The effect of seismic line disturbances on the abiotic variables in cold months, which has previously not been documented, was assessed in this study. The findings highlight warmer soils over the winter on the seismic line and later freezing of the top soil layers; these differences are likely to affect microbial activity and hence nutrient and carbon cycling. Furthermore, incoming radiation on the seismic line was 1.8 times higher than in the adjacent wooded peatland. Since the studied lines were much windier, this likely influences snowpack, which eventually affects soil moisture and subsequently hydrological condition. The soil temperature on the seismic line stays above freezing seven days longer on the east-west line than adjacent wooded peatland. However,

in the north-south line, soil temperature on the line remained above 0 °C throughout the entire non-growing season. Moreover, it was observed that this impact in October and April differs from colder months which might be related to high air temperature and melting condition. Unlike the previous reports on the growing season, the pattern of NR in cold months is quite different from growing seasons with higher negative net radiation on the line. To gain a better understanding of seismic line effects, future research should further characterize winter meteorological and soil conditions, including patterns of snow accumulation and ablation, across a wider range of seismic lines that vary in orientation, width, ecosite type and recovery status. Assessing the combined effects of all of these change across the whole annual cycle on ecosystem water cycling will provide valuable information on the potential cumulative impact of seismic line disturbances on watershed function.

Chapter 3.

Seismic line disturbances affect spatial and temporal patterns of snow accumulation in boreal forests

3.1. Abstract

Land preparation for geologic exploration has created a network of linear clearings known as seismic lines in the boreal forest. These anthropogenic disturbances alter the local hydro-climatological conditions within the ecosystems that they cross. However, the effect of seismic lines on wintertime conditions, especially snow accumulation patterns and melt dynamics, remains poorly understood. This study used time lapse photography to investigate whether snowpack conditions were affected by seismic lines by investigating average and maximum snow depth, when the snowpack reaches its maximum depth, when it disappears, and the length of the ablation period. We deployed 50 pairs of cameras (i.e., one on the seismic line, and another in the adjacent area; herein referred to as online and offline, respectively) across two study sites in northern Alberta on seismic lines with different orientations (i.e. E-W, N-S), widths (i.e. ≤ 5 m, > 5 m), and ecosite type (i.e. lowland, upland). From the analysis of snow depths between 2017 and 2021, statistically significant differences were observed for maximum snow depth, with the online values being 10% greater than offline. The average snow depth across all images with snow from all locations on the seismic line was 12% higher than offline, but the difference in average snow depth was not statistically significant. The maximum depth of snow on the line was reached five days later than offline and snow-free conditions occurred one day after offline, despite the greater maximum snow depth on the seismic line. The ablation duration (i.e., time from maximum snow depth to snow-free conditions) online was five days shorter than that offline, indicating faster snow loss on the seismic lines. Our results highlight that seismic line disturbances affect the spatial and temporal patterns of snow accumulation and melt in boreal forests, which will have run-on implications for soil thermal and hydrologic regimes, especially in the spring freshet. These results emphasize the need for research that addresses the larger-scale (i.e., catchment-scale) implications of greater snow accumulation on seismic lines that are prolific in northern Alberta.

Keywords: Seismic lines, Snow accumulation, Snow melt, Time lapse photography, Line width and orientation.

3.2. Introduction

The boreal region, characterized by long winter seasons with cold air temperatures, deep snow accumulation, and seasonal soil frost dynamics (Friesen et al., 2021), plays a pivotal role in regulating global energy, water, and carbon fluxes (Weiland et al., 2024; Swails et al., 2022; Van Huizen and Petrone, 2020). One of the key hydrological considerations during winter is the distribution of the snowpack, since snow on the ground mediates water and energy fluxes between the ground and the atmosphere, thereby affecting ecosystem functioning during both growing and non-growing seasons (Mott et al., 2018; Varhola et al., 2010). For example, Zhao et al. (2017) described how the snowpack regulates soil physiochemical and biotic properties at regional scales in boreal peatlands. A snow cover reduces the depth of soil freezing, given the relatively low thermal conductivity of snow (Van Huizen and Petrone, 2020). Hence, the insulating effect of a snow cover results in the soil temperature remaining close to zero even under freezing air temperatures (Sutinen et al., 2008). Additionally, a snow cover insulates the soil and protects it against extreme temperature fluctuations during the winter (Zhao et al., 2022), which influences the growing season length.

Site characteristics affect the depth of snow accumulation. For example, aspects with greater exposure to wind would have lower snow depths than areas sheltered by wind (Dharmadasa et al., 2024), and ground surfaces below dense tree canopies typically support lower snow depths than adjacent treeless sites owing to canopy interception of snow (Hojatimalekshah et al., 2021). Disturbances to the ground surface can therefore affect snow accumulation rates and patterns, thereby affecting the temperature of the underlying ground during winter. During snow-free seasons, ground temperatures remain affected since disturbances typically alter the energy balance of the ground surface and subsurface (Williams and Quinton, 2013). Furthermore, winter processes may affect summer soil temperatures, and this is known to drive carbon cycling in peatlands (Strack et al., 2018) and on seismic lines (Swails et al., 2022).

Resource exploration and development in the boreal region alter land cover with consequences for energy and mass exchange (Franklin et al., 2021, Bayatvarkeshi et al., 2025). Despite the prevalence of resource development and human footprint in the region (ABMI, 2023), the effects of these changes on the spatial and temporal patterns of snow accumulation remain understudied. This study investigates the impact of linear clearings, known as seismic lines, on the snowpack dynamics in the boreal forest of Alberta, Canada.

Seismic line disturbances alter ecosystems by fragmenting forest cover (Weiland et al., 2023, Dabros et al., 2018) and can contribute to anthropogenic climate change by increasing peatland greenhouse gas emissions (Strack et al., 2019). Due to the high density of seismic lines across the boreal forest (i.e., up to 60 km/km²; Shellian et al., 2024), this fragmentation has many ramifications for biodiversity and ecosystem processes, which have been reported previously, referring to the fact that the majority of the implications are measurable. For instance, previous research has investigated the effect of seismic lines and/or other linear disturbances such as winter roads on ecosystem conditions such as soil moisture and temperature (Dabros et al., 2017), solar radiation (Pohlman et al. 2007; William and Quinton, 2013), bulk density of the soil (Davies et al., 2025), and vapor pressure deficit (Franklin et al., 2021; Haag and Bliss, 1974; Pohlman et al., 2007), wind speed (Burton, 2002, Weiland et al., 2023), and hydraulic conductivity (Weiland et al., 2024). Although wintertime microclimatic conditions (Bayatvarkeshi et al., 2024) and basic snow properties (Weiland et al., 2024) on seismic lines have been evaluated, most studies focus on the summer period and growing season, and little information exists regarding the effect of these linear disturbances on the spatial and temporal patterns of snow accumulation.

When seismic lines are introduced, the tree canopy is removed. This increases both solar radiation (Franklin et al., 2021) and windspeed (Stern et al., 2018). The use of heavy equipment to remove the canopy along the line invariably compacts the ground surface, resulting in higher near-surface moisture contents compared with the adjacent undisturbed terrains (Davies et al., 2025; Weiland et al. 2024). While tree canopy removal reduces snowfall interception, and the resulting deeper snow accumulation on the ground (Weiland et al., 2024), can prolong the snow-cover period on linear disturbances (Haag and Bliss, 1974). A longer snow-cover period delays plant development, resulting in shorter growing season (Dabros, 2008; Bjorkman et al., 2015). Pomeroy et al. (2012) found that the clearance of 60% of canopy cover will induce a 45% increase in snowmelt volume. A rise of 16% and 21% in snow water equivalent following 40% and 50% tree removal have been detected by Woods et al. (2006) and Troendle and King (1987), respectively. An integrative review comparing snow properties in forested and open sites across Canada and EuroSpe indicated that the forest canopy controls 57% of snow accumulation and 72% of snow ablation (Varhola et al., 2010). It has also been reported that open areas have more snow accumulation with higher melt rate compared to forest-covered sites (Varhola et al., 2010). However, higher wind speed on the seismic line (Franklin et al., 2021; Bayatvarkeshi et al., 2024) might have a different effect on

snow accumulation. For example, Mott et al. (2018) highlighted the pivotal role of wind speed in the spatial variability of snow accumulation. It was also reported that high wind speed in open areas increases the frequency of blowing snow events and associated sublimation losses (Pomeroy and Gray, 1994), reducing snow depth (Dharmadasa et al., 2024). The study of Hojatimalekshah et al. (2020) demonstrated that there is a significant relationship between vegetation structure and snow depth, while snow melt in open areas is highly controlled by solar radiation and location of the study site.

Snow accumulation on the seismic line might be affected by high incoming radiation (Stern et al., 2018) which affects snow properties. Weiland et al. (2024) attributed the greater observed snow density on 7 m wide seismic lines to enhanced incoming radiation. Additionally, tree canopies in undisturbed areas reduce snow ablation by reducing incoming solar radiation (Varhola et al., 2010), a factor that increases the duration of snowmelt. Snowmelt rates in boreal forests can be 70% lower than in open areas (Boon, 2007; Teti, 2008). Similarly, Ketcheson et al. (2012) reported accelerated melting rates on a harvested (treeless) peatland compared to an adjacent forest-covered peatland, due to higher radiant and turbulent fluxes in the harvested area.

Snowpack dynamics, and ablation rates and patterns are altered by seismic line disturbances; however, extensive evaluation of these complicated interactions is still needed as the snowpack affects many ecosystem processes. For example, alterations to wintertime snow conditions might control hydrological conditions in the summertime. Peak soil moisture occurs on or within a few days after the removal of snowpack, typically declining into the summer season (Hammond et al., 2019). Since seismic lines change soil moisture (Weiland et al., 2023), shifts in the timing of snowmelt exacerbate soil moisture values in a disturbed peatland. Further, the timing of snowmelt drives the timing of the start of the growing season (Poulos et al., 2021), plant transpiration (Kraft and McNamara, 2022), and streamflow (Milly and Dunne, 2020).

Given the importance of the snowpack in the boreal region and widespread seismic line disturbance in northern Alberta, further research on the effect of these disturbances on snow accumulation and ablation dynamics is needed. However, accessing remote boreal forest locations in winter for field-based snowpack measurements is a logistical challenge, and thus, a shortage of in-field measurements constrains our wintertime observations of these important ecosystem alterations. The need to quantify the relationship between seismic line disturbance and snow

accumulation and melting has motivated the development of a time-lapse photography approach in this study. Therefore, the objectives of the current investigation are to: 1) compare the spatial patterns of snow depth on the seismic line to the adjacent natural area, 2) evaluate the timing of peak snow depth and snow-free conditions on seismic lines, 3) characterize the effect of seismic line disturbance on the rate of snowpack lowering / ablation rate, and 4) provide insights into the drivers of snow cover distribution within landscapes containing seismic lines.

3.3. Study Site and Methods

We sampled two study sites in northern Alberta, Canada (Figure 3-1) during the winters of 2017–2021. The Audet Lake (ADE) and Christian Lake (CHR) sites are located approximately 100 km north and 120 km east of Fort McMurray, respectively (Figure 3-1). This region is situated in the Western Boreal Plains ecoregion, which has a cold and sub-humid climate where most of the annual precipitation falls as rain (342 mm) with the majority delivered from May to August and the remainder falls as snow (114 mm of water equivalent) (Environment and Climate Change Canada, 2020; 1991-2020). The mean annual daily air temperature is $0.7 \pm 1.2^{\circ}\text{C}$ with the maximum typically occurring in July when daily air temperatures average $16.8 \pm 1.1^{\circ}\text{C}$ while the daily average low temperature is $-20 \pm 1.5^{\circ}\text{C}$ in January (Environment and Climate Change Canada, 2020; 1991-2020).

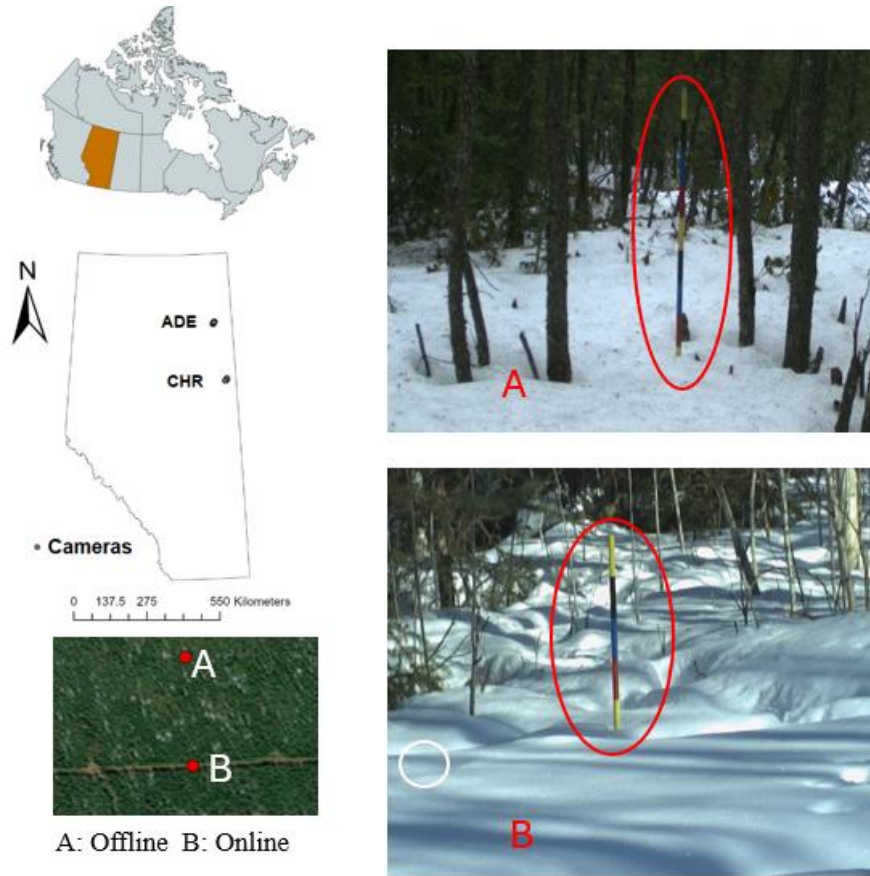


Figure 3-1 The location of installed cameras at the two study sites, ADE and CHR. At each red point at each study site, a pair of snow monitoring stakes was installed offline in undisturbed forest (A) and on the seismic line disturbance (B) and monitored with time lapse cameras.

At each site, we deployed 50 pairs of cameras (i.e., 100 cameras) across different stations between early October and the end of March, which were retrieved in July. Each station was equipped with two cameras (Reconyx PC900s), with one camera located on the seismic line (herein referred as “online”) and the other located in the adjacent natural area (herein referred as “offline”) (Figure 3-2). At the adjacent natural area, the camera position was determined based on targeting a detection zone ~5 m from the camera and achieving a 5 m wide by 10 m long view. Afterward, they were mounted to trees at a height of 1 m above the ground surface. Units deployed on the seismic line were mounted to the trees on the edge. To determine snow depth, photos were taken of a targeted point with a snow monitoring stake. These snow monitoring stakes were a 1.3 m painted conduit stake (aluminum, 13 mm diameter) driven 0.3 m into the ground, 5 m in front of the camera in the target area. The position of the snowpack surface on the date of the image could then be determined with ~1 cm accuracy by comparing it to the snow monitoring stake. More information about the

protocols of this project is available on the ABMI site (i.e., <https://abmi.ca/home/publications/551-600/599>).

During the period from 2017 to 2021, we captured over 15,000 photos from on the line and off the line with a precision of ± 1 cm; however, only images that were level, not blurry, and taken in the appropriate orientation were used to meet our intended purpose. Accordingly, approximately 10,000 high-quality photographs were used for this analysis. In addition to the snow depth extracted from the photos, the geographical coordinates of each camera, width and orientation of each seismic line, ecosystem type (i.e., upland or lowland), and type of dominant tree (i.e., coniferous or mixed) were also determined from remotely sensed estimations (Becker et al., 2021).

3.3.1. Data Analyses

Using the snowpack data captured from the cameras we determined several variables including snow depth on each date with an available photograph, date of maximum snow depth (DOY of max snow), snow free date (i.e., DOY of snow free), and the difference in each of these variables between on and offline. The difference between DOY of max and DOY of snow free represents the duration of the snowmelt period, or what we refer to in this paper as the snow ablation period. Throughout this paper, we present and discuss differences in the apparent rate of lowering of the snow surface, quantified using the snow depth measurements from the snow monitoring stake photographs (see below). We refer to the rate of change (i.e., lowering) of the snow surface as the ablation rate, which here represents the cumulative effect of snow melt, sublimation and densification during the snowmelt period. Accordingly, the ablation rate R_A is defined as:

$$R_A = \frac{d_{max}}{D_{max} - D_0} \quad (1)$$

where d_{max} is the maximum snow depth, D_{max} is the day of year when the snow cover was deepest, and D_0 is the day of year when the snow cover disappeared.

R software (R Core Team, 2024) was used to perform all statistical analyses. The analyzed variables were tested for normality prior to any parametric tests, and when necessary, appropriate transformations (e.g., log transformation) were implemented. We investigated the effect of seismic line structure on snowpack characteristics using only the data from the online cameras. Differences in snowpack characteristics in response to seismic line disturbance were evaluated with linear mixed effects models with location (on or off the seismic line), habitat (upland, lowland),

orientation (east-west, north-south), site (ADE, CHR), width (≤ 5 m, >5 m), and two-way interactions as the fixed effect and measurement spot as a random factor. The snowpack dynamics included average snow depth, max snow depth, DOY of max snow ($D_{\max}$, and DOY of snow free (D_0). The linear mixed effects model was applied using the function “lme” in the package “nlme” (Pinheiro et al., 2024). Significant variables in the model were assessed using the anova function in R and marginal p-values. The creation of the final models was based on step-by-step method, so that in each step non-significant variables were withdrawn from the model to identify a model with only significant variables. Variables in the final best-fit models were accepted as significant at the $p < 0.05$ level.

3.4. Results

Considering all snowpack data captured by the cameras from 2017 to 2021 (Figure 3-2), the snow depth offline was more variable than online at both sites, with a standard deviation of 15.9 compared to 13.6 cm. Considering all datasets, the temporal variation indicates that 2021 received more snow than others, with an average depth of 43 cm; the lowest recorded average snow depth was associated with 2017 (i.e., 20 cm).

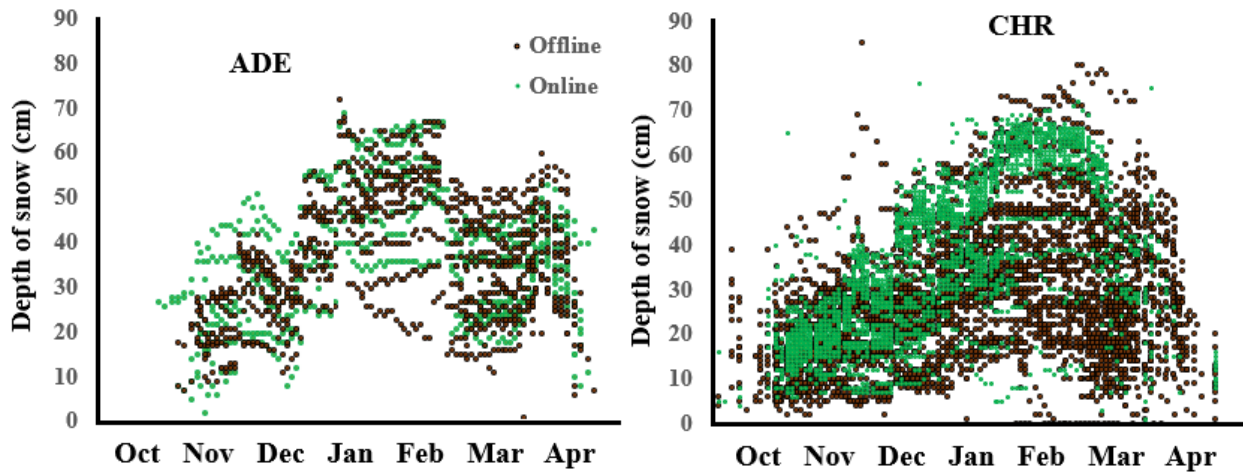


Figure 3-2 Snow depth observations from the paired online and offline cameras at the ADE and CHR from 2017-2021.

Table 3-1 The summary of final models to indicate the significant variables of each snowpack dynamics

Variable	Driver	df	denDF	F-value	P-value
DOY of snow free	Site	1	26	13.778	0.0010
DOY of max snow	Habitat	1	30	8.626	0.0124
Average of snow depth	Habitat	1	21	20.467	0.0002
Max snow depth	Habitat	1	30	20.345	0.0001
	Line	1	30	6.0936	0.0195

To compare the average snow depth using all measured values (on and offline), the impact of the site location on snow accumulation patterns illustrated that the ADE received 9% more snow than the CHR; however, the maximum snow depth in the CHR location was greater than the ADE by 8% (Figure 3-1). From the aspect of seasonal patterns of snow accumulation and loss, the peak snow depth and snow-free date at the ADE occurred 13 days after the CHR (Figure 3-3). Considering statistical analysis, the impact of the site was significant on the DOY of snow-free at a 99% confidence interval (Table 3-1).

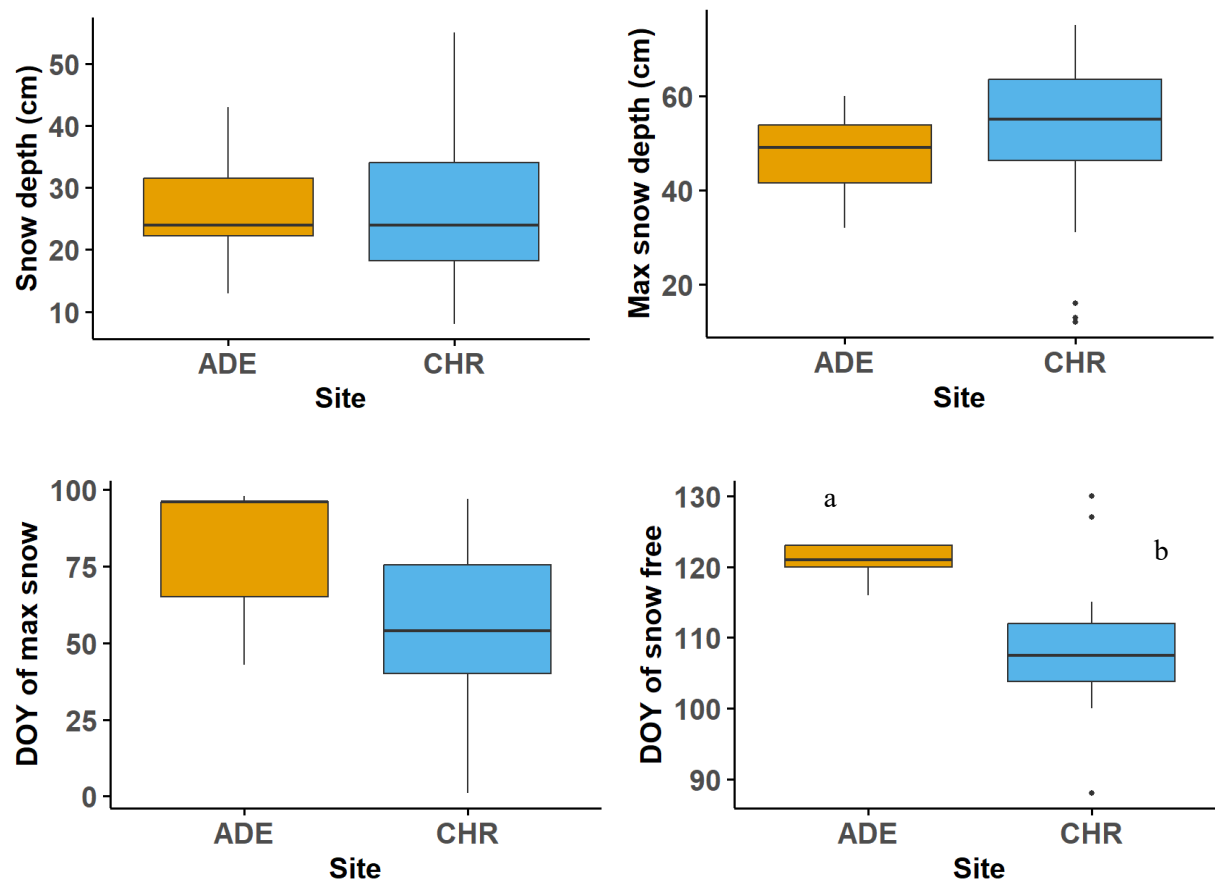


Figure 3-3 The impact of site location on the snow properties at the ADE (orange) and CHR (blue) study sites for all measurements (i.e., both online and offline cameras); the letters a and b refer to a significant difference at 0.05 level.

Using all measured values for snow depth online and offline indicates that the average snow depth on the line was 3 cm (i.e., 12%) higher than off the line; however, this difference was not statistically significant ($F=1.388$, $p=0.243$). Similarly, the maximum depth of snow on the line was greater than offline by 10% (Figure 3-4), being significant at a 95% confidence interval. This maximum snow depth occurred five days later online than offline and the snowpack disappeared on seismic lines on average one day after offline. These temporal differences in snowpack dynamics were not statistically significant (Table 3-1).

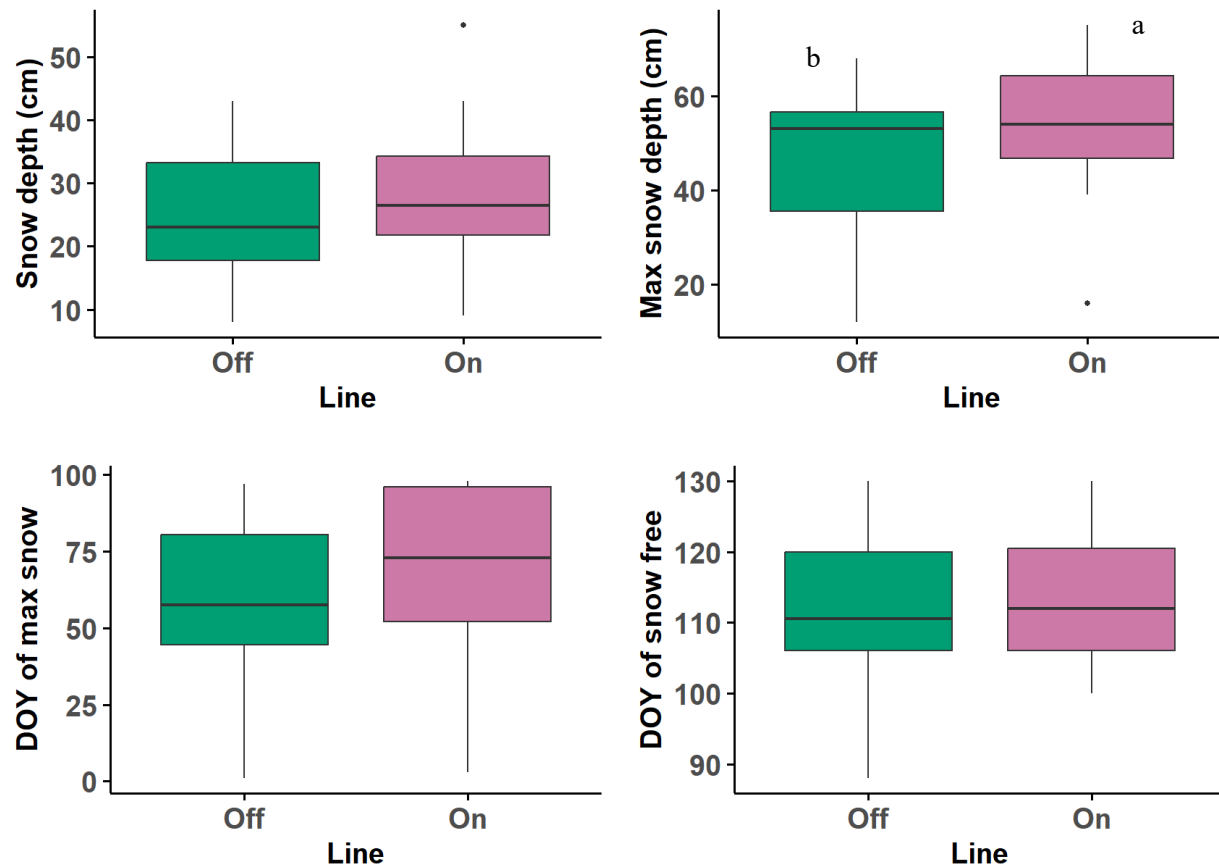


Figure 3-4 Observed snowpack depth (average and maximum from both ADE and CHR) and timing of maximum snow accumulation and snow-free conditions on the seismic line (“on”) (pink) and in the adjacent ecosystem (“off”) (green); the letters a and b refer to a significant difference.

Regarding the structure of seismic lines (i.e., considering only the online data), the orientation of the lines affected snowpack characteristics. We observed higher average snow depth on the north-south (hereafter referred to as N-S) oriented lines compared to the east-west (E-W) oriented lines by 39%; however, the peak snow depth on the N-S lines was 2% lower than on the E-W lines (Figure 3-5). Further, the maximum snow depth on the N-S lines occurred 11 days after that on the E-W and disappeared two days later than on the E-W oriented lines.

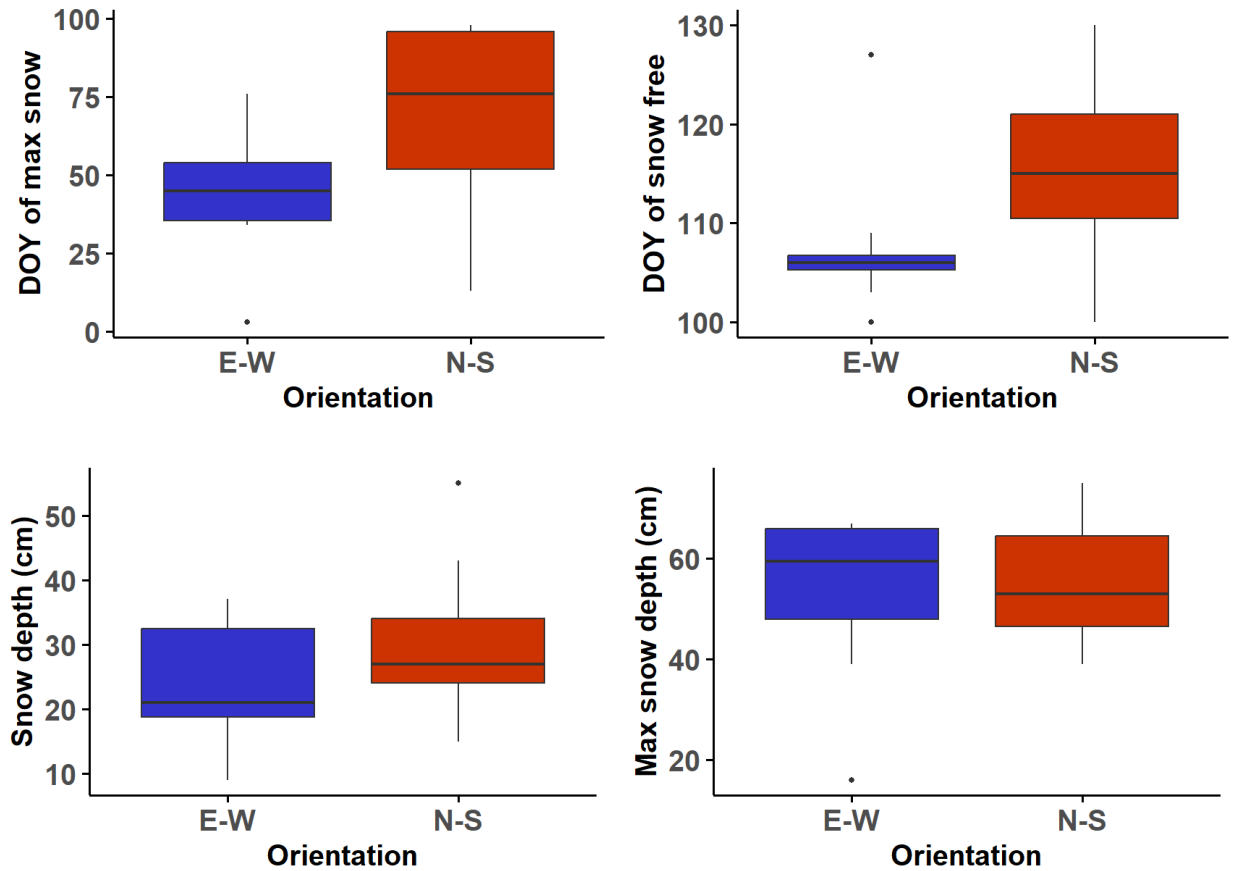


Figure 3-5 Observed snowpack depth (average and maximum from both online and offline datasets) and timing of maximum snow accumulation and snow-free conditions on seismic lines with different orientations (i.e., E-W oriented line in blue and N-S oriented line in red). Only the online data was used for this analysis.

In addition to the orientation of the seismic line, the width of seismic lines also resulted in differences in snow accumulation patterns. The average snow depth on the seismic line in wide lines (i.e., >5 m) was 1 cm greater than the narrow lines (≤ 5 m) (i.e., 30 cm compared to 29 cm). The peak snow depth in wide lines was 16% greater than the narrow ones (i.e., 57 cm to 49 cm). Peak snow depth on narrow lines (48% of all study lines were narrow) occurred seven days after wide lines (i.e., 52% of all study lines). Snow also disappeared with an 8-day delay in narrow lines compared with the wide ones; however, these differences were nonsignificant (Table 3-1).

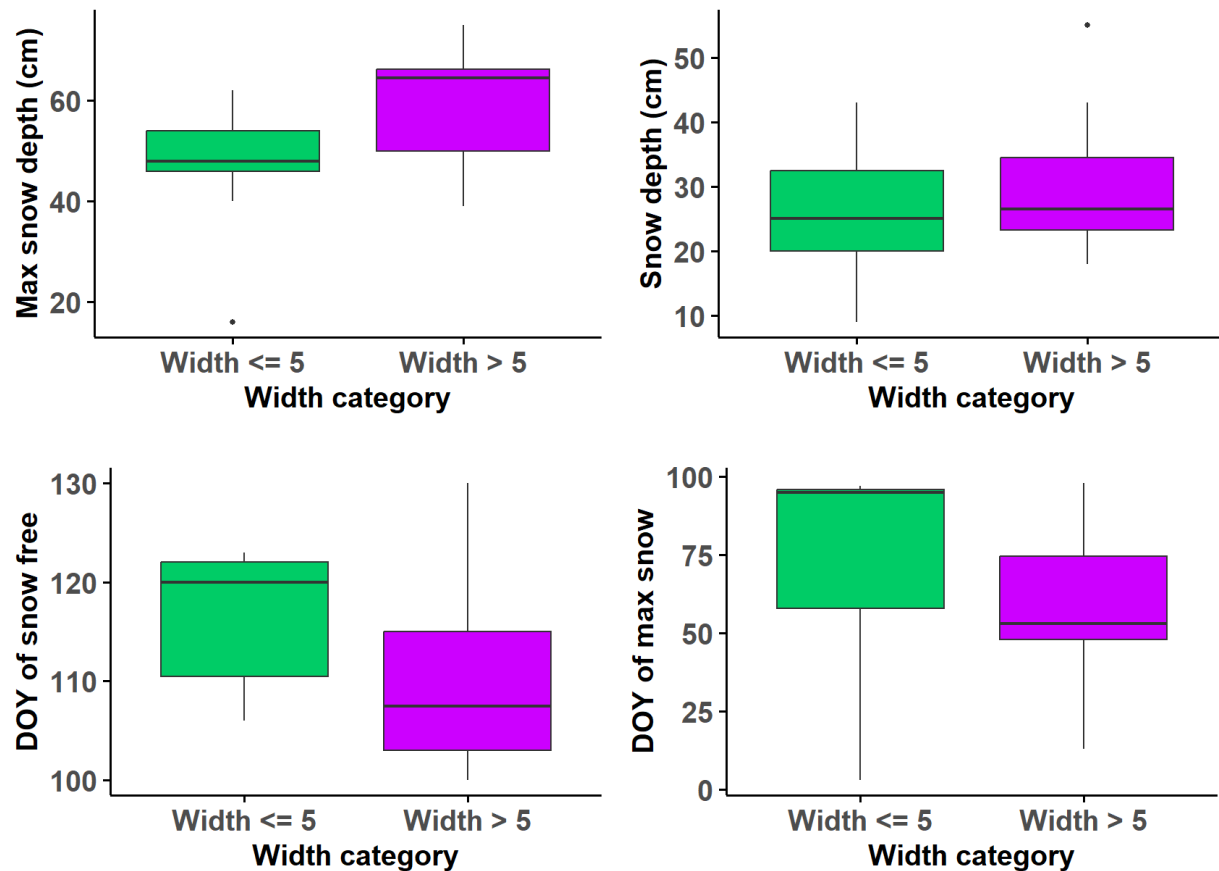


Figure 3-6 Observed snowpack depth (average and maximum from all datasets) and timing of maximum snow accumulation and snow-free conditions on seismic lines with different widths (i.e., width ≤ 5 m in green and width > 5 m in pink). Only the online data was used for this analysis.

The ecosystem type played a pivotal role in snowpack properties (Figure 3-7). The average snow depth from all measurements in wetlands was 56% higher than that in uplands, while the peak snow depth was greater in wetlands by 42%. The timing of the peak snow depth and snow-free conditions in wetlands occurred 13 and three days earlier than in uplands. These differences between upland and lowland ecosystems were statistically significant for all snow metrics, emphasizing the crucial function of ecosite type in the distribution of the snowpack.

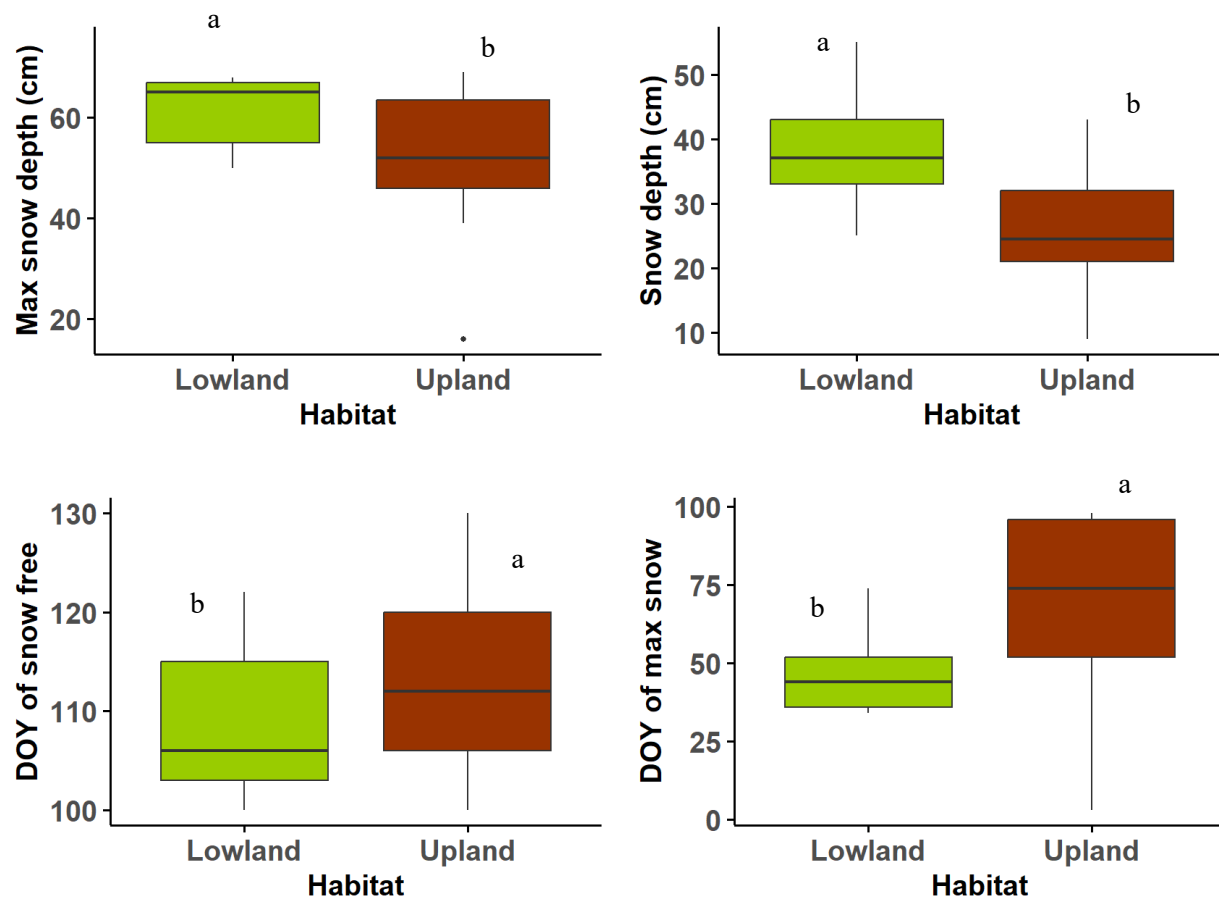


Figure 3-7 Observed snowpack depth (average and maximum from all datasets) and timing of maximum snow accumulation and snow-free conditions on seismic lines in upland and lowland ecosystems; the letters a and b refer to a significant difference.

When calculating differences in snowpack dynamics for each pair of cameras, variation in the local effect of the seismic line on snowpack dynamics is apparent (Table 3-2). Although average and maximum snow depth generally was higher online compared to offline, these differences occurred 58 and 42% of the time at ADE and 66 and 71% of the time at CHR, suggesting that in some cases, seismic lines can result in little change in snow depth or lower average and maximum depth. Similarly, timing of maximum depth and snow-free conditions were almost evenly split between earlier, later and no change across the camera pairs (Table 3-2).

Table 3-2 The summary of the difference in snowpack dynamics between on and offline

Site	Difference	Snow depth	Max snow (cm)	DOY of max snow	DOY of snow free
ADE	on>off	58%	42	52	52
	on<off	42%	58	33	29
	on=off	0	0	25	29
CHR	on>off	66	71	38	38
	on<off	24	24	24	33
	on=off	10	5	38	29

This variable response to the seismic line disturbance among camera pairs depends on both the site location and seismic line variables. Statistical analysis indicated that the difference in average snow depth between on and offline was significantly driven by seismic line width, direction, and the interaction of site and width (Table 3-3). Variation in the on and offline difference in maximum snow depth was controlled largely by orientation, and the interaction of line width and ecosite type (Figure 3-8). We did not find a significant relationship between any of our compiled variables about the seismic lines and differences between on and off the line for the timing of maximum snow depth or day of snow free conditions.

Table 3-3- The drivers of the difference in snow properties between on and offline

		df	denDF	F-value	p-value
Snow-depth (avg)	Width	1	15	5.095	0.0393*
	Orientation	1	15	1.440	0.0306*
	Site	2	15	7.763	0.0138*
	Width: Site	1	15	9.239	0.0083**
Snow-depth (max)	Orientation	1	16	3.958	0.0401*
	Width	1	15	2.015	0.1667
	Site	1	17	4.752	0.0436*
	Width: Site	1	16	8.716	0.0094***

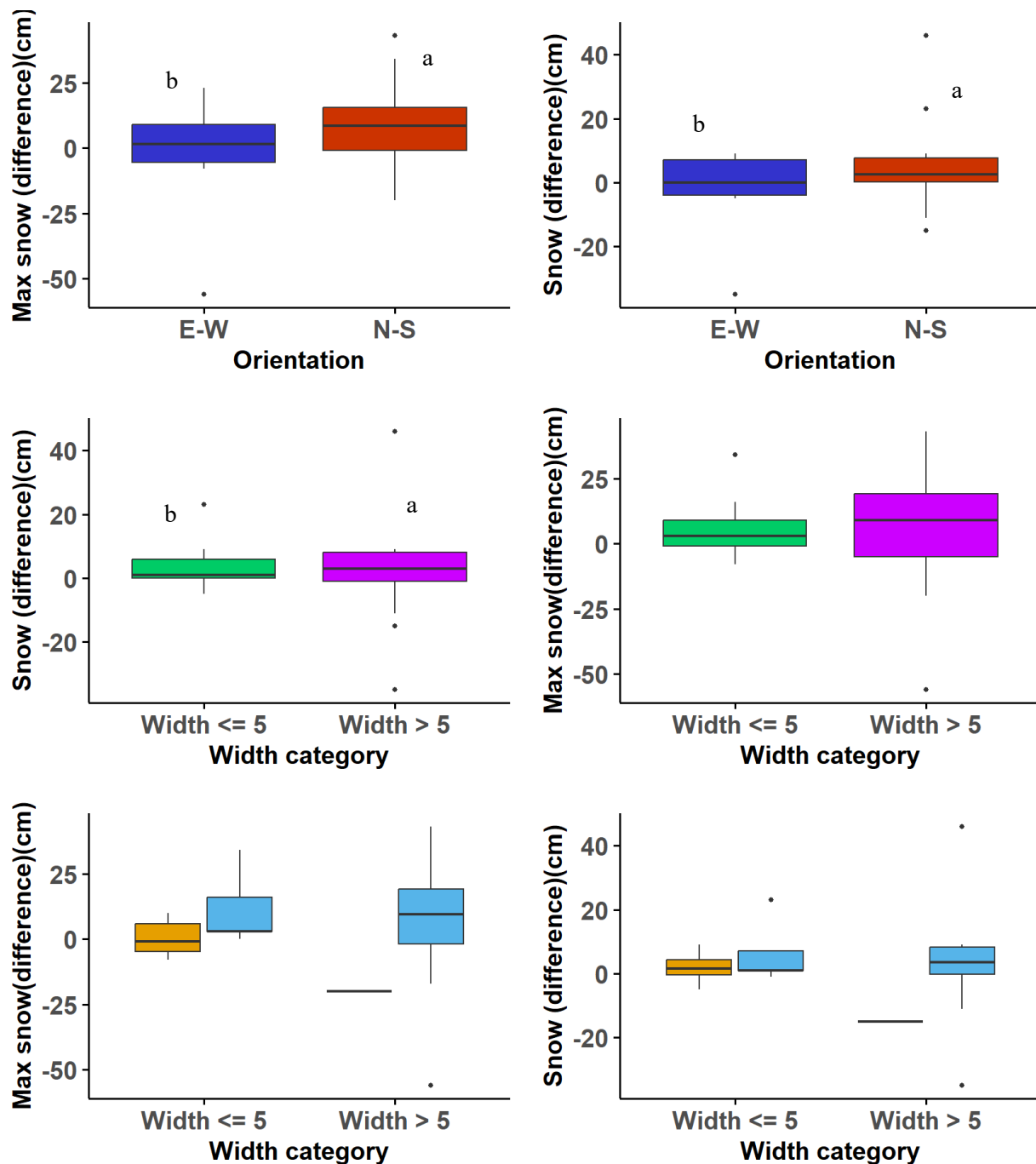


Figure 3-8 Differences in observed snowpack depth (average and maximum from all datasets) and timing of maximum snow accumulation and snow-free conditions between seismic lines (online) and the adjacent ecosystem (offline); the letters a and b refer to a significant difference. Note: differences were calculated by subtracting the online from the offline snow depth for each paired measurement location.

The difference between DOY of max and snow-free indicates that the ablation duration was five days shorter on the seismic line (47 days) than off the line (52 days). From the aspect of width, the ablation duration was five days shorter on narrow lines (46 days) than on wide lines (51 days). The

ablation duration in uplands was shorter than in wetlands. The impact of the orientation of lines on the ablation duration indicates that the snow on the ground in the N-S oriented lines melts faster than in the E-W oriented ones. Similar to other properties of snow cover, ablation duration is site-specific too.

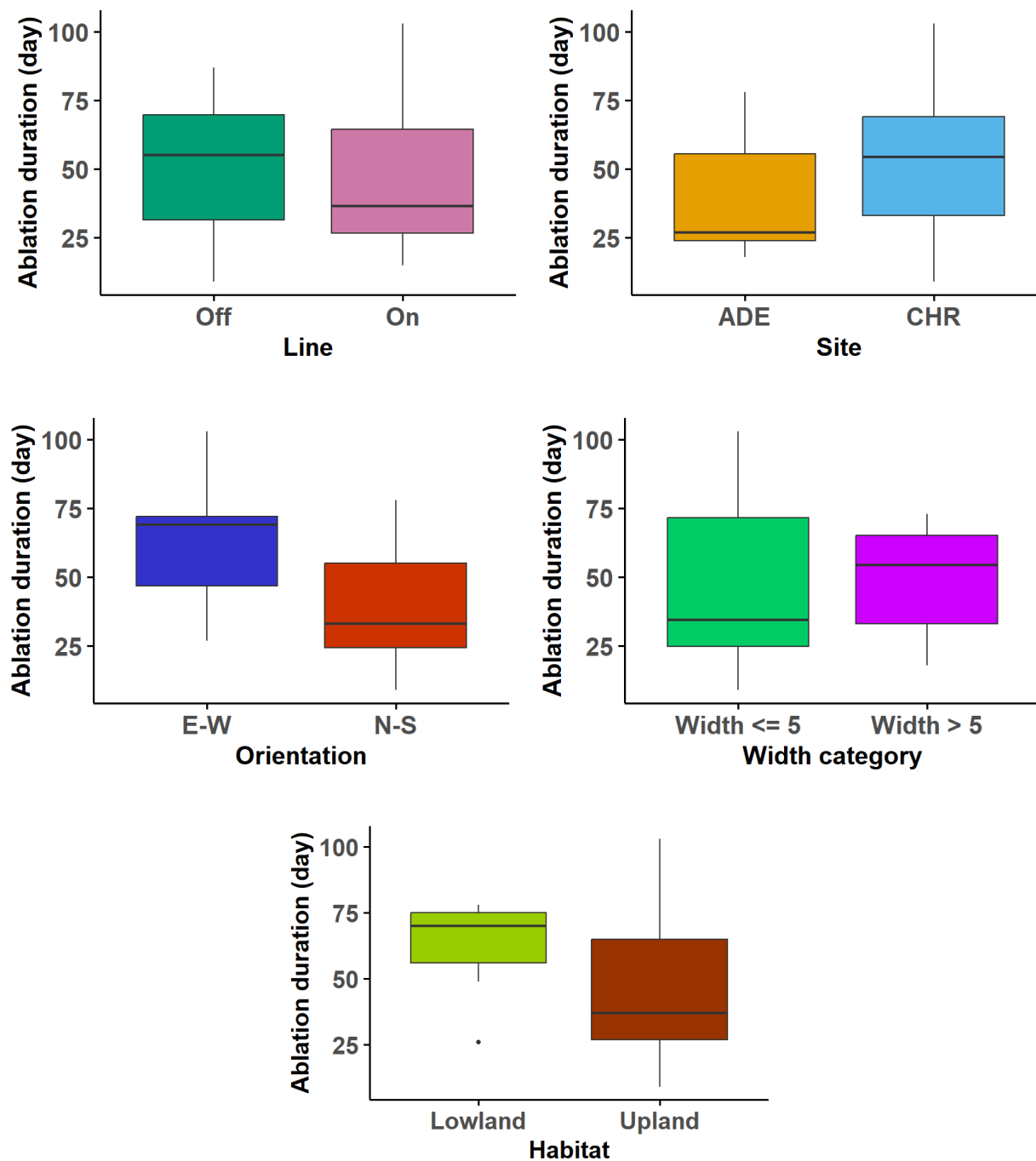


Figure 3-9 The difference in the ablation duration between seismic lines and the adjacent ecosystem from all datasets

As outlined in Equation 1 above, the rate of snow surface lowering, referred to here as the ablation rate, can be estimated by dividing the maximum snow depth (cm) by the ablation duration (days). Based on the results, the ablation rate at ADE (1.5 cm/day) was 19% greater than CHR (1.3 cm/day). Seismic lines demonstrated a 34% greater ablation rate than in the adjacent ecosystem (i.e., 1.6 cm/day on seismic lines compared to 1.2 cm/day off the lines), with greater ablation rates observed on wider seismic lines (1.4 cm/day) than narrow lines (1.3 cm/day). Regarding the ecosite (i.e., based on both online and offline data), the rate of snowmelt at uplands is faster than at wetlands, 1.4 cm/day compared to 1.1 cm/day (Figure 3-10). The N-S oriented lines had a 49% greater snowmelt rate than the E-W oriented lines (1.5 cm/day compared to 1.0 cm/day for N-S and E-W lines, respectively).

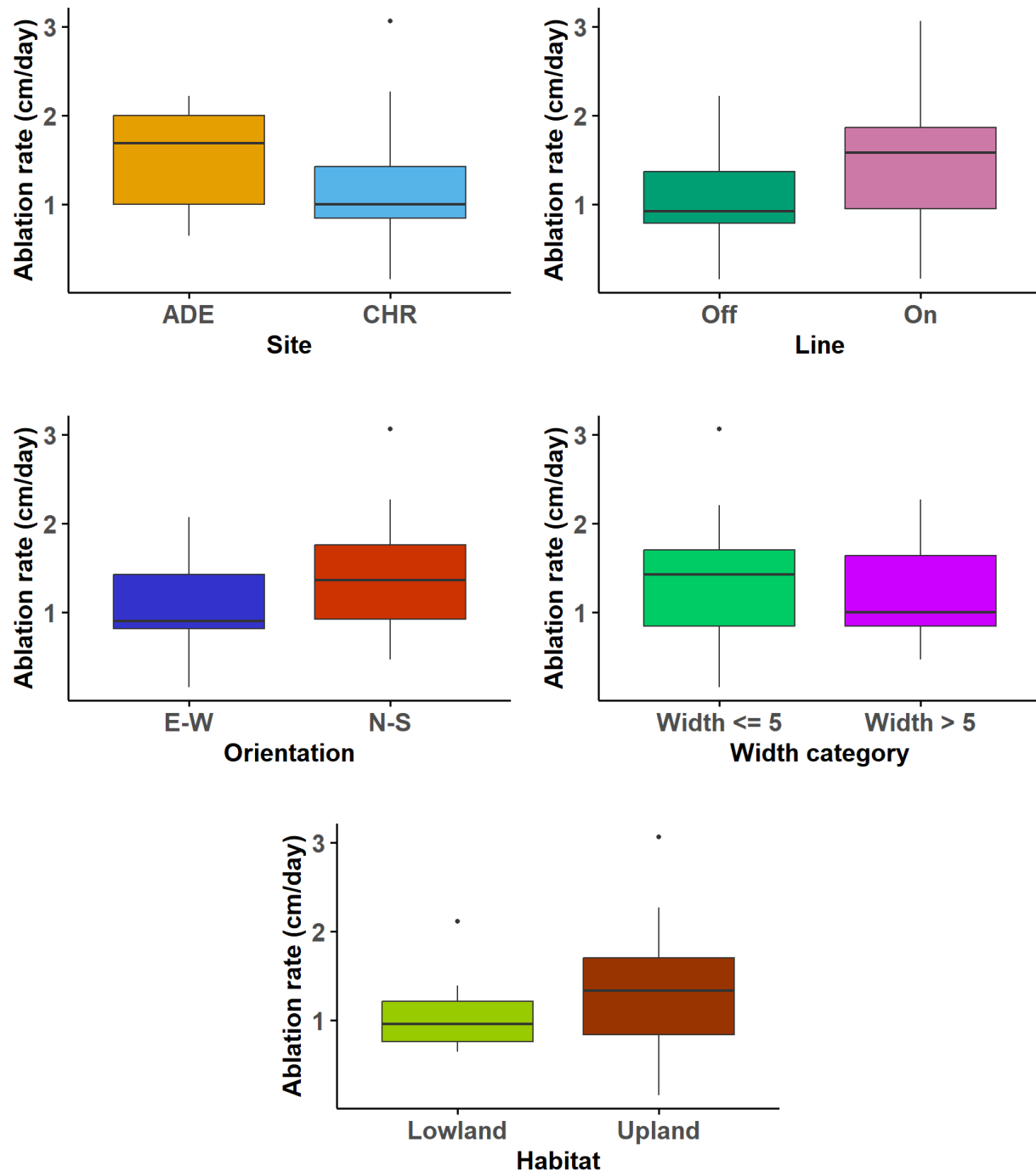


Figure 3-10- The difference in ablation rate between seismic lines and the adjacent ecosystem from all datasets

3.5. Discussion

Due to the importance of understanding the ecosystem alterations caused by seismic lines in the boreal region, investigations on wintertime conditions are as important as those on summertime. Accordingly, this study investigated the effect of seismic lines on the spatial and temporal patterns

of snow accumulation and whether the effect of seismic lines was dependent on local conditions. Changes to canopy structure and meteorological conditions caused by seismic lines could have a range of impacts on snow accumulation and loss. Elevated wind speed on seismic lines has been reported in both summer and winter studies (Franklin et al., 2020; Bayatvarkeshi et al., 2024; Weiland et al., 2023) and this higher wind speed can drive snow relocation and sublimation (Pomeroy and Gray, 1994), which might reduce snow depth (Dharmadasa et al., 2024). Moreover, higher incoming radiation on the seismic line (Bayatvarkeshi et al., 2024) indicates high available energy for sublimation. In contrast, the open area created by seismic lines should reduce snowfall interception and has been shown to enhance snow accumulation, with higher snow water equivalent observed on a small sample of seismic lines compared to the adjacent ecosystem (Weiland et al., 2024).

Our findings on 50 lines with different orientations and widths indicated that the lack of interception due to the removal of vegetation generally resulted in greater snow depth (both average and maximum) on seismic lines compared to offline locations (Figure 3-5). These findings illustrate that, although higher wind speed could reduce the snow accumulation, the lack of interception still resulted in increased snow depth on seismic lines. Weiland et al. (2024) observed greater snowpack density on seismic lines compared to the adjacent offsite locations, which was attributed to greater wind speeds and incident radiation on the seismic lines. Since our methods were only able to track snow depth, we could not assess changes in density, which if increased on seismic lines would indicate a greater change in snow water equivalent than for an equivalent change in snow depth off the line (Weiland et al. 2024).

We observed that the maximum snow depth occurred five days later on the seismic line than at offline locations (Figure 3-5). Possibly, wind speeds transport snow from tree canopies onto the adjacent line, redistributing fluffy layers and enhancing the duration of peak snow (i.e., DOY of max snow). Snow free conditions on the line also occurred one day later than off the line. Delay in the disappearance of snow on seismic lines has been reported previously (Haag and Bliss, 1974), which might be related to a higher albedo compared to undisturbed areas (Dabros et al., 2018). In the study of Cannon et al. (2021), albedo of snow in open areas (i.e., no trees) has been reported to be 0.80 compared to forest areas with 0.56, referring to high albedo of snow in open areas such as seismic lines. Higher maximum snow depth on the seismic lines than off the lines (e.g., Figure 3-5) also contributed to the delayed DOY of snow free conditions observed on lines (Figure 3-7).

High snow accumulation along with a longer period of snow on the ground provides an insulating layer that protects the soil against extreme temperature fluctuations during the winter and influences growing season length (Bayatvarkeshi et al., 2024). Therefore, wintertime processes may affect summer soil temperature, an important variable that drives soil carbon cycling (Swails et al., 2022). Kraft et al. (2022) observed that the snow free conditions were reached later in the forest than open areas. These conflict results largely correspond to different vegetation types, latitudes, snow climates, and the structure of the disturbance (Dickerson-Lange et al., 2021; Kraft et al., 2022).

Although the snowpack remained slightly longer on the line, considering the ablation period (i.e., the period between when the snow was at its maximum depth to the time when it disappeared), we observed that the duration from peak to snow free conditions was shorter on the seismic lines than in offline locations (Figure 3-10). These observations were likely driven by the higher wind speed and incident radiation that have been measured on seismic lines previously (Bayatvarkeshi et al., 2024; Franklin et al., 2021). The ablation rate also supported this pattern, being 34% higher on lines compared to offline locations (Figure 3-10). Since snowmelt is highly driven by incoming radiation (Stern et al., 2018), the high ablation rate on the line is likely related to the greater incoming radiation on the seismic line (Bayatvarkeshi et al., 2024). In the offline areas, incoming shortwave radiation is reduced owing to shading from the forest cover. Even though forest cover may increase net longwave radiation at the snow surface, it generally leads to net losses in the total energy budget available for snowmelt (Essery et al., 2008). The study of Varhola et al. (2010) revealed a higher ablation rate in open areas than below tree canopies, which is consistent with the present study. Several other studies have also reported lower snowmelt rates in forests with up to 70% reduction compared to open areas (Boon, 2007; Teti, 2008), which aligns with the current findings. Golding and Swanson (1986) stated that the effect of aspect on snow accumulation and disappearing is principally a function of exposure to solar radiation, highlighting this as a likely driving factor.

The greater snow depth on the line and rapid melt may also contribute to the higher soil moisture observed in summertime on seismic lines relative to the adjacent ecosystems (Weiland et al., 2024; Davies et al., 2025). It has been reported that the soil moisture content of landscapes affected by seismic lines is a major factor that controls the degree of woody vegetation recovery (Lee and Boutin, 2006; van Rensen et al., 2015). Our results indicate that this wet condition is not only

caused by the removal of microtopography (Pinzon et al., 2022), high bulk density of soil (Weiland et al., 2023), and microclimate condition (Franklin et al., 2021) but may also result from the difference in timing and depth of snow cover on the line. Thus, these altered wintertime conditions might be a contributing factor to the arrested recovery of woody vegetation often observed on seismic lines.

We observed that site-specific differences in snow depth between online and offline were significantly driven by width and orientation. Concerning the line orientation, the N-S oriented lines had slightly higher mean snow depth than the E-W oriented lines; however, the peak snow depth on the N-S was lower than on the E-W. When the difference between on and offline conditions for paired cameras was considered, N-S lines had a slightly greater difference for both mean and maximum snow depth. N-S lines would likely receive more direct incoming radiation Franklin et al. (2021) found that the N-S lines have the highest light intensity during summer. However, E-W line have a south facing forest edge and it has been reported that south-facing edges have greater shortwave radiation and are typically warmer and drier than north-facing edges (Wales, 1967; Matlack, 1993). Thus, this warm forest edges on E-W could reduce snow depth, which aligns with the current findings. Weiland et al. (2024) reported that the E-W oriented lines have greater SWE than the N-S, similar to the pattern in peak snow depth that we observed. Overall, these conflicting results likely arise from the fact that the local snowpack depends on several components such as type of ecosystem, the width of lines, the location of sites, and the density and type of tree species (Kraft et al., 2022; Mott et al., 2018; Varhola et al., 2010). For instance, we found that the average and maximum snow depth online in wetlands is higher than that in uplands with 56% and 42%, respectively. Peak snow depth and snow free conditions in wetlands appear with a 3–13-day delay compared to upland. Future studies on the effect of orientation should focus on pairing E-W and N-S lines within similar width and ecosite type.

In addition to the orientation, the width of seismic lines contributed to the snow distribution on seismic lines. It seems that the wider lines receive more snow than narrow ones (i.e., 1 cm). Due to high wind speed in open areas (Ketcheson et al., 2012), the maximum snow depth in narrow lines, which are less open, is greater than the wide lines. The width of lines also resulted in a delay of peak snow and snow-free condition so that on wider lines. However, the ablation rate was faster on narrow lines compared with wide lines. These results are associated with high maximum snow depth and short ablation duration on narrow lines than wide lines. The rate of snow depth loss on

wider lines was lower than offline. This condition results in a prolonged duration of snow on the ground along the wider lines compared to the narrow lines.

Although the difference in snow properties between online and offline was not significant, due to the high density of seismic lines, any small change in snowpack results in a significant shift on a large scale. Warmer soils in winter on seismic lines have been observed, resulting from small differences in snow depth and snow cover duration (Bayatvarkeshi et al., 2024). In addition, 3 cm more snow on the line with the prolonged duration of snow on the ground affects spring freshet in melting months. This implication along with shallow groundwater depth on the line (Weiland et al., 2024) raises potential runoff in peatlands disturbed by seismic lines. Accordingly, the impact of the seismic lines on snow properties could be significant at the catchment scale and necessitates more investigations. Furthermore, shifts in hydrological conditions in wintertime may be drivers of the recovery trajectory of the plant community in a peatland disturbed by seismic lines and should be considered when designing restoration strategies.

3.6. Conclusion

The impact of seismic lines on snow accumulation indicated that seismic lines receive higher snow than offline with a prolonged duration of snow on the ground, resulting in greater soil moisture on the line in melting seasons. It was also observed that the ablation duration on the line is shorter than offline. Considering the depth of max snow between online and offline, a faster ablation rate on the line was observed. These results could also exacerbate wetter conditions due to the high density of snow on the seismic line. The rapid ablation rate could lead to rapid snow melting, overwhelming the infiltration rate into the ground. This would be augmented by the greater bulk densities of near surface materials on the line. Therefore, at the larger, topographic scale, if the seismic line occupies a depression and has no surface flow route, flooding may result. Accordingly, different hydrological conditions resulting from seismic line creation might be one of the reasons for the arrested recovery of woody vegetation on the lines. Apart from hydrological aspect, more long-lasting snow on the seismic line might alter distribution of energy balance components due to high albedo of snow. Moreover, the insulating layer will result in warmer soil temperature under seismic lines, which in turn affects microbial activities and subsequently carbon dynamics. Additionally, we found that these differences are mostly driven by the structure of seismic lines, such as width and orientation, highlighting the importance of the structure of seismic lines on

hydrological processes. Although we observed a slight difference between snowpack dynamics online and offline, considering the high density of seismic lines, a small change will lead to a considerable shift in catchment scale. Therefore, a study of seismic lines on hydrological conditions in the catchment scale is required to manage water resources and restoration plans.

Chapter 4.

Seismic lines are associated with enhanced ground layer evapotranspiration in peatlands

4.1. Abstract

Evapotranspiration, the combined water loss through both evaporation from the ground surface and transpiration through the vegetation canopy, makes up a substantial portion of the water balance in peatlands in the western boreal region of Canada. Geologic exploration for petroleum resources has created a network of linear clearings, known as seismic lines, that have altered the local hydro-climatological conditions within the ecosystems that they cross, including peatlands. Accordingly, understanding the interaction between human activities and hydrological fluxes in peatlands is crucial to understanding the processes sensitive to these types of disturbances, especially in a region with a sub-humid climate. This study aims to assess the effect of seismic lines on evapotranspiration from the understory at different sites in northern Alberta. Actual evapotranspiration (AET) was measured using weighing lysimeters and chamber techniques, and potential evapotranspiration (PET) was calculated based on the Penman, and Priestley -Taylor equation. Understory AET on the seismic lines was 59% and 14% higher than in the adjacent ecosystem, based on lysimeter and chamber measurements, respectively. Furthermore, we also observed that the soil temperature, available photosynthetically active radiation (PAR), and plant community composition were the primary drivers of the AET measured using chambers, while wind speed and PAR controlled the AET measured by lysimeters. We estimated that ground layer PET on the line was 51% higher than off the line. These variations affected the Priestley-Taylor coefficient of evaporability (α) values so that the α value on the seismic line (0.73) was higher than off the line (0.61). Accounting for transpiration from trees, it was determined that the AET from seismic lines exceed the AET from adjacent areas by 31%. Considering the ubiquitous nature and high spatial density of seismic lines in the boreal region, these changes to a dominant water loss mechanism will have a considerable impact on hydrological fluxes and result in an altered water budget, with potential implications at the watershed scale.

Keywords: peatlands, oil sands exploration, evapotranspiration, lysimeter, chamber, soil temperature, plant community, coefficient of evaporability.

4.2. Introduction

Seismic lines are linear corridors created to transport the geological survey equipment needed to map subsurface petroleum deposits and can persist as narrow forest openings for decades (van Rensen et al., 2015). Forty six percent of all linear features across the Canadian boreal ecosystem are seismic lines (Pasher et al. 2013). A recent tally by ABMI (2021) revealed 823,831 documented kilometers of seismic lines, occurring at densities of up to 60 km/km² in Alberta, while Strack et al. (2019) estimate over 345,000 km of seismic lines crossing peatlands in the province. This linear disturbance removes the sparse tree canopy in peatlands, resulting in a loss of transpiration from the trees (Ohkubo et al., 2023) and a concurrent increase in available energy (Kettridge et al., 2012; Thompson et al., 2015), which likely influences the understory vegetation and soil evapotranspiration (ET) fluxes.

Evapotranspiration is the dominant hydrological flux in the western boreal regions in North America with a sub-humid climate (Scarlett et al., 2017; Van Huizen and Petrone, 2020), as it comprises a major water loss in both wet and dry years (Brown et al., 2010). It has been predicted that global warming will increase peatland ET more than forest ET, illustrating the importance of knowledge on the magnitude of, and controls on, peatland ET (Helbig et al., 2020). Peatland ET is driven by a variety of variables such as water availability as indicated by soil moisture (Brown et al., 2014, McCarter and Price, 2013) and groundwater table level (Sonnentag et al., 2010), intercepted precipitation (Ahrends and Penne, 2010), vapour pressure deficit (Admiral and Lafleur, 2007), net radiation (Van Huizen and Petrone, 2020), and understory/ground surface plant community (Ni-Meister and Gao, 2011), as well as the duration of the growing season (Brown et al., 2010). Seismic line disturbance results in higher soil moisture and greater soil temperatures on seismic lines than in the adjacent ecosystem (Dabros et al., 2017; Davidson et al., 2021; Weiland et al., 2023; Weiland et al., 2024), which affects the drivers of the ET. Removal of the canopy enhances the incoming light and radiative fluxes (Pohlman et al. 2007; William and Quinton, 2013), resulting in greater available energy for ET. Additionally, atmospheric conditions including air temperature and vapour pressure deficit control the evaporative water flux, and these components are also affected by seismic lines (Franklin et al., 2021; Haag and Bliss, 1974; Pohlman et al., 2007). Similarly, higher wind speeds are associated with enhanced ET rates (Carey, 2008), and higher wind speeds have been observed on seismic lines relative to wind speeds within the adjacent undisturbed area (Burton, 2002, Weiland et al., 2023, Bayatvarkeshi et al., 2024),

which also could contribute to enhanced ET rates on seismic lines. Therefore, the widespread presence of seismic lines influences ecosystem drivers of ET (Pickell et al., 2015) and thus likely alters potential and actual ET.

The effects of disturbance on peatland ET largely depend on the type of disturbance, time of operation, ecosite type, and weather conditions (Volik et al., 2020). The study of Kononovs et al. (2024) revealed that soil water content and temperature are not entirely consistent between seismic lines and undisturbed areas; instead, they vary according to a complex combination of factors and are highly site-specific. Morison et al. (2020) assessed ecosystem scale ET of burned and unburned peatlands and showed a significant reduction in ET rates in the burned site. Amiro et al. (2006) and Liu et al. (2006) found that removing vegetation will decrease transpiration and evaporation from interception; however, it accelerates the rate of evaporation from the soil surface leading to a net water loss for the ecosystem. Similarly, Kettridge et al. (2013) simulated the effects of tree canopy cover in forested peatlands on surface ET. Increases in tree canopy cover reduced ground layer ET by reducing energy availability and through changes in the moss community composition from *Sphagnum* to feathermoss dominance at higher tree densities (Kettridge et al., 2013). Many peatlands are exposed to linear disturbance for direct or indirect oil sands activities, particularly in northern Alberta (Strack et al., 2019). Despite the influence of seismic lines on the local hydrology (Weiland et al., 2024), no studies have conducted field measurements of the impact of seismic lines on peatland ET. A modelling study on hydrological processes in two ecosite types (lowland and upland) disturbed by seismic lines indicated a 33% reduction of ET compared to the adjacent natural area, driven largely by higher transpiration in the undisturbed areas (Kononovs et al., 2024). However, the high spatiotemporal variability of ET in this complex landscape is not adequately understood to provide insight into the impact of linear disturbance and land-use changes on local to regional water balance. The widely variable tree densities encountered among different ecosite types (e.g., lowlands compare to forested uplands) further complicate this relationship. Additionally, the presence of shallow water tables and the related near-saturated conditions on seismic lines crossing peatlands will persist, altering ecosystem functioning (Dabros et al., 2018). Based on the previous studies, the implications are visible and measurable. This fragmentation potentially facilitates peatlands to serve as significant water sources in the boreal landscape following seismic line operations (Wang et al., 2023).

Clearly, due to the alteration of the controlling variables caused by seismic lines, ET on seismic lines in peatlands is likely also altered; however, to our knowledge, no field measurements of ET on peatland seismic lines are available. Therefore, this study aims to evaluate the influence of seismic lines on peatland ground layer ET. The specific objectives of this study are: (a) to compare the ground layer AET on the seismic lines to that within the adjacent ecosystem using weighing lysimeter and closed chamber methods, (b) to estimate PET from the seismic line and adjacent forest area using energy and meteorological variables, and (c) to evaluate the impact of environmental and plant community factors on AET. The findings will broaden our knowledge of hydrological conditions affected by seismic lines, providing a better understanding of peatland response to these disturbances, and will help improve guidelines for forest restoration and peatland management.

4.3. Methods

4.3.1. Study sites

This study is based on lysimeter and chamber measurements of AET and monitored meteorological conditions in different seismic lines across northern Alberta (Figure 4-1). Lysimeter measurements were collected from various study sites in different years spanning the period of 2018 to 2023 (see Table 4-1 for a description of each study area and the specific measurement periods).

Table 4-1 The characteristics of the selected sites

Sites	Lines	Time of disturbance	Width (m)	Orientation	Peatland Class
Kirby South (KS) (2022*)	KS-1	1996	5	N-S	Wooded fen
	KS-2	1996	5	N-S	Wooded fen
	KS-3	1996	5	N-S	Wooded fen
	KS-4	1996	4	E-W	Wooded fen
	KS-5	2006	4	N-S	Wooded fen
Maqua (MS) (2023*)	MS	1998	8	E-W	Wooded fen
Peace River (2018*)	CC	2005	2-3	N-S	Wooded bog
	IP	1998	6-8	E-W	Wooded fen
	HV	1998	6-8	N-S	Wooded bog
Brazeau Dam (2019 and 2020*)	RF	1982	3	N-S	Shrubby fen
	PF	1982	5.5	E-W	Shrubby fen

KS and MS denote the Kirby and Maqua sites, respectively.

* Period of study

4.3.1.1. Fort McMurray: Kirby South and Maqua

Lysimeter measurements were undertaken May 30–August 13, 2022, on five seismic lines, and chamber measurements at one seismic line, at a peatland complex dominated by wooded fens located approximately 30 km south of the hamlet of Conklin, Alberta, Canada (55.372, -111.164; herein referred to as the ‘Kirby South’, or KS). Additionally, lysimeter and chamber measurements were made between May 30 to August 13, 2023, on a seismic line at a moderate-rich wooded fen peatland ~40 km south of Fort McMurray, Alberta (56.370, -111.289) referred to as the Maqua site (herein referred to as MS). Black spruce and tamarack are the dominant conifers at KS and MS. Thick mats of *Sphagnum* spp. (*Sphagnaceae*) and brown mosses (*Amblystegiaceae*) make up the ground cover, with sedges (*Carex* spp.) and shrubs often dominating the understory vegetation. Shrubs include willow (*Salix* spp.), dwarf birch (*Betula pumila*), Labrador tea (*Rhododendron groenlandicum*), green alder (*Alnus crispa*), and bog blueberry (*Vaccinium uliginosum*). Mean annual precipitation is 440 mm, average daily temperatures range from -15 °C to 17 °C, and the average growing season (frost-free period) is approximately 125 days (Natural Regions Committee 2006) with a humid continental climate classification based on Köppen.

4.3.1.2. Brazeau Dam

This study area is located in central Alberta, Canada approximately 11 km southwest of Brazeau Dam (52.889, -115.549) where chambers were used to measure ground layer AET in 2019. The region is classified as Boreal Plains Ecozone (Environment Canada, 2001) and Central Mixedwood Natural Subregion (AEP, 2006). Average temperatures range from -12 °C to 17 °C with an average of 97 frost free days per year (ECCC, 2021). The area receives an average 462 mm of precipitation per year, with most occurring during the growing season, May to August (ECCC, 2021). There is a gradient in water chemistry across the peatland the results in variation in bryophyte cover with true mosses more prevalent in the northern part of the Brazeau fen site and *Sphagnum* moss dominating the southern part. Throughout the site, sedges are common in the understory while the canopy is dominated by two tree species, Black Spruce (*Picea mariana*) and Tamarack (*Larix laricina*).

4.3.1.3. Peace River

Chambers were used to measure AET at three peatlands near the town of Peace River, Alberta in 2018. The first two study areas were approximately 40 km northeast of the town of Peace River, namely, Carmon Creek (CC), a wooded bog (56.362, -116.795), and Peace River complex (IP) a

wooded poor fen (56.397, 116.891). The last study site, Harmon Valley (HV) is a forested bog approximately 50 km southeast of Peace River, (56.201, 116.934). At both CC and HV bogs, the natural areas were dominated by black spruce (*Picea mariana*) and a ground layer of feathermoss (*Pleurozium schreberi*), rusty peat moss (*Sphagnum fuscum*), lingonberry (*Vaccinium vitis-idaea*), Labrador tea (*Rhododendron groenlandicum*), bog cranberry (*Vaccinium oxycoccus*) and lichens (e.g., *Cladina* spp.). At IP, vegetation at the natural fen was predominantly characterized by black spruce, willow (*Salix* spp.) and lichens while lines were mostly covered by water sedge (*Carex aquatilis*), patches of *Sphagnum* spp., brown mosses, and sparsely distributed willow saplings (Davidson et al., 2021). All seismic lines studied in near Peace River were devoid of trees taller than 1 m, irrespective of the age of the lines.

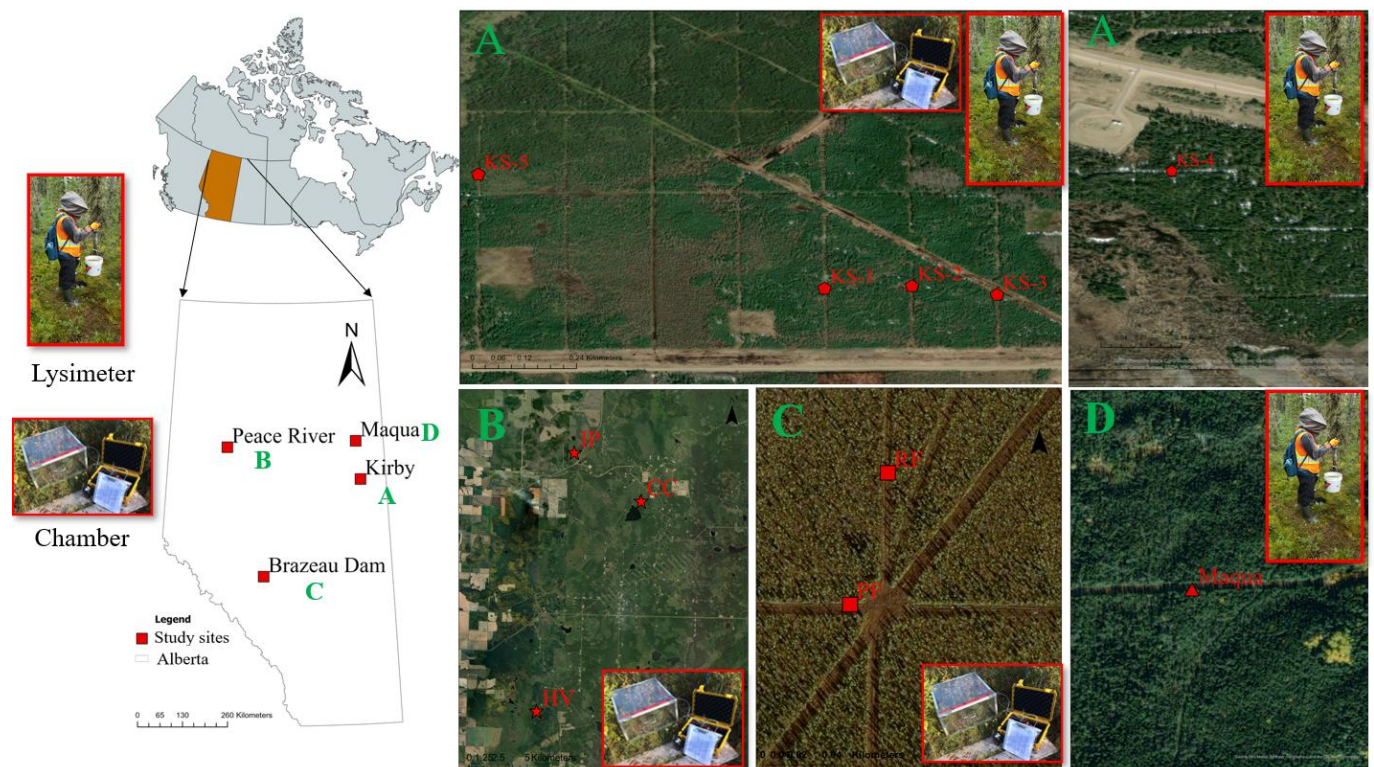


Figure 4-1 The location of the study sites to measure AET using chambers and lysimeters.

4.3.2. Experimental Design and Data Collection

4.3.2.1. Lysimeter-based AET Measurements

Lysimeters have been used extensively to measure the net movement of water across the soil-atmosphere boundary (Tanner and Thurtell, 1969; Seyfried et al., 2001; Scarlett et al., 2017). A

lysimeter is an enclosed volume of soil that is placed in the field and filled with representative soil and/or vegetation (Brutsaert, 1988). For this study, the lysimeter technique was used at KS and MS. For this purpose, weighing lysimeters were installed in each site to measure AET of the ground layer. Actual ET in the peatland was estimated using 40 (at KS) and 20 (at MS) plastic bucket lysimeters (area = 0.18 m²) filled with a 30 cm deep peat monolith with intact vegetation, similar to Van Seters and Price (2001) (Figure 4-2). The monolith was representative of the dominant surface (understory) vegetation, containing both *Sphagnum* and feathermoss ground cover with an ericaceous vegetation layer and shallow roots when present. The ericaceous vegetation layer included Labrador tea, green alder, and bog blueberry. The AET was typically measured daily (May 30–August 17, 2022, and July 10–August 13, 2023), except for rainy days, by weighing the lysimeters with a digital hanging scale (RMY-Salter-Brecknell-SA3N, 45 kg×0.009 kg). The daily change in mass was divided by the bucket area to estimate an AET flux over the period between measurements. Periods of time with rain between measurements were removed from the datasets.

To consider different conditions on the seismic line and adjacent area, four lysimeters were installed on the seismic line and three lysimeters on each side of the natural area (triplicates installed to increase the robustness of measurements given the greater extent of the microtopography in the natural area). Although the ground surface on the seismic line was largely flat on most lines, we considered two buckets for hummocks and two for hollows, then applied the average of these for the total AET from the seismic line. In the natural area, hummock ET was measured on one side of the seismic line, and hollow ET was measured on the other side of the seismic line, and then the average of hummock and hollow ET was considered as understory AET from the adjacent natural areas. In total, 24 lysimeters were installed on the seismic lines and 36 lysimeters were installed in the natural area. Soil temperatures were measured at the same time as the lysimeters at depths of 5, 10, and 15 cm next to the lysimeter location.



Figure 4-2 The weighing lysimeters to measure the actual evapotranspiration.

4.3.2.2. Chamber-based AET Measurements

The chamber technique is also an adaptable and small-scale method to measure instantaneous AET (Brown et al., 2014). This technique allows real time measurements in short time intervals, giving a more detailed estimation of the evaporation and evapotranspiration processes. This technique has been used to measure water loss in treetops (Poni et al., 1997), scrub (Centinari et al., 2009), herbaceous crops (Balogh et al., 2007; Burkart et al., 2007), forests in a semi-arid region (Yaseef et al., 2010), and peatlands (Phillips et al., 2016). With this method, the water vapor flow is measured for small areas between the soil surface and the atmosphere (Dugas et al., 1997). This is done through the placement of a known volume of chamber over an area of soil and vegetation, followed by measurement of the change in air temperature and relative humidity inside the portable chamber over a short time interval (e.g., a few minutes). The maximum rate of change in water vapor density with time is proportional to the evapotranspiration flow of the surface delimited by the portable chamber (Stannard, 1988). Distribution of chambers along hydrological and vegetation gradients allows for investigation of local controls on ET (Brown et al., 2010; Phillips et al., 2016).

At the KS, Brazeau Dam, and Peace River sites, pairs of 60 × 60 cm steel collars were installed at each sample plot in corresponding hummocks and hollows. A clear acrylic chamber measuring 60 × 60 × 30 cm was set into a groove along the top of the collar and this created a seal when filled with water. Air in the chamber was continuously circulated with a small battery-operated fan. Relative humidity, air temperature and photosynthetically active radiation (PAR) was measured in the chamber at 15 second intervals for 105–120 seconds (~ 2 minutes) using an infrared gas analyzer and associated sensors (EGM-4, PPSystems). A type-K thermocouple soil temperature probe was used to measure soil temperature at 2, 5, 10, 15, 20, 25, and 30 cm below the ground surface. The water table was measured in a shallow well installed adjacent to each plot. The ET rate was calculated using Equation 1 (McLeod et al., 2004; Brown et al., 2010):

$$ET = 3.6 \frac{MVC}{A} \quad (1)$$

where ET is the rate of ET (mm hr^{-1}), M is the slope of the linear change in vapor pressure over the sampling period ($\text{g/m}^3/\text{s}$), V is the corrected volume of the chamber (m^3) accounting for height of the ground surface relative to the collar, C is a correction factor (1.534) accounting for vapor absorption to the chamber (dimensionless), and A is the surface area (m^2) covered by the chamber (McLeod et al., 2004). The conversion factor 3.6 is used to convert the units of grams of water m^{-2} into units of an hourly rate (mm hr^{-1}). ET values were calculated by converting relative humidity values to vapor density values (as a function of chamber temperature) and determining the slope of the change in vapor density over the chamber closure period. The vapor pressure deficit was determined as the difference between the saturation vapor pressure (e_s) as a function of the instantaneous chamber temperature (T_c) and relative humidity recorded inside the chamber (RH), and the actual vapor pressure (e_a) (Nwaishi et al., 2020):

$$e_s = \frac{RH}{100} (6.11)(100.47)e^{\left(\frac{17.5 \times T_c}{241.2 + T_c}\right)} \quad (2)$$

$$e_a = \frac{RH}{e_s} \times 100 \quad (3)$$

All flux measurements were visually inspected and only those that showed a linear change in vapour density over time (i.e., no evidence of saturation) were retained. As such, any negative ET rates were discarded (~ 20% of data points).

4.3.3. Meteorological Conditions and Potential Evapotranspiration

Two meteorological stations were set up at MS and KS (at sub-sites named ‘Met line’), one in the middle of the seismic line and another at ~20 m from the center of the line into the adjacent

wooded fen. Each meteorological station consisted of a CR1000 data logger recording 30 minute averages of 60 second measurements of net radiation (NR LITE2, Campbell Scientific, USA), photosynthetically active radiation (PAR, Campbell Scientific, USA), air temperature and relative humidity (HMP155A, Campbell Scientific, USA), wind speed and direction (05103-10-L, Campbell Scientific, USA), rainfall (TE525M, Campbell Scientific, USA; 30 minute total values recorded), soil temperature (copper-constantan thermocouples), and volumetric water content of soil (TEROS 11/12, METER group). All instrumentation was installed at a height of 1.5 m above ground except the anemometer which was established at 2 m above the ground. The recorded 30-minute interval data were later converted to an hourly time scale on Python 3 (ipykernel) library in the environment of Jupyter. Due to a power issue on the data logger recording in the undisturbed area from July 14th to August 2nd at KS, there was a gap in the collected data during this period. The average tree height within the adjacent natural wooded fen peatlands was approximately 5 m, thus the meteorological variables measured at both the KS and MS sites represent conditions below the tree canopy. Since the seismic lines were cleared of trees, with only understory shrub vegetation regrowth present, there was no tree canopy present on the seismic lines. Therefore, differences between online and offline conditions represent changes to the understory and soil layer related to the loss of tree cover on the seismic line. Thus, the measurements reported in this study represent the conditions most likely to affect ground layer vegetation, establishing seedlings and soil organic matter cycling. The collected weather variables were utilized to estimate PET in these conditions. Among the mathematical approaches to estimate PET, the Penman equation and Priestley and Taylor equation (herein referred to as PT) are the most used and often integrated into soil-vegetation-atmosphere-transportation models (Van Huizen et al., 2014). The accuracy of these algorithms has been evaluated in the same region as the current study area by Van Huizen and Petrone (2020) and Van Huizen et al. (2024). Accordingly, in this study, PET was estimated with the Penman (Volik et al., 2020) (Eq. 4), and the PT equation (Leonard et al., 2022; Petrone et al., 2007) (Eq. 5) as follows:

$$PET_{\text{penman}} = \frac{\Delta(NR - Q_G) + \rho_a c_p C_{at}(e^* - e^a)}{\rho_w \lambda_v (\Delta + \gamma)} \quad (4)$$

$$PET_{\text{PT}} = \frac{\Delta(NR - Q_G)}{\rho_w \lambda_v (\Delta + \gamma)} \quad (5)$$

where PET is a daily value (mm day⁻¹), Δ is the slope of the saturation vapour pressure temperature curve (°C/kPa), ρ_a is the density of air (g/m³), c_p is the specific heat of air (MJ/kg K), C_{at} is the

aerodynamic conductance (m/day), ρ_w is the density of water (g/m³), γ is the psychrometric constant (kPa/°C), λ_v is the latent heat of vaporization (MJ/g), e^* and e^a are the daily average saturated and actual vapour pressures (kPa), respectively, NR is the sum of daily positive net radiation values (W/m²) and Q_G is ground heat flux (W/m²) (Table S1, Appendix B). This PET represents equilibrium potential evapotranspiration, which is a lower bound of the range in possible PET (Granger, 1989).

PET is related to AET via the coefficient of evaporability α . The term α is generally solved using (Wilson and Baldocchi, 2000):

$$\alpha = \frac{AET}{PET} \quad (6)$$

PET was calculated in Ref-Et software (Allen, 2011), which is designed to calculate standardized reference ET (Ahmadpari et al., 2019; DeJonge and Thorp, 2017). During these calculations Q_G was calculated based on the following equation:

$$Q_G = K \frac{dT}{dz} + c_w \Delta T \frac{dF}{dt} \quad (7)$$

Here, K is the thermal conductivity of the soil (W/(m °C)), dT/dz is the temperature gradient at the surface (°C/m), c_w is the volumetric heat capacity of water (MJ/(m³ °C)), ΔT is the difference in temperature between rainwater and the soil (°C) and dF/dt is the rate of rainwater infiltration (m/s). We assumed that there was no convection of heat from infiltrating rainwater, and 10% of net radiation used to represent Q_G . The required parameters and assumptions to estimate Q_G were obtained from the field measurements and the recommended values by Woo and Xia (1996).

To compare the transpiration from tree canopy with measured ground layer evapotranspiration, the reported contribution of transpiration to evapotranspiration was used based on previous investigations in similar forested peatlands (e.g., Kettridge et al., 2013; Warren et al., 2018; Gabrielli, 2016' these details are addressed in the results section).

4.3.4. Data Analyses

R software (R Core Team, 2024) was used to perform all statistical analyses. The analyzed variables were tested for normality prior to any parametric tests, and when necessary, appropriate transformations (e.g., log transformation) were implemented. Differences in ground layer AET in response to seismic line disturbance were evaluated with linear mixed effects models with location (on or off the seismic line) as the fixed effect and measurement spot (either lysimeter number or collar identity) as a random factor. To identify the environmental variables that had a dominant

influence on the observed evapotranspiration, a linear mixed effects model was applied, using the function “lme” in the package “nlme,” (Pinheiro et al., 2024) with fixed explanatory variables (i.e., soil temperature, groundwater depth, photosynthetically active radiation, wind speed) and collar/lysimeter name as the random intercept to account for repeated measures at each spot. Significant predictors in the model were assessed using the anova function in R and marginal p-values. Creating models was based on step-by-step method, so that in each step non-significant variables were withdrawn from the model to identify a model with only significant variables. Variables in the final best-fit models were accepted as significant at the $p < 0.05$ level.

4.4. Results

4.4.1. Environmental conditions

The average NR on the line was 65% higher than in the understory off the line at KS, and 203% higher at MS which was mostly associated with positive values on the seismic line and negative values off the line. This increased incident NR was accompanied by a small rise in air temperature at MS (14.6 °C off the line versus 15.0 °C on the line), but no clear change at KS (14.0 °C at both on and offline stations). There was an approximately 2 °C higher soil temperature at 15 cm depth on the line compared to both undisturbed sites (Table 4-2). More rainfall reached the ground surface on the seismic line (32% increase compared to natural at KS and 154% at MS) and was attributed to a lack of interception. Relative humidity on the line was slightly higher than off the line by 2%. The most visible change in weather variables was associated with wind speed which was 1.5 and 4.3 times higher on the line than off the line at KS and MS, respectively.

Table 4-2 Summary of the weather variables from May 30th to August 17th in 2022 at Kirby site (KS) and from July 10th to August 13th in 2023 at Maqua site (MS)

Site	Variable	Online				Offline			
		Avg	Min	Max	STD	Avg	Min	Max	STD
KS	Air temperature (°C)	14.0	6.0	25.0	3.6	14.0	6.2	21.1	3.4
	Vapor Pressure Deficit (kPa)	0.42	0.05	0.60	11.6	0.46	0.05	0.63	11.9
	Rainfall (mm)	157.9	--	--	0.2	120.4	--	--	0.3
	Wind speed (m s ⁻¹)	0.2	0	0.7	0.1	0.1	0.0	0.4	0.1
	Net radiation (W m ⁻²)*	138.5	-24.9	220.0	53.8	83.8	-277.1	235.9	79.4
	Soil temperature (°C)	11.4	5.1	17.9	2.8	9.4	2.1	14.9	3.5
MS	Air temperature (°C)	15.0	7.1	21.3	3.2	14.6	7.2	21.1	3.1
	Vapor Pressure Deficit (kPa)	0.5	0.03	0.6	14.1	0.5	0.02	0.6	15.7
	Rainfall (mm)	269.7	--	--	0.30	106.2	--	--	0.5
	Wind speed (ms ⁻¹)	0.4	0.1	0.9	0.2	0.1	0	0.2	0.0
	Net radiation (W m ⁻²)	133.7	-57.2	619.0	51.8	44.1	-65.9	653.8	23.8
	Soil temperature (°C)	12.5	6.6	15.0	1.9	9.7	4.9	12.9	2.1

*Only daytime NR was considered from 6 am to 6 pm

Measurements across the wider network of sites used in lysimeter and chamber measurements also indicated an increase in available radiation and higher soil temperatures (Ts) on the seismic lines (Table 4-3). Using this data, the average Ts at depths of 5, 10, and 15 cm on the line was 20% higher than off the line and photosynthetically active radiation (PAR) was 97% higher on the lines on average compared to the adjacent peatland understory. Moreover, groundwater depth (GWD) on the line was approximately 6 cm closer to the surface than offline, which increased the available water at the surface for evaporation. Plant community composition in lysimeters was dominated by non-vascular plants in both offline and online locations, while vascular plants had a higher percent cover on the line (12.2%) compared with that off the line (5.3%). Similarly, vegetation surveys from the chamber measurement locations indicated higher vascular plant cover on the line than off the line at 61.9 and 53.4%, respectively.

4.4.2. Actual evapotranspiration (AET)

Lysimeter measurements indicate that the AET measured on a seismic line varied from 1.68 to 2.11 mm day⁻¹ among study sites. The offline AET varied from 1.03 mm day⁻¹ to 1.32 mm day⁻¹. At KS, the average daily AET online was 66% greater than offline. Similarly, at MS, the average daily AET online was 1.68 mm day⁻¹ compared to offline with 1.1 mm day⁻¹. Statistical analysis

denotes that the impact of the site and seismic line on the AET were statistically significant ($F_{5,352}=5.75$; $p < 0.0001$) (Figure 4-3). The monthly variation of the lysimeter measurements indicated that the AET on the line was higher than off the line in June and August; however, the average AET on the line in July was lower than that off the line (Figure S1, Appendix B).

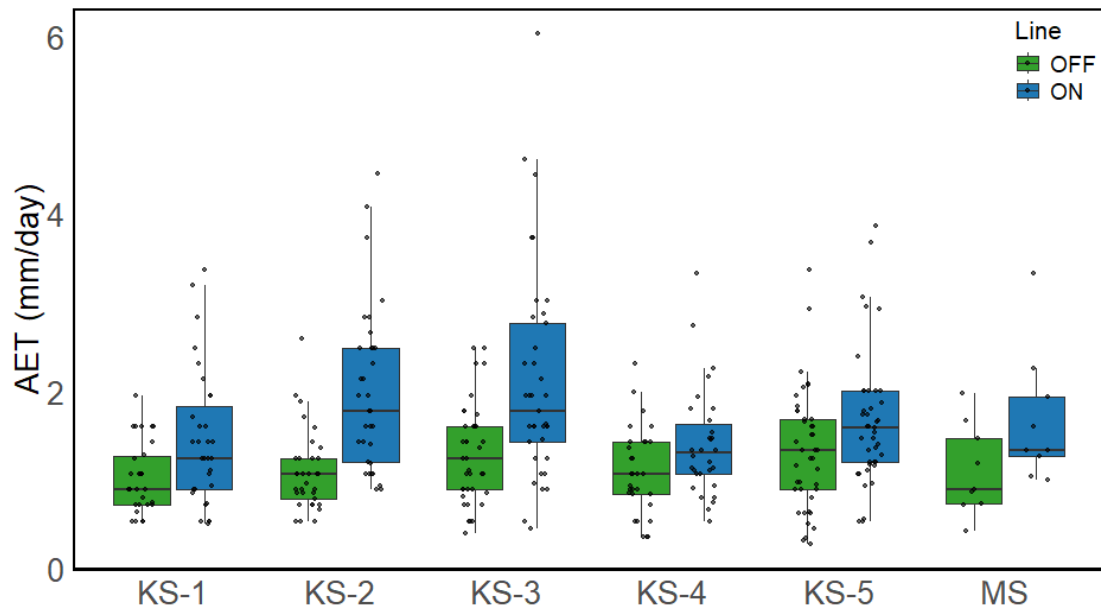


Figure 4-3 Spatial variability of actual evapotranspiration (AET) measured using lysimeters at different sites.

Actual ET estimated using the chamber method was consistently lower than lysimeter measurements (Table 4-3), reflecting the difference in temporal coverage and enclosed nature of the chamber-based measurements. Based on chamber measurements, the AET from seismic lines exceeded that off the line in all sites except the poor fen at Brazeau Dam. The greatest difference was observed at the IP line at Peace River with a 43% increase in AET on the line. The average AET on the line was 33% higher than off the line, 0.04 mm hr^{-1} compared with 0.03 mm hr^{-1} .

Table 4-3 The actual evapotranspiration (AET) and environmental variables^a of the seismic lines and off the lines measured by lysimeters (mm day⁻¹) and chambers (mmhr⁻¹).

Method (units)	Site	Line	AET (mm day ⁻¹ or mm hr ⁻¹)		Environmental variables								Plant cover (%)			
					Ts (°C)		GWD (cm)		PAR (umol m ⁻² .s)		WS (m s ⁻¹)		Vascular		Non-vascular	
			On	Off	On	Off	On	Off	On	Off	On	Off	On	Off	On	Off
Lysimeter (mm day ⁻¹)	Kirby	KS-1	1.8	1.0	12.1	9.5	--	--	--	--	--	--	6.7	1.3	76.7	94.0
		KS-2	2.0	1.1	13.9	11.1	--	--	--	--	--	--	13.3	0.8	60.0	93.8
		KS-3	2.1	1.3	13.1	10.3	--	--	--	--	--	--	19.3	4.0	59.0	93.8
		KS-4	1.7	1.1	9.8	10.0	--	--	--	--	--	--	2.0	4.2	84.8	94.8
		KS-5	1.7	1.3	11.3	7.8	8.7	16.1	457	311	0.23	0.11	13.8	6.2	73.8	93.8
	Maqua	MS	1.7	1.1	12.4	12.0	32.8	46.8	484	171	0.35	0.06	18.2	15.8	77.5	81.6
	Avg.		1.8	1.2	12.1	10.1	10.8	16.7	470	241	0.29	0.08	12.2	5.3	71.9	91.9
	Std. dev.		1.0	0.7	1.8	1.0	5.5	4.8	142	90	0.17	0.07	6.7	5.4	10.3	5.0
Chamber (mm hr ⁻¹)	Kirby	Met	0.02	0.02	12.8	14.1	8.0	32.1	941	683	--	--	111.8	81.2	55.3	92.2
	Peace	CC	0.05	0.03	12.5	13.1	10.0	18	701	492	--	--	21.2	16.4	85.5	92.8
	River	IP	0.04	0.03	10.0	10.4	0.8	5.7	695	434	--	--	49.6	19.6	56.7	75.7
		HV	0.05	0.04	10.9	9.8	16.7	13.1	691	566	--	--	21.8	24.1	92.5	88.1
	Brazeau	PF	0.03	0.04	16.2	15.0	10.0	15.6	1141	872	--	--	64.6	69.2	56.7	57.5
	Dam	RF	0.02	0.02	17.2	16.8	-0.8	-0.45	916	712	--	--	102.65	110	51.9	57
	Avg.		0.04	0.03	13.3	13.2	7.4	14.0	848	626	--	--	61.9	53.4	66.4	77.2
	Std. dev.		0.01	0.01	2.9	2.7	6.5	11.2	184	161	--	--	38.9	39.0	17.7	16.6

- a. Ts is the average of soil temperature at depths of 5, 10, and 15 cm, GWD is groundwater depth with negative values indicating inundation, PAR is photon flux density of photosynthetically active radiation, WS is windspeed measured at 2 m above the ground level.

The impact of abiotic and biotic variables on the AET measured using lysimeter and chamber methods demonstrated that variation in AET chamber measurements was significantly explained by PAR, Ts, and percentage of vascular plant community, with no significant interaction between these factors and position (e.g., on vs. off the line; Table 4-4). In both on and offline locations, chamber AET increased under higher PAR and soil temperature (Figure 4-4). The pattern with vascular plant cover was less clear with a small increase in AET under higher vascular plant cover off the line and the opposite patterns on the line. Based on lysimeter measurements, wind speed played a significant role in explaining AET variations with higher AET under greater WS. Apart from the WS, the impact of PAR on the AET was also significant showing the same increasing pattern observed for the chambers (Figure 4-5). In contrast to the chamber measurements, plant community did not explain a significant amount of the variation in AET from lysimeters. The strong relationship between the WS and the AET can be seen in both online and offline locations based on lysimeter measurements, where an increase in wind speed enhances evapotranspiration (Figure 4-4). This likely explains the lower estimated AET from chambers where the chamber separates the headspace from ambient wind conditions and circulation is controlled by a battery-operated fan.

Table 4-4 The summary of statistical analysis on the AET measured using lysimeter and chamber techniques and abiotic and biotic variables.

	numDF	denDF	F-value	P-value
ET- Chamber				
TS	1	428	5.08	0.02
PAR	1	428	32.07	<0.0001
Vascular	1	428	4.65	0.0001
Interception	1	428	11.61	0.0007
ET-Lysimeter				
PAR	1	75	6.27	0.014
WS	1	75	8.99	0.003
Interception	1	75	20.37	<.000

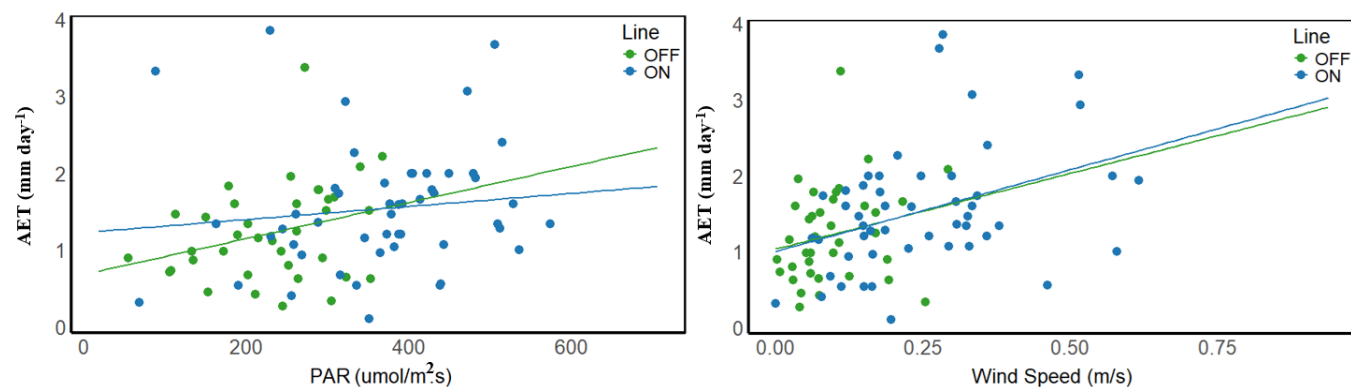


Figure 4-4 Actual evapotranspiration (AET) measured by lysimeters versus photosynthetically active radiation (PAR; left) and wind speed (right)

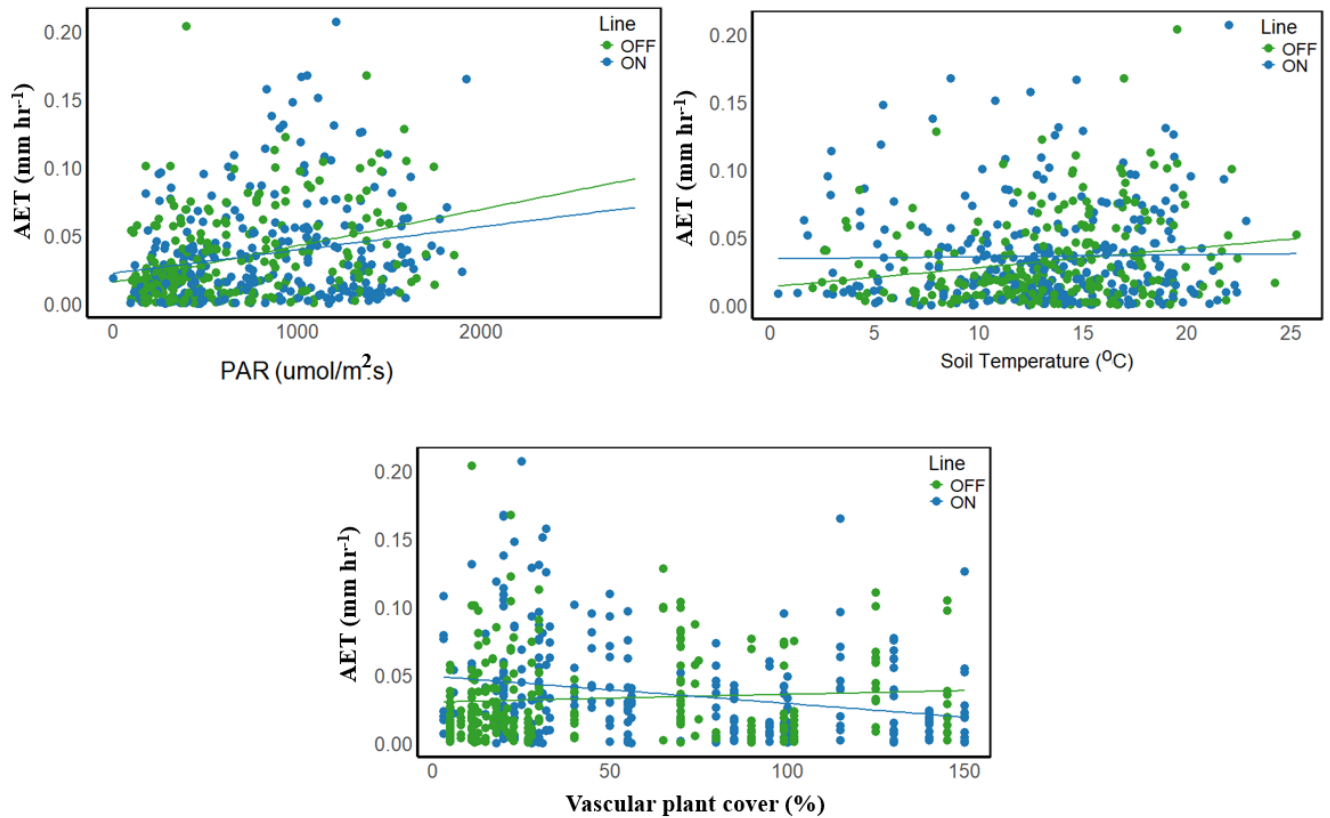


Figure 4-5 Actual evapotranspiration (AET) measured by chambers versus photosynthetically active radiation (PAR), average of soil temperature at depths of 5, 10, and 15 cm, and vascular plant cover.

4.4.3. Potential evapotranspiration (PET)

The calculated cumulative PET by the Penman and the PT methods were consistently higher on the line than offline at both KS and MS, representing different environmental conditions between online and offline (Figure 4-6). Despite the lack of data off the line at KS for 20 days due to power issues, the PET on the line was 58% higher than that off the line (2.23 mm day^{-1} versus 1.43 mm day^{-1}). At MS, this difference was 45%, with average PET on the line of 2.31 mm day^{-1} compared to 1.59 mm day^{-1} off the line. Comparison between the PET estimated by the PT and Penman method reveals that the PT estimates of PET are approximately 28% higher than Penman. This difference is more visible off the line than on the line.

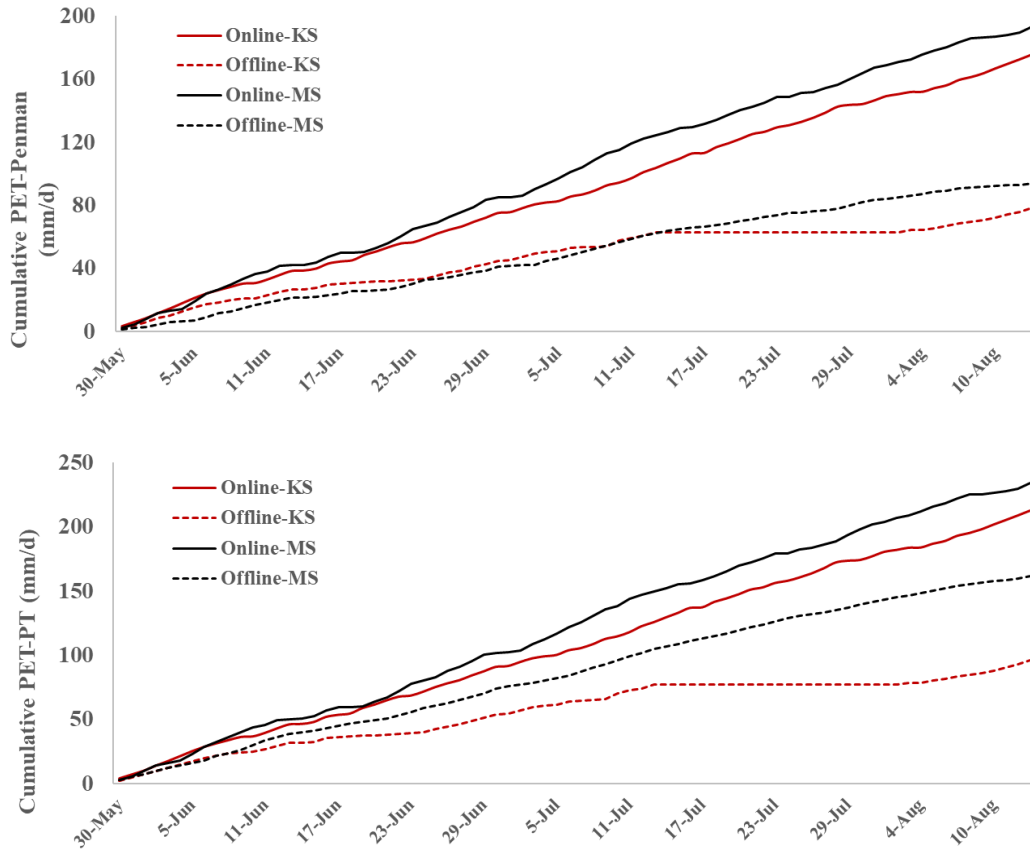


Figure 4-6 PET estimated by Penman and Priestley and Taylor (PT) from May 30th to August 13th, in 2022 at the KS and in 2023 at the MS.

4.4.4. The coefficient of evaporability (α)

Considering the average AET measured using lysimeters at KS in parallel with the PET calculated using Penman, the PET off the line was 14.8% higher than the AET off the line (2.07 mm day^{-1} compared with 1.8 mm day^{-1} ; Table 4-5). Therefore, the α coefficient on the line was slightly higher than off the line according to both the Penman and the PT methods, 0.92 compared to 0.91 using the Penman, and 0.76 compared to 0.74 using the PT method. At MS, although the PET was higher than the AET based on both the Penman and the PT methods, considering the Penman model, the α value on the line is similar to off the line (both are 0.80). However, based on the PT method, the α value on the line was higher than off the line (0.67 compared to 0.51). Although the difference is negligible based on the Penman model, the magnitude of the α coefficient on the line is generally higher than off the line. According to the PT method, the α value online is higher than offline, 0.73 compared with 0.61.

Table 4-5 The AET, PET, and α values based on the Penman and the PT method for each line.

Site	Line	Location	AET (mm day ⁻¹)	PET (mm day ⁻¹)		α	
				Penman	PT	Penman	PT
KS	avg.	Offline	1.16	1.28	1.57	0.91	0.74
		Online	1.87	2.04	2.47	0.92	0.76
MS	MS	Offline	0.99	1.23	1.95	0.80	0.51
		Online	1.68	2.11	2.5	0.80	0.67
Overall	--	Offline	1.08	1.24	1.76	0.87	0.61
	--	Online	1.8	2.07	2.48	0.87	0.73

4.4.5. Impact of the tree transpiration on ecosystem-scale AET

The AET in this study represents evapotranspiration from the understory; however, off the line areas are occupied by canopies dominated by black spruce. To examine the potential impact of black spruce transpiration on the total AET, different scenarios were considered based on previous studies. The contribution of black spruce transpiration to the AET at ecosystem scale has been reported in some studies (Table 4-6). To quantify how tree canopy affects the AET between on and off the line, the reported fraction from each investigation was considered as a scenario. The distinct fraction largely depends on the method used to measure transpiration, in addition to the location and characteristics of the study area (Table 4-6).

Table 4-6 The reported contribution of transpiration to AET in previous studies. The dominant canopy in all studies is black spruce with the ground is largely covered with moss (*Sphagnum* and/or *Feathermoss*)

Scenario	Source	T/ET	Study area	Method of measuring transpiration
A	Kettridge et al. (2013)	30%	Forested bog, Athabasca, Alberta	Simulation using The Boreal Ecohydrology Tree Algorithm model
B	Warren et al. (2018)	2%	Permafrost peat plateaus with interspersed permafrost-free bogs and fens, the Scotty Creek watershed, Northwest Territories	Eddy covariance
C	Gabrielli (2016)	44 %	Forested peatlands within the western boreal plain, Fort McMurray, Alberta	Sap flow
D	Helbig et al. (2016)	10%	A boreal forest-wetland landscape in the southern Taiga Plains	Sap flow and eddy covariance
E	Heijmans et al. (2004a)	25%	A black spruce forest in Fairbanks, central Alaska	Lysimeters and eddy covariance

The average of all AET measured using lysimeters was used to compare the transpiration of trees with the AET from seismic lines. It is clear that there is a considerable difference between the AET from the seismic line and transpiration from trees. Even under scenario C with the highest percentage of overstory transpiration (i.e., 40%), the AET from the seismic line is 11% higher than the transpiration from trees. Accordingly, despite the lack of trees on the seismic line, our results combined with this data compilation of overstory transpiration estimates indicate that the increase in evapotranspiration observed on the seismic line outweighs the transpiration of the black spruce canopy in the offline areas.

Table 4-7 The cumulative AET from the seismic line and the transpiration from the black spruce (T) under different scenarios from May 30th to August 13th

Scenario	T (mm)	AET understory offline (mm)	T + AET understory offline (mm)	AET-Online (mm)
A	24.7	82.2	106.9	131.3
B	1.6	82.2	83.8	131.3
C	36.2	82.2	118.4	131.3
D	8.2	82.2	90.4	131.3
E	20.5	82.2	102.7	131.3
Avg.	18.2	82.2	100.4	131.3

4.5. Discussion

Evapotranspiration, as the largest component of the water balance in peatlands in the Western Boreal Plain (Brown et al., 2010), is controlled by biotic and abiotic conditions. Clearing of trees and vegetation results in wind speeds that are 1.5 and 4.3 times higher on the seismic line than off the line at KS and MS, respectively (Table 4-2). High wind speed influences advection and subsequently drives higher evapotranspiration rates (Carey, 2008). Based on our statistical results, wind speed is the main driver of the AET measured using lysimeters. Apart from the wind speed, the removal of the canopy on the seismic line increases available energy for ground layer evapotranspiration (van Huizen and Petrone, 2020), with NR measured on the seismic line 72.2 Wm⁻² higher than in the understory off the line. Net radiation is the primary driver of the energy balance that regulates evapotranspiration rates, surface moisture content, soil temperature, and plant growth (Revel et al., 1984). Oogathoo et al. (2020) reported that solar radiation plays a key

role in the evapotranspiration of forest areas. High levels of available PAR on the line were also observed in parallel with greater net radiation, providing more incoming radiation for plants. The higher PAR on seismic lines compared to the adjacent area has also been reported by Stern et al. (2018) who measured a twofold increase and Franklin et al. (2021) with 3.8 times increase on the line. In the current study, the average of PAR measured on the line was $470 \mu\text{mol}/\text{m}^2 \text{ s}$ compared with $241 \mu\text{mol}/\text{m}^2 \text{ s}$ for off the line. Variation among studies and study locations within the present study are mostly related to differences in the width or orientation of seismic lines and canopy height and cover in the adjacent peatland (Hegels, 2023). Both lysimeter and chamber measurements indicated that greater PAR was associated with higher AET. Another component of the energy balance is soil temperature which explained a significant amount of the variation in AET measured using chambers (Table 4-3). Soil temperature on the line was approximately 2°C higher than off the line (Table 4-3). Accordingly, greater available energy at the ground layer on seismic lines is one factor that resulted in the higher measured AET (Table 4-5).

In addition to available energy, water availability can also affect AET rates in peatlands (Van Huizen and Petrone, 2020). Groundwater depth on the seismic line was 6–7 cm closer to the surface compared to off the line (Table 4-3). Simplification of microtopography or flattening of the ground surface by seismic line operation leads to a decreased surface elevation (Stevenson et al., 2019), which might be one of the reasons for low GWD on the seismic lines. For example, the partial removal and compression of the top peat layer during seismic line operation results in lowering elevation on the line which has been reported in several studies (Weiland et al., 2023; Pinzon et al., 2022). Weiland et al. (2023) indicated that the depth of groundwater on a seismic line within a peatland was on average 6 cm below ground surface (bgs), while it was 40 cm bgs in the adjacent natural peatland. Shallow groundwater depth helps maintain water supply at the evaporating soil surface and ensures water availability for vegetation, resulting in high evapotranspiration (Fraser et al., 2001). In addition, higher bulk density on the seismic line in surface soils has also been reported on seismic lines (Weiland et al., 2023; Kleinke et al., 2022; Davies et al., 2025), causing pore spaces to be smaller and less connected and can contribute to the higher soil moisture on seismic lines than in undisturbed areas. Therefore, from the aspect of available water, seismic line disturbances have higher water availability for evapotranspiration. Furthermore, tree shading counteracts light availability resulting in the higher surface resistance of moss against water loss

(Kettridge et al., 2013). Consequently, the required energy and water for evapotranspiration are greater on the seismic line, driving the higher AET measured on the line.

Although we observed higher AET on seismic lines than the adjacent understory across a range of wooded peatland using both lysimeter and chamber-based measurements, the AET measured using chambers was lower than the lysimeters, likely due to lack of wind under the controlled conditions. This may have also contributed to the observation that chamber measured AET from the seismic line was only 14% higher than off the line while lysimeters on lines had 68% higher AET than undisturbed understory. Since the peatland study sites in the present investigation have moss-dominated surfaces, the measured values are consistent with the previously reported magnitudes. For example, Gabrielli (2016) measured ET in a poor fen with an open canopy and dominant *Sphagnum* mosses near Fort McMurray, reporting an average AET of 0.8 mm day^{-1} . In another investigation, moss evaporation rates averaged 0.3, 0.9, and 1.5 mm day^{-1} in the dense forest dominated by *Hylocomium*, open forest by *Hylocomium* and *Sphagnum*, and bog by *Sphagnum*, respectively (Heijmans et al., 2004). Chamber measurements have been criticized on the basis that net radiation and microclimate within the chamber may not be representative of ambient conditions (McLeod et al., 2004), but they do provide an opportunity to investigate how variation in other environmental variables, such as water availability and plant community, contribute to variation in AET under similar atmospheric conditions. Our chamber measurements revealed that plant community composition affected the AET significantly at 99% confidence interval. Based on the observations, a higher percentage of vascular plants was associated with greater AET (Tables 4-3, 4-4). Previous studies have reported greater vascular plant cover on seismic lines compared to undisturbed peatlands, often with greater sedge cover on disturbed areas (Echiverri et al., 2020; Goud et al., 2024). According to both lysimeter and chamber measurements, the percentage of vascular plants on the seismic line in our study was 7-8% higher than that off the line and this shift in plant community composition also contributed to the higher AET measured on the line (Table 4-3; Figure 4-5).

Different abiotic conditions on the seismic line influenced PET in parallel with AET, enhancing PET on the line compared to off the line. The PET calculated using the Penman and the PT methods shows that the PET on the line was 51% higher than off the line. Moreover, the PT method estimates at 28% higher PET than the Penman model. These variations affected the calculated α values so that the α value on the seismic line was higher than off the line (0.65 compared with

0.59). Due to the wet conditions on the seismic line (i.e., shallow GWD; Table 4-3), it can be concluded that more available water likely contributed to the higher α values on the seismic lines, which is consistent with the study of Petrone et al. (2007). Petrone et al. (2007) also reported Priestley–Taylor coefficients of 0.69 for a riparian peatland (with characteristics ranging from bog to intermediate or poor fens) located in the western boreal plain of north-central Alberta, which aligns with our estimates. AET from *Sphagnum* was 60-80% of Penman PET and 80% of potential Priestly–Taylor evaporation in the study of Kellner (2001) on an open Swedish boreal bog. In that study, AET was estimated based on the Bowen ratio method while we measured the AET directly in the field by lysimeters. It was also notable that the average AET in this study is slightly lower than in some investigations. This difference is largely attributed to weather conditions in the study period. For example, in the study of Nicholls et al. (2016), the average AET is around 2 mm day⁻¹ with an average air temperature over 30 °C while in the present study, average air temperature was less than 25 °C over the study period.

Combined, our various PET and AET estimates indicate that water loss to evapotranspiration on the seismic line was greater than in the understory of the adjacent undisturbed peatland. Although the seismic line lacks a tree canopy, the enhanced AET water flux from the surface and understory vegetation exceeds the loss of transpiration through the (absent) tree canopy based on a literature compilation of black spruce transpiration in similar systems (Figure 4-6; Table 4-7). Even considering the highest percentage of transpiration (i.e., 40% of ecosystem AET in Table 4-7) in the natural area, the AET from the seismic line is 75% higher than the expected transpiration from the tree canopy. Therefore, it can be concluded that surface evaporation and understory transpiration comprise the primary elements of AET in forested peatlands. Waddington et al. (2009) mentioned that vascular plants can contribute up to 80% of ET in peatlands. Numerous forested peatlands feature sparse canopies characterized by low stem densities, typically influenced by constraints like nutrient availability and the hydrological conditions. Consequently, when the tree canopy is removed, as is the case on seismic lines, more available energy permeates the sub-canopy, understory layers (Baldocchi et al., 2000), leading to the understory vegetation and moss surface playing a predominant role in ecosystem energy exchange and evapotranspiration (Allen, 1990; Baldocchi et al., 2000; Villegas et al., 2010; Villegas et al., 2014; Vogel & Baldocchi, 1996; Yunusa et al., 1997). Canopy elements not only alter the immediate environment beneath them but also impact the surroundings in nearby areas, playing a crucial role

in open canopies characterized by distinct spatial variations in canopy composition. It is worth noting that shading also diminishes energy inputs both directly beneath the canopy and within openings in the canopy (Villegas et al., 2014).

A recent study (Kononovs et al., 2024) applied a hydrological modelling approach that predicted up to a 33% reduction in simulated evapotranspiration rates on seismic lines as compared to the adjacent area in a lowland and an upland site. Our results demonstrate the opposite finding, with up to 66% higher understory AET rates measured on the seismic lines relative to the adjacent ecosystem (Figure 4-3), as driven by higher PAR, soil temperatures and wind speeds measured on the seismic lines (Table 4-3). The AET rates we measured within the understory on and off the seismic lines was still higher on the seismic line than in the adjacent area when the literature-based estimated contribution of transpiration from the tree canopy of the adjacent ecosystem was included (Figure 4-3, Tables 4-3, 4-7). These differences highlight the complexity of ecosystem alterations caused by seismic lines. Differences between the studies likely arise due to the different approaches applied. In Kononovs et al. (2024), despite measured differences in weather variables on and off the seismic line, their model input data for the simulations of the evapotranspiration fluxes for both the seismic line and the adjacent undisturbed area was based on the weather data collected only on the seismic line, with the lower simulated ET rates on seismic lines attributed to the decreased vegetation abundance on seismic lines due to the loss of the canopy in their model simulations (Kononovs et al., 2024). However, our direct measurements of understory AET highlight that the typically higher wind speeds on seismic lines (e.g., Weiland et al., 2023, Bayatvarkeshi et al., 2024), greater incoming radiation and a shift in ground layer plant community composition all contribute to higher AET on seismic lines than the adjacent area (Figure 4-4). Since canopy transpiration accounts for 2 to 44% of the total AET flux from peatlands in northern Alberta (Table 4-7), the differences between the higher AET rates reported here on seismic lines in peatlands is primarily driven by the enhanced AET flux from the ground surface and understory-level vegetation present on the seismic lines and not the loss of canopy transpiration as modelled by Kononovs et al. (2024).

Overall, creating fragmentation in peatlands from seismic lines affects ecosystem functions from the aspect of water fluxes. However, these changes depend on the structure of the seismic lines. Variation of AET among different sites indicates that changes in AET in response to peatland canopy removal is likely associated with the width, age, orientation, and tree canopy of the natural

area. Together these components contribute to the complexity of estimating the exact change in evapotranspiration in response to seismic line disturbance. Nonetheless, our results demonstrate that across a range of study peatlands, AET from seismic lines is higher than from the adjacent ecosystem in a forested peatland, even considering potential scenarios of tree transpiration. Nevertheless, more research on evapotranspiration including direct measurement of transpiration also from the tree canopy under distinct seismic line configurations is needed.

4.6. Conclusion

This study was designed to understand and quantify the impact of seismic lines on evapotranspiration from wooded peatlands in boreal Alberta. Examining actual and potential evapotranspiration illustrated that the removal of the canopy associated with seismic line disturbance affects both biotic and abiotic conditions in the ground layer. On seismic lines, the removal of the tree canopy enhances wind velocity, increases incident net radiation and precipitation received in the understory, which subsequently increases both potential and actual evapotranspiration. From the aspect of drivers of evapotranspiration, greater energy and water availability alongside an increase in vascular plant cover contribute to the higher measured ground layer evapotranspiration. Soil compaction, commonly associated with seismic lines in peatlands, contributes to the higher ET rates and higher α coefficient observed on the seismic lines via higher soil moisture and shallower water table position and thus, greater water availability on the seismic lines. Additionally, the lack of tree canopy on the seismic lines is accompanied by a reduction in transpiration from the line; however, the findings indicated that evaporation from the surface moss and transpiration from the understory vegetation layers is substantially higher than transpiration from trees. It is worth mentioning that black spruce was the dominant plant community in the forested area in the present study. Therefore, the results might vary in different plant communities and distinct seismic line structures in other locations. Accordingly, more investigation on actual evapotranspiration to take into account tree canopy transpiration is required in future research.

Chapter 5.

Assessing the effects of seismic line disturbance on boreal peatland water balance using CoupModel

5.1. Abstract

The slow recovery of trees in peatlands disturbed by seismic lines, linear clearings that arise from geologic exploration, has spurred scholarly investigation into the underlying factors. The effect of tree canopy removal and soil disturbance on local water balance along seismic lines is one of the unanswered questions in past studies. Hence, this study aimed to quantify the impact of seismic lines on water balance components using a process-based model, CoupModel. Simulated values were compared with field measurements from a seismic line located near Fort McMurray, Alberta, Canada. The simulations indicated higher soil moisture and temperature on the seismic line compared to undisturbed conditions, which aligned with the field measurements. Furthermore, the predicted shallower groundwater depth on the line was consistent with the field observations. The simulated actual evapotranspiration (AET) on the line was 6% higher than off the line, which is less of an increase than previously documented. It was also found that understory evaporation dominated the AET from the seismic line and the adjacent natural area, and thus loss of overstory transpiration due to online canopy removal was more than balanced by higher ground layer evaporation. However, greater available water from higher effective precipitation and lateral flow outweighed the high AET on the seismic line, resulting in the seismic line having higher water storage than off the line by 5 mm. Using a sensitivity analysis, we observed that a small change in soil compaction (i.e., a 20% increase) caused a substantial increase in drainage, runoff, soil moisture, and water storage. Furthermore, environmental condition (e.g., soil temperature) changed proportionally in response to seismic line creation in dense-canopy peatlands, particularly with an increase in transpiration and a decrease in soil temperature. This initial model-based exploration of water balance changes in response to seismic line disturbance illustrates local response; future research should explore the impact of seismic lines on the catchment scale to better understand the cumulative impact of these disturbances on water balance in boreal ecosystems.

Keywords: CoupModel, Water storage, Actual evapotranspiration, Soil compaction.

5.2. Introduction

Peatlands account for 30–60% of the land cover in boreal regions and play a pivotal role in regional hydrology (Tam et al., 2019; Wang et al., 2021). Expanding resource extraction, coupled with a warming climate, impacts peatland function, including water balance. In Alberta's boreal forest, oil sands development has resulted in a network of disturbances, with the most widespread type being linear clearings, called seismic lines, that are used for geologic exploration. Seismic lines in Alberta are the dominant line type (e.g., roads), representing 58% of all linear footprints (Dabros et al., 2018; Shellian et al., 2024), with at least 345,000 km of these lines crossing peatlands (Strack et al., 2019). Despite their prevalence, the effect of seismic line disturbance on peatland hydrology remains unclear. This study applies a process-based modelling approach calibrated with field measurements to investigate potential changes in peatland water balance in response to seismic line disturbance.

Considering precipitation as a key water input of peatlands, seismic line impacted areas are expected to have more precipitation reaching the ground surface than adjacent natural areas because of the absence of trees and reduced interception in the impacted area (Kononovs et al., 2024). Snowfall interception is also reduced, which has been shown to enhance snow accumulation (Weiland et al., 2024), resulting in longer lasting snow cover on linear disturbances that function as a snow catchment basin (Haag and Bliss, 1974). The recent study of Bayatvarkeshi et al. (2025b) also revealed that seismic lines have higher snow accumulation and prolonged duration of snow on the ground compared to adjacent undisturbed forests, although local variations were related to ecosite type and width and orientation of the seismic line. These changing snowpack conditions have the potential to alter patterns of soil water storage and runoff during spring snowmelt.

Regarding water loss by evapotranspiration (ET) from seismic lines, incoming radiation to the understory on the lines is higher than in the natural area (Pohlman et al., 2007; William and Quinton, 2013), resulting in greater available energy for ET. High wind speed on the line (Bayatvarkeshi et al., 2024) also triggers higher latent heat flux (Burton, 2002; Weiland et al., 2023). Although the removal of trees on the lines may reduce ecosystem transpiration through loss of overstory cover (Kononovs et al., 2024), high evaporation from moss can outweigh transpiration from trees, leading to higher ET from seismic lines (Bayatvarkeshi et al., 2025a). However, this process depends on plant community composition. For instance, black spruce with narrow structure and needle leaves transfers more radiation to the ground and might have less transpiration

than other species (Angstmann et al., 2012; Mao et al., 2017). Accordingly, predicting ET from peatlands disturbed by seismic lines will likely be site-specific and dependent on canopy composition and leaf area.

The local water balance on a seismic line crossing a peatland may also be altered by changes in groundwater and surface water inflows and outflows. Soil compaction associated with seismic line disturbance affects soil moisture (Davidson et al., 2021), and microtopography reduction results in lower relative elevation (Weiland et al., 2023), which might orient water flow along the line (e.g., Williams et al., 2013). From the aspect of groundwater depth (GWD), Weiland et al. (2023) indicated that the GWD on the seismic lines is closer to the surface, which can provide a saturated layer that influences surface water flow. Accordingly, seismic line disturbances are expected to affect all hydrological components, but the magnitude and combined effects of these shifts on local water balance remain unclear. While field-based measurements of the response of peatlands to seismic line disturbance are needed, the widely distributed nature of the disturbance, potential for site-specific responses (e.g., Weiland et al., 2024), and the high cost and logistical challenges of fieldwork in the region require alternative approaches. Thus, modelling might be a suitable alternative method for investigating the effects of seismic lines on peatland water.

Modelling can be a valuable tool to support understanding of the complex and intricate processes that support ecosystems resulting from the interactions between the biotic responses to disturbances and their interplay with multiple abiotic factors over many different spatial and temporal scales (Sturtevant and Fortin, 2021). Several studies have modeled hydrological processes in peatlands (e.g., Dimitrov et al., 2022; Mozafari et al., 2023). Lapen et al. (2005) used a two-dimensional steady-state finite-element groundwater flow model to simulate groundwater flow in two peat complexes. Sutton and Price (2020) modeled the partitioning of soil moisture between evaporation and groundwater recharge in a reclaimed upland by HYDRUS-1D. Kelbe et al. (2016) applied MODFLOW to simulate groundwater function in wetlands. The SIMGRO model was examined by Querner et al. (2010) to simulate hydrological processes in three peatlands under different hydrological situations. The Peatland Hydrologic Impact Model (PHIM) was used to estimate the effects of peat mining and upland forest harvesting on streamflow by Brooks and Kreft (1989). The WBalMo model was evaluated to determine the impact of climate change on the water balance of fen wetlands (Dietrich et al., 2008). From the aspects of scale, small-scale models have been noted for their ability to capture fine local variations and heterogeneities, as well as

being more sensitive to disturbances. In contrast, large-scale models offer a broader perspective, providing a more comprehensive view and describing average properties (Mozafari et al., 2023; Lawrence et al., 2019). Although there are a variety of hydrological models in peatlands, the bottom line is to create a model that can differentiate hydrological conditions in disturbed peatlands from natural areas (Whitfield et al., 2009). CoupModel (Jansson, 2012; He et al., 2021) is a one-dimensional process-based model that simulates the energy and water balance components in peatlands (He et al., 2016). This model has successfully simulated the energy and water balance of managed European treeless peatlands (Metzger et al., 2015), a continental bog in Canada (He et al., 2023), and incoming radiation on a seismic line (Williams and Quinton, 2013). Therefore, to understand the effects of seismic line disturbance on peatland hydrology, our study aims meet three objectives: 1) Assess the suitability of CoupModel-1D to predict hydrological effects of seismic lines in peatlands by comparing model outputs to field measurements; 2) Evaluate the effect of seismic line disturbance on peatland water balance components; and 3) Determine how the effect of seismic line disturbance on peatland water balance varies due to variations in peatland (e.g., canopy cover) and seismic line characteristics (e.g., extent of soil compaction). The findings will help us understand how seismic line disturbances vary across the landscape, particularly on the local scale. Therefore, understanding the water balance components affected by seismic lines on the local scale will provide insight into the hydrological responses of a peatland to seismic line disturbances on the catchment.

5.3. Materials and Methods

5.3.1. Modelling water balance

To achieve the objectives highlighted above, CoupModel v6.1.5.0 (Jansson, 2012; He et al., 2021) was used for simulations in this study. This coupled one-dimensional mass and energy model includes detailed soil physics, hydrology, photosynthesis, and ecosystem respiration that can simulate peatland hydrology dynamics and carbon cycling (He et al., 2016). A detailed description of the model can be found in Jansson and Karlberg (2010). The main structure is a one-dimensional, vertical model, with one or two layers of vegetation on a multi-layered soil profile (Figure 5-1). The CoupModel allows the user to select between different sub-models, equations, and complexities of the equations applied for the soil, plant, and atmosphere nexus. Since the creation of seismic lines results in changes in energy balance, plant community, physical properties of soil, and subsequently water flow, two separate models were created for the study: one for

seismic line (herein referred to as online) and another for the adjacent natural area (herein referred to as offline). Because of the differences between the online and offline's abiotic components, initial variables for soil and plant modules were used to create their models (See Table S1, Appendix C). The main differences between the online and offline models were soil properties and plant community height and composition (Davies et al., 2025; Davidson et al., 2021; Bayatvarkeshi et al., 2024). Soil properties are associated with the soil module, and the plant community is related to the plant module. The parameters of the soil module differ between the two models (i.e., online and offline models). The difference is associated with the physical properties of the subsurface associated with the soil module, such as bulk density and hydraulic conductivity, which drive other hydrological parameters. We specified a soil profile containing two layers, 0-40, and 40-100 cm depth from the surface. For parameterizing the peatland's soil water retention, we used the van Genuchten ($m, n, \alpha, \theta_s, \theta_{wilt}, \theta_r$) soil retention curve option of CoupModel. Due to the lack of field measurements in deep layers, we assumed that the physical properties of soil online and offline are similar at the depth of 40–100 cm, aligning with observations reported by Kleinke et al. (2022) and Weiland et al. (2024), while the values of parameters were different from surface to 40 cm between the two models mostly due to soil compaction and subsequently higher soil density online compared to offline (Table S2, Appendix C). Regarding the plant module, since the ground is generally covered by moss online and offline (Echeverri et al. 2023, Goud et al. 2024), one layer of moss was considered in both models; however, offline contained trees as well. Therefore, the offline model had two plants (i.e., moss and trees), and the online model included one plant (i.e., moss). For each plant, the canopy properties, such as depth of rooting zone, leaf area index (LAI), and height, were considered in both models. Initial values were based on field measurements and literature reviews (Table S2, Appendix C).

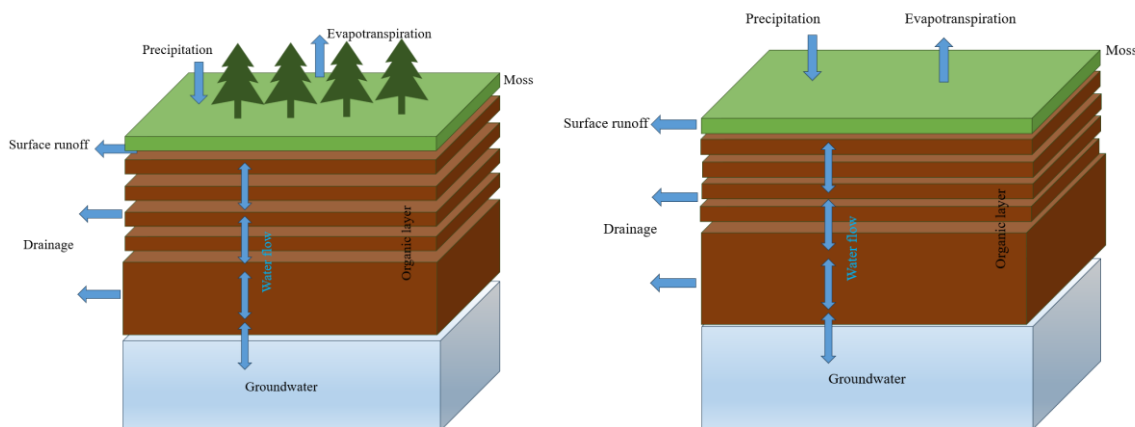


Figure 5-1 The conceptual models of CoupModel created for online (right) and offline (left)

Meteorological data are the driving variables of the model. The required data includes precipitation, air temperature, humidity, wind speed, and global radiation. Due to the lack of global radiation measurements in the field, this variable was downloaded from the NASA power provider (<https://power.larc.nasa.gov/>). We also used winter precipitation from a nearby station (the Fort McMurray CS station, 40 km from the study site) to consider snow data in modelling. Other required variables were collected from a meteorological tower deployed at a boreal peatland field site with a seismic line disturbance (Table 5-1, with more details on the study site in Section 2.2). It is worth noting that the same driving variables were considered for both models, and based on conditions measured on the seismic line, as the lack of canopy created conditions similar to open or above-canopy conditions for incoming energy and water.

To calibrate and evaluate the performance of the models, we compared simulated values of soil temperature and volumetric moisture content at 15 cm, to field observations. In particular, statistical indices of root mean square error (RMSE), indicating the average magnitude of the differences between simulated and observed values, and correlation coefficient (r) illustrating the strength and direction of the linear relationship between two variables, were used to assess the performance of the model relative to observed data. Calibration was completed for the time period of September 2022 to November 2023 to optimizing model results to low RMSE and high r values (Table S2, Appendix C). Validation was then completed for the time period of November 2023 to May 2024. The suitability of the developed models to characterize shifts in hydrological conditions was further evaluated by comparing differences in the online and offline predictions for AET and groundwater depth (GWD).

5.3.2. Study sites and calibration/validation datasets

In order to calibrate and validate the model, we measured a suite of meteorological and hydrological variables on a seismic line (online) and adjacent peatland at a wooded fen in the boreal region of Northern Alberta, approximately 40 km south of Fort McMurray, Canada (56.370638 N, -111.2897 W; Figure 5-2) from September 27, 2022, to May 8, 2024. The site, known as the Maqua site (MS), included an 8 m wide seismic line oriented in an east-west direction. At this site, the overstory is mainly black spruce (*Picea mariana*) with an Ericaceous shrub layer dominated by *Ledum groenlandicum* (Labrador tea) and common nonvascular species, including red-stemmed feather moss and *Sphagnum* species. We conducted a tree survey on July 22–24, 2023, considering two plots on the seismic lines and two plots on each side of the undisturbed area, at least 10 m from the edge of the seismic line, where each plot was 100 m². According to this survey, the density of trees on the seismic line was 5550 stems/ha, with mostly short trees in the ground layer (<1.4 m). In contrast, the undisturbed peatland has a tree density of 11,650 and 13,600 stems/ha on the north and south sides of the seismic line, respectively, with a mean height of 5 m (full vegetation details can be seen in Bayatvarkeshi et al., 2024). The mean annual daily temperature is 0.7 ± 1.2 °C, with the maximum typically occurring in July when daily temperatures average 16.8 ± 1.1 °C (Environment Canada, 2020).

Two meteorological stations were set up at MS, one in the middle of the seismic line and another 20 m from the center of the line in the adjacent forested fen (Figure 5-2). Each meteorological station recorded net radiation (NR LITE2, Campbell Scientific, USA), air temperature and relative humidity (HMP155A, Campbell Scientific, USA), wind speed and direction (RM Young, Campbell Scientific, USA), rainfall (TE525M, Campbell Scientific, USA), soil temperature at depths of 5, 10, and 15 cm (copper-constantan thermocouples), and volumetric water content of soil at the same depth as the soil temperature measurements (TEROS 11/12, METER group). CR1000 data loggers (Campbell Scientific) measured the variables every 60 seconds and recorded average values every 30 minutes (except rainfall, which was recorded as 30-minute totals) at a height of 1.5 m above ground, except the anemometer, which was established at a height of 2 m above ground. The recorded 30-minute interval data were later converted to an hourly time scale (by averaging, except for precipitation by summing), on Python 3 (ipykernel) library in the environment of Jupyter. As the adjacent natural ecosystem has an average tree height of 5 m, the meteorological station at both sites measured conditions below the tree canopy,

representing conditions most likely to affect ground layer vegetation, establishing seedlings, and the soil layer. As mentioned in Section 2.1, we used precipitation, air temperature, humidity and windspeed from the online station to drive both online and offline models for calibration (September 27, 2022, to November 7, 2023), and validation (November 8, 2023, to May 8, 2024; Table 5-1).

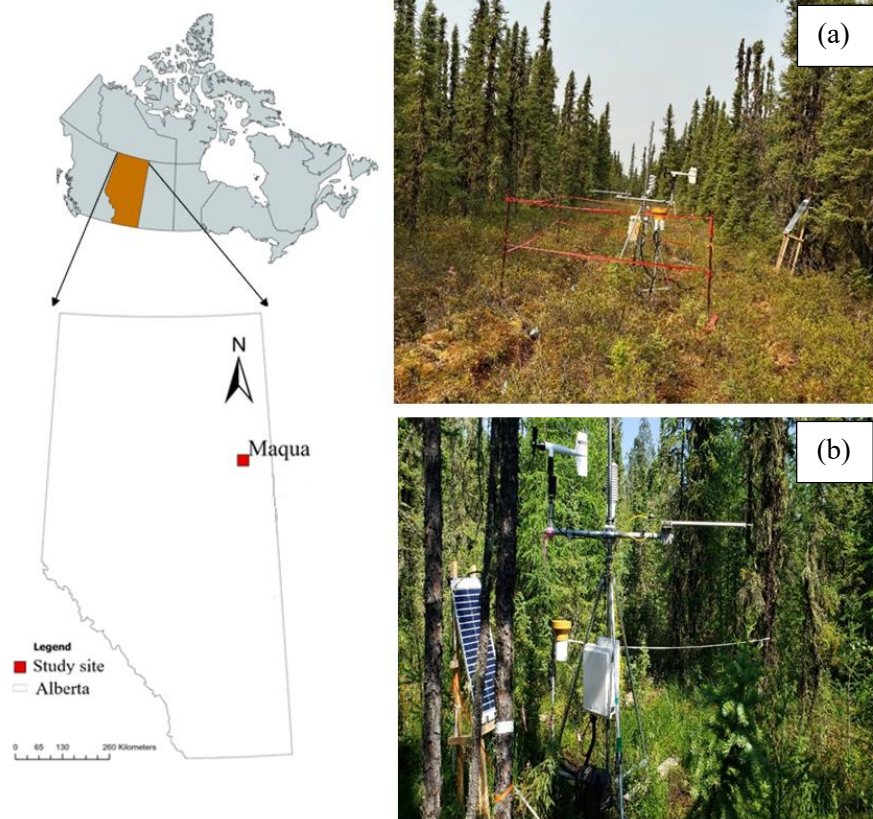


Figure 5-2 Location of the seismic line at the Maqua site (MS) as reference site for the model calibration and validation. Meteorological data were collected from meteorological stations on the line (a) and off the line (b)

Table 5-1 The summary of forcing data and calibration/validation variables for modelling.

Variables	Line	Forcing data					Calibration		Validation	
		Ta ¹	RH	Prec	WS	GR	VWC	Ts	VWC	Ts
		°C	%	mm d ⁻¹	M s ⁻¹	KJ/m ² /day	%	°C	%	°C
Average	On	-1.5	73.1	0.9	0.4	9674	40.0	4.7	27.9	-0.5
	Off	-1.5	73.1	0.9	0.4	9674	25.0	3.6	21.4	-4.1
Minimum	On	-42.3	27.1	0.0	0.0	860	19.6	-1.5	18.7	-3.0
	Off	-42.3	27.1	0.0	0.0	860	12.9	-14.4	15.3	-18.2
Maximum	On	21.3	98.9	49.3	1.7	31020	80.0	15.6	88.1	4.0
	Off	21.3	98.9	49.3	1.7	31020	48.9	19.3	36.3	11.6
Standard deviation	On	13.0	14.7	3.4	0.3	7475	16.0	5.6	14.5	1.1
	Off	13.0	14.7	3.4	0.3	7475	6.9	8.8	5.7	5.0

¹ Ta: Air temperature; RH: Relative humidity; Prec: Precipitation; WS: Wind speed; GR: Global radiation; VWC: Volumetric water content; TS: Soil temperature

Additional datasets to assess patterns of AET and GWD were collected from a series of lines across northeastern Alberta with snowpack measurement across a network of stations with time lapse photographs as described in Bayatvarkeshi et al. (2024) and Bayatvarkeshi et al. (2025a, b).

5.3.3. Sensitivity analysis

To address the third objective of this study, which sought to understand how variation in peatland conditions and seismic line characteristics influences water balance, we undertook a local sensitivity analysis (LSA) for the online and offline models. These LSA simulations aimed to answer specific questions related to parameter-process interactions and their effects on the study site's water balance components. The LSA was completed manually in a stepwise approach, starting by first identifying the most sensitive soil hydraulic properties to seismic line operation (i.e., soil compaction) and peatland vegetation characteristics (i.e., tree cover/LAI). Based on results from initial alterations of 10 parameters (Table S3, Appendix C), we selected the van Genuchten soil parameters (n and m) for the soil compaction simulations and the LAI of trees for the peatland vegetation simulation. For the LSA process, the magnitude of each related parameter (x) was separately increased/decreased by 20 percent, and simulated values ($output_{1.2x}$) were compared with the initial numbers ($output_x$) as recommended by Lenhart et al. (2002).

$$Percentage\ of\ sensitivity_x = \frac{|output_x - output_{1.2x}|}{output_x} \times 100 \quad (1)$$

It should be noted that the initial assignment of parameter values for the sensitivity analysis was informed by field measurement, literature, and default values of CoupModel (Table S2, Appendix C). For soil compaction, we adjusted only the near surface soil in the online model, representing more extensive soil changes that can be associated with greater soil disturbance during line construction. For peatland vegetation, we altered only the LAI of the tree layer in the offline model to represent varying extents of canopy cover among different peatlands.

5.4. Results and discussion

The online and offline models were developed using driving variables with different soil and plant modules. Since the first step in modelling is to ensure model accuracy, the calibration and validation results are presented first, followed by a discussion of the outputs.

5.4.1. Calibration and validation

Field-based measurements of soil moisture and temperature were used to calibrate and validate the models. The accuracy of models in simulating the relevant variables in calibration for soil temperature indicates that both models can identify the pattern of soil temperature changes (Figure 5-3). The magnitude of RMSE (2.8 and 4.9 °C) and *r* values (0.82 and 0.94) emphasize the proficiency of the model in simulating soil temperature. Validation of the model also emphasize the accuracy of models in estimating soil temperature with high values of *r* (0.70 and 0.86) and low values of RMSE (3.3 and 3.1 °C). Higher soil temperature in cold months on the seismic line compared to offline was observed in simulated values. The minimum soil temperature measured and simulated were -3 °C and -13.7 °C online, and -18.2 °C and -16.3 °C offline, respectively. Conversely, the soil temperature in the growing season on the seismic line was cooler than off the line. The maximum soil temperature measured and simulated were 15.6 °C and 11.9 °C on the line, and 19.3 °C and 12.2 °C off the line. High soil temperature on the seismic lines in winter might be associated with high incoming radiation in linear disturbances due to high snow cover (Williams and Quinton, 2013). In chapter 4, warmer winter soils on seismic lines were also reported and it was suggested that deeper snowpack on the line insulates the soil and protects it against extreme air temperature fluctuation during the wintertime. Due to the impact of snow accumulation on soil temperature (Bayatvarkeshi et al., 2025b), one reason for the mismatch between measured and simulated values during the non-growing season might be the lack of snow measurements for validation, and hence, underestimation of snowpack online or overestimation of snowpack offline.

Cool soil temperatures in summertime might be related to wetter conditions on the lines. Williams and Quinton (2013) stated that wet soil has a higher heat capacity that buffers soil temperature fluctuation on seismic lines and keeps it cooler.

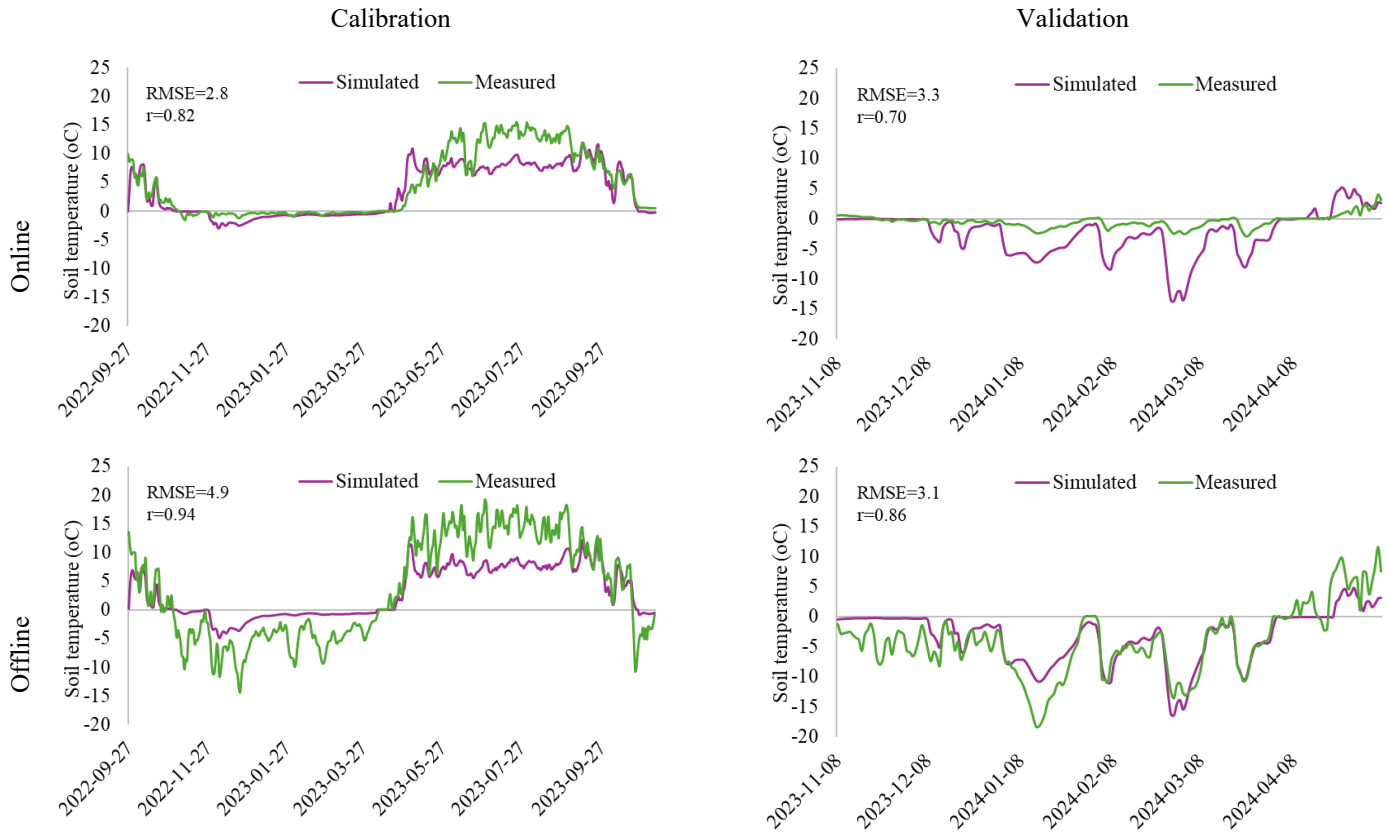


Figure 5-3 Soil temperature values at a depth of 15 cm in calibration and validation phases

Seismic lines are also typically associated with higher soil moisture than in undisturbed areas (Weiland et al., 2024). CoupModel simulated substantially higher VWC online than offline in calibration phase, matching well the measured patterns. The pattern was observed in validation too, emphasizing an acceptable performance of the models. The wetter conditions on seismic lines might be related to a combination of soil compaction and removal of the uppermost soil layer during clearing (Davies et al., 2025) that contributes to shallow groundwater depth (Weiland et al., 2024). Near surface soil moisture strongly depends on the physical properties of moss (Goetz, 2014) and varies across seasons (Siwach et al., 2023). Accordingly, mismatches in simulated values during certain periods might be due to the absence of seasonal measurements of soil physical properties or specific vegetation composition specification in the model structure. In the

models developed here, a single measurement of soil physical properties has been used in the calibration phase; however, incorporating temporally varying measurements could improve simulation accuracy. Siwach et al. (2023) also mentioned that the physical properties of moss vary over time and during different seasons.

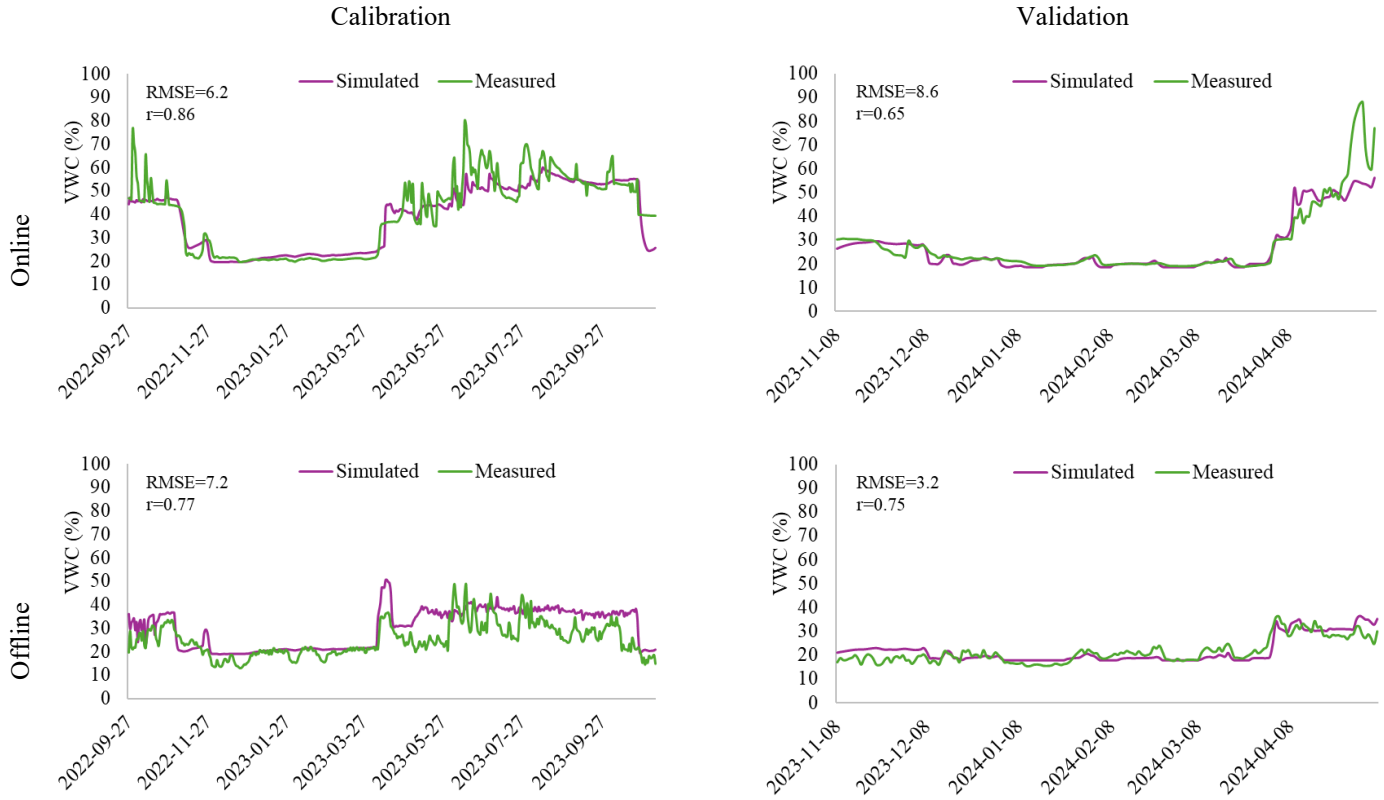


Figure 5-4 Soil volumetric water content (VWC) at a depth of 15 cm in the calibration and validation phases

5.4.2. Comparing water balance components online and offline

Evaluation of statistical analysis in calibration and validation phases demonstrates that the performance of models was reliable for soil temperature and moisture (Figure 5-3 and 5-4). Here, we describe the simulated water balance components to assess how seismic line disturbance has altered local hydrology. The simulated values of the AET for online and offline indicate that the AET from the seismic line is slightly higher than offline, average of 1.3 mm/day compared to 1.2 mm/day (Figure 5-5). Both models produce a seasonal pattern of high AET in the growing season and low values in cold months. Bayatvarkeshi et al. (2025a) conducted lysimeter measurements from the same study site and reported an AET on the line that exceeded the ground layer offline,

average of 1.7 mm/day relative to 1.1 mm/day, respectively. The field measurements from another location, the Kirby site (Bayatvarkeshi et al., 2025a), also indicated higher AET from online compared to offline (i.e., 1.9 mm/day to 1.2 mm/day; Bayatvarkeshi et al., 2025a). Therefore, it can be inferred that the simulated patterns well represent the measured ones.

Partitioning annual AET to evaporation and transpiration indicated that evaporation from moss (i.e., transpiration from understory was considered as evaporation) outweighs the transpiration from trees in the offline model, 176.5 mm compared to 46.3 mm (Table 5-2). Based on these simulations, 20% of the AET offline is associated with transpiration of the canopy, while 80% is related to evaporation from moss, emphasizing the pivotal role of evaporation from the moss in AET from peatlands. Accordingly, despite the lack of trees, the AET from online remains slightly higher than offline due to a substantial increase in moss evaporation (Table 5-2). Our simulated pattern is similar to that reported in previous studies, where the fractional contribution of total evaporation was 70–80% of the total evapotranspiration in the peatlands in western Canada (Basu and Sauchyn, 2022). Similarly, Lafleur and Schreder (1994) revealed that a *Sphagnum* and feathermoss surface cover can account for as much as 65% of the total water loss from the ecosystem. Therefore, evaporation from moss plays a pivotal role in AET in boreal peatlands and our simulations, both online and offline. The AET measured by lysimeters by Heijmans et al. (2004b) in the dense forest, open forest, and bog (*Sphagnum*) were 0.3, 0.9, and 1.5 mm/day, respectively, which further points out high evaporation from *Sphagnum* moss in sparse canopies. It is worth noting that the dominant tree species in the present study is black spruce. Due to the narrow canopy and low density of black spruce, low transpiration can be justified (Heijmans et al., 2004b).

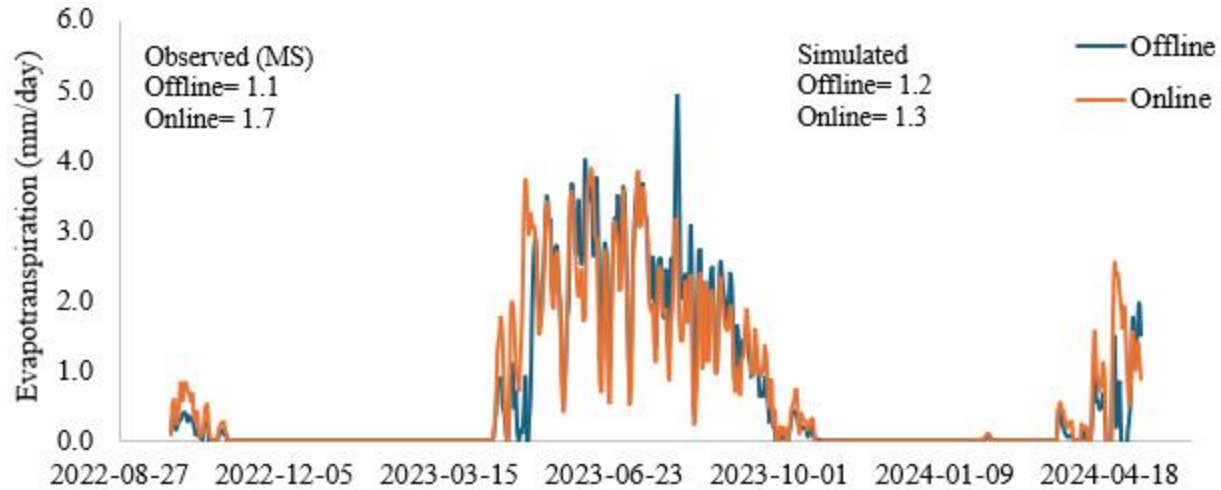


Figure 5-5 The simulated AET on the line and off the line. Values for offline and online listed on the left side of the panel at MS (Maqua site)

Due to the removal of vegetation and microtopography, seismic line operation results in shallow groundwater depth (GWD) (Weiland et al., 2024). The simulated GWD values using CoupModel in the present study indicate that the GWD is close to the surface online in most months except for the melting period (i.e., April and June). There is a big difference between the GWD online and offline in the melting period (i.e., from April 2023 to June 2024). This pattern might be related to snowpack properties. Due to a lack of field measurements, we collected snow data from a nearby weather station, which might affect the mismatch between the simulated values of GWD online and offline in cold months and the subsequent melting period (Figure 5-6). The shallow GWD online is consistent with the field measurements in August from MS with GWD 32.8 cm online compared to 46.8 cm offline, which is consistent with observations from other similar sites (Kirby, 8.7 cm online to 16.1 cm offline; Bayatvarkeshi et al., 2025a). The simulated values for August are 41.6 cm offline and 37.2 cm online, which aligns with observed values at the same time.

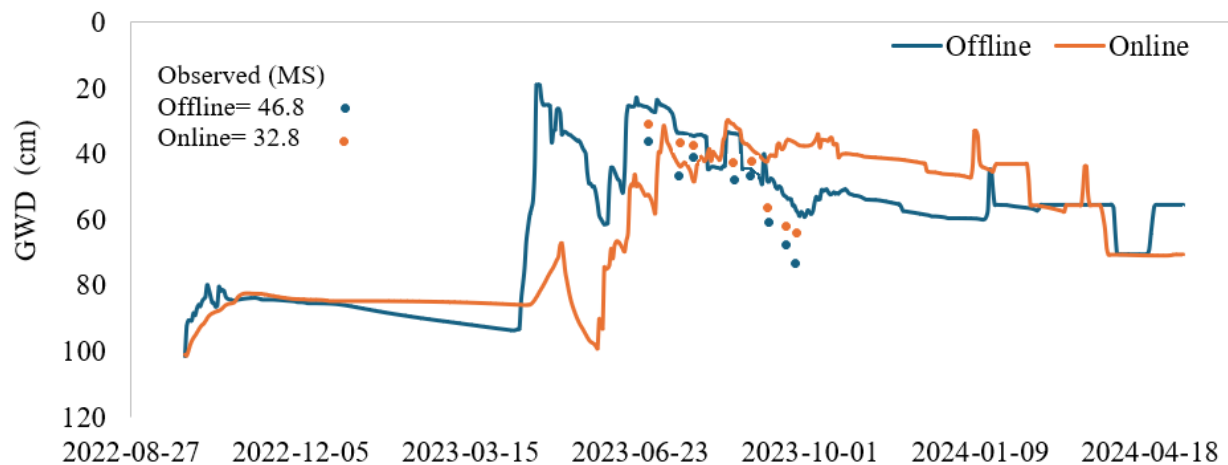


Figure 5-6 Groundwater depth (GWD) simulated on the line and off the line. Values for offline and online listed on the left side of the panel at MS (Maqua site) are from groundwater well measurements made adjacent to the meteorological stations at each site.

The snow depth measured in the study region at the Fort McMurray airport in 2022-2023 (20 cm) was higher than in 2023-2024 (4 cm) (ECCC, 2024). Air temperature measurements indicate that the average from December 2022 to March 2023 was colder than the same period in the following year, -14°C compared to -10°C . Seismic line disturbance has the potential to affect the snowpack in multiple ways. The lack of interception is expected to increase the snowpack online, while high wind speed might blow snow and reduce snow accumulation. Simulated snow depth values on the line and off the line were quite similar, including the maximum snow depth (Table 5-2; Figure S1–Appendix C). Evaluating snow depth images using the time-lapse photography technique across 50 paired on and offline locations across the study region, Bayatvarkeshi et al. (2025b) observed that the snow depth on the line is slightly higher than offline in some sites. This outcome might be related to reduced incoming radiation caused by tree shading that preserves the snow underneath (Pomeroy et al., 2009). Although we did not have snow measurements at MS for model validation, comparing the simulated values with the observations from the nearby meteorological station demonstrates that the pattern of snow depth variation is similar to the simulated values (Figure S1, Appendix C); however, the simulations are higher than the nearby station (i.e., the Fort McMurray CS station, 40 km from the study site). The simulated snow depth across the whole modelled period online and offline is 5 cm (i.e., 97 %) higher than the observed values from the nearby station. Regarding simulated snow density, seismic lines have slightly denser snow than offline, 90.5 kg/m^3 compared with 89.9 kg/m^3 (Table 5-2). This finding emphasizes that high wind speed blows fluffy

layers of snow (Mott et al., 2018), resulting in a high density of snow. Mott et al. (2018) revealed that wind-driven processes play a key role in all stages of the evolution of seasonal snow. The study of Weiland et al. (2024), based on field measurements, also illustrated higher snow density on the line than off the line; however, they mentioned that this difference is site-specific. Moreover, snow densification online might be related to exposure to more sunlight (Bayatvarkeshi et al., 2024), as there is a direct relationship between sunlight and snow density (Zhang et al., 2023). The high snow density causes a prolonged duration of snow on the ground, which was reported by Bayatvarkeshi et al. (2025b). As a consequence, longer lasting snow on the ground functions as an insulator layer to increase soil temperature (Figure 5-3; Bayatvarkeshi et al., 2024). Moreover, as observed in field studies, high snow density in a thicker snowpack results in higher snow water equivalent online (from 8.3 mm to 46.7 mm) (Weiland et al. 2024).

Regarding other water balance components, simulated drainage and runoff online might be higher than offline. As saturated hydraulic conductivity generally declines with depth at the study sites, a shallow GWD promotes drainage through the more permeable surface layers (Price et al., 2008). In addition, there is a higher possibility for the runoff online relative to offline because higher bulk density is reported in soil online which can increase higher soil moisture (Word et al., 2022). Furthermore, the removal of vegetation and the upper layer of soil for seismic line creation in parallel with high bulk density provides shallow GWD (Weiland et al., 2024). High precipitation online due to the lack of trees also contributes to more available water online. Altogether, an increase in available water along with high bulk density increases the potential for saturated conditions online, resulting in surface runoff, particularly during melting seasons due to ground ice. Several studies have illustrated that high soil bulk density due to compaction reduces water permeability and subsequently translates into increased surface runoff (Kim et al., 2010; Munkholm et al., 2003). Braverman and Quinton (2016) highlighted that the seismic line contributes to increasing the runoff-contributing area, especially in the spring snowmelt period and in response to large summer rain events.

According to the incoming and outgoing water from the online and offline, both models predict a small annual surplus in the year of measurement, with the simulated water storage online higher than offline by 27 % (i.e., 5 mm) (Figure 5-7). However, both water storage online and offline has partially the same pattern. The magnitude of storage online and offline peaked at the melt period in both study years. The greater surplus online illustrates that the greater available water online

outweighs the higher AET. Greater water availability arises from a lack of interception that results in throughfall of over 30% (i.e., 80 mm) more online than offline (Table 5-2). Low-lying conditions due to surface compaction/soil removal during seismic line construction (Weiland et al., 2014; Davies et al., 2025) also contribute to greater drainage from the line. Increased available water comes from incoming precipitation due to a lack of interception (Bayatvarkeshi et al., 2025b) and redistribution of water through runoff and groundwater flow due to high soil compaction (i.e., less infiltration) (Davies et al., 2025) on the seismic lines. In other words, the seismic line functions as a water catchment resulting in it retaining more water due to soil compaction than the natural area, consistent with the shallower GWD often reported on seismic lines (Lovitt et al. 2018). The capacity of seismic lines in filling depression water storage has been reported by Williams et al. (2013). However, these results might differ in different types of ecosystems and depending on the landscape position of the disturbance, as site-specific variation in water balance components on seismic lines has been reported by Kononovs et al. (2024) and Weiland et al. (2024).

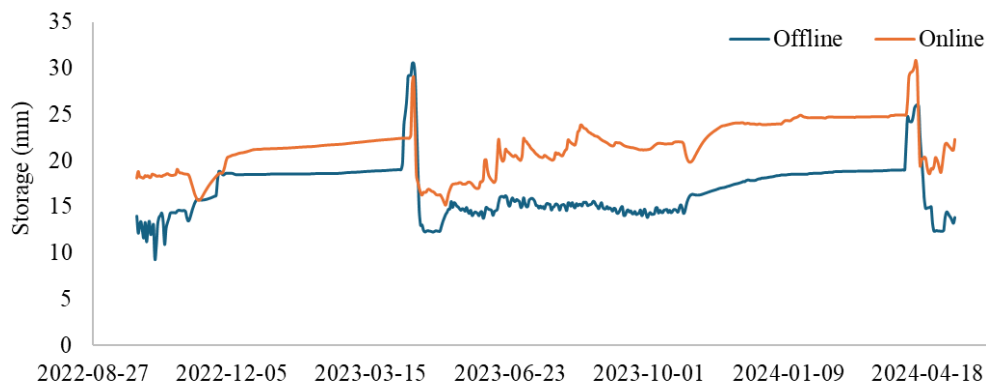


Figure 5-7 The simulated storage on the line and off the line.

Table 5-2 Annual water balance and environmental components (from October 2022 to 2023) simulated using the CoupModel online and offline and affected by $\pm 20\%$ change in soil compaction and LAI.

Variables	Units	Online	Offline	Soil compaction (online)		LAI (offline)	
				-20%	+20%	-20%	+20%
Evapotranspiration	mm	237.8	225.0	233.3	212.0	224.6	224.9
Evaporation	mm	237.8	183.6	233.3	212.0	191.6	176.2
Transpiration	mm	--	41.5	--	--	33.0	48.7
Drainage	mm	89.5	30.7	77.5	141.4	30.2	30.3
Runoff	mm	178.6	55.3	165.9	231.9	55.3	54.9
Throughfall	mm	350.8	269.8	350.8	350.8	271.2	268.7
Precipitation	mm	350.8	350.8	350.8	350.8	350.8	350.8
Water storage	mm	21.5	16.8	20.0	26.0	16.8	16.8
GWD*	cm	42.7	44.8	48.3	36.9	44.5	44.7
Snow density	Kg/m ³	90.5	89.9	90.5	90.5	89.9	89.9
Snow depth**	cm	33.6	33.6	33.6	33.6	33.6	33.6
Max snow depth	cm	63.2	63.2	63.2	63.2	63.2	63.2
Ts	°C	1.7	1.1	1.6	1.7	1.1	1.1
VWC	%	34.9	27.5	32.4	41.9	27.5	27.5

* From June to November

**From November to March

5.4.3. Local sensitivity analysis

Since seismic line creation largely refers to tree removal, which changes the vegetation characteristics of peatlands (e.g., LAI) and soil compaction in affected area, our LSA studied how these biotic and abiotic changes will influence the response of a peatland's water balance components to seismic line disturbance (Table 5-2). In addition, our LSA simulations showed that the peatland's water balance components are sensitive to LAI and soil compaction (van Genuchten equation) (Table S3-Appendix C). A 20% increase in van Genuchten water retention parameter (i.e., m and n) to simulate greater soil compaction increased drainage and runoff by 58% and 30%, resulting in shallower GWD by 6 cm and increased VWC by 20%. Contrarily, a 20% decrease in the water retention parameter to simulate reduced soil compaction led to lower drainage and runoff by 13% and 7%, respectively, along with a 7% decrease in VWC and a 6 cm deeper GWD. These findings show that a small change in soil compaction leads to a substantial shift in water balance components, especially drainage and runoff as water outputs. Accordingly, losing water from the seismic line with high compaction outweighs the high subsurface water with VWC and shallow

GWD. As can be seen from Table 5-2, an increase in soil compaction reduces AET by 11%. High soil temperature (T_s) (i.e., 6%) affected by soil compaction might also result from high soil moisture. The impact of less soil compaction on AET and T_s is less than an increase in n value which considered as increase in compaction (i.e., 2% drop in AET and T_s). Regarding soil water storage, higher soil compaction provides more water storage by 21%; however, a 20% decrease in compaction reduces water storage by 7%. Overall, the impact of an increase in soil compaction on environmental and water balance components is substantially higher than when compaction is reduced.

Across the landscape, peatlands vary in their extent of tree cover (i.e., LAI), and this likely affects the extent of water balance alteration that results from seismic line disturbance. The impact of changing canopy LAI offline can be mostly seen in evaporation, transpiration, and T_s . A 20% increase in LAI raises transpiration by 18%; however, it reduces evaporation by 4%. In contrast, a 20% decrease in transpiration and a 4% increase in evaporation result from a 20% decrease in LAI. Nevertheless, the total AET is not affected within this range of LAI as changes in transpiration are balanced by opposite shifts in evaporation, and in all cases, AET offline remained lower than online. The impact of LAI can also be observed in T_s , where higher LAI results in cooler soils. Since dense-canopy peatlands result in lower T_s , seismic line clearing in these peatlands results in a greater shift in soil temperature patterns, with potential implications for understory plant communities and soil carbon cycling (e.g., Strack et al., 2018). It is worth noting that the dominant tree species in the study site was black spruce, which naturally has low LAI. Therefore, the impact of seismic lines on dense-canopy peatlands with trees with high LAI is likely to result in more severe changes to the soil thermal regime. These implications illustrate that water balance components affected by seismic line creation substantially depend on plant community composition and soil compaction. Accordingly, any small changes in the operations during seismic line creation might lead to a substantial shift in water balance and environmental conditions, likely contributing to the observed variation in tree regrowth among peatland seismic lines.

5.4.4. Potential catchment scale impacts of seismic line disturbance: Limitations of one-dimensional modelling framework

The present study provides a first investigation into the potential impact of seismic line disturbance on peatland water balance. In general, we observed higher AET, runoff, drainage, and water

storage online than offline. Since we used CoupModel to create one-dimensional simulations of on and offline conditions, we were unable to explore how the structure of the seismic line disturbance and interconnectivity of these linear clearings may affect local and catchment scale hydrological responses. For example, previous studies have shown that the width and orientation of the seismic line affect a range of local responses (Franklin et al. 2021; Stern et al. 2018; Bayatvarkeshi et al. 2025b). One of the implications of orientation is the impact on the available light by shading the line (Franklin et al., 2021; Hegels, 2023). Therefore, tree shading can also affect evaporation from the moss layer and understory species composition, leading to transpiration variation (Kettridge et al., 2013).

Further, the connectivity of seismic lines may affect their impact on the catchment scale. Our CoupModel simulations predict a clear increase in drainage and runoff on seismic lines that may enhance lateral hydrologic connectivity both within peatlands and among peatland and upland systems. The study of Williams et al. (2013) also revealed that there is connectivity of water flow between adjacent peatlands disturbed by seismic lines. Weiland et al. (2024) also highlighted the site-specific hydrological conditions in peatlands disturbed by seismic lines. The dynamic interaction between upland and lowland at the catchment scale has been reported by Thompson et al. (2014), indicating the importance of the study of the hydrological condition on a large scale. Accordingly, future work modelling water balance at the catchment scale while incorporating the hydrological impacts of seismic line disturbance will provide important insights into water resources management. Due to the limitations of one-dimensional models, two or three-dimensional models will be needed to connect both online and offline models.

5.5. Conclusion

By removing canopy cover and changing soil properties, seismic line disturbances affect local peatland water balance, but few studies have explored the effect of these documented changes on the components of the water balance collectively. Here, we used a modelling approach, supported by extensive field measurements, to assess the potential effect of seismic lines on peatland water balance components and site-specific conditions that could alter this response. The findings indicated that although AET online is higher than offline, greater water inputs due to lack of interception resulted in a greater surplus of water as storage on the seismic line than in the undisturbed areas. Additionally, a lower elevation on the line might result in an influx of lateral

flow from the higher adjacent area, which subsequently enhances water storage online. It was also observed that change in seismic line operation (i.e., soil compaction and removing trees) can cause a significant shift in water balance and environmental components (e.g., soil temperature). Although the current model was created for one line, we demonstrated that relatively simple changes to vegetation and soil conditions to represent seismic line disturbance in process-based models could effectively capture measured hydrological changes. Thus, modelling can be used as an effective tool to supplement field campaigns and broaden our knowledge of the implications of seismic lines on the catchment scale. Nevertheless, due to the limitations of the one-dimensional model, we could not capture the impact of local conditions (e.g., seismic line width and orientation) or the connectivity of lines. Therefore, creating a model that includes a network of linear disturbances at a broad scale will provide further insights into the impact of seismic lines on catchment scale water balance.

Chapter 6.

Conclusion

6.1. Summary and Conclusions

6.1.1. Summary of results

This research examined the impacts of seismic line disturbances on peatland hydrology during both cold and growing seasons. As few studies on the hydrological impacts of seismic exploration have been conducted, results from this study advance our understanding of the potential importance of these linear disturbances on the water balance in boreal Alberta. Field measurements and modelling revealed that in cold season, soil temperatures on seismic lines were consistently warmer, delaying topsoil freezing, with some north–south lines remaining above 0 °C all winter. It was also observed that seismic lines received and retained more snow than adjacent forested peatlands, resulting in greater snow depth, longer snow duration, and higher albedo. Moreover, net radiation during winter showed a distinct pattern, with more negative values on seismic lines than in adjacent peatlands. Regarding growing season, AET was higher on seismic lines due to greater incident radiation, wind speed, precipitation input, water availability, and vascular plant cover. It was also found that soil compaction and a shallower water table increased surface evaporation. Furthermore, increased moss evaporation compensated for the reduction in overstory transpiration, and greater precipitation input led to slightly higher water storage than in undisturbed areas.

The results indicate that seismic line effects extend beyond the growing season, influencing winter soil thermal regimes, snowpack dynamics, and radiation balance. Warmer winter soils may enhance microbial activity and alter nutrient and carbon cycling. Longer-lasting snow could delay the growing season onset, affect plant transpiration, and increase spring streamflow. In the growing

season, changes in canopy structure and soil hydrology enhance ground-level evapotranspiration but can still result in greater water storage due to increased precipitation inputs.

These findings suggest that seismic line development modifies year-round hydrological processes in peatlands, with consequences for energy balance, carbon cycling, vegetation dynamics, and water yield. The orientation and width of seismic lines further influence these responses, highlighting the importance of site-specific assessments.

Previous studies have focused predominantly on the growing season, overlooking the hydrological and energy balance implications during winter. This research addresses that gap by providing the first integrated assessment of seismic line impacts on cold-season soil temperatures, snowpack properties, and radiation patterns in peatlands. By linking these cold season changes to subsequent spring and summer hydrological processes it offers a more complete, year-round understanding of how seismic lines alter peatland water balance and ecosystem function.

Since biotic and abiotic conditions of seismic lines change over time, the current findings might change in parallel with the shift in the ecosystem. In other words, the implication of seismic lines from the aspect of hydrology might be accelerated or decelerated with time following disturbance. Regarding the previous reports, seismic lines do not follow a successful trajectory, hence it is hard to predict the future conditions of the lines and subsequently their long term implications. The application of process-based modelling to investigate seismic line effects on water balance in Chapter 5 provide a first basis for an approach to investigate longer term impacts through simulation studies.

6.1.2. Implications for seismic line recovery

This study on the effect of seismic lines on hydrological conditions in both growing and non-growing seasons emphasizes the shift in water balance components in peatlands disturbed by seismic lines. Accordingly, changes in hydrological conditions, including evidence of greater water storage on seismic lines, might be one of the reasons that woody vegetation does not grow back and does not follow the expected successional trajectory on seismic lines. These findings contribute to restoration planning by highlighting the importance of considering hydrological conditions in disturbed peatlands. The results of this study indicate that seismic lines retain more snow and delay soil freezing compared to the surrounding peatland. These findings suggest that restoration practices need to carefully consider how to manage surface energy and soil temperature regimes. For instance, mulching could potentially be applied to reduce heat accumulation and surface drying during summer, thereby counteracting some of the increased energy fluxes we observed. At the same time, winter-based practices such as mounding remain effective because they can restore microtopography and hydrological pathways while minimizing additional disturbance during thawed conditions. Together, these approaches highlight how our results can inform the timing and selection of restoration strategies that target both the thermal and hydrological impacts of seismic lines. Therefore, a successful restoration plan is not only about creating microtopography on seismic lines but also paying attention to hydrological components by modelling to identify hydrological limitations to return of forest cover and develop restoration techniques that address them.

6.2. Future research needs

Results from this study demonstrate that the presence of seismic line disturbance alters water balance components in boreal peatlands not only in the growing season but also in the non-growing season. However, the extent of the alterations is largely driven by the structure of the seismic line

(e.g., width, orientation) and its location (e.g., latitude, peatland type, canopy characteristics of the undisturbed peatland). Accordingly, this study might orient further research on seismic lines as follows:

6.2.1. From the aspect of field measurements:

The study of wintertime conditions was based on 1-year measurements, and long-term monitoring in parallel with measuring further variables, specifically energy balance components and snowpack characteristics, is essential to broaden our knowledge of the impacts of seismic lines in non-growing seasons. From the aspect of snowpack dynamics, the snowpack properties reported in this thesis were based on time-lapse photography; however, field measurements of snow including snow density and snow water equivalent are essential to broaden our knowledge of snowpack properties and how they are affected by seismic lines. Regarding evapotranspiration, this part of the study was based on field measurements from untreated seismic lines; however, more studies are required to consider the effect of restoration treatments. It is worth noticing that the impact of seismic line structure including orientation, width, age, and type of ecosystem on the AET remains less understood. We also measured understory AET; however, further investigations are required to study the AET from above the canopy and/or include measurement of tree transpiration (e.g., using sapflow sensors). Overall, although our results indicate an increase in water loss as AET, it is worth mentioning that black spruce was the dominant tree in the forested area in the present study. Therefore, the results might vary in different ecosite types with varying canopy compositions and distinct seismic line structures in other locations, necessitating more investigations.

6.2.2. From the aspect of modelling

Modelling was based on a short-term dataset; however, long-term information is required to improve the proficiency of models in future studies. The results also obtained from one-site

data; however, the connectivity of seismic lines was not examined in this model. Furthermore, the models did not consider the impact of structure of lines such as orientation and width; however, based on field measurements, the structure of seismic lines is a significant driver of hydrological conditions, which was overlooked in the study. Moreover, since the study was carried out using a one-dimensional model, we did not capture the interaction between online and offline. Perhaps, 2-D or 3-D models will be able to include the interaction in the catchment scale.

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APPENDICES

Appendix A

Table S1- Number of individual trees at Maqua site, Fort McMurray, Alberta, in the summer of 2023^a.

Plot	Height	Center (100 m ²)	South (100 m ²)	North (100 m ²)
1	<1.4 (m)	52	30	30
	>1.4 (m)	4	57	52
	DBH ^b (cm)	1.48	3.02	6.39
	Density (stem/ha)	5600	8700	8200
2	<1.4 (m)	50	7	33
	>1.4 (m)	5	178	118
	DBH (cm)	0.26	3.62	3.97
	Density (stem/ha)	5500	18500	15100
Average	<1.4 (m)	51	18.5	32.5
	>1.4 (m)	4.5	117.5	85
	DBH (cm)	0.87	3.32	5.18
	Density (stem/ha)	5550	13600	11650

- a. The center plots are located completely on the seismic line. South and north plots are in the adjacent undisturbed forested moderate-rich fen.

Table S2- The accuracy of used sensors at meteorological stations (Source: <https://s.campbellsci.com/>)

Sensor	Variables	Accuracy
NR LITE2	Net Radiation	±5%
HMP155A	Air Temperature	• ± (0.226 - 0.0028 x temperature)°C (-80° to +20°C) • ± (0.055 + 0.0057 x temperature)°C (+20° to +60°C)
HMP155A	Relative Humidity	• ±1% RH (at 15° to 25°C, 0 to 90% RH) • ±1.7% RH (at 15° to 25°C, 90 to 100% RH) • ± (1.4 + 0.032 × reading) % RH (at -60° to -40°C) • ± (1.2 + 0.012 × reading) % RH (at -40° to -20°C) • ± (1.0 + 0.008 × reading) % RH (at -20° to +40°C) • ± (1.2 + 0.012 × reading) % RH (at 40° to 60°C)
05103-10-L	Wind direction	±3°
05103-10-L	Wind speed	±0.3 m/s or 1% of reading
PAR	Photosynthetically Active Radiation	< 5%
Thermocouples*	Soil temperature	+/- 0.25%
TE525M	Rainfall	±1 % at rates up to 1 in./hr

* <https://www.thermocoupleinfo.com/thermocouple-types.htm>

Table S3- Hourly STD of variables at the Tamarack site

Month	Hour	Offline					Online				
		TS	WS	WD	TA	RH	TS	WS	WD	TA	RH
Apr	0	0.33	0.13	67.87	3.38	13.18	0.02	0.84	85.64	3.81	15.89
	1	0.33	0.15	68.88	3.65	13.47	0.02	0.81	89.62	3.99	16.18
	2	0.32	0.15	67.19	3.82	13.28	0.02	0.83	88.02	4.14	15.43
	3	0.32	0.18	71.14	4.14	13.29	0.02	0.71	89.50	4.27	15.01
	4	0.32	0.15	70.70	4.31	12.90	0.02	0.65	92.95	4.36	14.28
	5	0.32	0.20	69.53	4.40	12.50	0.02	0.68	92.68	4.54	14.12
	6	0.32	0.15	71.56	4.38	12.24	0.02	0.70	96.77	4.52	13.73
	7	0.31	0.16	69.47	4.39	12.78	0.02	0.73	98.08	4.48	14.07
	8	0.31	0.18	72.55	4.08	13.97	0.02	0.78	82.30	4.03	14.59
	9	0.31	0.24	72.38	4.09	16.20	0.02	0.89	65.36	3.98	16.15
	10	0.31	0.23	70.76	4.29	16.55	0.03	0.91	47.30	4.41	17.13
	11	0.31	0.25	68.73	4.66	17.39	0.03	0.96	52.54	4.80	18.14
	12	0.30	0.26	70.28	4.88	18.86	0.02	0.98	58.84	4.91	19.07
	13	0.30	0.21	73.86	5.10	19.45	0.03	0.94	53.12	5.10	19.36
	14	0.30	0.24	71.25	5.34	19.75	0.03	0.94	54.41	5.43	19.96
	15	0.30	0.25	73.19	5.42	20.08	0.03	0.92	64.16	5.45	20.26
	16	0.30	0.26	68.79	5.32	20.28	0.03	0.92	60.54	5.40	20.55
	17	0.30	0.23	62.96	4.97	20.25	0.03	0.87	47.68	5.14	20.56
	18	0.30	0.20	67.25	4.76	18.86	0.03	0.87	60.62	5.04	19.67
	19	0.29	0.16	69.17	4.56	17.58	0.03	0.74	54.41	4.92	18.79
	20	0.29	0.09	69.23	4.27	15.75	0.03	0.66	79.29	4.55	16.88
	21	0.29	0.09	72.71	3.97	14.65	0.03	0.73	89.13	4.28	15.77
	22	0.29	0.09	70.42	3.86	13.85	0.03	0.86	87.33	4.34	16.21
	23	0.29	0.14	68.07	3.80	14.07	0.03	0.87	81.23	4.35	16.70
Mar	0	0.19	0.06	58.30	6.50	11.24	0.02	0.73	110.20	6.77	12.44
	1	0.19	0.06	58.53	7.02	11.42	0.02	0.71	103.13	7.26	11.73
	2	0.19	0.06	59.30	6.92	9.61	0.02	0.71	110.80	7.17	10.42
	3	0.19	0.06	59.24	7.14	9.74	0.02	0.65	105.04	7.33	9.16
	4	0.18	0.06	60.52	7.07	7.65	0.02	0.66	110.48	7.30	7.46
	5	0.18	0.06	57.99	7.56	7.68	0.02	0.60	106.20	7.77	7.12
	6	0.18	0.08	60.28	7.76	7.00	0.02	0.64	117.86	7.96	6.61
	7	0.18	0.07	61.17	7.73	6.07	0.02	0.63	120.46	7.91	5.56
	8	0.18	0.08	60.95	7.65	5.54	0.02	0.63	119.27	7.85	5.04
	9	0.18	0.03	58.01	7.51	5.24	0.02	0.57	124.45	7.59	5.17
	10	0.18	0.03	62.36	6.32	7.06	0.02	0.68	88.55	6.19	6.95
	11	0.18	0.06	63.61	5.63	10.92	0.02	0.80	73.99	5.60	11.33
	12	0.17	0.08	64.20	5.52	13.57	0.02	0.87	74.64	5.51	13.39
	13	0.17	0.10	62.97	5.33	13.58	0.02	0.74	59.87	5.46	13.67
	14	0.18	0.15	62.25	5.42	16.28	0.02	0.82	72.04	5.40	15.09
	15	0.18	0.15	62.59	5.64	16.73	0.02	0.73	68.31	5.57	16.32
	16	0.17	0.14	64.92	5.73	17.26	0.03	0.70	72.22	6.02	17.93
	17	0.17	0.14	61.88	5.79	17.62	0.02	0.72	67.88	6.34	17.96
	18	0.17	0.14	63.21	5.83	17.59	0.02	0.55	81.05	5.98	17.77
	19	0.17	0.09	59.99	5.99	16.68	0.02	0.52	86.33	6.16	17.10
	20	0.17	0.08	56.93	6.00	14.62	0.02	0.46	108.59	6.13	14.94
	21	0.17	0.09	56.48	5.78	12.32	0.02	0.64	114.38	5.87	12.62
	22	0.18	0.08	54.64	5.90	11.09	0.02	0.59	122.74	6.06	11.50
	23	0.18	0.07	54.67	6.31	11.42	0.02	0.68	118.54	6.62	12.62
Feb	0	0.39	0.14	39.77	11.96	8.52	0.03	0.60	80.78	12.14	8.40
	1	0.40	0.15	42.11	11.56	7.51	0.03	0.60	88.59	11.75	7.02
	2	0.38	0.21	35.33	11.86	7.06	0.03	0.53	91.72	12.05	6.45
	3	0.39	0.19	34.29	12.05	6.23	0.03	0.54	84.83	12.18	5.73
	4	0.39	0.16	39.11	11.93	5.89	0.03	0.45	81.51	12.11	5.56
	5	0.40	0.19	35.45	11.96	5.89	0.03	0.45	84.35	12.13	5.62
	6	0.41	0.19	34.04	11.86	6.04	0.03	0.48	90.65	12.01	5.70
	7	0.40	0.19	32.06	11.32	5.45	0.03	0.50	89.85	11.48	5.29
	8	0.38	0.16	27.33	10.98	5.45	0.03	0.42	97.74	10.96	6.08
	9	0.38	0.13	32.05	10.79	5.33	0.03	0.47	86.06	10.75	6.31
	10	0.38	0.13	42.07	10.94	6.00	0.03	0.60	72.30	10.86	6.02
	11	0.38	0.14	42.28	9.09	7.78	0.03	0.75	57.29	9.01	7.72
	12	0.41	0.17	47.28	8.36	9.38	0.03	0.72	53.59	8.28	8.89
	13	0.40	0.17	44.56	8.26	10.52	0.03	0.75	53.23	8.19	10.49
	14	0.39	0.17	48.97	8.88	11.64	0.03	0.76	56.81	8.65	14.95

Jan	15	0.40	0.15	43.55	8.24	12.94	0.03	0.68	73.98	7.98	16.50
	16	0.38	0.13	44.79	8.51	13.45	0.03	0.76	68.26	8.56	14.42
	17	0.39	0.07	41.85	8.62	12.70	0.03	0.73	75.10	8.74	12.67
	18	0.39	0.08	46.40	9.51	11.49	0.03	0.72	79.60	9.80	12.17
	19	0.40	0.17	47.02	10.55	10.34	0.03	0.78	85.51	10.79	10.71
	20	0.41	0.12	41.69	10.53	9.07	0.03	0.75	70.01	10.71	9.73
	21	0.39	0.13	41.16	11.12	8.66	0.03	0.69	70.75	11.31	8.97
	22	0.32	0.05	22.81	8.24	5.08	0.03	0.61	97.61	8.50	6.57
	23	0.32	0.05	22.81	8.24	5.08	0.03	0.61	97.61	8.50	6.57
	0	0.13	0.08	50.13	6.08	3.54	0.01	0.58	67.83	6.07	3.32
	1	0.15	0.14	50.65	6.16	3.60	0.01	0.55	67.49	6.13	3.29
	2	0.16	0.16	51.13	5.64	3.48	0.02	0.59	64.51	5.62	3.09
	3	0.16	0.15	49.86	6.17	3.74	0.02	0.53	70.68	6.21	3.24
	4	0.16	0.16	50.55	6.44	3.68	0.01	0.66	65.01	6.46	3.16
	5	0.17	0.14	43.35	6.35	3.54	0.01	0.71	68.26	6.34	2.98
	6	0.17	0.15	41.04	6.69	3.60	0.01	0.69	63.45	6.71	3.13
	7	0.17	0.15	41.68	6.62	3.59	0.01	0.55	69.20	6.65	3.20
	8	0.16	0.15	40.73	6.56	3.54	0.01	0.38	69.01	6.62	3.18
	9	0.16	0.13	41.57	6.42	3.33	0.02	0.48	78.36	6.49	3.14
	10	0.17	0.11	40.03	6.48	3.40	0.02	0.44	72.59	6.64	3.18
	11	0.17	0.11	41.96	6.39	3.17	0.02	0.44	71.80	6.48	3.03
	12	0.17	0.15	47.90	6.17	3.53	0.02	0.47	63.99	6.16	3.29
	13	0.17	0.18	44.59	6.12	3.69	0.02	0.46	60.02	6.04	3.48
	14	0.17	0.15	43.74	6.02	4.10	0.02	0.48	58.35	5.96	3.69
	15	0.17	0.12	43.63	5.89	4.19	0.02	0.36	57.21	5.94	3.95
Nov	16	0.17	0.12	47.97	5.87	4.52	0.02	0.32	62.16	5.81	6.34
	17	0.17	0.11	49.86	5.60	4.27	0.02	0.42	75.66	5.36	5.44
	18	0.17	0.11	45.88	5.49	3.48	0.02	0.34	85.61	5.45	3.56
	19	0.18	0.11	44.62	5.60	3.25	0.02	0.41	68.47	5.58	3.10
	20	0.18	0.13	49.21	5.73	3.27	0.02	0.47	77.11	5.67	3.00
	21	0.18	0.13	51.30	5.83	3.16	0.02	0.65	66.94	5.81	3.03
	22	0.18	0.13	52.02	5.93	3.15	0.02	0.54	70.50	5.89	2.90
	23	0.19	0.14	47.74	5.93	3.49	0.02	0.51	69.68	5.93	3.29
	0	0.58	0.15	49.50	8.01	9.96	0.72	0.59	60.32	7.93	7.49
	1	0.58	0.12	49.64	8.09	10.05	0.71	0.57	55.31	8.01	7.85
	2	0.58	0.14	45.60	8.16	10.21	0.70	0.61	61.00	8.07	7.91
	3	0.58	0.10	43.37	8.25	10.53	0.70	0.56	61.83	8.22	8.70
	4	0.58	0.11	38.60	8.40	10.54	0.69	0.51	57.94	8.36	8.82
	5	0.58	0.13	44.80	8.48	10.48	0.69	0.52	54.51	8.44	9.16
	6	0.58	0.12	46.71	8.62	10.60	0.68	0.45	58.13	8.60	9.56
	7	0.58	0.12	40.43	8.71	10.42	0.67	0.46	64.55	8.70	9.25
	8	0.58	0.11	33.35	8.63	11.71	0.67	0.40	52.89	8.62	9.50
	9	0.58	0.13	31.45	8.54	11.93	0.66	0.35	52.14	8.50	10.17
	10	0.57	0.13	31.02	8.27	11.03	0.66	0.33	64.73	8.22	9.21
	11	0.57	0.15	28.84	7.72	11.05	0.65	0.31	60.41	7.56	9.06
	12	0.56	0.19	31.88	7.36	11.59	0.64	0.38	54.90	7.25	9.67
	13	0.54	0.21	40.05	7.33	12.41	0.64	0.46	46.53	7.19	10.42
	14	0.52	0.16	41.64	7.37	12.48	0.63	0.48	48.59	7.40	11.38
	15	0.51	0.14	40.34	7.40	12.18	0.63	0.48	51.13	7.85	13.56
	16	0.50	0.16	39.77	7.44	11.48	0.63	0.57	52.06	7.37	10.40
	17	0.49	0.16	40.34	7.46	10.59	0.62	0.52	57.20	7.28	9.24
	18	0.49	0.20	41.00	7.63	10.39	0.62	0.50	56.04	7.35	8.30
	19	0.49	0.20	42.76	7.76	10.38	0.62	0.52	55.31	7.55	8.77
	20	0.48	0.19	42.65	8.03	10.94	0.62	0.57	54.83	7.70	8.57
Oct	21	0.48	0.18	44.35	8.19	10.78	0.61	0.61	55.16	7.97	8.79
	22	0.49	0.16	48.81	8.30	10.18	0.61	0.60	56.59	8.12	8.24
	23	0.49	0.20	41.00	7.63	10.39	0.61	0.65	56.30	8.22	7.57
	0	1.78	0.19	54.74	5.29	16.22	1.58	0.63	66.20	5.21	15.35
	1	1.73	0.22	52.72	5.31	15.26	1.55	0.59	56.56	5.23	14.50
	2	1.71	0.23	50.53	5.59	16.01	1.55	0.63	59.90	5.45	15.39
	3	1.70	0.23	51.79	5.82	16.72	1.56	0.59	65.36	5.66	15.42
	4	1.66	0.25	51.73	5.38	15.31	1.53	0.51	66.94	5.26	14.39
	5	1.64	0.20	51.64	5.00	13.73	1.53	0.57	77.86	4.99	13.47
	6	1.63	0.20	47.49	5.00	13.81	1.51	0.53	78.48	5.03	13.56
	7	1.62	0.22	51.19	5.01	13.89	1.51	0.53	80.49	5.04	13.51
	8	1.61	0.20	46.25	5.00	14.06	1.51	0.53	80.08	5.08	13.92

	9	1.59	0.21	51.29	5.05	15.42	1.50	0.55	74.66	5.03	14.96
	10	1.58	0.21	53.81	5.63	16.84	1.49	0.58	76.97	5.47	15.64
	11	1.56	0.28	55.12	6.11	17.40	1.49	0.61	55.30	6.03	16.18
	12	1.62	0.32	56.32	6.25	17.58	1.50	0.55	47.10	6.33	17.17
	13	1.64	0.37	58.41	6.39	17.90	1.51	0.58	49.05	6.51	17.23
	14	1.67	0.32	59.64	6.52	18.60	1.52	0.61	46.39	6.68	17.79
	15	1.71	0.32	52.40	6.74	19.22	1.57	0.62	53.04	7.12	18.80
	16	1.77	0.36	55.20	6.46	20.10	1.64	0.63	45.01	6.69	19.43
	17	1.83	0.34	58.00	6.56	19.32	1.65	0.54	56.58	6.56	18.47
	18	1.84	0.32	57.89	6.17	20.93	1.64	0.59	74.60	6.07	19.81
	19	1.86	0.23	57.37	5.53	19.29	1.63	0.54	78.25	5.39	18.35
	20	1.84	0.23	57.23	5.32	18.78	1.61	0.55	85.30	5.20	17.68
	21	1.76	0.23	56.37	5.28	17.95	1.58	0.54	86.14	5.14	16.81
Dec	22	1.76	0.23	56.66	5.12	17.83	1.58	0.56	85.69	5.01	16.78
	23	1.72	0.24	57.97	5.29	17.14	1.56	0.59	78.75	5.21	16.18
	0	0.28	0.08	49.96	7.36	3.88	0.13	0.56	64.06	7.49	4.09
	1	0.28	0.08	50.86	7.26	3.73	0.13	0.56	66.58	7.44	3.86
	2	0.28	0.08	50.93	7.51	3.91	0.13	0.55	77.15	7.66	4.01
	3	0.27	0.07	53.52	7.66	4.07	0.13	0.64	73.76	7.79	4.12
	4	0.27	0.07	53.30	7.79	4.05	0.13	0.62	74.90	7.91	4.13
	5	0.26	0.06	52.62	7.91	4.03	0.13	0.64	77.86	8.04	4.18
	6	0.26	0.12	50.70	8.01	3.96	0.13	0.66	77.97	8.14	4.05
	7	0.26	0.06	48.41	7.94	3.93	0.13	0.61	83.70	8.11	4.09
	8	0.26	0.09	51.63	8.11	4.07	0.13	0.51	87.88	8.29	4.08
	9	0.27	0.06	52.35	7.62	3.89	0.13	0.59	80.21	7.76	3.86
	10	0.26	0.06	54.26	7.91	3.91	0.13	0.66	73.07	8.00	3.91
	11	0.26	0.06	55.17	7.95	3.63	0.13	0.62	72.61	8.04	3.86
	12	0.26	0.06	56.54	7.67	3.61	0.13	0.63	75.97	7.75	3.83
	13	0.26	0.06	57.57	7.17	3.55	0.13	0.58	73.84	7.15	3.77
	14	0.25	0.06	55.03	6.85	3.86	0.13	0.58	62.56	6.79	3.95
	15	0.25	0.06	54.93	6.71	3.82	0.13	0.66	54.83	6.53	6.16
	16	0.25	0.07	54.00	6.69	3.58	0.13	0.60	57.37	6.56	4.15
	17	0.25	0.07	53.64	6.76	3.70	0.13	0.57	56.20	6.72	3.88
	18	0.25	0.06	52.07	7.00	3.69	0.13	0.58	64.10	6.99	3.77
	19	0.25	0.07	51.06	7.12	3.78	0.13	0.56	68.92	7.12	3.90
	20	0.25	0.06	49.16	7.19	3.92	0.13	0.58	64.00	7.27	3.96
	21	0.26	0.06	51.14	7.22	3.80	0.13	0.60	68.64	7.34	3.91
	22	0.25	0.08	51.11	7.36	4.01	0.13	0.55	69.94	7.56	4.06
	23	0.25	0.08	51.22	7.53	4.12	0.12	0.58	68.78	7.65	4.20

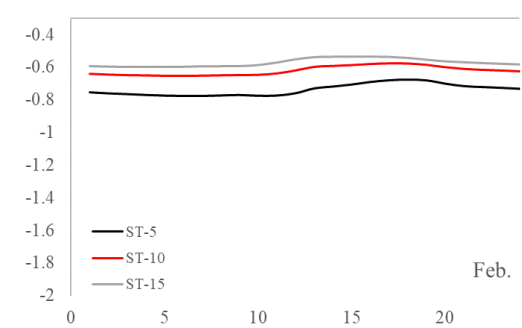
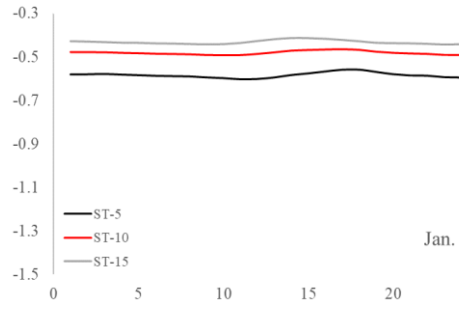
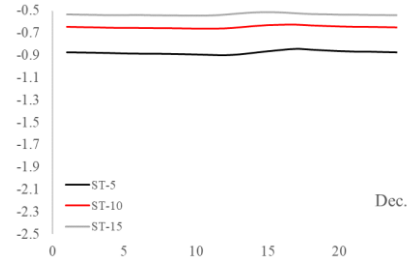
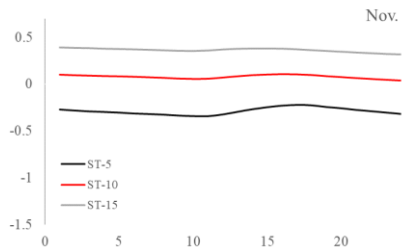
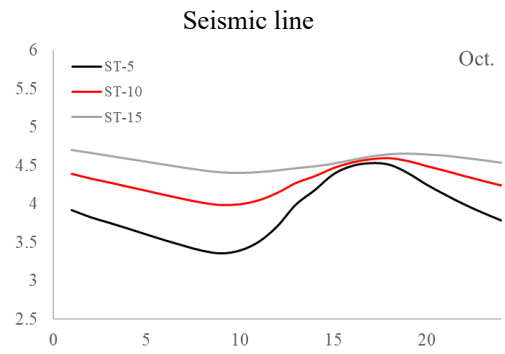
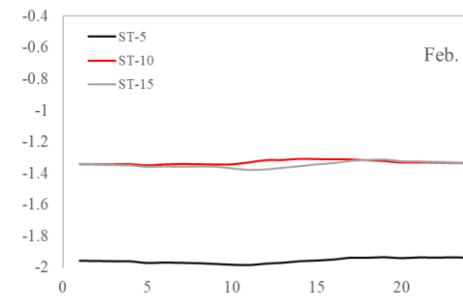
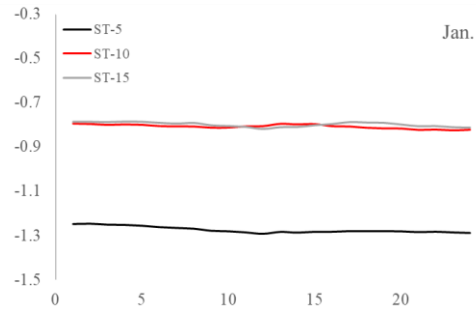
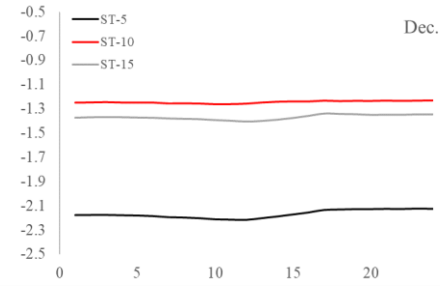
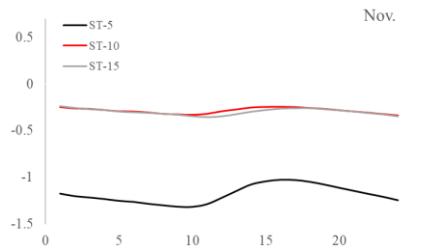
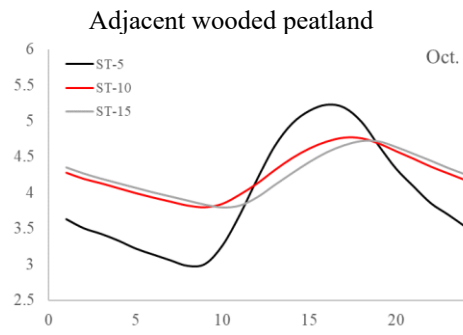
Table S4- Hourly STD of variables at the Maqua site

Month	Hour	Offline							Online						
		TA	RH	WS	WD	NR	PAR	TS	TA	RH	WS	WD	NR	PAR	TS
Apr	0	4.04	16.56	0.08	85.23	7.50	0.00	0.41	4.18	17.40	0.33	93.92	21.72	0.00	0.13
	1	4.13	16.70	0.08	83.67	8.86	0.00	0.39	4.40	17.32	0.35	83.13	21.99	0.00	0.13
	2	4.41	16.71	0.09	80.32	7.59	0.00	0.37	4.68	17.23	0.40	89.44	20.94	0.00	0.13
	3	4.43	15.87	0.08	87.22	7.25	0.00	0.37	4.81	16.58	0.43	97.16	20.82	0.00	0.13
	4	4.41	14.44	0.08	102.22	6.86	0.00	0.36	4.81	15.59	0.48	91.31	19.88	0.00	0.13
	5	4.33	14.21	0.09	77.67	6.46	3.79	0.36	4.75	14.81	0.47	95.40	19.45	6.04	0.13
	6	4.00	15.11	0.10	78.57	6.94	12.81	0.35	4.36	15.71	0.40	99.11	13.46	40.17	0.12
	7	3.66	15.30	0.08	83.29	10.87	30.79	0.36	3.70	15.35	0.39	81.51	118.71	101.14	0.12
	8	4.12	17.47	0.10	98.67	46.36	244.38	0.39	4.16	17.23	0.40	84.19	211.94	204.49	0.13
	9	4.68	18.97	0.12	99.10	62.23	406.93	0.46	4.64	18.53	0.46	64.50	285.72	290.54	0.15
	10	5.07	20.06	0.13	91.92	155.90	486.61	0.54	4.97	19.39	0.33	82.56	212.97	343.09	0.18
	11	5.16	20.68	0.14	111.27	56.72	95.46	0.68	5.16	19.81	0.40	55.34	291.76	324.39	0.22
	12	5.27	20.93	0.14	103.12	32.14	371.63	0.72	5.23	20.43	0.43	66.40	245.05	437.78	0.26
	13	5.51	21.22	0.14	108.40	34.63	290.83	0.88	5.47	20.47	0.37	73.83	198.52	406.02	0.30
	14	5.70	21.47	0.13	107.82	37.37	128.97	1.10	5.48	20.84	0.34	68.27	143.24	362.78	0.30
	15	5.45	21.54	0.14	96.06	90.12	66.67	1.05	5.62	20.56	0.38	86.81	84.73	259.40	0.27
	16	5.33	24.10	0.13	102.89	22.89	98.67	1.00	5.49	23.57	0.35	70.65	87.63	280.46	0.25
	17	5.24	21.63	0.12	86.99	16.89	63.10	0.88	5.42	21.90	0.31	79.38	127.71	205.54	0.23
	18	5.17	21.74	0.09	86.10	19.69	19.04	0.77	5.33	20.79	0.26	93.29	147.71	149.59	0.20
	19	4.96	19.47	0.08	89.46	10.57	10.12	0.68	5.11	19.00	0.26	97.72	41.24	51.36	0.19
	20	4.65	17.87	0.07	106.22	9.23	3.33	0.59	4.80	17.76	0.24	107.37	25.26	7.14	0.17
	21	4.43	17.91	0.08	96.19	7.93	0.00	0.52	4.56	17.46	0.23	95.26	22.89	0.00	0.15
	22	4.41	18.41	0.08	77.32	6.81	0.00	0.47	4.57	18.21	0.30	102.49	22.71	0.00	0.14
	23	3.93	20.61	0.06	99.20	8.01	0.00	0.52	4.17	20.35	0.35	104.83	2.04	0.00	0.11
Mar	0	6.63	10.82	0.02	109.74	5.93	1.34	0.39	6.89	11.89	0.28	88.02	11.11	0.00	0.11
	1	6.68	9.52	0.03	111.84	5.89	0.00	0.39	7.03	10.59	0.25	99.22	9.79	0.00	0.11
	2	6.93	8.68	0.02	110.27	6.33	0.00	0.39	7.17	9.08	0.22	94.97	10.31	0.00	0.11
	3	7.03	8.10	0.03	110.05	5.47	0.00	0.39	7.26	8.18	0.21	97.32	10.63	0.00	0.12
	4	7.25	7.94	0.02	104.30	4.43	0.00	0.40	7.52	7.62	0.21	91.30	9.11	0.00	0.12
	5	7.15	6.51	0.02	107.83	4.78	0.00	0.40	7.40	6.39	0.22	90.58	8.87	0.00	0.12
	6	6.98	5.99	0.01	100.12	5.02	1.87	0.40	7.17	5.53	0.21	98.41	8.75	2.34	0.12
	7	7.06	5.46	0.01	97.64	4.21	14.32	0.40	7.09	5.32	0.22	95.25	6.59	26.89	0.12
	8	6.44	5.41	0.01	105.01	8.84	31.45	0.41	6.58	5.22	0.20	74.31	9.06	74.72	0.12
	9	5.73	12.96	0.03	108.05	14.73	160.49	0.40	5.95	12.11	0.18	67.19	20.13	163.12	0.12
	10	6.05	16.05	0.04	97.22	18.88	331.13	0.41	6.05	15.31	0.19	53.60	26.13	193.11	0.12
	11	6.14	16.71	0.05	98.87	15.40	66.67	0.41	6.24	16.17	0.17	62.35	114.70	293.70	0.12
	12	6.01	18.17	0.07	107.38	21.38	80.69	0.42	6.18	16.89	0.22	67.45	74.59	278.15	0.12
	13	5.88	18.10	0.07	121.88	29.33	95.86	0.41	6.14	16.88	0.22	69.45	62.40	317.28	0.12
	14	5.80	17.51	0.07	110.86	17.29	151.08	0.41	6.03	16.84	0.22	73.87	87.98	284.17	0.11
	15	5.66	17.50	0.07	107.30	34.66	59.85	0.41	5.93	16.85	0.25	70.60	74.30	245.92	0.11
	16	5.57	17.00	0.07	121.96	9.18	43.88	0.40	5.86	17.28	0.29	65.60	21.16	156.68	0.11
	17	5.64	17.99	0.06	115.96	7.73	40.95	0.41	5.77	17.43	0.30	81.51	13.94	87.42	0.11
	18	5.51	16.57	0.04	112.79	6.52	12.28	0.40	5.77	16.82	0.26	89.93	25.40	45.81	0.11
	19	5.46	13.98	0.04	106.06	8.38	2.69	0.41	5.53	14.00	0.28	84.61	16.68	7.80	0.11
	20	5.79	11.96	0.03	115.01	6.44	0.00	0.40	5.96	11.94	0.29	88.54	14.05	0.00	0.10
	21	6.10	12.12	0.03	114.31	6.48	1.34	0.40	6.39	12.67	0.27	88.26	14.46	0.00	0.10
	22	6.38	12.52	0.03	105.39	6.09	1.34	0.39	6.60	12.59	0.28	81.03	12.44	0.00	0.10
	23	6.44	12.19	0.03	105.84	5.87	0.00	0.39	6.65	12.55	0.28	90.71	11.68	0.00	0.10
Feb	0	11.19	8.13	0.04	116.71	5.82	0.00	0.79	11.66	8.73	0.43	90.46	8.87	0.00	0.33
	1	10.92	8.67	0.06	118.25	3.28	0.00	0.77	11.33	8.49	0.55	90.42	13.41	0.34	0.31
	2	11.11	7.68	0.03	113.12	4.19	0.00	0.79	11.67	7.37	0.52	104.39	15.67	0.34	0.32
	3	11.34	8.13	0.01	118.45	5.87	0.00	0.81	11.73	7.65	0.53	89.42	22.00	0.00	0.32
	4	11.35	7.33	0.02	123.98	16.69	0.00	0.81	11.75	7.51	0.57	91.10	43.45	0.00	0.32
	5	10.59	7.43	0.02	115.43	7.57	0.00	0.76	10.91	7.41	0.49	85.78	12.40	0.00	0.31
	6	10.87	8.10	0.04	118.57	4.33	0.00	0.77	11.18	7.66	0.50	85.54	12.34	0.47	0.30
	7	11.48	8.91	0.02	118.80	8.95	1.34	0.85	11.89	8.58	0.45	81.45	12.41	2.89	0.34
	8	9.66	8.58	0.02	106.50	7.66	1.87	0.80	10.00	8.16	0.52	73.65	11.69	13.75	0.31
	9	9.27	8.01	0.02	107.63	10.63	7.10	0.79	9.56	7.86	0.45	83.79	12.06	22.24	0.32
	10	8.57	9.04	0.03	108.68	8.10	8.79	0.77	8.79	10.60	0.44	81.55	18.90	87.25	0.30
	11	8.43	9.60	0.03	106.34	7.46	10.03	0.79	8.70	12.40	0.45	76.74	31.77	88.78	0.29
	12	8.64	11.34	0.04	106.94	6.39	9.81	0.80	8.88	12.86	0.43	76.02	30.78	72.67	0.30
	13	8.31	11.06	0.04	109.21	6.35	8.94	0.81	8.52	13.56	0.37	70.36	26.78	61.84	0.30
	14	8.15	11.35	0.03	111.38	6.19	8.19	0.76	8.32	13.86	0.41	79.21	17.22	42.82	0.29
	15	8.21	11.21	0.03	111.95	4.24	5.45	0.75	8.35	13.80	0.34	88.44	21.23	21.78	0.28
	16	9.49	11.29	0.02	117.42	6.24	3.33	0.81	9.79	12.78	0.36	83.99	13.09	12.80	0.30
	17	9.73	10.99	0.02	109.90	6.12	0.00	0.81	10.20	11.89	0.41	84.77	12.22	1.06	0.30
	18	10.52	10.01	0.01	108.06	3.94	0.00	0.76	11.07	10.88	0.40	92.27	11.70	0.00	0.30
	19	10.65	10.28	0.02	108.57	4.52	0.00	0.78	11.09	10.80	0.34	78.38	10.54	0.00	0.31
	20	11.33	9.70	0.03	113.04	6.08	0.00	0.78	11.94	10.78	0.41	90.02	15.14	0.00	0.30
	21	10.35	8.18	0.01	114.38	5.69	0.00	0.81	10.77	8.95	0.27	94.33	8.55	0.00	0.30
	22	10.35	8.18	0.01	114.38	5.69	0.00	0.81	10.77	8.95	0.27	94.33	8.55	0.00	0.30
	23	10.35	8.18	0.01	114.38	5.69	0.00	0.81	10.77	8.95	0.27	94.33	8.55	0.00	0.30

Jan	0	6.08	4.77	0.01	58.60	2.39	0.00	0.34	6.37	5.02	0.36	106.89	6.34	0.00	0.15
	1	6.17	4.82	0.01	69.45	2.26	0.00	0.35	6.48	5.12	0.40	107.17	8.81	0.00	0.15
	2	6.29	4.94	0.01	52.73	2.58	0.00	0.35	6.63	5.38	0.42	115.86	6.37	0.00	0.15
	3	6.38	5.10	0.01	54.90	2.58	0.00	0.35	6.70	5.39	0.46	98.59	7.35	0.00	0.15
	4	6.49	5.08	0.02	39.57	2.30	0.00	0.35	6.82	5.35	0.45	117.26	13.08	0.00	0.16
	5	6.59	5.22	0.02	67.69	3.03	0.00	0.35	6.78	5.24	0.47	105.32	31.28	0.00	0.16
	6	6.45	4.96	0.01	57.63	3.44	0.00	0.36	6.55	5.07	0.43	92.84	15.82	0.00	0.16
	7	6.42	5.23	0.01	60.63	3.13	0.00	0.36	6.51	5.11	0.41	100.90	9.47	0.00	0.16
	8	6.48	5.30	0.01	39.95	7.09	0.00	0.36	6.56	5.04	0.39	107.32	8.44	0.47	0.16
	9	6.27	5.20	0.01	42.56	8.32	1.87	0.37	6.35	4.95	0.37	98.12	8.80	4.17	0.17
	10	6.01	4.91	0.00	42.91	3.65	8.13	0.36	6.12	4.85	0.42	98.95	5.80	16.73	0.17
	11	5.87	5.01	0.02	45.28	4.53	16.22	0.37	5.98	5.17	0.42	104.43	6.96	23.01	0.17
	12	5.75	4.95	0.03	56.78	3.78	15.92	0.37	5.91	5.67	0.40	101.95	8.74	21.13	0.16
	13	5.70	4.76	0.02	51.84	3.58	15.28	0.38	5.86	5.94	0.41	91.37	10.57	21.42	0.16
	14	5.69	4.72	0.01	46.94	4.00	14.19	0.37	5.92	6.35	0.37	84.59	14.11	26.39	0.16
	15	5.59	4.49	0.01	40.10	2.79	7.90	0.38	5.82	5.93	0.35	105.28	8.51	29.73	0.16
	16	5.51	4.46	0.01	47.44	2.90	0.00	0.38	5.67	5.02	0.33	83.82	9.83	9.76	0.16
	17	5.52	4.10	0.01	37.92	3.08	0.00	0.38	5.69	4.77	0.38	107.79	14.56	1.36	0.16
	18	5.44	4.30	0.01	47.57	4.11	0.00	0.39	5.70	4.67	0.42	104.11	9.75	0.00	0.16
	19	5.70	4.62	0.01	56.75	3.84	0.00	0.38	5.95	4.58	0.39	105.00	10.24	0.00	0.16
	20	5.84	4.49	0.01	63.98	2.95	0.00	0.39	6.03	4.38	0.36	102.02	10.50	0.00	0.16
	21	5.88	4.72	0.00	63.01	2.42	0.00	0.39	6.08	4.55	0.34	107.14	9.48	0.00	0.16
	22	6.03	4.81	0.01	63.07	2.20	0.00	0.39	6.30	4.97	0.35	105.75	5.57	0.00	0.16
	23	6.28	4.94	0.01	67.59	2.43	0.00	0.39	6.49	4.93	0.32	93.00	7.19	0.00	0.16
Nov	0	7.80	7.79	0.01	120.10	5.49	0.00	0.73	8.22	10.15	0.40	98.91	16.97	0.00	0.65
	1	7.87	7.67	0.02	101.32	4.57	0.00	0.75	8.30	10.53	0.36	88.79	13.37	0.00	0.64
	2	7.83	7.87	0.03	126.52	4.40	0.00	0.69	8.23	10.30	0.37	103.11	12.92	0.00	0.61
	3	7.94	8.15	0.04	121.01	4.76	0.00	0.68	8.32	10.51	0.35	107.60	14.67	0.00	0.61
	4	7.98	8.02	0.03	123.74	5.74	0.00	0.68	8.41	10.47	0.34	94.71	16.13	0.00	0.60
	5	8.10	8.30	0.02	99.70	4.55	0.00	0.66	8.66	10.61	0.34	108.85	13.71	0.00	0.58
	6	8.31	7.86	0.04	72.17	4.87	0.00	0.66	8.75	10.17	0.32	96.20	13.53	0.00	0.57
	7	8.25	7.77	0.03	89.63	4.97	2.25	0.66	8.71	10.74	0.32	108.90	13.63	2.57	0.56
	8	8.51	8.69	0.03	95.08	4.74	4.95	0.70	9.01	11.17	0.34	99.96	14.03	12.09	0.57
	9	7.48	7.57	0.05	90.56	7.97	16.61	0.68	7.76	10.06	0.32	94.32	14.74	31.93	0.57
	10	6.95	7.98	0.03	116.14	9.06	11.51	0.69	7.17	10.02	0.36	85.79	13.24	35.87	0.58
	11	6.94	8.89	0.03	118.27	13.50	19.44	0.64	7.03	10.74	0.42	73.80	18.05	58.46	0.56
	12	6.97	9.12	0.03	126.27	31.66	11.87	0.63	7.05	10.91	0.43	87.69	14.13	55.73	0.55
	13	7.03	8.54	0.03	107.24	4.34	12.73	0.61	7.15	11.07	0.42	69.20	15.31	47.30	0.55
	14	7.13	9.64	0.03	118.22	3.79	11.16	0.59	7.37	11.11	0.37	86.98	13.60	41.76	0.54
	15	7.04	8.56	0.03	115.17	4.62	4.92	0.58	7.33	10.79	0.35	100.26	18.00	25.62	0.53
	16	7.17	7.25	0.04	102.95	6.36	2.80	0.58	7.42	10.50	0.41	95.27	22.66	7.08	0.52
	17	7.18	6.46	0.02	110.23	6.93	0.00	0.58	7.59	9.78	0.41	83.37	20.80	0.00	0.51
	18	7.51	7.71	0.03	116.24	6.29	0.00	0.59	7.86	10.62	0.49	96.33	20.25	0.00	0.51
	19	7.55	6.92	0.02	101.09	5.62	0.00	0.60	7.99	9.30	0.47	98.11	18.75	0.00	0.51
	20	7.99	8.27	0.03	111.04	5.41	0.00	0.61	8.47	10.30	0.50	96.78	20.13	0.00	0.51
	21	8.11	7.79	0.03	109.03	5.18	0.00	0.62	8.64	10.33	0.46	102.01	17.93	0.00	0.51
	22	8.10	7.60	0.02	120.49	4.91	0.00	0.63	8.58	10.02	0.41	98.49	16.35	0.00	0.51
	23	12.27	9.96	0.03	46.56	7.93	0.00	0.74	12.90	11.86	0.54	103.88	20.40	0.00	0.14
Oct	0	5.19	15.86	0.07	112.33	5.84	1.34	1.91	5.53	17.10	0.43	78.90	17.00	0.00	1.99
	1	5.24	15.51	0.07	104.61	5.96	1.34	1.89	5.67	16.99	0.46	86.39	17.34	0.00	1.96
	2	5.47	15.55	0.06	104.56	5.95	0.00	1.88	5.86	16.95	0.48	86.04	19.44	0.00	1.93
	3	5.07	15.22	0.05	96.27	6.29	1.34	1.86	5.45	15.90	0.51	90.95	19.12	0.00	1.89
	4	5.10	14.79	0.05	98.46	6.05	0.00	1.82	5.38	15.47	0.47	83.74	17.96	0.00	1.86
	5	5.17	14.76	0.05	107.88	7.12	1.87	1.79	5.45	15.77	0.45	81.97	16.27	0.00	1.82
	6	5.08	15.31	0.06	111.16	5.73	0.00	1.76	5.32	16.33	0.47	73.54	15.83	0.00	1.78
	7	4.95	15.77	0.04	99.61	9.06	3.79	1.73	5.18	16.47	0.42	81.04	17.50	11.29	1.76
	8	5.18	17.18	0.05	91.09	8.68	14.30	1.73	5.47	17.51	0.43	65.00	17.51	34.48	1.74
	9	5.37	17.82	0.07	83.46	11.64	52.36	1.75	5.67	17.43	0.52	70.25	25.54	68.24	1.74
	10	6.14	17.64	0.09	101.96	11.78	314.86	1.82	6.17	17.21	0.59	50.97	34.86	99.13	1.76
	11	6.40	16.80	0.11	79.50	17.70	43.56	1.88	6.51	17.05	0.58	66.97	90.08	239.77	1.80
	12	6.80	16.88	0.11	91.46	17.42	50.28	1.96	6.77	16.89	0.54	43.76	39.98	146.09	1.90
	13	6.81	17.26	0.13	103.99	28.16	35.14	2.02	6.82	17.34	0.50	46.34	43.37	143.21	1.98
	14	6.77	18.14	0.14	103.58	11.79	148.36	2.04	6.80	18.06	0.55	66.95	59.50	186.87	2.06
	15	6.69	19.49	0.13	90.15	9.91	20.86	2.07	6.82	19.75	0.49	57.50	26.06	96.84	2.11
	16	6.52	20.13	0.13	95.92	7.99	12.79	2.08	6.67	20.27	0.52	57.64	21.29	62.73	2.15
	17	5.90	19.26	0.10	120.56	5.84	8.05	2.08	6.09	19.84	0.50	78.47	16.47	33.25	2.17
	18	5.37	17.65	0.08	103.37	6.16	2.80	2.05	5.50	18.85	0.46	85.38	17.08	7.54	2.16
	19	5.25	17.09	0.09	111.18	6.84	0.00	2.02	5.50	18.49	0.49	84.16	18.42	0.00	2.12
	20	5.31	16.20	0.07	110.81	5.76	0.00	1.99	5.65	18.18	0.46	73.91	17.33	0.00	2.08
	21	5.04	16.06	0.06	103.61	5.67	0.00	1.96	5.49	17.78	0.44	78.86	16.95	0.00	2.03
	22	5.02	16.15	0.08	115.62	6.27	0.00	1.91	5.44	17.77	0.43	75.77	18.66	0.00	1.98
	23	4.93	15.67	0.06	102.69	5.54	0.00	1.88	5.32	17.15	0.43	75.43	17.31	0.00	1.93
Dec	0	7.32	6.18	0.01	110.78	2.76	0.00	0.54	7.52	6.01	0.40	101.78	8.06	0.00	0.28
	1	7.46	6.34	0.01	116.24	2.04	0.00	0.53	7.55	6.03	0.40	112.74	7.11	0.00	0.28
	2	7.43	6.13	0.01	113.73	2.60	0.00	0.53	7.54	5.99	0.40	96.09	7.48	0.34	0.28

3	7.54	6.30	0.00	114.54	1.83	0.00	0.53	7.64	6.18	0.38	96.82	6.72	0.00	0.29
4	7.72	6.38	0.01	112.61	2.12	0.00	0.52	7.81	6.26	0.38	89.05	5.96	0.34	0.29
5	7.89	6.48	0.01	116.96	2.04	0.00	0.52	8.07	6.33	0.34	110.42	7.22	0.49	0.29
6	7.94	6.56	0.01	112.61	1.98	1.34	0.53	8.06	6.30	0.31	106.48	5.90	0.34	0.29
7	8.06	6.43	0.03	112.34	3.14	0.00	0.53	8.23	6.37	0.35	104.30	6.51	0.49	0.30
8	8.12	6.75	0.01	112.54	1.98	0.00	0.54	8.33	6.43	0.28	107.84	5.23	0.34	0.30
9	8.07	6.33	0.01	112.60	2.88	2.25	0.55	8.28	6.33	0.31	106.18	4.99	3.96	0.30
10	7.79	6.00	0.03	116.88	3.62	5.45	0.55	7.95	5.98	0.35	99.34	7.33	12.51	0.31
11	7.32	5.62	0.04	114.97	4.27	9.54	0.55	7.38	5.56	0.33	93.47	7.18	22.51	0.31
12	6.69	5.40	0.04	111.82	4.67	13.31	0.55	6.73	5.23	0.32	89.34	6.92	26.94	0.30
13	6.63	5.75	0.04	116.72	3.32	15.58	0.55	6.65	5.26	0.30	97.44	6.27	30.32	0.30
14	6.66	5.70	0.04	116.26	2.57	15.07	0.54	6.75	5.24	0.29	88.44	7.67	23.06	0.29
15	6.63	5.71	0.03	117.80	2.30	4.53	0.54	6.82	5.19	0.29	91.87	9.29	13.30	0.29
16	6.82	6.08	0.03	109.79	2.29	1.87	0.54	6.98	5.37	0.30	92.80	8.30	2.84	0.29
17	7.20	6.22	0.01	113.42	2.07	0.00	0.54	7.31	5.39	0.35	106.96	8.24	0.00	0.29
18	7.15	5.95	0.01	115.08	3.18	0.00	0.54	7.23	5.44	0.42	86.85	7.66	0.00	0.28
19	7.22	6.21	0.01	107.01	2.26	0.00	0.55	7.29	5.83	0.39	93.42	8.06	0.00	0.28
20	7.37	6.33	0.01	103.25	1.89	0.00	0.54	7.48	5.91	0.42	98.67	6.41	0.00	0.28
21	7.58	6.60	0.01	114.64	1.71	0.00	0.54	7.73	6.18	0.44	108.58	8.64	0.00	0.28
22	7.66	6.12	0.01	100.46	2.35	0.00	0.55	7.88	6.15	0.42	96.64	8.41	0.00	0.28
23	7.66	6.38	0.00	114.79	3.27	0.00	0.55	7.88	6.38	0.43	101.19	7.78	0.00	0.28

Soil Temperature (°C)



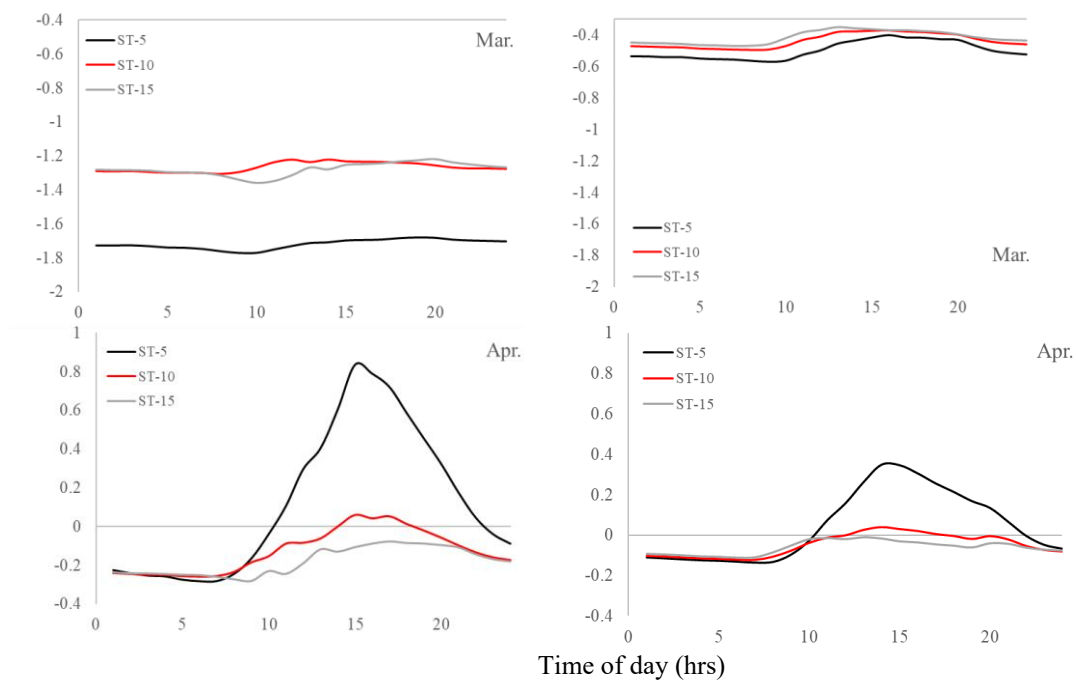


Figure S1- The average hourly soil temperature for each month plotted by time of day October 2022 to April 2023

Appendix B

Table S1- The required parameters to estimate PET.

Parameter	Formula	Descriptions
Δ	$\frac{2504 \exp(\frac{17.27T}{T+237.2})}{(T+237.3)^2}$	
T	Air temperature (°C)	
γ	0.000665 P	
λ	2.45 MJ/kg	
P	$101.3(\frac{293 - 0.0065Z}{293})^{5.26}$	Z is elevation (m)
e^*	$\frac{e^o(T_{max}) + e^o(T_{min})}{2}$	
e^o	$0.6108 \exp(\frac{17.27T}{T+237.3})$	
c_p	$1.013 \times 10^{-3} \text{ MJ kg}^{-1} \text{ C}^{-1}$	
C_{at}	$\frac{\ln(\frac{Z_w - d}{Z_{om}}) \ln(\frac{Z_h - d}{Z_{oh}})}{0.41^2 u_z}$	Z _w =Height of wind measurements Z _h = Height of humidity and air temperature measurements d=zero plane displacement height (m). =0.67h Z _{om} =Roughness length governing momentum transfer (m), =0.123h Z _{oh} = Roughness length governing transfer of heat and vapour (m), =0.0123h Wind speed at height of z (ms ⁻¹) H= mean height of the vegetation, m
ρ_a	$3.486 \frac{P}{1.01(T+273)}$	
ρ_w	10^6 g/m^3	

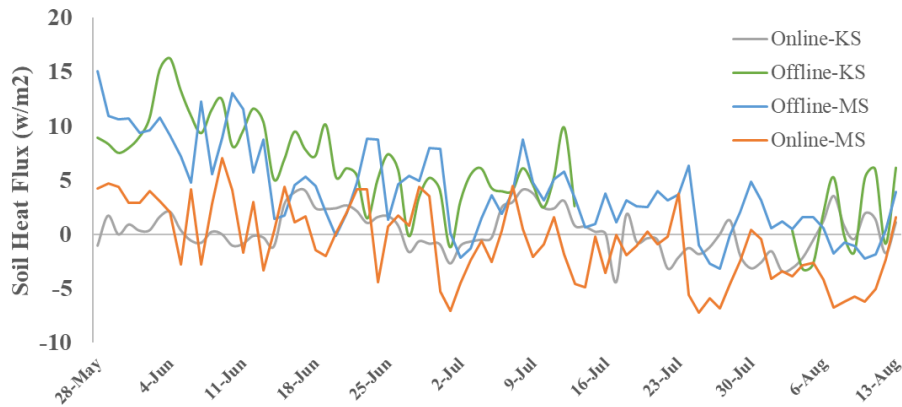


Figure S1- Soil heat flux variation between on and off the line at both sites from May 30 to August 13 in 2022 at KS and 2023 at MS

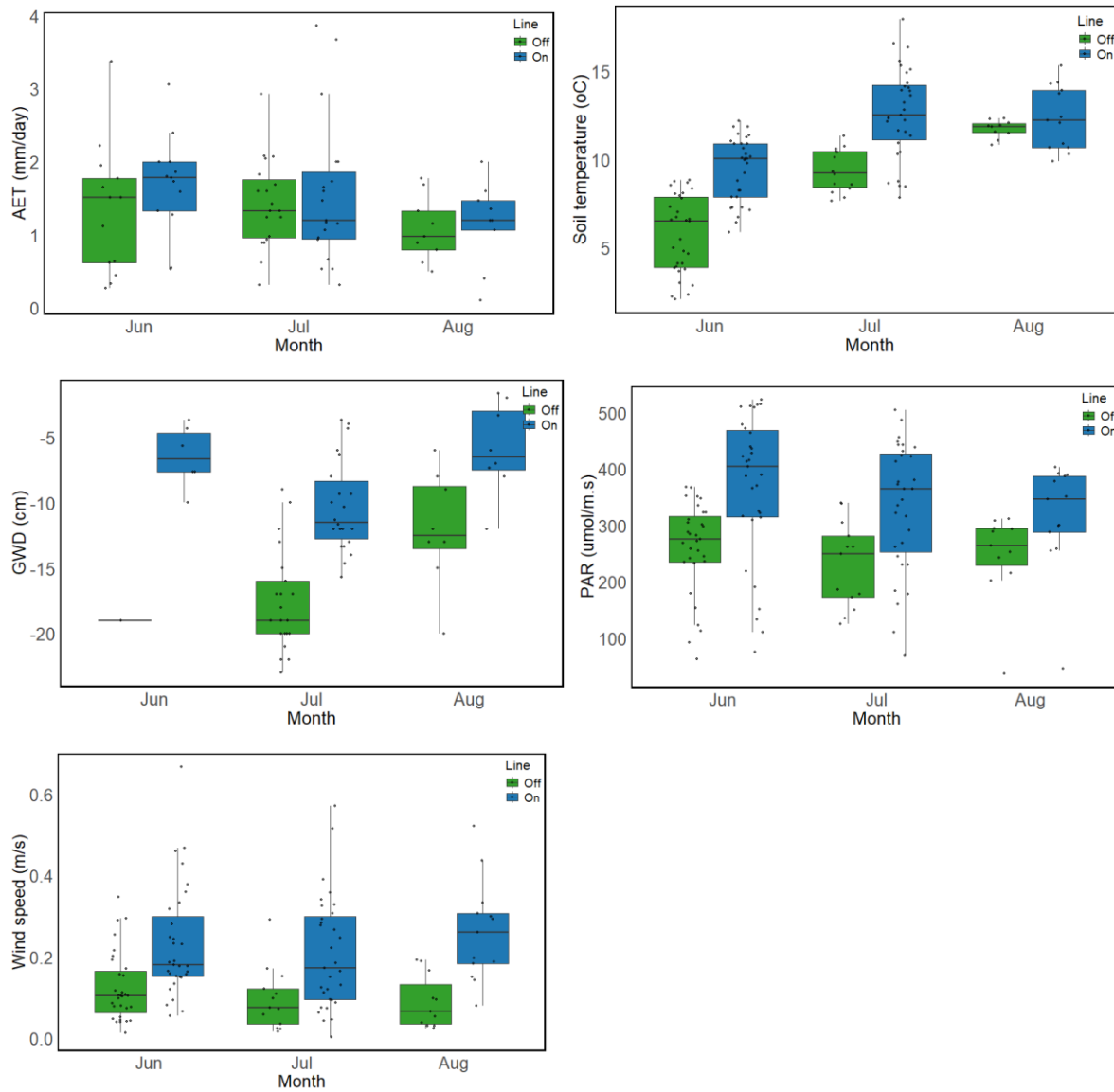


Figure S2- The monthly variation of AET and the drivers based on lysimeter measurements

Appendix C

Table S1- Structure of the model based on changes in the modules.

Modules	Name	Online Options	Offline Options
Drainage and deep percolation	Physical Drain Eq	Linear Model	Linear Model
Interception	Prec Interception	--	on
	Snow Interception	--	on
Meteorological Data	Cloud Input	Estimated (sunshine)	Estimated (sunshine)
	Hum Rel Input	Read from PG-file	Read from PG-file
	Prec Input	Read from PG-file	Read from PG-file
	Temp Air Input	Read from PG-file	Read from PG-file
	Vapour Air Input	As relative humidity	As relative humidity
Model structure	Evaporation	Radiation input style	Radiation input style
	Ground Water Flow	on	on
	Plant Type	Explicit big leaves	Explicit big leaves
	Snow Pack	on	on
	Soil Vapour	Soil and Snow Vapour flow	Soil and Snow Vapour flow
	Water Eq	On with complete soil profile	On with complete soil profile
Plant	Above Table	No	No
Radiation properties	Long Wave Balance	Two separate formulas	Two separate formulas
Snowpack	Snow Ploughing	Driven by Snow Mass	Driven by Snow Mass
Soil Hydraulic	Conductivity Function	Power of effective saturation	Power of effective saturation
	Hydraulic Functions	Genuchten	Genuchten
	Matric Conductivity	Function of total conductivity	Function of total conductivity
Soil evaporation	Evaporation Method	Iterative Energy Balance	Iterative Energy Balance
	Surface Temperature	F (E-balance Solution)	F (E-balance Solution)
Soil heat flows	Convection flow	Not accounted for	Not accounted for
	Initial Heat Conditions	Temp (z)- Estimated	Temp (z)- Estimated
Technical	Type Of Driving File	Standard driving file	Standard driving file
	Validation Mode	six	six

Table S2- List of used parameters for calibration

	Modules	Table name	Value	Unit s							Reference		
Online	Parameter tables	Plant	Canopy height - multiple canopies	0.1	#							Garisoain et al. (2023)	
			Leaf Area Index - multiple canopies	10	m ² /m ²								
		Soil Hydraulic	Root depths - multiple canopies	-0.1	m								
			Genuchten, water retention, measured horizons	0-0.4	m	0.47 (m)	1.6 (n)	0.11 (α)	80 (θ _s)	37 (θ _{wilt})	35 (θ _r)		Price and Whittington (2010).
				0.4-1	m	0.35 (m)	1.8 (n)	0.06(α)	86(θ _s)	40(θ _{wilt})	46(θ _r)		
		Hydraulic conductivity, measured horizons	0-0.4	m	3500 (Matrix)	4500 (Total)	8 (Macro pore)				Liu and Lennartz (2019)		
			0.4-1	m	450 (Matrix)	450 (Total)	4 (Macro pore)				Boelter (1968)		
		Drainage and deep percolation	Drain Spacing	1000	m								
			GW Source Flow	0.4	mm/day								
			GWSource Layer	1	#								
	Meteorological data	Temp Air Ampl	15	°C							Environment Canada (2020)		
		Plant Radiation Properties	Tem Air Mean	0.7	°C							Finne et al. (2023)	
			Albedo Leaf	--	%								
			Albedo	17	%								
Soil Thermal	Albedo Dry	22	%							Field measurements			
	Albedo Wet	--	%										
	Latitude	56.37	-										
	Organic Layer Thick	1	m										
Offline	Parameter tables	Plant	Canopy height - multiple canopies	4	m							Bond-Lamberty et al. (2002)	
			Leaf Area Index - multiple canopies	0.1	m ² /m ²								
		Soil Hydraulic		2	m ² /m ²								
			Root depths - multiple canopies	10	m ² /m ²								
				Root depths - multiple canopies	-0.5	m							Tarroux et al. (2014)
		Genuchten, water retention, measured horizons	-0.1	m							Price and Whittington (2010).		
			0-0.4	m	0.3 (m)	1.25 (n)	8.5 (α)	91 (θ _s)	36 (θ _{wilt})	36 (θ _r)			
			0.4-1	m	0.35 (m)	1.8(n)	0.06(α)	86(θ _s)	40(θ _{wilt})	46(θ _r)			
		Hydraulic conductivity, measured horizons	0-0.4	m	15800 (Matrix)	15800 (Total)	7 (Macro pore)				Boelter (1968)		
			0.4-1	m	450 (Matrix)	450 (Total)	6 (Macro pore)				Boelter (1968)		
	Para	Drainage and deep percolation	Drain Spacing	1000	m								
			GW Source Flow	0.1	mm/day								

Meteorological data	GWSource Layer	1	#	Environm ent Canad (2020)
	Temp Air Ampl	15	°C	
Plant	Tem Air Mean	0.7	°C	Berglund and Mace (1976).
	Albedo Leaf	20	%	
Radiation Properties	Albedo	--	%	Finne et al. (2023)
	Albedo Dry	25	%	
Soil Thermal	Albedo Wet	18	%	Field measurem ents
	Latitude	56.37	-	
	Organic Layer Thick	1.2	m	

Table S3-Sensitivity of analysis of modelling

Line	Variables	Plant community composition					Soil properties		Site location		
		Canopy height	LAI	Root depth	Albedo leaf	Albedo moss	Genuchten	Hydraulic conductivity	Organic Layer Thick	Tem Air Mean	Latitude
Online	Snow depth	0.00	0.00	0.00	---	0.00	0.02	0.00	0.00	0.00	0.02
	Water storage	0.10	0.38	0.03	---	0.59	1.52	0.24	0.00	0.02	2.41
	Drainage	0.19	2.18	1.09	---	1.45	18.90	0.36	0.00	0.93	4.02
	Runoff	0.09	1.09	0.54	---	0.85	12.00	0.08	0.00	0.51	2.60
	Evapotranspiration	0.01	0.62	0.14	---	1.22	0.19	0.08	0.00	0.09	3.87
	GWD	0.04	0.65	0.11	---	1.00	15.04	0.41	0.00	0.86	2.34
	Snow density	0.00	0.00	0.00	---	0.00	0.09	0.01	0.00	0.00	0.08
	Ts	0.16	9.50	0.04	---	0.99	1.11	0.20	0.00	1.46	5.40
	VWC	0.14	0.43	0.01	---	0.30	4.93	0.28	0.00	0.09	1.24
	NR	0.06	2.82	0.22	---	5.50	0.10	0.12	0.00	0.20	118.44
Offline	Snow depth	0.01	0.03	0.02	0.05	0.00	0.06	0.04	0.02	0.02	0.00
	Water storage	0.02	0.30	0.23	0.97	0.55	30.53	0.80	0.16	0.43	0.32
	Drainage	4.24	0.29	0.62	6.55	27.23	105.61	8.86	18.45	8.21	14.69
	Runoff	3.79	6.46	5.50	6.74	4.67	5.87	5.13	0.51	11.14	1.62
	Evapotranspiration	2.03	1.63	0.28	0.09	0.37	3.07	0.97	0.13	0.62	0.77
	GWD	0.10	0.46	1.26	1.63	1.52	6.19	0.14	0.26	0.92	1.03
	Snow density	0.06	0.05	0.04	0.09	0.01	0.70	0.10	0.07	0.05	0.03
	Ts	0.07	11.21	3.78	4.19	1.40	4.40	2.75	2.95	0.83	9.05
	VWC	0.81	1.25	0.43	0.11	0.18	32.58	0.38	0.35	0.62	0.55
	NR	0.01	0.16	0.32	14.90	10.93	6.81	1.79	0.41	0.32	81.08

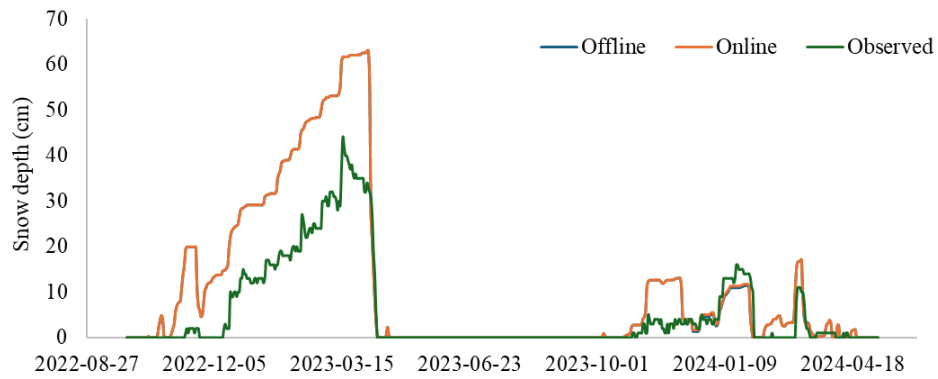


Figure S1- The simulated snow depth on the line and off the line and the observed values from the nearby station (i.e., the Fort McMurray CS station (ECCC, 2024), 40 km from the study site).