Growing season evapotranspiration in boreal fens in the Athabasca Oil Sands Region: Variability and environmental controls

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Abstract
Current efforts to assess changes to the wetland hydrology caused by growing anthropogenic pressures in the Athabasca Oil Sands Region (AOSR) require well-founded spatial and temporal estimates of actual evapotranspiration (ET), which is the dominant component of the water budget in this region. This study assessed growing season (May–September) and peak growing season (July) ET variability at a treed moderate-rich fen and treed poor fen (in 2013–2018), open poor fen (in 2011–2014), and saline fen (in 2015–2018) using eddy covariance technique and a set of complementary environmental data. Seasonal fluctuations in ET were positively related to net radiation, air temperature and vapour pressure deficit and followed trends typical for the Boreal Plains (BP) and AOSR with highest rates in June–July. However, no strong effect of water table position on ET was found. Strong surface control on ET is evident from lower ET values than potential evapotranspiration (PET); the lowest ET/PET was observed at saline fen, followed by open fen, moderately treed fen, and heavily treed fen, suggesting a strong influence of vegetation on water loss. In most years PET exceeded precipitation (P), and positive relations between P/PET and ET were observed with the highest July ET rates occurring under P/PET $\leq$ 1. However, during months with P/PET $>$ 1, increased P/PET was associated with decreased July ET. With respect to 30-year mean values of air temperature and P in the area, both dry and wet, cool and warm growing seasons (GS) were observed. No clear trends between ET values and GS wetness/coldness were found, but all wet GS were characterized by peak growing seasons with high daily ET variability.

KEYWORDS
actual evapotranspiration, boreal fens, eddy covariance, interannual variability, potential evapotranspiration, precipitation, Western Boreal Plains, wetland hydrology

1 | INTRODUCTION

The Athabasca Oil Sands Region (AOSR) of the Western Boreal Plains (WBP) contains the third largest proven oil reserve in the world (British Petroleum, 2018). Oil sands extraction in the region has affected globally significant ecosystem functions of the boreal forest, including water and carbon cycling in peatlands (Ficken et al., 2019; Rooney et al., 2012; Volik et al., 2020; Webster et al., 2015).
Peatlands are recognized as essential components of the AOSR landscape (AEP, 2016; Devito et al., 2005; Vitt et al., 1996) due to their natural ability to accumulate and store vast quantities of carbon (Pelster et al., 2009; Vitt et al., 2000) and store and provide water to downstream ecosystems (Ferone & Devito, 2004; Thompson et al., 2015). As a result of this global importance, protection and maintenance of boreal peatlands under human and natural disturbances has gained attention from both the public and scientific community over the past several decades (Government of Alberta, 2017; Rooney et al., 2012; Turetsky et al., 2002).

Many studies have demonstrated that the maintenance of natural hydrologic conditions is critical for proper peatland functioning as peatland water levels and subsurface flow either directly or indirectly governed all biogeochemical and ecological processes (Bridgham et al., 1998; Evans et al., 2000; Macrae et al., 2006; Waddington et al., 2015). Consequently, monitoring of hydrologic conditions in peatlands is considered a necessary component of the Oil Sands Monitoring Program which was established to detect the effects of industrial development on natural ecosystems (Ciborowski et al., 2012; Eaton & Charette, 2016). In addition, creation of suitable hydrologic conditions (i.e., water table depth within the upper 0.3 m of the peat column, Borkenhagen & Cooper, 2016) supporting peat formation has been recognized as a necessary step for peatland re-establishment within post-mining landscapes (Borkenhagen & Cooper, 2019; Nwaishi et al., 2015; Price et al., 2010) to mitigate wetland losses in the AOSR (Government of Alberta, 2015). Creation and maintenance of such conditions require understanding of hydrological functioning of natural peatlands and their ability to regulate water losses which is of particular interest under sub-humid climate (Alberta Government, 2013; Peters et al., 2006; Petrone et al., 2007; Phillips et al., 2016) and existence of decadal wet and dry cycles (Chasmer, Devito, et al., 2018; Devito et al., 2017; Government of Alberta, 2013), understanding of long-term ET dynamics in peatlands is necessary to evaluate variability in ecohydrological feedback to natural and anthropogenic changes and to reveal controls on ET that can be used to reduce evaporative demand in constructed peatlands (Devito et al., 2012; Nichols et al., 2016; Scarlett et al., 2017).

Water and energy fluxes have been assessed in natural (Brown et al., 2014; Petrone et al., 2001) and constructed (Nicholls et al., 2016) wetlands in the WBP. These studies have shown that ET in the region is governed by vegetation characteristics and hydrologic conditions and can therefore be considered as an integrating indicator revealing changes in vegetation and hydrology and overall hydrologic functioning of peatlands (Nwaishi et al., 2015). Despite improvement in our understanding of atmospheric, soil, and vegetation controls on ET in WBP peatlands (Brown et al., 2010, 2014; Petrone et al., 2007; Phillips et al., 2016) and constructed fens in the AOSR (Nicholls et al., 2016; Scarlett et al., 2017), it is still necessary to establish a baseline of peatland ET in the AOSR, as well as to detect and characterize changes in ET under decadal wet and dry cycles (Devito et al., 2012). As such, this study aims to evaluate the inter-annual variation of ET in AOSR fens using eddy-covariance data for the growing season (May–September) over a 7-year period (2011–2018) that included cold and warm, dry and wet years. Specifically, our study objectives are to: (1) evaluate the effect of environmental conditions on ET rates; and (2) characterize ET changes over time in boreal fens.

2 | METHODS

2.1 | Study area

The study was conducted at four fens in the north-eastern part of Alberta (Figure 1a,b), in the Central Mixedwood Subregion of the Boreal Plains Ecozone (Natural Regions Committee, 2006). Saline and Poplar Fens were located within the McMurray Lowlands while JACOS (Japan Canada Oil Sands Limited) Fen was situated within Wabasca Lowlands and Pauciflora Fen was situated within the Stony Mountain Uplands (Figure 1c). The AOSR is characterized by a sub-humid climate, with a mean annual temperature of 0.2°C and annual precipitation of 460 mm (Government of Canada, 2017); however, the Stony Mountain Uplands have been shown to receive more precipitation (+55%) compared to the McMurray lowlands (Wells et al., 2017).

Pauciflora Fen (56°56′ N, 111°33′ W) is an ~0.11 km² poor moderately treed fen enclosed by forested uplands and underlain by glacial deposits composed of silt and clay (Fenton et al., 2013). Surface elevation at Pauciflora Fen ranges from ~743–745 masl. The thickness of peat varies across the peatland, from 0.5 m along the forested slopes to more than 12 m in the northern part of the fen (Wells et al., 2017). pH of near-surface groundwater within the fen ranges from 5.5–6 (Murray et al., 2017). This fen is dominated by Carex limosa, Carex aquatilis, Sphagnum spp. (predominantly S. angustifolium, S. capillifolium and S. magellanicum), Picea mariana, Betula glandulosa, Oxycoccus microcarpus, Chamaedaphne calyculata and Andromeda polifolia (Bocking et al., 2017; Wood et al., 2016).

Poplar Fen (56°22′ N, 111°14′ W) comprises several heavily treed moderate-rich fens (total fen area: 0.7 km²), and is situated within a meltwater channel belt of glaciofluvial sediments composed of sand and gravel (McPherson & Kathol, 1977). Peat depth ranges from 1.2–3.0 m, decreasing to <0.5 m along the margin (Elmes et al., 2018). pH of near-surface groundwater within the fen had a range of 6.8–7.0 (Elmes & Price, 2019). The fen has vegetation cover dominated by Larix laricina, Betula glandulosa, Picea mariana, Equisetum fluviatile, Smilacena trifolia, Carex spp. and moss including Polytrichum spp., Torsenthyphnum spp. and Sphagnum spp. (Goetz & Price, 2015; Wood et al., 2016).

Saline Fen (56°34′ N, 111°16′ W) is a ~0.27 km² open fen surrounded by a generally flat and homogeneous landscape underlain by fine-grained glaciolacustrine sediments. The elevation within the fen varies from 397 to 401 masl (Wells & Price, 2015a). Groundwater and surface water are dominated by Na⁺ and Cl⁻ while Ca²⁺, Mg²⁺ and SO₄²⁻ are also present (Volk et al., 2017); electrical conductivity of near-surface groundwater ranges from 19 to >60 mS cm⁻¹ (Wells & Price, 2015b). pH of near-surface groundwater within the fen ranges from 6.5–7.5 (Wells & Price, 2015a). The site is characterized by a well-developed ridge-depression patterned surface and numerous
shallow ponds in the southern and central parts of the peatland. *Juncus balticus*, *Hierochloe hirta* ssp. *arctica*, *Calamagrostis inexpansa*, *Hordeum jubatum* are a dominant within ridges while *Triglochin maritima* is the dominant species within depressions; areas with the highest salinity are occupied by halophyte vegetation such as *Plantago maritima*, *Salicornia rubra*, *Suaeda calceoliformis* (Volik et al., 2018).

JACOS Fen (56°19’ N, 111°39’ W) is a ~ 0.46 km² poor open fen located within flat and homogeneous landscape in the Hanging Stone Creek watershed, with elevation varying from 560 to 564 masl (Wood et al., 2016). The fen is resting on glaciofluvial deposits rich in silt and clay (Fenton et al., 2013). The thickness of peat across the peatland ranges from 1 to >5 m (Wood et al., 2016). Vegetation cover is composed of *Sphagnum* spp., *Polytrichum* spp., *Cladonia stellaris*, *Rhododendron groenlandicum* and *Vaccinium vitis-idaea* (Wood et al., 2016).

### 2.2 Field measurements

Measurements of water fluxes and environmental variables were conducted during May–September that was considered the growing
season (GS) at JACOS in 2011–2014, at Saline in 2015–2018, at Pauciflora in 2013–2018, at Poplar in 2013–2018; a detailed list of measured variables by years and sites is provided in Table S1. At each fen we measured rainfall (P; Onset Hobo RG3 or TR-525m), net radiation (Rnet; Kipp and Zonen NR-Lite2 or CNR4), ground heat flux (Qg; Huskflux HPS01-L or HPS01SC-L), air temperature and relative humidity (Tair and RH; Onset HOBO Pro V2) and soil temperature (Tsoil; K/T type Thermocouple wire) at 0, 10, 25 and 50 cm below ground surface (bgs). The vapour pressure deficit (VPD) was calculated as the difference between saturated vapor pressure (VPsat) and the vapor pressure of air (VPair), both using Tair and RH.

\[
\text{VPD} = \text{VPsat} - \text{VPair},
\]

where,

\[
\text{VPsat} = \frac{610.7 \times 10^{7 \text{Tair}/237.3 + \text{Tair}}}{1000}
\]

and,

\[
\text{VPair} = \frac{610.7 \times 10^{7 \text{Tair}/237.3 + \text{Tair}}}{1000} \times \frac{\text{RH}}{100}.
\]

In addition, each fen had an eddy covariance system (EC) consisting of a closed-path or open-path infrared gas analyzer (IRGA; H2O and CO2; Li-7200 or Li-7500; Li-COR Biosciences, Lincoln, Nebraska, USA) and 3D sonic anemometer (Gill Windmaster Pro or Campbell Science Inc. Csat-3). The depth to water table (WTD) was measured in a fully slotted PVC (1–2” inner diameter) well using a pressure transducer (Onset Hobo U20 or Van Essen Mini Diver), corrected for barometric pressure using an above ground pressure transducer to measure atmospheric pressure. All auto-logging WTD measurements were corroborated using manual measurements every 2–4 weeks. All monitoring equipment for each fen is summarized in Table S2.

Meteorological parameters were sampled at a 5 s scan rate and averaged for 30-minute intervals. IRGAs with 3D-dimensional sonic anemometers were sampled at a frequency of 10 Hz and fluxes calculated every 30 min. IRGAs were calibrated at the beginning and during each study period (according to manufacturer recommendations) using a zero gas and two-point span calibration to account for any drift in sensor sensitivity, which remained within 5% over the duration of each study period. Data gaps (in precipitation and air temperature) from equipment malfunction were filled using the closest neighbouring meteorological stations at Fort McMurray (for Pauciflora, Saline, and JACOS Fens) or Mildred Lake (for Poplar Fen). At Saline Fen, continuous WTD data were missing during July–September in 2015, so manual weekly measurements of WTD were used. JACOS did not have auto-logging WTD and therefore only manual measurements were recorded. Daily ET rates were not gap-filled to avoid possible misinterpretation of relationships between ET and environmental variables. Missed and gap-filled data are identified in their respective figures.

### 2.3 Data analysis

Daily average values of environmental variables were calculated by averaging all available 30-min data with the exception of precipitation and evapotranspiration totals, which were calculated as daily sums. All raw EC data were processed and averaged into 30-min timestamps where corrections for coordinate rotation (double rotation; Kaimal & Finnigan, 1994), time lag and sensor separation (Fan et al., 1990), density effects (Burba et al., 2012), periods of low turbulence based on the inflection point of frictional velocity (u*), and energy balance closure (Brown et al., 2014; Foken, 2008; Petrone et al., 2015) were applied. The Kljun et al. (2004) footprint analysis was used to constrain water fluxes to within the desired fen boundaries. These estimates of actual evapotranspiration were compared to the potential evapotranspiration (PET) estimated using the Penman–Monteith model (Penman, 1948; Monteith, 1965; Allen et al., 1998)

\[
\lambda\text{PET} = \frac{\Delta (R_{\text{net}} - Q_g) + \frac{\rho_e}{\rho_a} (\text{es}_r - \text{es}_a)}{\Delta + \gamma (1 + \frac{1}{\text{es}_a})}.
\]

where \(R_{\text{net}}\) and \(Q_g\) represent the net radiation and ground heat flux, respectively, \(e_s\) is the saturation vapour pressure (kPa), \(e_a\) is the actual vapour pressure, \(\Delta\) is the slope of vapour pressure curve, \(\rho_a\) is density of the air, \(\gamma\) is the psychrometric constant, \(C_p\) is the specific heat of dry air, and \(\lambda\) is the latent heat of vaporization. Assumptions were made that bulk surface aerodynamic resistance \(r_{a,b}\) was equal to 1 and canopy surface resistance \(r_c\) was 0, as no Leaf Area Index or stomatal resistance was determined in this study.

### 2.4 Statistical analyses

Relationships between environmental variables and ET rates at Pauciflora, Poplar and Saline Fens were analyzed using Pearson’s correlation coefficient (r) based on daily values; due to lack of continuous WTD measurements at JACOS and Saline in 2015, relations between ET and WTD were assessed using trends in median monthly values in box-and-whisker plots. Due to data gaps and uneven data distribution, mean/median seasonal ET values were not calculated and analyzed. However, interannual variability in ET rates were assessed based on mean peak growing season (July) ET rates \(\text{ET}_J\) as July was characterized by most complete data (Table S3) compared to other months at all sites. Variability of \(\text{ET}_J\) was assessed by the coefficient of variation (CV). Interannual differences in \(\text{ET}_J\) and environmental variables (WTD, P, Tair, Rnet) within sites and among sites were detected using one-way ANOVA (α = 0.05) as July data were characterized by normal distribution (assessed by kurtosis and skewness coefficients) and homogeneity of variance (assessed by Levene’s test). Tukey–Kramer test was performed to reveal differences between sites and years; the test was chosen due to unequal size of samples. All statistical analyses were done using R (RStudio Team, 2015).
3 | RESULTS

3.1 | Climatic variability

In 1988–2018, long-term mean air temperature (AT) and total precipitation (TP) were 13.5°C and 276.2 mm for May–July, and 17.4°C and 75.4 mm in July, respectively (Government of Canada, 2019). With respect to long term mean value (LTV) of AT and TP during GS and in July, studied years can be divided into warm dry (AT > LTV, TP < LTV), warm wet (AT > LTV, TP > LTV), cool dry (AT < LTV, TP < LTV), and cool wet (AT < LTV, TP > LTV). Analysis revealed that 2013 GS was warm and wet at all sites while 2014, 2015 and 2017 GS were dry at all sites (except 2014 at Pauciflora Fen). The 2018 and 2016 GS were wet at all sites (Figure 2a). July of 2013 was cool and dry while July of 2014 2016, 2017 was warm and dry at all sites except Pauciflora Fen. The 2018 and 2016 GS were wet at all sites (Figure 2a). July of 2013 was cool and dry while July of 2014 2016, 2017 was warm and dry at all sites except Pauciflora Fen. The 2018 and 2016 GS were wet at all sites (Figure 2a). July of 2013 was cool and dry while July of 2014 2016, 2017 was warm and dry at all sites except Pauciflora Fen. The 2018 and 2016 GS were wet at all sites (Figure 2a). July of 2013 was cool and dry while July of 2014 2016, 2017 was warm and dry at all sites except Pauciflora Fen. The 2018 and 2016 GS were wet at all sites (Figure 2a). July of 2013 was cool and dry while July of 2014 2016, 2017 was warm and dry at all sites except Pauciflora Fen. The 2018 and 2016 GS were wet at all sites (Figure 2a). July of 2013 was cool and dry while July of 2014

3.2 | Interannual variation of evapotranspiration rates

During the study period, GS ET rates ranged from 0.5 to 5.4 mm day$^{-1}$ while ET$$_J$$ ranged from 0.8 to 5.4 mm day$^{-1}$, with the highest rates at Pauciflora Fen followed by Poplar, JACOS, and Saline Fens (Figures 3–5; Tables S4–S7). In general, monthly median GS ET rates decreased from July to September at all sites during all GS. The highest daily ET rates were observed in July, except in 2017 at Saline Fen and in 2015 at Pauciflora Fen. In general, monthly median ET rates were the highest in June–July, except at Pauciflora Fen (2015, 2017, 2018), Poplar Fen (2015, 2017), Saline Fen (2017, 2018) when the highest monthly median ET rates were observed in May. The lowest daily and monthly ET rates were observed in September at all sites during all GS. Total ET$$_J$$ ranged from 42 to 116 mm (Figure 6a,b; Tables S4–S7). While differences in ET$$_J$$ between all sites were significant ($p < 0.05$), interannual differences in ET$$_J$$ within sites were significant ($p < 0.05$) at Pauciflora and Saline Fens only. Coefficient of variation (CV) of daily ET in July were lowest at Saline Fen, followed by JACOS, Poplar and Pauciflora Fens (Figure 6c). Over the studied
period, ET/PET ratio during GS and in July was lower than 1 (average 0.8 ± 0.1) at all sites (Figure 6f); the highest ratio was observed at Poplar Fen followed by Pauciflora, JACOS, and Saline Fens. Mean values of ET and environmental variables were not significantly different from median values.

3.3 Interannual variability in environmental conditions

The depth to water table varied from 0.57 below the ground surface to 0.04 m above the ground surface; Poplar and Saline Fens were characterized by greater WTD fluctuation comparatively to Pauciflora and JACOS Fens (Figures 3–5; Tables S4–S7). Overall, two main trends were observed at all sites: (1) gradual decline in median WTD from May to September (in 2015, and 2017; except Poplar Fen in 2015); and (2) fluctuating WTD (other years).

Total monthly P ranged from 2 to 243 mm (Figures 3–5; Tables S4–S7). The lowest total GS P was observed in 2015 at Pauciflora, Poplar, Saline Fens, while 2012 had lowest total GS P at JACOS. The highest total GS P was observed at Poplar and JACOS Fens in 2013 and at Saline and Pauciflora Fens in 2016 (Figures 3–5; Tables S4–S7). July P/PET ratios changed from 0.3 to 1.6 (Figure 6d). July 2018 was characterized by the highest P/PET, P/ET J at Pauciflora, Poplar, and Saline Fens (Figure 6d,e). P/PET ≤1 were associated with increasing mean daily ET J rates and total ET J while
P/PET > 1, corresponded to decreasing mean daily ETJ rates and total ETJ (Figures 2c,d and 6a,b,d).

Daily $R_{\text{net}}$ ranged from 2 to 231 Wm$^{-2}$ while daily $T_{\text{air}}$ varied from -5.6 to 28.5°C and VPD ranged from 0.2 to 2.4 kPa. At all sites, the seasonal variation of daily $R_{\text{net}}$, $T_{\text{air}}$, and VPD showed a mid-summer peak every year, except 2013 when increased $T_{\text{air}}$ and $R_{\text{net}}$ in May were observed (Figures 3–5; Tables S4–S7).

### 3.4 Relations between ET and environmental variables

Strong positive significant correlations ($r > 0.50$, $p < 0.05$) between ET and $T_{\text{air}}$, $R_{\text{net}}$, and VPD were found at Pauciflora, Poplar, JACOS Fens (Figures 7 and 8). The warmer years (e.g., 2013, 2016, 2017) at Pauciflora and Poplar Fens were characterized by stronger correlations between ET and $T_{\text{air}}$. 

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**FIGURE 5** Evapotranspiration (ET), water table depth (WTD), cumulative precipitation, vapour pressure deficit (VPD), air temperature, and net radiation at Saline Fen in 2015–2018 (a) and JACOS Fen in 2011–2014 (b).
and $T_{\text{air}}, R_{\text{net}},$ and VPD rates compared to colder years (Table S8, Figures 7 and 8); however, this tendency was not observed at JACOS Fen. Correlations between ET and $T_{\text{air}}, R_{\text{net}},$ and VPD were not significant at Saline Fen (Figures 7 and 8). No strong significant correlation between WTD and ET rates was observed at any site (Figure 8). Strong significant positive correlation ($r > 0.9, p < 0.05$) between daily $\text{ET}_j$ and $\text{PET}$ was observed at Pauciflora, Poplar, and JACOS Fens (Figure 9).

### DISCUSSION

#### 4.1 Seasonal ET variability and relations with environmental conditions

During the study period, variability of growing season ET rates at Pauciflora, Poplar, Saline and JACOS Fens were comparable to values...
reported by other studies from WBP (e.g., Brown et al., 2010; Phillips et al., 2016). Overall, variability of growing season ET rates at four fen sites were characteristic of the WBP with the highest rates in June–July when the warmest $T_{\text{air}}$ and the highest $R_{\text{net}}$ and VPD were observed (Amiro et al., 2006; Baldocchi et al., 2000; Brown et al., 2010; Cienciala et al., 1998; Grelle et al., 1997; Lafleur et al., 1997; Phillips et al., 2016; Rouse, 2000). Although ET rates are typically low during early growing season (May) due to sparse vegetation (Brown et al., 2014; Phillips et al., 2016), relatively high ET rates were measured in May at Pauciflora and Saline Fens in 2017 and 2018. Such elevated ET rates can be related to high water availability caused by inundation over frozen saturated peat; substantial seasonal ground ice can maintain saturated conditions near the surface during the melt season (Van Huizen et al., 2020). From August to September, ET rates gradually decreased as $T_{\text{air}}$, $R_{\text{net}}$, and VPD declined and vegetation began to senesce (c.f. Kim & Verma, 1995; Lafleur et al., 1997). Strong significant correlations between ET and $T_{\text{air}}$.
Rnet, and VPD that were observed at Pauciflora, Poplar, and JACOS Fens (Figures 7 and 8, Table S8) are consistent with studies from peatlands outside the WPB, confirming that Tair, Rnet, and VPD are important drivers of peatland ET (Admiral et al., 2006; Admiral & Lafleur, 2007; Baldocchi et al., 2000; Kellner, 2001; Lafleur, 2008; Lafleur & Roulet, 1992; Priban & Ondok, 1985; Souch et al., 1998).

Our study shows that ET rates at studied fens were site-specific and resulted from the interaction between regional and local conditions (e.g., vegetation composition; topographic characteristics), which is consistent with other studies that revealed the importance of large- and small-scale controls on ET (Green et al., 2020; Lafleur et al., 2005). In this study ETj was smaller than PET, which supports the presence of surface controls on ET found by Petrone et al. (2007), Waddington et al. (2015), Hokanson et al. (2016) and James (2017), who reported autogenic feedbacks such as turbulent and radiative sheltering, and vegetation controls that can moderate evaporative

**FIGURE 8**  Relations between vapour pressure deficit (VPD) and evapotranspiration (ET) at (a) Pauciflora and (b) Poplar Fens (2013–2018), (c) Saline Fen (2015–2018) and JACOS Fen (2011–2014) and between evapotranspiration (ET) and water table depth (WTD) at Pauciflora and Poplar Fens (2013–2018), and Saline Fen (2016–2018). In 2016, more than 50% of data were missed at Saline Fen.
losses within peatlands. Petrone et al. (2007) and Green et al. (2020) found that turbulent sheltering from surface transitions can reduce the atmospheric demand for ET within the region that is sheltered from the prevailing wind. However, this can also result in higher ET rates where flow reattachment occurs, causing spatially varying evaporative demand across the peatland surface. Furthermore, vegetation and transition edges can modify radiative budgets across the surface where shading can decrease the available energy for evaporation thereby decreasing ET rates (Cleugh, 1998; Kettridge et al., 2013). Lastly, surface vegetation composition influences ET rates by controlling transpiration rates through stomatal dynamics and the plant's ability to access groundwater (Strilesky & Humphreys, 2012; Kettridge et al., 2013). Links between ET and PET revealed by strong significant correlation are consistent with findings of Lafleur et al. (2005) who suggested that ET appears to be related strongly with PET. Notably, ET/PET during peak growing seasons were lowest at saline and open (JACOS) fens, followed by the moderately treed fen (Pauciflora) and heavily treed fen (Poplar). These contrasting differences support the notion that vegetation imposes a strong influence on water loss. In addition, open fens (e.g., Saline and JACOS Fens) had lower total ET, and daily ET, rates while treed fens (Pauciflora and Poplar Fens) had significantly higher total ET, and daily ET, rates. This can be explained by the ability of trees to transmit water from deeper soil layers and maintain ET until the water table decreases below the rooting zone (Angstmann et al., 2012; Kettridge et al., 2013; Lafleur et al., 2005). A lower ET/PET at moss-dominated JACOS Fen is likely due to the hydrological feedback of a lower WTD lowering the moss capitulum and/or stem water content in Sphagnum or brown mosses, respectively, which quickly decreases the vertical hydraulic gradient across the unsaturated zone in the upper moss layers (Goetz & Price, 2015; McCarter & Price, 2014). This can limit the water availability if that rate is lower than the PET demand. Further drying of the moss can indirectly change the surface resistance and albedo, which will further decrease ET (Price, 1991; Waddington et al., 2015).

Previous community-scale study at Saline Fen (Phillips et al., 2016) revealed strong physiological control of vegetation on ET due to dominance of salt-tolerant vascular vegetation. In agreement with aforementioned study, we found a strong effect of vegetation on ET as evident from the weak correlation ($r < 0.5, p > 0.05$) between ET and $T_{air}$, $R_{net}$, and VPD at Saline Fen, in contrast to other sites (Figures 7 and 8, Table S8). Such discrepancy can be explained by the ability of halophytes and salt-tolerant species that are dominant at Saline Fen to modulate water movement in order to mitigate salt stress (Munns, 2005; Parida & Das, 2005; Phillips et al., 2016).

4.2 Interannual ET variability

The AOSR falls within the sub-humid climate that is characterized by PET exceeding P for most years (Brown et al., 2010; Devito et al., 2005, 2012; Petrone et al., 2007). In our study, in most Julys, PET was greater than P, except 2016 in Pauciflora, 2018 at Pauciflora and Poplar Fens, 2012 and 2013 at JACOS Fen (Figure 2c,d).
deviation suggests that there is variability in weather that can generate exceptions to sub-humid conditions. Notably, P/PET > 1 was associated with decreased ET and negative correlation between P and ET while when P/PET < 1, P and ET were positively correlated (Figure 2c,d). Such relations are not surprising as PET is driven by changes in energy and temperatures and reflects an upper limit to ET rates that is rarely reached in the northern peatlands (Lafleur et al., 2005), and thus, water availability defines actual ET (Waddington et al., 2015). However, increased P, coupled with decreased energy influx and lower temperatures can produce a surplus of water that cannot be evaporated, and as a result, ET rates become energy limited. This is also supported by a strong positive correlation between $R_{net}$, $T_{air}$ and ET on daily scales (Figures 3–5).

The existence of decadal wet/dry cycles in the WBP has been reported by several studies (Chasmer, Devito, et al., 2018; Devito et al., 2017; Government of Alberta, 2013). Since the 2000's, the Fort McMurray area has experienced a decline in precipitation (Government of Canada, 2019). According to the estimation of cumulative departure from long-term mean precipitation (CDLM) (Volik et al., 2017; Wells & Price 2015b), a dry period (CDLM<0) started in 2015. However, at studied sites, no clear common interannual trends in ET related to CDLM in the region were observed. Overall, multiyear ET, trends were site-specific, but some associations between ET, and wetness/warmness of peak growing seasons were found. For example, cold and dry (with respect to long-term mean values in the region) Julys (e.g., 2015 at Pauciflora) had lower ET, while warm and dry Julys were characterized by higher ET, at Poplar and JACOS Fens (Figures 2b,d and 6b). The only exception was July 2016 at Poplar Fen when ET was lower, but this inconsistency can be attributed to alteration of ET rates by wildfire that occurred at the fen in that year (Elmes et al., 2018). In contrast, warm and dry Julys at Saline Fen were characterized by reduced ET that can be explained by dominance of salt-tolerant vegetation (see above).

At studied sites, wet peak growing seasons were characterized by higher variability in daily ET, rates (Figures 2b and 6c). Such variability can be related to the distribution of P during GS. In general, the high monthly total precipitation values were often attributed to large rain events that are typical to the WBP (Brown et al., 2010, 2014; Phillips et al., 2016). Such rain events were often associated with dramatic peaks in daily ET that are consistent with previous findings, suggesting that ET rates rise after precipitation events due to intense evaporation of water that was intercepted and held in the canopy (Brown et al., 2014). However, the interannual fluctuations in July P were larger compared to variation of ET, which can be explained by the ability of surface characteristics (e.g., vegetation, peat properties) to modulate water loss (Waddington et al., 2015) and maintain relatively consistent ET regardless of short-term changes in water input.

4.3 Implications for wetland monitoring in the AOSR

The Oil Sands Monitoring (OSM) program has recently been created to assess the cumulative environmental impacts of anthropogenic activity associated with oil sands development (AEP and ECCC, 2018). OSM is a collaboration of many projects that monitor atmospheric, biotic, wetlands, and other important environmental features. Wetland monitoring requires the complete understanding of natural wetland function and the disturbances directly or indirectly associated with oil sands activities. Monitoring of wetland hydrologic functioning has been recognized as a significant component of wetland monitoring in the AOSR (Ciborowski et al., 2012; Eaton & Charette, 2016; Volik et al., 2020) and outside the region (McLaughlin & Cohen, 2013). Hydrologic functioning of wetlands is commonly evaluated based on hydrological regime and groundwater exchange that involve WTD measurements; however, in the AOSR where ET is a major part of water balance, measuring of ET can be crucial for reliable quantification of wetland hydrological functioning.

In addition to existing recommendations for fen hydrology monitoring (e.g., Ciborowski et al., 2012; Eaton & Charette, 2016; Volik et al., 2020), the following points should be considered:

1. Insignificant interannual differences in ET at each of the three freshwater fens suggests that the fens were able to maintain relatively consistent water loss during peak growing seasons despite significant variability in P. Consequently, it can be speculated that extreme changes in ET during peak growing season can indicate the alteration of hydrological functioning of fens in the AOSR.

2. Our study has shown that ET is more variable during wet GS, and also ET is more strongly influenced by $R_{net}$ and $T_{air}$ during warm GS. Consequently, timing and interpretation of ET measurements seems to be important for remote sensing, which has been increasingly used for the monitoring of wetland ecological and hydrological conditions at various spatial scales (Chasmer, Devito, et al., 2018; Chasmer, Baker, et al., 2018; Gillanders et al., 2008; Montgomery et al., 2019). As remote sensing data represent a series of images, it is very important that the images provide realistic snapshots of hydrological conditions.

3. Our study suggested that ET rates are site-specific, and not only climatic conditions, but also the type of vegetation influenced ET rates. Consequently, development of benchmark ET values for fens in the AOSR requires careful consideration of fen types and related variability in vegetation cover. This is of particular importance for remote sensing that can be potentially used for ET monitoring (Chasmer, Baker, et al., 2018).

4. PET estimation is widely used to approximate ET over wetlands (German, 2000; Shoemaker & Sumner, 2006), and our findings supported the usefulness of PET for freshwater fens. However, appropriate coefficients (based on vegetation cover and fen type) have to be applied. For example, based on this study the following coefficients seems to be useful: 0.9 for moderate-rich treed fens, 0.7 for poor treed fens, 0.6 for poor open fens. However, these values were estimated based on peak growing seasons at limited number of sites, so more accurate estimation using wider range of environmental conditions and all fen types is necessary.
4.4 | Implications for fen construction in the AOSR

Maintaining a shallow and stable water table has been considered as one of the main aims for fen establishment and further functioning (Ketcheson et al., 2016; Price et al., 2010). While the amount of precipitation at constructed fens cannot be manipulated (unless artificial watering will be applied), water loss can be reduced by the modification of the microclimatic regime at the peatland surface. Our study supports previous findings suggesting that $R_{\text{net}}$ has a strong control on ET, so changes to energy fluxes through the alteration of local conditions such as land transitions (light shading and turbulent sheltering) (Cleugh, 1998; Green et al., 2020; Kettridge et al., 2013; Petrone et al., 2007) and surface vegetation selection could be used to modulate ET rates (Green et al., 2020; Striletsky & Humphreys, 2012; Waddington et al., 2015).

Our results are consistent with previous studies (Brown et al., 2010; Phillips et al., 2016) showing an important role of vegetation cover in ET regulation. In particular, our findings suggest that treed fens had higher ET rates and higher ET/PET ratios due to the ability of trees to maintain ET despite water table decreases. Consequently, at least in the early part of the reclamation process, construction of open fens dominated by mosses and herbaceous plants should be prioritized over treed fens in order to reduce water losses from constructed wetland ecosystems.

As mining activities have been disturbing the natural sedimentary sequences, exposing salt-rich layers at the surface, post-mining landscapes are anticipated to have elevated salt content (Rooney et al., 2012; Trites & Bayley, 2009). Current fen construction efforts (Price et al., 2010; Vitt & House, 2015) have shown that the establishment of freshwater boreal peatland communities can be challenging in the early part of the reclamation process, and salt-tolerant wetland communities seem to be widespread at constructed fens (Trites & Bayley, 2009; Vitt et al., 2016). Our study has shown that salt-tolerant vegetation can significantly modify ET within saline fens as evident from low ET/PET ratio, while the hydrometeorological regime had weak controls on ET. Consequently, it might be more challenging to regulate ET within constructed saline fens using surface features (e.g., topography, sheltering, connectivity, etc.) because any manipulation of local settings has to be evaluated based on the effect of vegetation, which is not straightforward due to the physiological response of plants to salinity stress.

4.5 | Limitations and future research

Limitations of studies of this nature include data gaps that occur due to malfunction of equipment, and periods of atmospheric instability (see Gap-filling and Statistical analyses sections); all missed or gap-filled data are identified on Figures 3–5. Missing periods of data reduce confidence in relationships between climatic variables and ET. Furthermore, ET was measured at only four fens and do not represent all of the topography, geology, and vegetation variability of the AOSR. The limitations of this study point towards questions to be addressed by further research. Since interannual variability in this study was assessed based on ET rates during peak GS (July), future study is necessary to evaluate such variability during the whole GS. Future studies should quantify total annual ET and ET during the whole GS, as they were not determined in the current study.

5 | CONCLUSION

Multiyear growing season ET at four fens in the AOSR, was measured using eddy covariance technique to reveal controls on ET, coupled with seasonal and interannual ET variability. ET rates were positively related to net radiation, air temperature and vapour pressure deficit and showed typical WBP patterns with highest rates in June–July. No strong links between ET and water table position on ET were found at any of the four fens. Surface controls (vegetation, in particular) play a significant role in ET regulation, as evident from PET exceeding ET at seasonal and interannual scales and from higher ET rates at treed fens.

Despite significant differences in ET rates among sites, multiyear peak growing season ET rates were relatively similar at each freshwater fen suggesting that the fens were able to maintain ET rates within a certain range despite P variability, evidence of their importance as water storage units in the landscape. Although wet GS were characterized by higher daily ET variability, no clear links between ET rates and climatic variability were found.

Spatial and temporal patterns in ET in the region, governed by vegetation characteristics and hydrologic conditions, are clearly integrating indicator of changes in vegetation and hydrology at a range of scales, and by extension their overall hydrologic functioning. Thus, this study demonstrates the importance of monitoring ET to understand the hydrological functioning of natural and constructed fens. However, we urge continued studying of ET in a wider range of environmental conditions and at all fen types.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.
Baldocchi, D., Kelliher, F., Black, T. A., & Jarvis, P. (2000). Climate and vegetation controls on evapotranspiration from a peat bog in eastern Canada. *Agricultural and Forest Meteorology*, 144, 213–229.

Admiral, S. W., & Lafleur, P. M. (2007). Modelling of latent heat partitioning at a bog peatland. *Agricultural and Forest Meteorology*, 144, 213–229.

Admiral, S. W., Lafleur, P. M., & Roulet, N. T. (2006). Controls on latent heat flux and energy partitioning at a peat bog in eastern Canada. *Agricultural and Forest Meteorology*, 140, 308–321.

Ahmad, S., Hörmann, G., Zantout, N., & Schrautzer, J. (2020). Quantifying actual evapotranspiration in fen ecosystems: Implications of management and vegetation structure. *Ecohydrology and Hydrobiology*, 20, 382–396. https://doi.org/10.1016/j.ecohyd.2020.04.001.

Alberta Environment and Parks (AEP). (2016). *Alberta wetland restoration directive*. Retrieved from https://open.alberta.ca/publications/9781460131497#detailed

Alberta Environment and Parks (AEP), Environment and Climate Change Canada (ECCC). (2018). *Oil Sands Monitoring Program*. Annual Report for 2017–2018. Retrieved from https://open.alberta.ca/dataset/db8e811a-962e-4c1e-b2c2-f4f0b8d9ad7a/resource/35be766d-08e4-4d28-bf89-b92a7f3abf79/download/asm-annual-report-2017-2018-signed-by-aep-eccc.pdf

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration—Guidelines for computing crop water requirements—FAO Irrigation and drainage paper 56*. FAO, Rome, Italy, 300(9), D05109. Retrieved from https://www.fao.org/3/X0490E/x0490e000.htm

Amiro, B. D., Barr, A. G., Black, T. A., Iwashita, H., Kljun, N., McCaughey, J. H., ... Saigusa, N. (2006). Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. *Agricultural and Forest Meteorology*, 136(3–4), 237–251. https://doi.org/10.1016/j.agnfmeteor.2004.11.012.

Angstmann, J. L., Ewers, B. E., & Kwon, H. (2012). Size-mediated tree transpiration along soil drainage gradients in a boreal black spruce forest wildfire chronosequence. *Tree Physiology*, 32, 599–611.

Baldocchi, D., Kelliherr, F., Black, T. A., & Jarvis, P. (2000). Climate and vegetation controls on boreal zone energy exchange. *Global Change Biology*, 6, 69–83.

Bockning, E., Cooper, D. J., & Price, J. S. (2017). Using tree ring analysis to determine impacts of a road on a boreal peatland. *Forest Ecology and Management*, 404, 24–30. https://doi.org/10.1016/j.foreco.2017.08.007.

Borkenhagen, A., & Cooper, D. J. (2016). Creating fen initiation conditions: A new approach for peatland reclamation in the oil sands region of Alberta. *Journal of Applied Ecology*, 53(2), 550–558. https://doi.org/10.1111/1365-2664.12555

Borkenhagen, A. K., & Cooper, D. J. (2019). Establishing vegetation on a constructed fen in a post-mined landscape in Alberta’s oil sands region: A four-year evaluation after species introduction. *Ecological Engineering*, 130, 1–11. https://doi.org/10.1016/j.ecoleng.2019.01.023.

Bothe, R. A., & Abraham, C. (1993). *Evaporation and evapotranspiration in Alberta 1986 to 1992 addendum*. Surface Water Assessment Branch, Technical Services & Monitoring Division, Water Resources Services, Alberta Environmental Protection.

Bridgham, S. D., Updegraff, K., & Pastor, J. (1998). Carbon, nitrogen, and phosphorus mineralisation in northern wetlands. *Ecology*, 79, 545–1561.

British Petroleum. (2018). *BP statistical review of world energy. 67th addition*. Retrieved from https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review-bp-stats-review-2018-full-report.pdf

Brown, S. M., Petrone, R. M., Chasmer, L., Mendoza, C., Lazerjian, M. S., Landhäuser, S. M., Silins, U., Leach, J., & Devito, K. J. (2014). Atmospheric and soil moisture controls on evapotranspiration from above and within a Western Boreal Plain aspen forest. *Hydrological Processes*, 28(15), 4449–4462. https://doi.org/10.1002/hyp.9879.

Brown, S. M., Petrone, R. M., Mendoza, C., & Devito, K. J. (2010). Surface vegetation controls on evapotranspiration from a sub-humid Western Boreal Plain wetland. *Hydrological Processes*, 24(8), 1072–1085. https://doi.org/10.1002/hyp.7569.

Burba, G., Schmidt, A., Scott, R. L., Nakai, T., Kathilankal, J., Fratini, G., Hanson, C., Law, B., McDermitt, D. K., Eckles, R., Furtaw, M., & Velgersdyk, M. (2012). Calculating CO2 and H2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. *Global Change Biology*, 18, 385–399.

Chasmer, L. E., Devito, K. J., Hopkinson, C. D., & Petrone, R. M. (2018). Remote sensing of ecosystem trajectories as a proxy indicator for watershed water balance. *Ecohydrology*, 11(7), 1–16. https://doi.org/10.1002/eco.1987

Clborowski, J. J. H., Grjigic-Mannion, A., Kang, M., Zeng, H., Kovalenko, K., Bayley, S. E., & Foote, A. L. (2012). Development of a regional monitoring program to assess the effects of oil sands development on wetland communities. Final Report for the Cumulative Environmental Management Association (CEMA). Retrieved from http://library.cemaonline.ca/ckan/dataset/32df09ea2-d585-4729-bc29-586469b3075/resource/0fd027c-55a5-4780-bb67-5a229c99659e/download/rwdevelopmentofaregionalmonitoringprogram.pdf

Cienciala, E., Running, S. W., Lindroth, A., Grelle, A., & Ryan, M. G. (1998). Analysis of carbon and water fluxes from the NOPEX boreal forest: Comparison of measurements with FOREST-BGC simulations. *Journal of Hydrology*, 212–213, 62–78.

Cleugh, H. A. (1998). Effects of windbreaks on airflow, microclimates and crop yields. *Agroforestry Systems*, 41, 55–84. https://doi.org/10.1023/A:100619805109.

Devito, K. J., Redd, L., Gan, T., Mendoza, C., Petrone, R., Silins, U., & Smerdon, B. (2005). A framework for broad-scale classification of hydrologic response units on the Boreal Plain: Is topography the last thing to consider? *Hydrological Processes*, 19(8), 1705–1714. https://doi.org/10.1002/hyp.5881.

Devito, K. J., Mendoza, C., & Qualizza, C. (2012). Conceptualizing water movement in the Boreal Plains. *Implications for watershed reconstruction*. Environmental and Reclamation Research Group for the Canadian Oil Sands Network for Research and Development. Retrieved from https://era.library.ualberta.ca/items/d934019b-141c-4da4-8495-cb6346f575cf

Devito, K. J., Hokanson, K. J., Moore, P., Kettridge, N., Anderson, A., Chasmer, L., Hopkinson, C., Lukenbach, M., Mendoza, C., Morissette, J., Peters, D., Petrone, R., Silins, U., Smerdon, B., & Waddington, M. (2017). Landscape controls on long term runoff in subhumid heterogeneous Boreal Plains catchments. *Hydrological Processes*, 31, 2737–2751. https://doi.org/10.1002/hyp.12123.

Eaton, B., & Charette, T. (2016). *Drivers, stressors, and indicators of wetland change in Alberta’s Oil Sands Region – potential for use in wetland monitoring*. Retrieved from https://www.abmi.ca/home/publications/451-500-455.html?cbjssessionid=A4840F6A2E8CF67A556E191CD56AD

E79?mode=detail&andsubject=aquatic
Volik, O., Petrone, R. M., Hall, R. I., Macrae, M. L., Wells, C. M., Elmes, M. C., & Price, J. S. (2017). Long-term precipitation-driven salinity change in a saline, peat-forming wetland in the Athabasca Oil Sands Region, Canada: A diatom-based paleolimnological study. *Journal of Paleolimnology*, 58(4), 533–550. https://doi.org/10.1007/s10933-017-9989-4

Volik, O., Petrone, R. M., Wells, C. M., & Price, J. S. (2018). Impact of salinity, hydrology and vegetation on long-term carbon accumulation in a saline boreal peatland and its implication for peatland reclamation in the Athabasca Oil Sands Region. *Wetlands*, 38, 373–382. https://doi.org/10.1007/s13157-017-0974-5

Waddington, J. M., Morris, P. J., Kettridge, N., Granath, G., Thompson, D. K., & Moore, P. A. (2015). Hydrological feedbacks in northern peatlands. *Ecohydrology*, 8(1), 113–127. https://doi.org/10.1002/eco.1493.

Webster, K. L., Beall, F. D., Creed, I. F., & Kreutzweiser, D. P. (2015). Impacts and prognosis of natural resource development on water and wetlands in Canada’s boreal zone. *Environmental Reviews*, 23(1), 78–131. https://doi.org/10.1139/er-2014-0063

Wells, C., Ketcheson, S., & Price, J. (2017). Hydrology of a wetland-dominated headwater basin in the Boreal Plain, Alberta, Canada. *Journal of Hydrology*, 547, 168–183. https://doi.org/10.1016/j.jhydrol.2017.01.052

Wells, C. M., & Price, J. S. (2015a). A hydrologic assessment of a saline-spring fen in the Athabasca oil sands region, Alberta, Canada - A potential analogue for oil sands reclamation. *Hydrological Processes*, 29(20), 4533–4548. https://doi.org/10.1002/hyp.10518

Wells, C. M., & Price, J. S. (2015b). The hydrogeologic connectivity of a low-flow saline-spring fen peatland within the Athabasca oil sands region. *Hydrogeology Journal*, 23(8), 1799–1816. https://doi.org/10.1007/s10040-015-1301-y

Wood, M. E., Macrae, M. L., Strack, M., Price, J. S., Osko, T. J., & Petrone, R. M. (2016). Spatial variation in nutrient dynamics among five different peatland types in the Alberta oil sands region. *Ecohydrology*, 9(4), 688–699. https://doi.org/10.1002/eco.1667

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