Assessing the effects of resource extraction and climate-related disturbances on the growth of *Picea mariana* (Mill.) B.S.P. (Pinaceae) in boreal peatlands in the Hudson Bay Lowland, Canada

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SUMMARY

The peatland-dominated Hudson Bay Lowland (HBL) is facing increasing pressures from climate change and resource extraction operations. Despite the potential for widespread changes in water availability to occur, information about hydrological and ecological feedbacks in the HBL remains limited. This study, located near the De Beers Victor diamond mine ~90 km west of Attawapiskat (Ontario, Canada), investigates the influence of mine dewatering activities ('pumping') and climatic variability on the radial growth of black spruce (*Picea mariana* (Mill.) B.S.P.) trees. Tree stem disks were collected from stunted black spruce trees in one reference (n=25) and three mine-affected bogs within the area of dewatering influence (n=41) along a transect of variable underlying aquitard (marine sediment) thickness. Pumping was not found to have influenced annual ring-width indices (RWIs) in mine-affected areas with either thick (6 to >18 m) or thin (< 5m) underlying marine sediment, as these sites showed similar growth patterns to the reference site during the period of mine operation. Analyses of the influence of climate on tree radial growth (1970–2018) using 20-year moving windows showed significant ($p < 0.05$) positive correlations (Pearson R) between residual RWI and mean monthly air temperature, including June (1979–2007 excluding the window of 1986–2006), August (1989–2018) and September (1984–2009). In addition, for the period during which ground temperature data were available (2011–2018), significant negative correlations were detected between residual RWI and mean monthly soil temperatures in late winter and early spring. The above relationships highlight the importance of both growing and shoulder season conditions for tree growth. As the HBL continues to respond to climate change, the growth response and potential proliferation of black spruce will undoubtedly influence the water balance and hydrological function of bog peatlands in the region.

KEY WORDS: black spruce, dendrochronology, hydrometeorological data, James Bay Lowland

INTRODUCTION

The Hudson Bay Lowland (HBL) is the third largest wetland complex in the world (Heginbottom *et al.* 1995) with roughly 90 % of its land area covered by patterned bog and fen peatlands (Glaser *et al.* 2004). Peatland development in the HBL is enhanced by cool and humid meteorological conditions as well as by the presence of a fine-grained marine sediment aquitard, which constrains hydrological connectivity between the peatlands and the Silurian limestone bedrock aquifers below (McDonald 1969, Martini 1981), helping to sustain shallow water tables. As a result of these factors, peatlands act as important water storage and conveyance features, providing runoff and sub-surface flow to down-gradient streams and rivers (Richardson *et al.* 2012, Orlova & Branfireun 2014, Balliston & Price 2022) and an essential source of freshwater to the brackish Hudson and James Bays (Rouse *et al.* 1992).

Due to its northern extent, the HBL is particularly sensitive to hydrometeorological changes (i.e., increasing temperatures and changing weather patterns) induced by climate change (Smith & Burgess 2004). Prior climate models simulated for the region have predicted a continued increase in air temperature and soil moisture variability (Gagnon & Gough 2005, Furgal & Prowse 2008); however, changes to the timing and quantity of precipitation are less certain (Gagnon & Gough 2005). The region also faces increasing pressure from proposed and existing resource extraction operations such as the proposed Ring of Fire mineral deposit project (Ontario Ministry of Energy, Northern Development and Mines 2020) and the De Beers Victor diamond mine (hereafter referred to as 'the Victor Mine') located 90 km west of Attawapiskat, Ontario (Whittington & Price 2013). At the Victor Mine, which operated from 2007 to 2019, high-volume groundwater extraction was required to maintain minable conditions, which caused the water level to fall from near surface to approximately 275 m below the ground surface at its deepest position in 2019 (Wood Environment & Infrastructure Americas 2021). This caused a local cone of groundwater depression in the upper bedrock formation underlying the marine sediment aquitard, across an area of roughly 350 km^2 around the mine (Itasca 2015).

Changes in direction and/or strength of the (downward) hydraulic gradients between peatland and underlying mineral aquifers can cause a deepening of peatland water tables (Whittington & Price 2013, Balliston & Price 2023), which can subsequently influence the growth dynamics of trees that inhabit these systems. Artificial water table drainage (through ditches) was shown to enhance the growth of black spruce in a treed fen in the boreal plains of Alberta through enhanced soil aeration and warmer soil temperatures (Silins & Rothwell 1998, Macdonald & Yin 1999). Increases in tree growth can subsequently lead to water table feedbacks which further enhance water table variability (Waddington *et al*. 2015). These feedbacks include increased transpiration and interception (positive drying feedback), changes to peat hydrophysical properties due to enhanced decomposition (positive), increased shading and reduced moss evaporation (negative), and altered aerodynamic resistance to evapotranspiration which may increase surface roughness (positive) up to a threshold at which tree density becomes high enough to form a smoother aerodynamic surface (negative).

Few studies in the HBL have focused on the growth of peatland black spruce, except for those by Talarico (2009) and Perrette (2010) which addressed the effects of mining within the first few years of pumping. Furthermore, no studies have investigated the sensitivity of HBL black spruce to climatic factors in a mine dewatered environment. The research reported here aimed to better understand the hydrological and hydrometeorological limitations to the growth of black spruce in the HBL and the sensitivity of this species to drying conditions. The specific objectives were to:

1. identify the primary climatic and hydrological factors that limit or enhance black spruce growth in HBL bogs by combining a dendrochronological approach with collection of comprehensive hydrometeorological data; and
2. assess whether reduced water availability to peatlands (over 12 years of mine pumping) has led to an increase in the radial growth of black spruce and whether this response is related to thickness of the underlying confining layer.

METHODS

Study site

The study was conducted in the vicinity of the Victor Mine (51° 51′ 13″ N, 83° 56′ 26″ W) in the James Bay Lowland (JBL), which is the southern portion of the larger Hudson Bay Lowland (HBL) of Ontario (Figure 1). The JBL has a humid microthermal-subarctic climate, according to the Köppen Climate Classification System (Peel *et al*. 2007). The nearest weather station, Lansdowne House (270 km southwest) reported 40-year (1979–2018) average January and July temperatures of -21.5 °C and 15.7 °C, respectively. Average annual precipitation over the same period was 665 mm (Environment Canada 2015). *Sphagnum* (moss) is the dominant peat-forming genus in this area, with additional cover of lichens, ericaceous shrubs and trees (Sjörs 1963). Black spruce (*Picea mariana* (Mill.) B.S.P.) is the dominant tree species in bogs of the region (Pereg & Payette 1998). Individual trees are typically stunted as their growth is limited by the saturated conditions (poor soil aeration) (Lahde 1969, Mannerkoski 1985), low soil temperatures (Rothwell 1991) and low nutrient availability (Humphrey & Pluth 1996) in peatland systems. Larger black spruce trees are typically restricted to bedrock outcrops (bioherms) and areas close to streams and rivers where lower water tables provide better growing conditions.

Site selection

Tree-ring samples were collected from three bog systems within the 1 m drawdown contour (Itasca 2015) of the mine-affected area and one reference bog outside of the mine-affected area (Figure 1). Mine-affected bog sampling locations were located along a groundwater monitoring transect ~3.5–4.5 km northwest of the Victor Mine (see Whittington & Price 2012 for a detailed description of the transect). Within this area, the thickness of marine sediment (MS) varies and is thickest (>18 m) at the centre of the transect, becoming progressively thinner towards the ends of the transect where MS thickness reaches zero at the two bioherms. The peat layer also becomes progressively thinner toward the bioherms, eventually disappearing (Whittington & Price 2013). Previous studies had found that bog areas overlying thinner MS are susceptible to enhanced water table decline from mine dewatering (Balliston & Price 2023). Therefore, mine-affected locations were divided into separate groups characterised by thin (4 locations) or thick (5 locations) MS. Two locations within 100 m of each bioherm were designated as thin MS locations (Figure 1c). The remaining five locations, designated as thick, were in areas with MS thicknesses ranging from 6 m to >18 m.

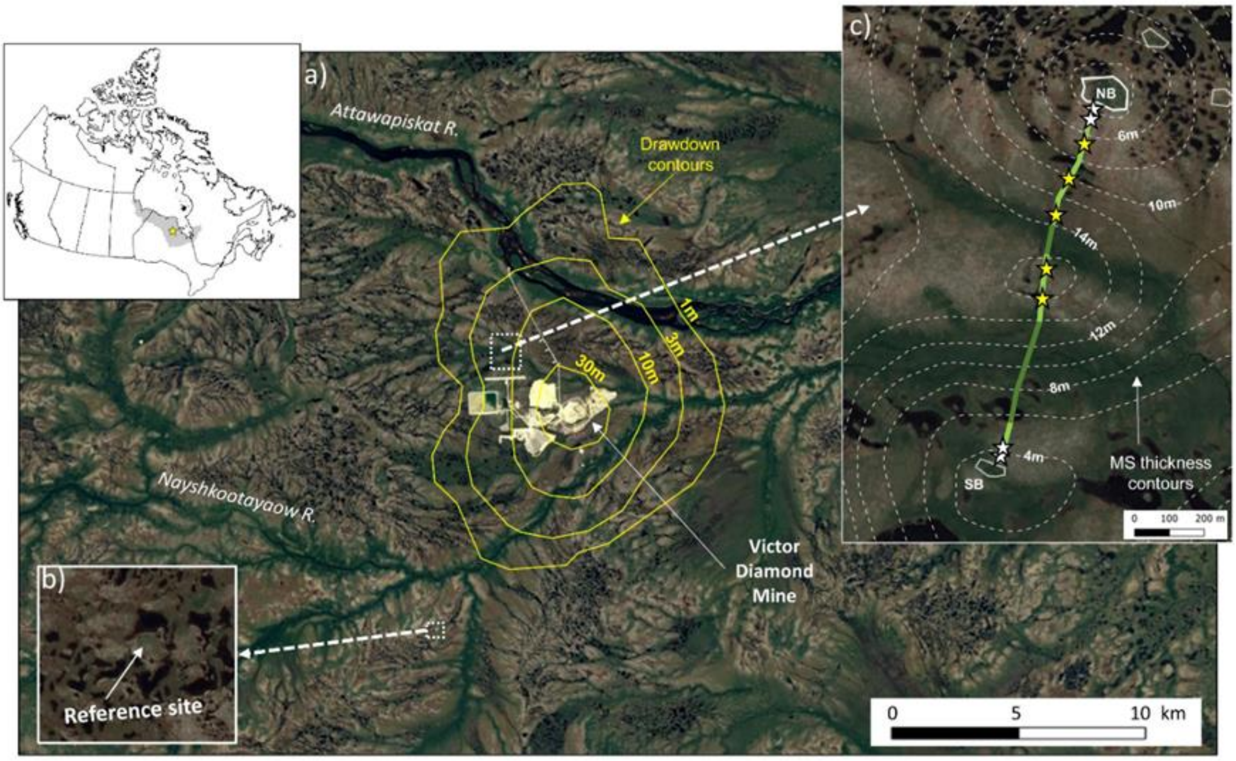

Figure 1. a) Map of the Victor Mine area in the HBL (see inset map of Canada), with drawdown contours (yellow) for the upper Attawapiskat formation underlying the marine sediment confining layer (Itasca 2015). Included are zoomed-in locations of b) the reference site outside of the mine-affected area and c) the main sampling transect situated between the 3 m and 10 m drawdown contours. In c), SB and NB represent the south and north bedrock outcrops, respectively, and the dashed white contour lines indicate marine sediment thickness (terrain maps obtained from Google Earth).

Tree sample collection, processing, and analysis

In the late summer of 2019, tree stem disks were obtained at the reference bog (n=25) (Figure 1b) and at nine groundwater monitoring locations in mine-affected bog (n=3–5 per location, 41 total) along the main transect (Figure 1c). Stem diameter ranged from 0.7 to 2.1 cm (mean = 1.3 cm) at the reference site, and from 0.8 to 2.5 cm (mean = 1.5 cm) at the combined mine-affected locations. Samples were taken at breast height (1.3 m) and shipped to the University of Waterloo for processing. Each sample was sanded to progressively finer grits, up to 600 grit, to reveal the annual growth rings.

Sanded tree stem disks were analysed by counting and measuring rings along two radii using a Velmex Tree Ring Measuring System (www.velmex.com) with a precision 0.001 mm. Quality assurance of ring width measurements was performed in RStudio using the "dplR" package (Bunn *et al.* 2020). Due to the stunted nature of the trees that were sampled, some difficulties in discerning individual rings were experienced, specifically for more recent years. All individual ring-width series were crossdated to detect measurement errors and the presence of false or missing rings. Series radii with low inter-series correlation values (p-values > 0.05) were either reanalysed or substituted by measuring and analysing rings from a different area of the stem disk. Samples that could not yield satisfactory p-values (> 0.05) after several reanalyses were discarded from the final chronologies. Ultimately, this led to the omission of four reference and six mine-affected samples, yielding final sample sizes of 19 and 35 for reference and mine-affected locations, respectively. During this process, a small subset (n=6) of individuals displayed an extra ring in the 2006 growth year. This subset exhibited stronger relationships in the climate analysis and, therefore, a gap was added in 2006 to all series which did not display this extra growth ring. Additional information regarding the analysis of the anomalous growth year is available in Appendix 1.

For each sample, the ring widths of both radii were averaged (so only one series per tree sample was included in the final chronologies) and then detrended using a negative exponential model to account for age-related growth trends. Detrended series within each respective location ('reference', 'mine-affected all', 'mine-affected thin MS', and 'mine-affected thick MS') were then averaged yielding four standardised 'master' ring-width index (RWI) chronologies. Residual master chronologies are also established during the chronology building phase, removing autocorrelation from the series and rendering it more suitable for climate analysis (Speer 2010). In addition, a master residual chronology was developed from all significantly correlated series (i.e., from reference and mine-affected chronologies) for climatological analyses.

Hydrometeorological analysis

Hydrometeorological data were obtained primarily from two nearby meteorological tower (MET) stations located at or near the Victor Mine, one close to the original exploration camp (52° 48' 11.37" N, 83° 52' 23.95" W) which was operational from March 2000 to December 2008, and one within the mine operation (52° 50' 3.34" N, 83° 53' 36.83" W) that operated from January 2009 to December 2018. Both stations provided hourly measurements of air temperature (T_{air}) (Figure A2.1a in Appendix 2), relative humidity and total precipitation (P) (Figure A2.1b).

Although precipitation was recorded at the Victor MET throughout the entire year, the data were proven unreliable during shoulder seasons when temperatures were below freezing because it was measured with a non-heated tipping bucket. Therefore, precipitation data for shoulder months as well as outside the Victor monitoring window (2000–2018) were supplemented with data from Lansdowne House (280 km southwest) Environment Canada station (Environment Canada 2021). RWI was correlated against total monthly precipitation for each year.

Snowpack depth was measured at the original MET station from 2000 to 2007, and both air temperature and relative humidity from 2007–2018; these datasets were both gap-filled and extended outside their respective monitoring periods using data from the Moosonee (280 km southeast) and Lansdowne House Environment Canada stations (Environment Canada 2021). Gaps in the snowpack record were present in both datasets, therefore the more complete dataset (Moosonee) was regressed and transformed against Victor MET (R^2 = 0.86, $p < 0.01$) and gap-filled using regressed and transformed Lansdowne House data (R^2 = 0.88, $p < 0.01$) (see Balliston & Price 2022 for more information). RWI was correlated with the average monthly snowpack depth of the regressed, transformed and gap-filled dataset.

An instrumented carbon flux tower station, installed ~5 km from the reference bog site by the Canadian Ministry of Environment, Conservation and Parks (MECP), recorded ground temperature at 0.02, 0.05, 0.1, 0.2, 0.5 and 1.0 m below ground surface (b.g.s.) from March 2011 to December 2018 in one bog hummock and one bog hollow (https://ameriflux.lbl.gov; Todd & Humphreys 2018). To determine whether ground temperature influenced tree growth, RWI values were correlated with the average monthly hollow and hummock ground temperatures at the 5 cm and 10 cm depths for each year (Pearson's R). Daily average air temperature data from the MECP flux tower were regressed with those from the Victor station to ensure comparability between locations. This regression yielded an R^2 of 0.99, confirming strong relationships between the data collection locations.

Daily measurements of water table position, expressed in metres relative to ground surface (negative values indicating water table below ground) were made at the reference site from 2007 to 2018, using a logging pressure transducer (Mini-Diver, Schlumberger Water Services, Waterloo, Canada) (Figure A2.1d). When water table data were not available, values were estimated using linear regressions with a nearby monitoring well ($R^2 = 0.93$, $p < 0.01$). RWI was regressed against average monthly water table position for each year.

As the T_{air} observations recorded at Victor MET did not span the full duration of the tree-ring chronology (1970–2018), a locally adjusted T_{air} time series was generated for the climate analysis using a gridded climate reanalysis product. Average hourly temperature data were extracted from the ERA5 reanalysis preliminary extension (1969–1978; REF) and the ERA5 reanalysis (1979–2019; REF) datasets for the ~30 km^2 grid-cell corresponding to the study area. Hourly data were aggregated to daily means and regressed against average daily temperatures recorded at Victor MET (2000 to 2019). The analysis showed strong agreement between the two datasets (R^2 = 0.99; $p < 0.001$), so the resulting regression equation was used to adjust the ERA5 time series across the full span of years covered by the tree-ring chronology (1969–2018). The locally adjusted ERA5 time series was then aggregated to monthly means for the climate analysis (Figure A2.1a,b). Vapour pressure deficit (VPD) (Figure A2.1c) was calculated using daily values of mean air temperature and relative humidity, and mean monthly VPD correlated against RWI, as VPD has been shown to directly influence stomatal conductance (Oren *et al.* 1999) and, thus, tree growth.

Statistical analyses

To address whether mine dewatering had a significant effect on the radial growth of black spruce in bogs, standardised chronologies for reference and mine-affected locations were compared both visually and statistically. A paired t-test was conducted on the 'mine-affected all' standardised chronology to determine whether RWI was significantly different during the 11-year periods prior to (1996–2006) and after (2008–2018) pumping. A t-test was also conducted on the difference in RWI between the 'mine-affected all' and 'reference' chronologies (for each year, residual difference RWI = mine-affected RWI - reference RWI) between the same two time periods to determine whether differences between the two locations had changed following pumping. The same methodology was applied for thick and thin MS mine-affected locations to assess whether trees in these locations responded differently to mine dewatering.

Finally, the master residual chronology (combining all correlated reference and mine-affected locations) was used in a climatological analysis to identify any broader influence of climate variables on tree growth. This included Pearson correlation tests of ring width index (RWI) against monthly averages of VPD and water table position for the period when local hydrometeorological data were available (2000–2018), and against average monthly T_{air} and P over 20-year moving windows using the extended meteorological dataset (the larger time window was used to better incorporate climatological trends). In addition, for the period over which local data were available, linear regressions were performed between annual RWI and monthly mean hummock and hollow ground temperatures at depths of 0.05 and 0.1 m b.g.s.

RESULTS

Tree-ring analysis

Summary statistics for all chronologies are reported in Table 1, and tree age and associated diameter at breast height (DBH) for all tree cores in Figure A2.2. For the trees sampled in this study, there was a weak ($R = 0.15$ but significant ($p < 0.05$) positive relationship between tree age and DBH. Standardised chronologies for reference and mine-affected locations showed similar growth patterns over the 49-year (1970–2018) period, with deviations occurring in the mid-1970s and late-1980s to mid-1990s (Figure 2). During the period of mine-related groundwater extraction (2007–2018), mean standardised RWI was similar between reference (mean = 0.96) and mine-affected (mean = 0.98) locations. Differences were evident in 2008, when RWI was considerably higher for the mine-affected chronology; and in 2015 when, in contrast to the reference location, the mine-affected chronology showed a trend of decreasing RWI. However, following a two-sample t-test on the disturbed chronology, it was determined that there were no significant differences in standardised RWI between the eleven years prior to and the eleven years after pumping began in 2007 ($t_{11.8} = 0.82$; $p = 0.43$). Furthermore, no significant differences were detected in the difference of RWI between mine-affected and reference chronologies, eleven years prior to versus eleven years after pumping ($t_{17.3} = 0.39$; $p = 0.7$). During the four years between 2014 and 2017, when the cone of depression at the mine progressed to its deepest level (~170 m b.g.s.; Itasca 2015), both locations followed similar growth trends. The last year of growth (2018) displayed increased growth for the reference location that was much more pronounced relative to the mine-affected peatlands.

Individual standardised chronologies for mine-affected locations of thick (n=20) and thin (n=15) MS are illustrated in Figure 2. In general, several differences were detected between the two chronologies, specifically in the 1970s, late 1980s to early 1990s and in 2010, 2011 and 2015. During the late 1970s and in 2010 and 2011, RWI for the mine-

Table 1. Summary statistics for the reference, various disturbed, and merged datasets for the chronology interval 1969–2018. Numbers in parentheses are standard deviation (STD).

Statistic	Reference	Mine-affected:			Merged
		All	Thick MS	Thin MS	
Number of series	21	33	20	15	53
Average series length (years)	32	27	25	27	29
Mean series intercorrelation	0.51 (0.13)	0.55 (0.14)	0.55 (0.12)	0.52 (0.13)	0.55 (0.12)
Mean series autocorrelation	0.68 (0.22)	0.62 (0.20)	0.58 (0.23)	0.63 (0.17)	0.63 (0.20)
Mean series ring width (mm)	0.13 (0.09)	0.21 (0.13)	0.21 (0.14)	0.22 (0.12)	0.18 (0.12)

affected areas underlain by thin MS followed a trend of lower growth relative to mine-affected areas underlain by thick MS. No significant differences in standardised RWI were observed between the time windows pre (1996–2006) and post (2008–2018) pumping commencement (thick MS $t_{12.6} = 0.95$; $p = 0.36$ and thin MS $t_{11.9} = 0.58$; $p = 0.57$). Additionally, no significant differences in RWI were found between the affected and reference locations (Thick MS: $t_{16.3} = 0.78$; $p = 0.44$; Thin MS: $t_{19.9} = -0.31$; $p = 0.76$) over these same time periods.

The final residual chronology (Figure 3) included a total of 53 tree samples, 20 from the reference site and 33 from the mine-affected transect. Residual

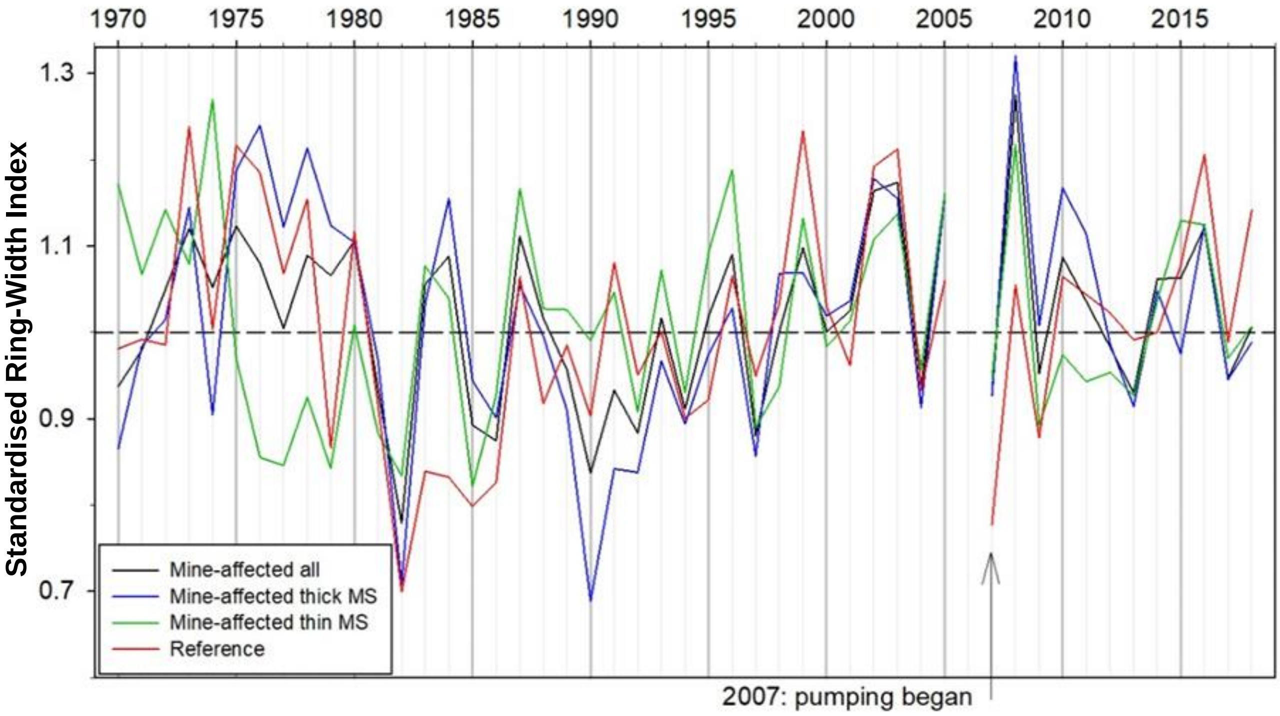

Figure 2. Standardised ring-width index of reference and mine-affected locations, with mine-affected locations also divided into areas of thick and thin underlying marine sediment aquitard.

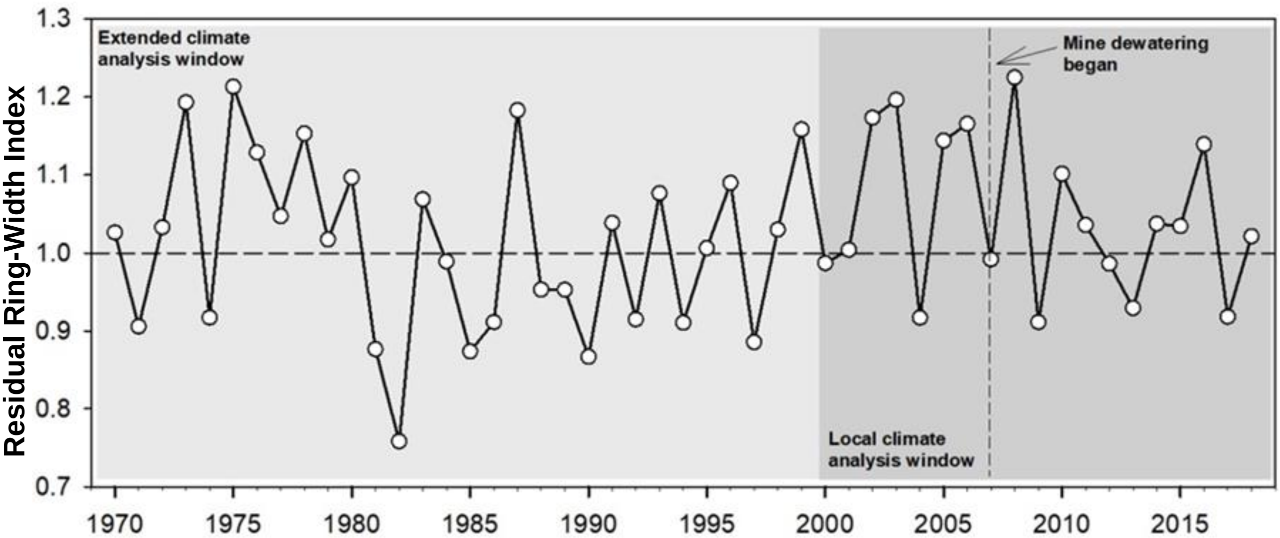

Figure 3. Chronology of residual RWI for the merged dataset, which included tree samples from nine bog sites along the mine-affected transect and at the reference bog located ~10 km from the mine.

RWI ranged from 0.76 to 1.23 with a period of below-average growth from 1981 to 1990 (excluding the years 1983 and 1987) and isolated years of below-average growth in 1992, 1994, 1997, 2004, 2009,2013 and 2017. In contrast, a period of above-average growth was detected from 1973 to 1980 (excluding 1974), 2002 to 2008 (excluding 2004 and 2007), and in the isolated years 1974, 1976, 1987, 1999, 2010 and 2016 (Figure 3). Figure 4 illustrates the exceedance probability of residual RWI for the merged dataset over the period of study, which states the probability of specific growth index for a given year based on the 49-year (1970–2018) period. For the period during which the mine was operational, RWI spanned a wide range of growth conditions, from the 2nd to the 82nd percentile, with 2008 and 2009 being the lowest and highest growth years, respectively, during this shorter period (Figure 4).

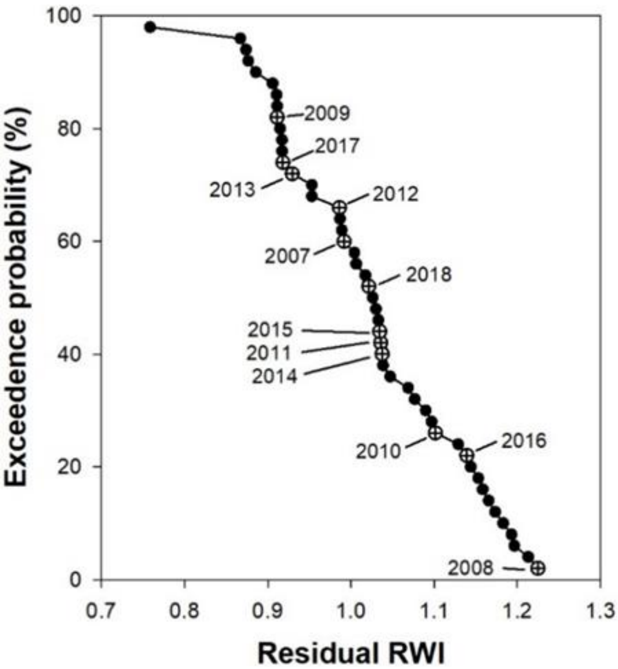

Figure 4. Exceedance probability curve of residual RWI for the merged dataset from 1970 to 2018. Years that fell within the period of dewatering are labelled.

Climatological analysis

For the extended climate dataset (1970–2018), significant positive relationships ($p < 0.05$) with residual RWI were detected for August T_{air} for all 20-year windows between 1989 and 2018, for September T_{air} for all 20-year windows between 1984 and 2009, and for June T_{air} for 20-year windows from 1979 to 2004 and between 1988 and 2007(Figure 5a). In addition, significant negative relationships were detected between residual RWI and mean monthly October T_{air} for windows between 1978 and 1999 and from 1982 to 2001. Prior to 1978, no 20-year windows of mean monthly T_{air} from April to October correlated with residual RWI (Figure 5a). The positive correlation of growth with August T_{air} generally increased over the study period while April correlations weakened. Months from November to March were excluded due to weakness of correlations over the study period.

Few significant relationships were detected between residual RWI and monthly precipitation during the period 1970–2018 (Figure 5). A significant negative relationship occurred with April P from 1975 to 1994, 1978 to 2001 and 1985 to 2004, and with October P from 1993 to 2012 (Figure 5b). A positive relationship occurred with July P between 1997 and 2017, and in general strengthened between the beginning and end of the study period.

Significant correlations were detected between residual RWI and mean monthly hummock soil temperature at 0.05 to 0.1 m b.g.s. (Table A2.1). The strongest of these relationships (negative) occurred in late winter and early spring months, including mean February soil temperature at 0.05 and 0.1 m b.g.s. ($R = -0.87$, $p = 0.01$ for both). Significant negative correlations were also detected at depth 0.1 m in March ($R = 0.81$, $p = 0.02$) and April ($R = 0.74$, $p = 0.04$). A significant positive correlation with hummock soil temperature at 0.05 m b.g.s. was also detected for December ($R = 0.70$, $p = 0.05$). Non-significant correlations occurred at depth 0.05 m for March ($R = 0.62$, $p = 0.09$) and at depth 0.10 m for December ($R = 0.64$, $p = 0.09$) (Table A2.1). In addition, a significant relationship ($R = 0.74$, $p = 0.03$) was detected between residual RWI and the day (ranging from 26 Oct to 18 Nov) on which the rooting zone became frozen in the autumn (fall) / winter from 2011 to 2017. No significant correlation was found between residual RWI and hollow soil temperature for any month.

For the 12-year window for which water table data were available, no significant correlations (Pearson R) with RWI were detected for any month; however, the relationships were consistently negative (Table A2.2). For the 17–18-year window for which monthly VPD data were available (Figure A2.1c), a significant positive correlation ($R = 0.57$; $p < 0.05$) was detected between RWI and mean August VPD (Table A2.2).

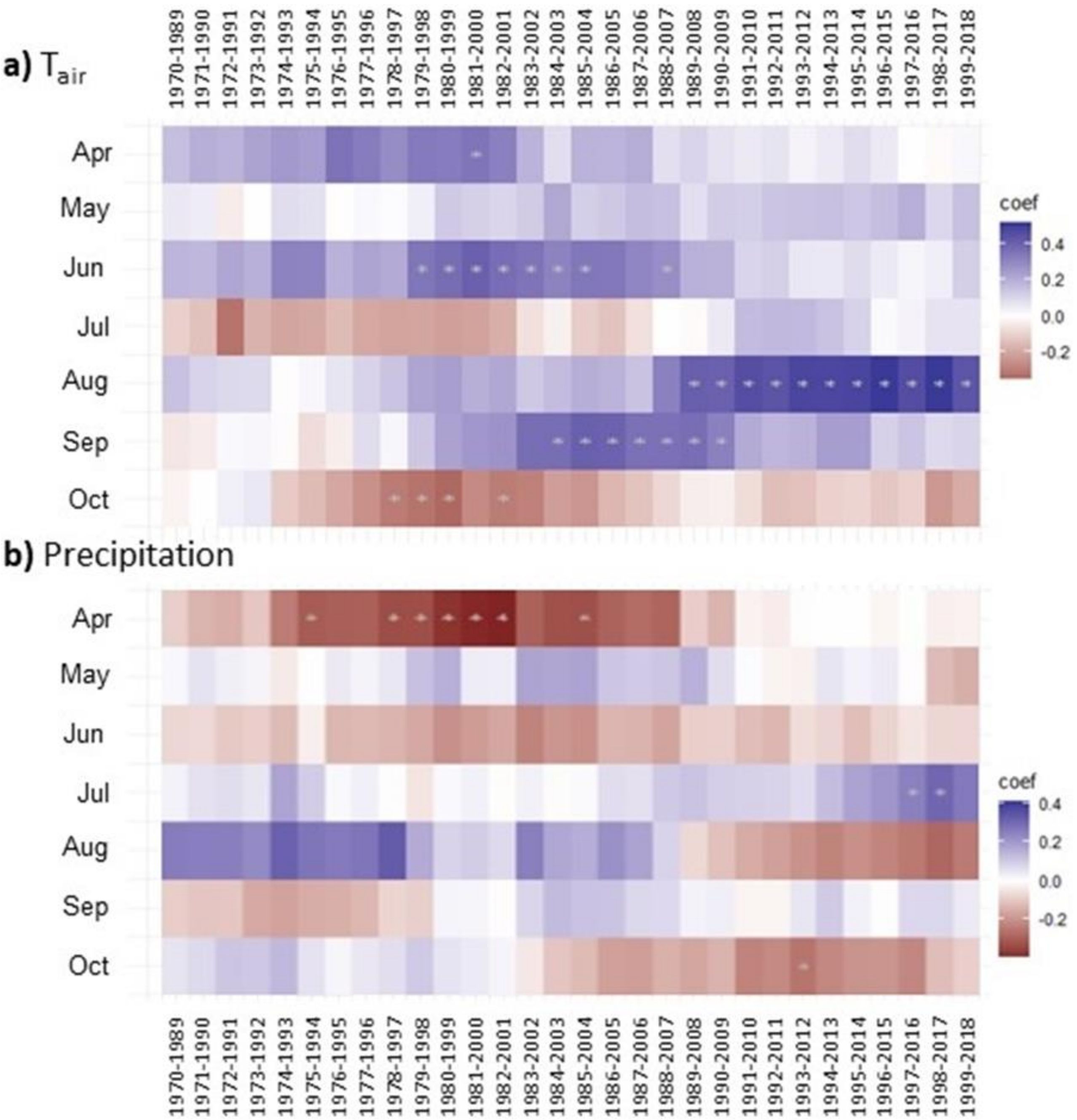

Figure 5. Correlations (Pearson R) over a moving 20-year window of residual RWI for the merged chronology with monthly (April–October) total precipitation and average air temperature from the extended meteorological dataset. An asterisk denotes a significant correlation ($p < 0.05$) for a given window.

DISCUSSION

Sensitivity of the growth of black spruce to water table position

Our analyses found no statistically significant relationships between the radial growth of black spruce and average monthly water table position, suggesting that trees are not particularly sensitive to changes in soil water availability at this location. In western Quebec HBL black spruce along a latitudinal gradient, positive correlations were found between growth and mid-summer (June–July) precipitation, but this was limited to more southerly locations and these correlations were absent at a latitude comparable to our study (Huang *et al*. 2010). Similarly, Dymond *et al.* (2019) found that black spruce lacked sensitivity to mean annual water table position in peatlands in Minnesota (USA) over a 45-

year monitoring period (1966–2010). This lack of sensitivity suggests that peatland black spruce in that region exhibited a great elasticity to the range of hydrometeorological conditions observed over the monitoring period, even under hydrological disturbance. Similar findings were reported by Elmes *et al.* (2022), who detected no significant changes in tree growth due to the construction of a road (perpendicular to groundwater flow) and below-ground pipeline (aligned obliquely to flow) through a fen-dominated hydrological catchment. The authors considered that, although these disturbances had affected water table dynamics, the cross-drainage networks in place (i.e., culverts) were sufficiently effective in promoting flow to avert significant effects on tree growth (Elmes *et al.* 2022). In contrast, Bocking *et al.* (2017) detected substantial die-off of black spruce in a road-influenced poor fen in the Western Boreal Plain, northern Alberta, which was attributed to beaver damming and subsequent inundation around the culvert. Although die off was attributed solely to changes in water table, the effect was threshold-based, as trees rooted above a certain elevation were less affected by culvert blockage (Bocking *et al.* 2017). In our study there was no evidence of such disturbances causing inundation, suggesting that water tables in the reference site were typically deep enough to not limit growth.

The lack of response to water level may be explained by the root system characteristics of black spruce trees, which are almost exclusively adventitious in structure (DesRochers & Gagnon 1997) and, in forested bogs, are highly correlated with the average depth of the water table (Lieffers & Rothwell 1987). As a result of this morphological characteristic, roots of mature black spruce remain near the peat surface, and thus are less likely to respond to lowering of the water table. In addition, the black spruce in our study were typically associated with *Sphagnum* hummock microforms. This is consistent with previous studies illustrating that black spruce can often be restricted to hummock microforms in peatlands (Horton & Lees 1961, (Mannerkoski 1985, Lieffers & Rothwell 1986). *Sphagum* hummock microforms are elevated (by up to several decimetres) relative to adjacent pool and lawn microforms (Nungesser 2003), and have better capillary water transport capabilities which allow them to maintain optimal soil moisture conditions and avoid desiccation better than hollow microforms (Rydin 1993, Bien 1999).

The above morphological characteristics of peatlands and black spruce may also explain the lack of sensitivity of growth in this study to precipitation, as near-surface soil moisture variability would be reduced as the peat surface rises and descends with changes in response to water table fluctuations (Balliston & Price 2020) (i.e., mire breathing; Roulet 1991). This is consistent with results from Nicault *et al*. (2015), who analysed 93 black spruce clusters in the east Hudson and James Bay boreal forests over a 40-year period (1961–2004) and found weak relationships (R^2 ~0.1–0.3) between annual growth and precipitation (Nicault *et al*. 2015). We suggest that the relationship between precipitation and the growth of black spruce is largely non-linear and likely to be related to a threshold of water availability during the growing season.

Influence of mine dewatering on the growth of black spruce

Given the lack of sensitivity of black spruce in our study to precipitation and water table position, it is unsurprising that we were unable to detect any pronounced differences in growth trends between mine-affected and reference locations at areas of both thick and thin MS aquitard (Figure 2). Furthermore, correlations between areas of thick and thin MS were strong during the period of mine operation. Generally, where water table decline was enhanced in areas underlain by thin MS, an increase in radial growth would be expected (cf. Macdonald & Yin 1999, Pellerin & Lavoie 2003, Linderholm & Leine 2004) due to enhanced soil aeration (Lahde 1969, Mannerkoski 1985) and higher soil temperatures (Rothwell 1991), whereas the opposite was observed during this period (Figure 2). However, a recent study of black spruce growth on discontinuous permafrost peatlands showed a decrease in radial growth due to drought conditions induced by temperature increase and permafrost thaw (Sniderhan & Baltzer 2016). The dry summer conditions of both 2011 and 2012 (Whittington & Price 2013, Balliston & Price 2022) may represent the moisture threshold for growth in bog areas with thin underlying marine sediment.

It is important to note that if dewatering were to continue beyond the actual period of mine operation (past 2019), further peatland drainage would have been maintained. It is possible that, with continued drainage combined with enhanced water losses and reduced water availability due to climate change, water table position and precipitation could eventually impose a greater influence on black spruce growth. This may be relevant to future mining endeavours in the region (i.e., Ring of Fire), where drawdown and pumping requirements may differ from those at the Victor Mine, and may persist for a longer period of time, particularly within the context of cumulative effects with climate change in this region.

Climatic factors influencing the growth of black spruce

RWI displayed a negative relationship with mean monthly hummock soil temperature in late winter and early spring (Table A2.1). This may be explained by several biological factors dependent on soil warming and cooling, particularly during winter and spring months. For example, Fréchette *et al.* (2011) found that faster soil warming in spring caused slower recovery of chlorophyll fluorescence, maximum rate of electron transport and photosynthesis, along with lower foliar nitrogen concentrations, for upland black spruce in boreal Quebec, which reduced growth. Conversely, delayed soil thawing in spring did not appear to impede the recovery of photosynthesis (Fréchette *et al.* 2011). The variability of spring temperature has also been shown to influence growth. Freeze-thaw events in early spring, following melt, have been shown to reduce soil microbial populations (by up to 50 %; Schimel & Clein 1996), leading to lower foliar nitrogen availability during the growing season (Clein & Schimel 1995).

Correlations detected between RWI and temperature of hummock peat (where most tree samples were obtained) were absent in hollow peat (results not shown in this study). Hummock microforms often comprise a greater proportion of vascular vegetation, specifically with adventitious roots, as they aid in reinforcing the hummock structure (Pouliot *et al.* 2011). Strong correlations may also be attributed to their deeper water tables (Balliston *et al.* 2018) and lower near-surface moisture contents (van Huizen *et al.* 2020) and thus lower volumetric heat capacity (Kujala *et al.* 2008) relative to hollow microforms. These differing thermal properties would leave hummock microbial populations more vulnerable to freeze-thaw conditions. Both faster soil warming and increased frequency of freeze-thaw events may be exacerbated over time by climate change in the event of warming air temperatures, longer growing seasons (IPCC 2021) and increased climate extremes (IPCC 2014), rendering hummock black spruce vulnerable to reduced growth.

Significant correlations were also detected between residual RWI and mean monthly air temperature from 1978 to 2018 (Figure 5a). Collectively, the relationships demonstrate the importance of growing season warmth on the radial growth of black spruce in the region. The significant relationship with spring and summer air temperatures (here June and August) has been well documented in studies ranging from open tundra (Churchill Manitoba, positive correlation with July temperatures; Mamet & Kershaw 2011) to the eastern boreal forest (northern Quebec, positive correlation with July temperatures; Huang *et al*. 2010). Positive correlations of RWI with winter and early spring temperatures found in subarctic northern Quebec black spruce (Huang *et al*. 2010) are absent in this study. The correlation in this study between January–March air temperature and hummock soil temperature at depths of 0.05 and 0.1 cm b.g.s. is low (R^2 = 0.43 and R^2 = 0.22, respectively), suggesting it is soil temperature rather than air temperature that controls growth in this area. High spatial and temporal variability of growth sensitivity to air temperature has also been observed in previous studies on boreal trees, illustrating the often localised nature of black spruce growth dynamics in northern landscapes facing a complex interplay of temperature and moisture related stressors (Lloyd & Fastie 2002, Mamet & Kershaw 2011).

It is worth noting that during the early to mid-1970s (specifically in April and August), monthly precipitation exhibited stronger correlations with residual RWI than T_{air}. This may highlight that the relative influence of the T_{air} and P climatic factors change over time in response to larger-scale climate cycles in the HBL. For example, the 1970s were cold relative to the rest of our record and, therefore, precipitation may play a stronger role during this time. Unfortunately, our cores did not date back beyond 1970, and future studies should focus on peatlands in the HBL with older tree stands to identify whether these relationships vary in response to large-scale climate cycles.

Climate models predict that the effects of climatic change will be most pronounced at high latitudes and include warming temperatures and longer growing seasons (IPCC 2021). Furthermore, studies in the HBL have suggested that bogs are most likely to show changes (increases) in productivity resulting from climate change during shoulder seasons (Helbig *et al.* 2019). Slight increases in precipitation are generally expected (Fekete *et al.* 2010); however, they may not be sufficient to effectively offset increases in evapotranspiration due to warming (Fekete *et al.* 2010, Collins *et al.* 2013). Therefore, it is likely that the HBL will experience a net drying effect due to climate change (i.e., enhanced evapotranspiration demand and water table decline) through longer and warmer growing seasons. Our results highlight a particular sensitivity of black spruce in HBL bogs to spring and late summer temperatures as well as to indicators of growing season length, specifically the period for which the rooting zone is thawed. Other long-term studies on black spruce within boreal peatlands and forests have reported both positive (Beck *et al*. 2011) and negative (Lloyd & Bunn 2007) growth responses to increasing temperature, and that response is often highly variable between individual stands and trees (Nicault *et al*. 2015, Sniderhan & Baltzer 2016). This is perhaps due to the large range of temperatures in which black spruce can thrive, growing at 70 % photosynthetic optimum at temperatures between 0 °C and 35 °C (Bonan & Sirois 1992) and at 90 % between 15 °C and 25 °C (Lamhamedi & Bernier 1994), suggesting it is the interaction of temperature with other factors found here, such as frost formation and thaw, that may be controlling growth. Bogs in the region are likely to experience an increase in afforestation which may be enhanced by certain feedbacks (e.g., increased transpiration) leading to further drying (Farrick & Price 2009). However, recent negative trends in black spruce growth related to temperature-induced drought stress and the large variability in response increase the complexity of this projection (Sniderhan & Baltzer 2016).

Implications for future mining operations and climate change

This pilot study is the first to address the combined influence of climate variability and high-volume groundwater extraction on the annual radial growth of black spruce, a dominant tree species in the Hudson Bay Lowlands. Our analyses found no detectable effect of mine dewatering on the growth of black spruce in our mine-affected bog locations, irrespective of the thickness of the underlying marine sediment aquitard. This is reflected by the absence of correlation between annual ring-width index (RWI) and monthly water table position. However, it is worth noting that the operation size and lifespan of the Victor Mine (2007–2019) may be small compared to operations that could occur within the Ring of Fire in future, and additional studies are necessary to understand thresholds of the buffering capacity of autogenic processes that are characteristic of peatlands.

Climate variability, specifically growing season warmth and duration, appears to have outweighed the influence of industrial dewatering activities on tree growth. The strongest relationships detected for the RWI of bog black spruce in the HBL were positive correlations with average monthly temperatures in June, August and September for several 20-year windows from 1979 to 2018, as well as negative correlations with near-surface hummock soil temperatures in late winter and early spring from 2011 to 2018. These relationships point to the importance of growing season length and warmth for tree growth.

In the context of ongoing climate change, climate models for the HBL predict continuing increases in air temperature and meteorological variability, which would undoubtedly influence growing conditions for black spruce, notably in the shoulder seasons. Improved growing conditions and increased growing season length can be expected to lead to an increase in tree growth and water use, and could thus lead to several water table feedbacks associated with afforestation that would influence the hydrological regime of peatlands in the area, which provide an important source of freshwater to the brackish Hudson and James Bays.

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AUTHOR CONTRIBUTIONS

MCE and NEB initiated the study. NEB obtained tree core samples and MCE conducted all laboratory analyses. ELD provided dendrochronological expertise during laboratory analyses and baseline analysis of the data. MCE and NEB and wrote the first draft. All authors contributed to interpretation of the results, writing, and editing of the final manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Appendix 1

Supplementary information for missing ring

During the analyses, a subset (n=8) of discarded wood samples correlated highly with one another and displayed an extra ring in the mid 2000s (the black symbols in Figure 2a). Residual RWI for this subset displayed a poor relationship with the original merged chronology prior to the mid-2000s (Figure 2a), and the two chronologies were not statistically similar (R = -0.27; $p > 0.05$). However, during the climate analyses, the chronology for the subset of samples with an extra ring displayed stronger correlations relative to the merged subset. To explore the potential for a missing ring in the original merged chronology, a one-year gap was added and every ring measurement prior to 2007 was set to one year earlier (Figure 2b). This resulted in a stronger, positive and significant relationship (R = 0.46; $p < 0.05$) between RWI in the subset and in the adjusted merged chronology along with much stronger correlations with climatic variables over the entire period. For all chronologies (reference, mine-affected all, mine-affected thick MS, mine-affected thin MS, and merged), a one-year gap was added at 2006 unless one of those cores belonged to the subset that displayed the extra ring, establishing adjusted chronologies for all five groupings (referred to hereafter by their original group names). This also allowed more cores (primarily those from the subset displaying an extra ring) to be included, as they now exhibited strong correlations with the additional cores. This yielded final sample sizes of 21, 33, 20, 15 and 53 for reference, mine-affected all, mine-affected thick MS, mine-affected thin MS and merged chronologies, respectively. Therefore, all chronologies had a missing RWI value in 2006 except for the merged dataset, which was supplemented with the 2006 RWI value from the small subset of cores which had the extra growth ring.

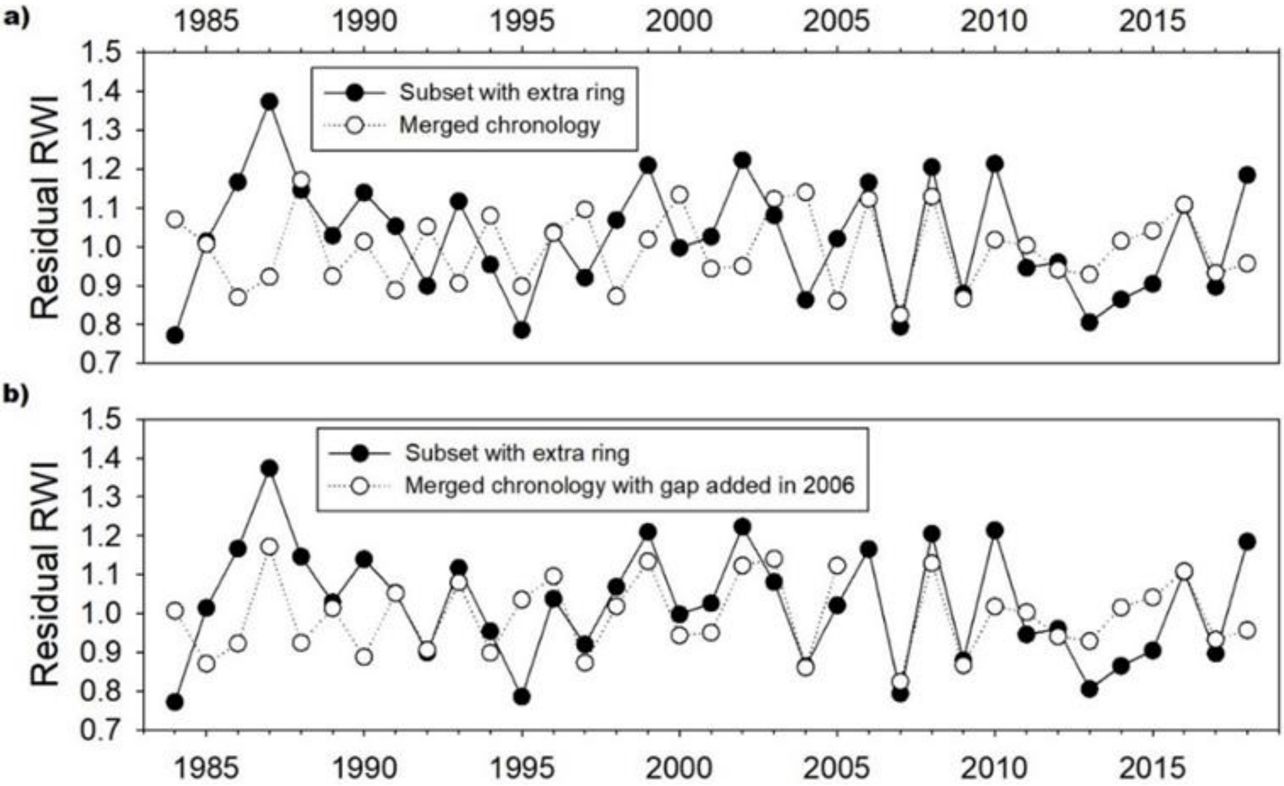

Figure A1.1. Comparisons of residual RWI for the original merged chronology and the subset of samples that displayed an extra ring for 2006. This includes a) a condition where no adjustments were made, and b) a condition where a gap was inserted into the merged chronology at 2006. Note: A RWI > 1 denotes above-average growth for a given year, and a RWI < 1 denotes below-average growth.

Appendix 2

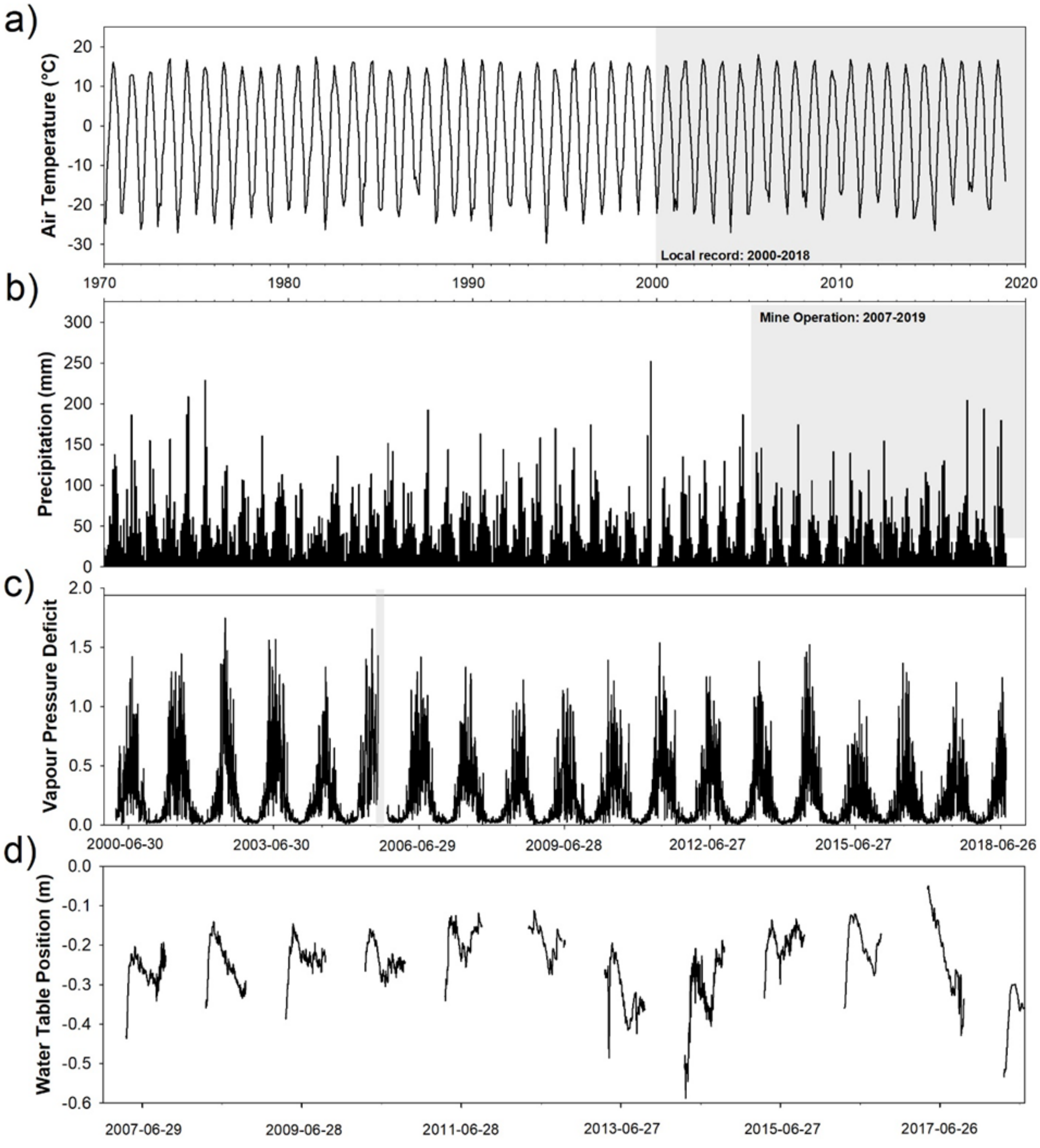

Figure A2.1. Summary of hydrometeorological data obtained near the Victor Mine, and used for climate analysis, including monthly a) average air temperature and b) total precipitation (1970-2018), daily c) vapour pressure deficit (2000-2018) and d) water table position (2007-2018).

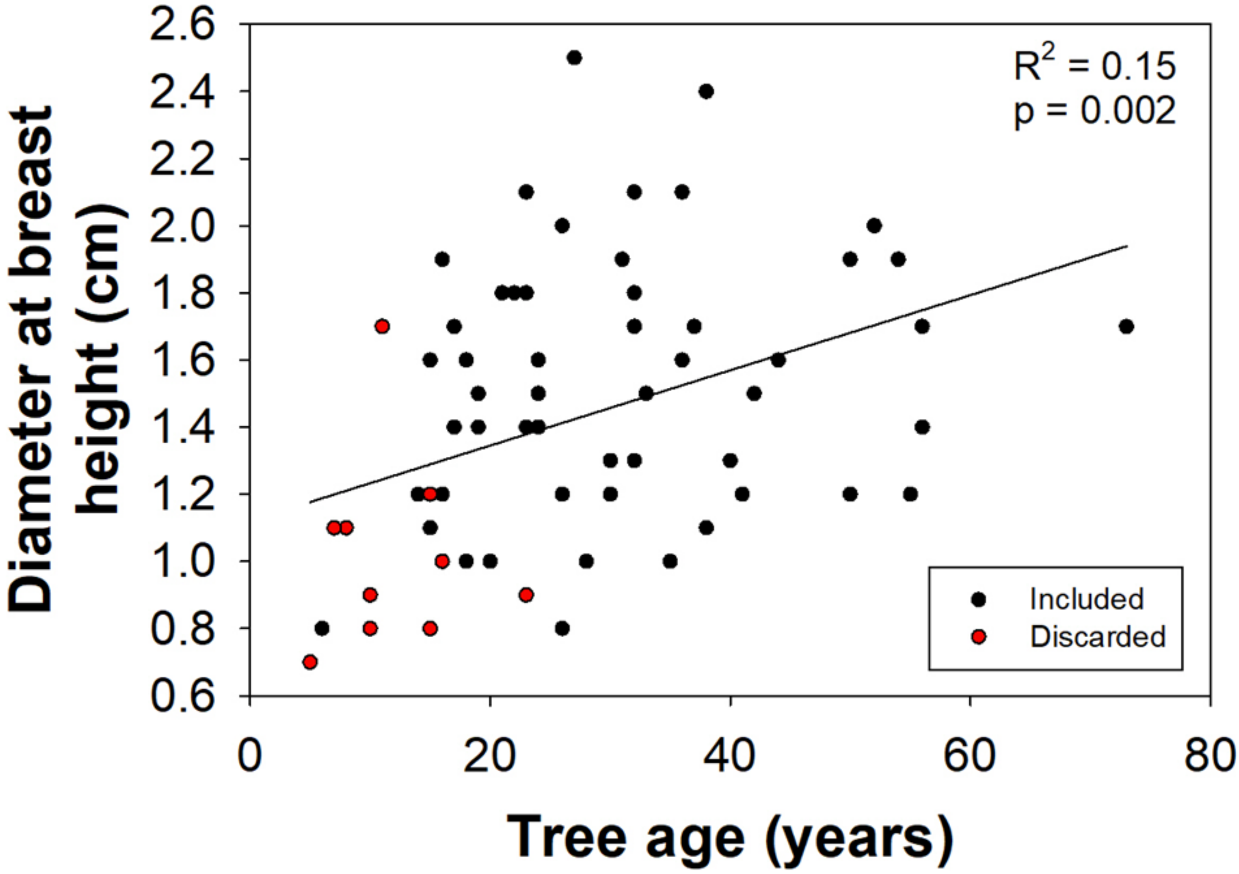

Figure A2.2. Scatter plot of tree age versus diameter at breast height (DBH) for stem discs obtained from disturbed and undisturbed locations. Note: these numbers are also for trees that were not included in the final chronologies.

Table A2.1. Summary of linear regressions between RWI and monthly mean soil temperature for hummock microforms at 5 cm and 10 cm below ground surface (b.g.s.). Note that R^2 values are only reported for p-values less than 0.1.

Month	5 cm b.g.s.		10 cm b.g.s.	
	R2	p-value	R2	p-value
Jan	NA	NA	NA	NA
Feb	-0.71	0.01	-0.72	0.01
Mar	-0.28	0.09	-0.59	0.02
Apr	NA	NA	-0.47	0.04
May	NA	NA	NA	NA
Jun	NA	NA	NA	NA
Jul	NA	NA	NA	NA
Aug	NA	NA	NA	NA
Sep	NA	NA	NA	NA
Oct	NA	NA	NA	NA
Nov	NA	NA	NA	NA
Dec	0.40	0.05	0.30	0.09

Table A2.2. Summary of correlations (Pearson R) of residual RWI for the merged chronology, for which monthly values are reported in Figure 9. The bolded R coefficient with an asterisk indicates a significant ($p < 0.05$) relationship.

Month	Water table (m)	VPD
May	-0.09	0.32
Jun	-0.10	0.28
Jul	-0.19	0.16
Aug	-0.24	**0.57***
Sep	-0.13	0.11