Hydrometeorological conditions preceding wildfire, and the subsequent burning of a fen watershed in Fort McMurray, Alberta, Canada

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Abstract. The destructive nature of the ~590,000 ha Horse River Wildfire in the Western Boreal Plain (WBP), northern Alberta in May of 2016 motivated the investigation of the hydrometeorological conditions that preceded the fire. Historical climate and field hydrometeorological data from a moderate-rich fen watershed were used to identify a) whether the spring 2016 conditions were outside the range of natural variability for WBP climate cycles; b) explain the observed patterns in burn severity across the watershed; and c) identify whether fall and winter moisture signals observed in peatlands and lowland forests in the region are indicative of wildfire. Field hydrometeorological data from the fen watershed confirmed the presence of cumulative moisture deficits prior to the fire. Hydrogeological investigations highlighted the susceptibility of fen and upland areas to water table and soil moisture decline over rain-free periods (including winter), due to the watershed's reliance on supply from localized flow systems originating in topographic highs. Subtle changes in topographic position led to large changes in groundwater connectivity, leading to greater organic soil consumption by fire in wetland margins and at high elevations. The 2016 spring moisture conditions measured prior to the ignition of the fen watershed were not illustrated well by the Drought Code (DC) when standard overwintering procedures were applied. However, close agreement was found when default assumptions were replaced with measured duff soil moisture recharge and incorporated into the overwintering DC procedure. We conclude that accumulated moisture deficits dating back to the summer of 2015 led to the dry conditions that preceded the fire. The infrequent coinciding of several hydrometeorological conditions, including low autumn soil moisture, a modest snowpack, lack of spring precipitation, and high spring air temperatures and winds, ultimately led to the Horse River wildfire spreading widely and causing observed burn patterns. Monitoring soil moisture at different land classes and watersheds would aid management strategies in the production of more accurate overwintered DC calculations, providing fire management agencies early warning signals ahead of severe spring wildfire seasons.

1 Introduction

The sub-humid Athabasca oil sands region (AOSR) of the Western Boreal Plain (WBP) comprises a

mosaic of small lakes, forested uplands, and wetlands primarily as peatlands (Devito et al., 2012). Bogs

are defined as ombrogenous peatlands, receiving water exclusively from atmospheric sources (Ingram,

1983). Conversely, fens receive water from both atmospheric and surface water and/or groundwater

sources. In the WBP, fens are distinguished into three primary types (poor, moderate-rich, and extreme-

rich) based on differences in water chemistry, indicator plant species, and species richness (Vitt et al.,

1995). In the AOSR, moderate-rich fens are the primary peat-forming wetland (Chee and Vitt, 1989).

The hydrology of bog, poor fen (Ferone and Devito, 2004; Wells et al., 2017) and saline fen (Wells et

al., 2015a, 2015b) systems have been studied in the WBP, however, the hydrology of moderate-rich fen systems in the AOSR remains largely unexplored.

Water availability in the WBP is constrained by annual precipitation rates that are typically less than potential evapotranspiration (PET) demands (Marshall et al., 1999; Bothe and Abraham, 1993). Consequently, the timing, frequency, and magnitude of wildfires is dictated by variability of the hydrometeorological conditions over the growing season (Abatzoglou and Kolden, 2011; Flannigan and Harrington, 1988), where moisture deficits accumulate in upland duff (Keith et al., 2010) and near-surface peat horizons (Lukenbach et al., 2015) over extended dry periods. Consumption of surface and ground fuels in flaming and smouldering combustion during wildfires in the WBP can total 3 kg m^{-2} (Forestry Canada Fire Danger Group, 1992) to upwards of 4 kg m^{-2} in forested peatland dominated by conifers (Benscoter and Wieder, 2003). Wildfire effects a variable, yet considerable area (~208,000 ha; 2006-2015) of Alberta on an annual basis (Government of Alberta, 2017). During these fires large quantities of terrestrial carbon stock held within WBP peatlands are liberated to the atmosphere, estimated at 4700 Gg C released per year, from Continental Western Canada alone (Turetsky et al., 2002); the peat is vulnerable to combustion and deep smouldering (Benscoter et al., 2011; Turetsky et al. 2011). Over the past decade, there has been increasing concern over longer fire seasons in Alberta (Wotton and Flannigan, 1993; Flannigan et al., 2013; Kirchmeier-Young et al., 2017), and an increase in large high-intensity wildfires (Tymstra et al., 2007), and total burned area each year (Podur and Wotton, 2010).

The majority of summer wildfires are ignited by lightning (Tymstra et al., 2005), when wildfire behaviour can be predicted by drying signals in shallow forest duff horizons with relatively simple drying mechanisms (Wotton et al., 2005). Unlike summer fires, spring wildfires usually have human caused ignition sources (e.g. recreational vehicle exhausts or unextinguished cigarettes), and are harder to predict given that widespread fires occur regardless of the presence of moisture deficits (Amiro et al., 2009). These spring fires therefore possess less obvious antecedent moisture signals, given that they occur post-snowmelt, an important rewetting period for wetlands and forested uplands in the region (Smerdon et al., 2008; Redding and Devito, 2011).

In Canada, early spring fire susceptibility is typically predicted with the Canadian Forest Fire Weather Index (FWI) System, a component of the Canadian Forest Fire Danger Rating System (CFFDRS) (Lawson and Armitage, 2008). The Drought Code (DC) is a component of the FWI which applies to slow-drying deep forest organic layers often found throughout the WBP, layers that can enhance wildfire intensity (Van Wagner, 1987). The DC is a semi-physical model which uses precipitation inputs and predicts water loss as a function of daily noon temperature and day length, to estimate the moisture content of deep organic layers that typically dry logarithmically based on an estimated 53-day period required to lose two thirds of held moisture (Lawson and Armitage, 2008). Values of the DC range from 0 (saturated soils at surface) to over 800 (residual soil moisture only), representing the origins of the index as representing the slow drying of stored water in Pacific coastal slash fuels (Turner, 1972). DC values have been related to peatland water table (Waddington et al.,

2012) as well as the extent of peatland burned area (Turetsky et al., 2004). These DC calculations, although based on typical wetting and drying rates of relatively deep upland fuels (Lawson and Armitage, 2008) and regarded as general estimates, can be important predictors for fire managers immediately following snowmelt, especially when additional soil moisture information is lacking. Given the large moisture deficits that can develop in deeper upland organic layers, the DC is overwintered to incorporate the effect of fall DC and winter precipitation into the next year's starting value. Overwintering calculations generally include estimates of total winter precipitation from nearby climate stations, along with two estimated coefficients, which include a carry-over effect to adjust for antecedent (fall) moisture conditions, and the wetting efficiency fraction of the snowpack to the specific soil layer (Lawson and Armitage, 2008). These coefficients, however, can be ignored if direct measurements of recharge into forest soils are available.

During the spring of 2016, the ~590,000 ha Horse River Wildfire spread into the city of Fort McMurray, and subsequently advanced across the boreal mosaic of mixedwood uplands and peatlands. The destructive nature of the Horse River Wildfire, specifically the imminent threat to nearby inhabitants causing widespread evacuation (MNP, 2017) and the subsequent $3.58 billion of direct insurance and infrastructure losses that resulted (IBC, 2016), motivated the investigation of the hydrological and meteorological conditions that led up to the fire. Currently, it is unknown if the exceptionally warm and dry conditions were also manifested by significant moisture deficits in the peatland watersheds surrounding the community. This study provides a useful means of explaining why

watersheds in the region are especially vulnerable to wildfire in the early spring, and how management agencies can better detect these early moisture signals that are a potential indicator of future high-intensity spring wildfires.

We capitalize on an opportunity to explore pre-fire hydrometeorological data obtained from Poplar Fen from 2011-2016, an instrumented moderate-rich fen watershed that burned on May 17, 2016. The specific objectives of this research are 1) to use a combination of historical climate and field hydrological data to characterize the hydrometeorological conditions preceding the burning of a moderate-rich fen watershed to determine whether these conditions were outside the range of natural WBP climate cycles; 2) to use these hydrological data to explain the observed patterns in burn severity across the watershed; and 3) to identify whether hydrological data and hydrogeological setting parameters of the watershed can serve as indicators of deep smouldering and combustion risk.

2 Study Site

Situated within the Athabasca region of the Boreal Plains ecozone (Ecoregions Working Group, 1989), 'Poplar Fen' (56°56'N, 111°32'W; Fig. 1) is a ~2.5 km^2 treed moderate-rich fen watershed, located 25 km north of Fort McMurray, Alberta (Fig. 1). This watershed is characterized by low relief topography (~10 m), with undulating sand/gravel uplands, and interconnected moderate-rich fens. Average annual

air temperature (1981-2010) is 1°C; average annual precipitation is 419 mm, with ~75% falling as rain (Environment Canada, 2017).

The fen areas at Poplar Fen are underlain by thin (~10 cm) heterogeneous deposits of fine-grained silty sand of relatively low hydraulic conductivity that constrict recharge to an underlying outwash sand/gravel layer and favour saturated peat-forming conditions. Maximum peat depth ranges from 1.2–3.0 m, decreasing to <0.5 m along the margin tracts between fen and upland. Ground surface and water table elevations generally decrease from upland to margin to fen, and from southeast to northwest. Uplands are underlain by Brunisols in topographic highs, and by Luvisols in riparian areas.

Tamarack (*Larix lariciana*) and black spruce (*Picea mariana*) are the dominant tree species within moderate-rich fen areas, with a surface cover of the mosses *Tomenthypnum nitens, Aulacomnium palustre, Pleurozium schreberi,* and from the genus *Sphagnum* (*S. fuscum* and *S. capillifolium*). Margins are characterized by a sparse *P. mariana* overstory, with *S. fuscum* and the feathermosses *Hylacomium splendins* and *P. schreberi*. Upland areas are dominated by *P. mariana* and feathermosses in riparian zones, with jack pine (*Pinus banksiana*) and aspen (*Populus tremuloides*) mixedwood overstory and lichen ground cover, in topographically higher areas.

3 Methodology

3.1 Historical data collection

A 20-year record of meteorological data were obtained from Alberta Agriculture and Forestry through the Alberta Climate and Information Service (Alberta Agriculture and Forestry, 2017). This included daily values of precipitation (rainfall and snowfall) and air temperature, which were estimated for the Poplar Fen area (township: T092R10W4) using an inverse-distance weighting interpolation procedure (IDW). Data from 2-7 stations were used for the IDW over the 20-year period with the nearest station (Mildred Lake; Fig. 1) located ~12 km from Poplar Fen. Rainfall and snowfall were totaled for every hydrological year (Oct. 01–Sep. 30). Additional average daily wind speed and relative humidity values were obtained from the Mildred Lake climate station for the 2015-16 winter and early spring (Alberta Agriculture and Forestry, 2017). A seven-year record of snow-water equivalent (SWE), the depth of water contained within the snowpack, was also obtained from a snow pillow located at Gordon Lake, ~70 km from Poplar Fen (Alberta Environment and Parks, personal communication). This record provided information on SWE accumulation/ablation as well as peak SWE prior to snowmelt from Oct. 2009 to Apr. 2016. Snow-free conditions were estimated for each year by identifying the day when <20% of the snow mass was remaining.

3.2 Field data collection

Hydrological data were collected between 2011 and 2016. Initial instrumentation included a water table monitoring well in a fen area (NW fen) located in the northwest section of the watershed, and a well in

the adjacent margin area (NW margin), located ~140 m south of the fen well (Fig. 1) at an elevation ~0.65 m greater than the fen. NW fen water table was monitored from June 2011 to May 2016 using either a logging pressure transducer (from 2011–12; Schlumberger Mini-Diver) or a capacitance water level recorder (from 2013–16; Odyssey Dataflow Systems Ltd.). In spring 2015, additional groundwater monitoring focused on two fen areas located at contrasting low (lower) and high (upper) topographic elevations, which varied by ~0.7 m (Fig. 1). Groundwater monitoring nests were installed in the lower (n=4) and upper (n=3) fen areas and adjacent margins (n=4) (Fig. 1). Screened wells and piezometers (20 cm screened intake) were constructed from PVC (2.5 cm I.D.) pipe and installed into the different substrates in grouped nests. Nests typically comprised a fully-slotted well, with piezometers installed in mid-peat (0.6–0.75 m depth) and underlying mineral (1.25–1.85 m depth). Logging pressure transducers were installed in a well and in a piezometer situated in the underlying mineral layer, for one nest each in the lower and upper areas (Fig. 1). Nests were measured manually on a weekly basis between May–August, 2015, and again in early October. Vertical hydraulic gradients were calculated between water table and hydraulic head in the underlying mineral layer for each nest in the lower and upper fen areas, using standard methods (Freeze and Cherry, 1978). Fen ground temperatures were monitored within close proximity to the NW fen well between fall 2012 and summer 2016 using two thermocouple arrays, buried at 0.1 and 0.2 m depth below surface. Temperatures were logged half hourly and daily averages were calculated for each depth.

Precipitation was measured in an open area of the site with a logging Onset RG3-M tipping bucket rain gauge; missing daily totals (Oct–May) were supplemented with interpolated rainfall data for the Poplar Fen area (Alberta Agriculture and Forestry, 2017). Between Mar. 21 and Apr. 19, 2016, snow surveys were conducted using a Meteorological Service of Canada (MSC) snow tube. Measurements of snow depth were taken at 178 locations, ~ 10 m apart along a zig-zag transect that extended through all major land class for Poplar Fen (Fig. 1). SWE was recorded every ~20 m. Peak SWE was represented by the first snow survey on Mar. 21, 2016 and an area-weighted SWE contribution for each land class was estimated from the proportional area for each respective class.

Volumetric water content (VWC) was recorded half-hourly from June 2015 to May 2016 in upland duff and margin peat soils, with arrays of Stevens Hydra-II probes (Fig. 1;2). Two weeks of data (May 2–May 17, 2016) could not be salvaged due to fire damage to the logger. The probes were calibrated in-laboratory to the respective soil types.

3.3 Drought Code

The Drought Code (DC) was calculated using the 'cffdrs' package in R statistical program (R Core Team, 2016) for the 2015 growing season using data obtained from the Mildred Lake climate station (Alberta Agriculture and Forestry, 2017). This included noon measurements of air temperature and cumulative precipitation from the previous 24 hours. The DC was started on Apr. 12, 2015, following three days of noon temperatures of 10°C or higher, using default presets, including a starting DC of 15.

The starting DC becomes less imperative over a fire season as it will be corrected after sufficient rainfall (Alexander, 1982), thus, an overwintering procedure is essential for improving accuracy predominantly in the early months of a fire season. The DC was run until Oct. 31, 2015 (a standardized end date) and the code then overwintered for spring 2016 using a range of different approaches following methods outlined by Van Wagner (1987). The startup moisture equivalent (Q_S) of the DC was determined by Eq. (1):

$$Q_S = aQ_f + b(3.94r_w), \tag{1}$$

where Q_f is the moisture equivalent of the DC on October 31, 2015, r_w is total winter precipitation (mm), and 'a' and 'b' are coefficients chosen to estimate the carry-over fraction of last fall's moisture, and estimate the fraction of snowmelt retained in the duff layer, respectively. Q_f is calculated by Eq. (2):

$$Q_f = 800 \exp(-DC_f/400) \tag{2}$$

where DC_f is the final DC value on Oct. 31, 2015. The startup DC value can then be calculated from Eq. (3):

$$DC_S = 400 \ln(800/Q_S), \tag{3}$$

The values for *a* and *b* in equation 1 are typically determined by provincial fire management agencies (Lawson and Armitage, 2008). Though organic soil moisture data are available in this instance, in this study we examine both the observed soil moisture data, in addition to variations on DC start and overwinter values using less detailed information, to compare predictions of organic soil moisture at the time of the fire made without the benefit of in-situ observations.

Startup and overwinter upland duff DC were calculated four different ways (Table 1), each reflecting specific information of the hydrometeorological environment. For scenario 1, startup DC was estimated for the upland duff from a linear regression between DC and measured duff VWC from Jun. 27–Oct. 31, 2015, and calculated based on the starting VWC for Apr. 19. Scenarios 2-4 were then calculated with the overwintering procedure (Equations 1, 2 and 3). For scenario 2, the startup DC was calculated using total winter precipitation values obtained from the Fort McMurray airport climate station and default carry-over and wetting-efficiency values (0.75) from the cffdrs package (Lawson and Armitage, 2008). For scenario 3, the startup DC was calculated from peak SWE data from snow survey data of Poplar Fen and carry-over (0.5) and wetting-efficiency (1.0) values used by Alberta Agriculture and Forestry. Scenario 4 applied the directly measured duff recharge (a mm value input, inferred from the upland duff site moisture probe) to the overwintering procedure, which eliminated the need for a precipitation value as well as estimates of carry-over and wetting-efficiency. Following these methods, four differing startup DC values were generated for the upland duff. The DC was then calculated four times, corresponding to each startup DC value, starting at Apr. 19 and were ran until May 17, 2016.

3.4 Burn depth and fuel consumption

Measurements of burn consumption of organic soils were made in fen, margin, and upland areas that burned using differential GPS (Leica GS14 GNSS) survey data obtained pre- (October 2015) and post-fire (October 2016) from well-inferred surface (elevation of PVC top minus distance to ground surface) elevations; the difference between soil surface elevations at piezometer nests were compared between 2015 and post-fire 2016. This included nests from Poplar Fen additional (5 fen, 5 margin, and 10 upland nests) to those identified in Fig. 1 (not shown). Average vertical elevation (surface) change was calculated for each nest location. Depth changes were averaged for burned fen, margin, and upland organic soils, and these depths multiplied by previously measured average bulk density values for each soil type to estimate terrestrial fuel loss.

4 Results

4.1 Hydrometeorology

Precipitation observations from 1996-2016 interpolated for Poplar Fen averaged 380±17(SE) mm total precipitation with 284±15 mm falling as rain and 96±6 mm as snow (Table 2). For the four hydrologic years of high burned area in the spring, total winter snowfall was below average for all years except for 1997-98. The lowest total snowfall was measured in hydrologic years 1998-99, 1999-00, and 2008-09, all years with low burned area in the spring. Peak SWE from Gordon Lake snow pillow from 2009-2016 (Fig. 3) averaged 120±10 mm. Peak SWE prior to snowmelt in hydrological years 2010-11 and

2015-16 was not especially low, and despite the modest SWE available for melt, the snow-free day of year (80% of peak SWE melted) during these years was not significantly earlier than the other 5 years on record. Total rainfall was below average in only two (1997-98 and 2010-11) of the four hydrological years with large spring burned areas, the bulk of precipitation occurred in the summer for all four years (Table 2). Cumulative post-melt rainfall until May 15 averaged 25.5 ± 3.3(SE) mm between 1997 and 2016 (Fig. 3). Three of four hydrological years with high burned area in the spring were below the 20-year average rainfall, 2001-02 being the lowest and 1997-98 just above average. In 2015-16, only 8.5 mm of rain fell following snowmelt prior to ignition of the Horse River Wildfire, and only 0.3 mm fell over the next two weeks leading up to the burning of Poplar Fen watershed (Fig. 3). The hydrological year with the lowest early spring cumulative rainfall in the 20-year record was 2007-08 (1 mm), a year of low burned area in the spring (Natural Resources Canada, 2017). However, during this year a total of 151 mm of snow fell in the area, 55 mm more than the 20-year average (Table 2), and snow-free conditions were not reached until Apr. 30.

Over the 2015-16 winter (mid Oct. – mid Apr.), average air temperatures were -6.5°C, 2.9°C warmer than for the previous 19-hydrologic year (1996-2015) average (-9.4°C). Periodic warm spells were observed in late January and February, when air temperatures rose above freezing for several consecutive days (Fig. 4a). Manual snow measurements yielded an area-weighted average peak SWE of 105 mm (Fig. 4d) on Mar. 21, 2016, 2 mm higher than the peak measured at the Gordon Lake snow pillow. In spring 2016, the primary snowmelt period occurred between Mar. 21 and Apr. 19. Air

temperatures did not deviate far from the 20-year normal during this time, with the exception of Mar. 27-30, when daily maximum air temperatures in the area rose to over 9°C. The strongest deviation prior to the fire was measured following snowmelt when maximum daily air temperatures reached 27°C and 33°C in April and May, respectively. At this time, average daily relative humidity decreased (Fig. 4b) and average daily wind speeds exceeded 20 km hr^{-1} prior to the fire's ignition (Fig. 4c).

4.2 Hydrology

The NW fen (Fig. 1) water table range was ~0.79 m, (+0.12 m to -0.66 m) between Jun. 08, 2011 and May 17, 2016 (Fig. 5). Average NW margin water table was 0.32 m lower than NW fen between 2011 and 2015. Both NW fen and margin exhibited relatively low water tables (dry conditions) at the beginning, increased water table in the middle years (wetter conditions), and lower water tables in a drying period towards the end of the 5-year record. The late fall and early spring NW fen water table was near or above ground surface in hydrological years 2012-13 and 2013-14 (Fig. 5), which corresponded with delayed ground thawing at 0.1 and 0.2 m peat depths until mid-May. Conversely, year 2014-15 water table was ~0.2 m b.g.s. in the fall and at the surface in the early spring, which began to decline rapidly in June (Fig. 5). This hydrological year corresponded with delayed ground thawing until mid-May at only 0.2 m peat depth. Furthermore, between 2011-2015, NW fen water table underwent periods of decline over the summer in all years except 2013. By early fall, the NW fen water table in all five years reached an annual low, and in 2012-2014, rose in the late fall prior to freeze-up.

Conversely, rainfall was not sufficient in 2011 and 2015 to raise the fall NW fen water table above the low levels observed in the summer (Fig. 5).

The 2015-16 hydrologic year began with water levels that were among the lowest in the six-year record (Fig. 5). By the end of winter, all manually-surveyed fen monitoring wells were empty of water (water tables >0.8 m b.g.s.). The comparison of fall 2015 logged water levels to manual winter 2016 observations (before snowmelt recharge and before pressure transducers were installed for the 2016 field season) evidenced an additional 0.12-0.26 m water table decrease, demonstrating mid-winter water table decline and drying of overlying peat substrate. Ground thawing at 0.1-0.2 m depth occurred in mid-April (earlier than 2013-15) toward the end of snowmelt, and at this time (Apr. 16, 2016) the NW fen water table had increased to 0.67 m b.g.s. The remaining snowmelt period initiated a water table rise of 0.46 m to 0.21 m b.g.s. on May 03, which then decreased in the total absence of rainfall to 31 cm b.g.s on May 17, the day that Poplar Fen area burned over (Fig. 5).

To examine how fen areas of varying topographic position were wetting and drying over the 2015 growing season, water table and hydraulic gradients were compared between the contrasting upper and lower fen areas (Fig. 6). Average water table depth below surface differed by 0.05 m between upper (0.22 ± 0.05(SD) m) and lower (0.17 ± 0.04(SD) m) fen nests. In both areas, hydraulic head in underlying mineral layers mirrored the water table profile (Fig. 6). Vertical hydraulic gradients (a metric of groundwater recharge/discharge) in both upper and lower fen areas were strongest when water

tables were highest, and weakened (less groundwater recharge to the fen) during periods when rainfall was less abundant. Throughout the entire monitored period, the lower fen nests had the strongest average hydraulic gradients (0.021 ±0.008(SE)), showing groundwater discharge that remained positive throughout the measurement period. Conversely, upper fen nests had weaker hydraulic gradients (-0.007 ±0.004(SE)), which experienced flow reversals (downward), and were negative throughout most of the year. Margin areas exhibited the lowest water tables, as well as hydraulic gradients (-0.03 ±0.03(SE)) (recharge), over the 2015 growing season (Fig. 6).

Between June and October 2015, duff and margin peat VWC (both at ~0.2 m b.g.s.) averaged 0.33 and 0.41 m^3 m^{-3}, respectively, with a higher coefficient of variation for duff (0.21) compared to margin (0.06) peat (Fig. 7). The duff experienced extended drying periods in the summer-fall, and by freeze-up, reached the minimum VWC for 2015 (0.24 m^3 m^{-3}). Margin peat VWC had also reached a minimum by fall (0.39 m^3 m^{-3}), however, values were similar to late spring 2015 VWC (~0.42 m^3 m^{-3}). During winter 2015-16 (Oct. 31 - Mar. 21), VWC in the duff and margin peat decreased an additional 0.06 and 0.03 m^3 m^{-3}, respectively, and following snowmelt, increased from 0.19 to 0.32 m^3 m^{-3} and 0.36 to 0.38 m^3 m^{-3}, respectively. Two weeks prior to the Horse River Wildfire, upland duff and margin peat VWC were 0.31 and 0.37 m^3 m^{-3}, respectively (Fig. 7), and likely continued to decrease prior to the fire in the absence of rainfall.

4.3 Drought Code

Following the first month of start up in 2015, the DC illustrated an inverse relationship with upland duff VWC (R = -0.94; p<0.001) (Fig. 7); the dry conditions caused DC to increase from 18 to 496, between Apr. 12–Oct. 31. VWC on Oct. 31 and the corresponding DC were chosen to represent the final fall moisture and DC equivalent values for the various overwintering DC calculations. The overwintering period ran from Oct. 31, 2015 to Apr. 19, 2016, the day following three consecutive days with noon air temperatures $\geq$ 12°C. For scenario 1, the 2016 spring start up DC was predicted based on the relationship between upland duff DC and VWC in 2015, and a 2016 spring start up DC of 357 was estimated given a starting soil moisture of 0.37 m^3 m^{-3} (Fig. 7). Scenarios 2 and 3 produced startup values using the overwintering procedure with standard carry-over and wetting-efficiency coefficients, resulting in start up DCs of 242 and 212 respectively. Scenario 4 used the overwintering procedure with no precipitation values or default coefficients, rather with directly measured duff recharge from Oct.31 to Apr. 19. Snowmelt increased duff VWC by 0.13 m^3 m^{-3} in the ~0.25 m thick soil horizon, resulting in 32 mm of recharge (35% of estimated upland snowfall), yielding a startup DC of 321. DC was then calculated from Apr. 19 to May 17, 2016, and all starting DCs increased 131 units over that time period (Table 3).

4.4 Burn depth and fuel consumption

Greatest depth of burn was measured in the margins (0.13±0.01 m) with lower (0.10±0.02 m) burn depths measured at upland locations (Table 4). Burn depth values in burned fen areas were 78-83%

lower than margin and upland areas. Estimated fuel consumption rates (depth of burn x average bulk density) generally echoed the trends in surface change with slight differences due to higher bulk density measured in margin peat. No surface changes or fuel consumption were observed in the lower fen area.

5 Discussion

5.1 Pre-fire meteorology

Within the Boreal Plain region of northeastern Alberta, average precipitation is less than potential evapotranspiration in most years (Bothe and Abraham, 1993). Consequently, water deficits are common in the WBP, relying on infrequent wet periods every 10-15 years to replenish storage deficits (Marshall et al., 1999; Devito et al., 2005). Historical precipitation data illustrate that rain and snow patterns are variable in the Western Boreal Plain (Table 2; Fig. 3). Total snowfall was near or below average during years during which spring wildfires burnt large areas. Although modest snowfalls are a recurring influence, they do not necessarily dictate fire magnitude; five years with spring wildfires of low burn area were identified, possessing similar (or lower) total snowfall values than large spring burn area years (Table 2). Earlier snowmelt can extend the dry WBP spring and drying of organic soils, which could therefore extend the period over which spring fires can be generated (Westerling et al., 2006). However, the timing of snowmelt in the WBP does not appear expedited in years of large burned area in the spring, with no significant patterns in the timing of snow-free conditions observed in the seven-year Gordon Lake snow pillow record (Fig. 3). However, years of high total annual snowfall all align with years with low burned area in the spring (Table 2). This suggests that large SWE can contribute to

decreasing the total annual area burned in the spring. Low and infrequent early precipitation events occurred in three of four years with high burned area in the spring. However, due a large proportion of rainfall in continental western Canada generally occurring in summer (Smerdon et al., 2005), dry early spring is not exceptional, and not restricted to years of high burned area in the spring. The year with the lowest early spring cumulative rainfall in the 20-year record was 2008; however, above average snowfall and late snow-free conditions decreased wildfire susceptibility in the spring, further demonstrating the importance of a large snowmelt for reducing wildfire vulnerability (CFRC, 2001).

The 2015-16 hydrological year experienced the second warmest winter temperatures over the past 20 years. Periodic rises in air temperature above freezing conditions throughout the winter (Fig. 4a) supplied energy for mid-winter snowmelt and sublimation (Pomeroy et al., 1998), potentially decreasing available peak SWE for the spring snowmelt period. The modest snowpack melted over a 31-day period. Immediately following snowmelt, high air temperatures, low relative humidity and high wind speeds (Fig. 4b; c) created weather conditions optimal for the spread of wildfire (Van Wagner, 1977). Similar mild winter temperatures and warm, dry spring conditions were present in previous years of high spring time burned area in 1968, 1998, 2002, and 2011. These years produced fires of a similar magnitude and total area burned to the Horse River fire of 2016 (Hirsch and de Groot, 1999; Tymstra et al., 2005; FTCWRC, 2012).

5.2 Pre-fire hydrology

A five-year (2011-2016) water table record illustrated the susceptibility of Poplar Fen to extended drying periods, with years of high spring (2011 & 2016) and summer (2015) burned area corresponding with low water table position (Fig. 5). At Poplar Fen, water tables also decreased over winter periods in the absence of precipitation-driven recharge. These prolonged periods of water table decline were evidenced by logged water table and mineral piezometer observations from the lower and upper fen areas (Fig. 6). In these areas, hydraulic head in the underlying mineral substratum (~1.5 m b.g.s.) closely mimicked the pattern of the water table, suggesting that the underlying groundwater at Poplar Fen is derived mostly from local recharge, rather than from regional groundwater, which would have a more stable hydraulic head (Siegel and Glaser, 1987). Therefore, peatlands that are supplied mainly by local groundwater (such as Poplar Fen) become particularly vulnerable to wildfire during high-risk fire weather conditions (Lukenbach et al., 2017).

Spring NW fen water table position was also related to the persistence of a frozen upper saturated zone. For example, near surface water tables in fall of 2012 and 2013 (Fig. 5) allowed for relatively homogenous over winter freezing of the upper saturated zone (Price, 1983), which reduced the permeability of the peat (Roulet and Woo, 1986; Quinton et al., 2009) and helped store subsurface water over the winter periods (Price and FitzGibbon, 1987). Ground ice persisted into mid-late May in 2013 and 2014, thus limiting snowmelt water infiltration (Roulet and Woo, 1986) and subsurface water loss to the underlying silty sand and outwash layers (Price and FitzGibbon, 1987). Conversely, the

shallow (0-0.2 m) peat had reached above freezing temperatures by the end of snowmelt (mid-April) in 2016, suggesting that low (~0.55 m b.g.s.) fall 2015 water tables had prevented the near-surface ground ice. Consequently, the entire saturated zone was free to recharge the underlying mineral layers over the 2015-16 winter, and during the 2016 snowmelt period, meltwater infiltrated readily to recharge the relatively deep water table. Thus, high antecedent fen water levels provide an important mechanism for overwinter storage and maintaining higher spring water levels.

Post-snowmelt 2016, the NW fen water table (0.3 m b.g.s.) was ~0.3 m lower than the water table observed mid-June, 2011 (Fig. 5), a period without rainfall and with high burned area in the spring when the 2011 Richardson Fire reached a size similar to the Horse River Wildfire (Pinno et al., 2013). Surprisingly, spring 2016 water tables were more comparable to levels measured in the spring of 2012 (Fig. 5), a year of low burned area in the spring. The lower burned area was likely attributed to larger and more frequent rainfall events (an additional 14 mm) recorded in the region during the 2012 spring season. Peatland water table position, therefore, likely cannot serve as a stand-alone metric for estimating fen wildfire susceptibility in the region, without considering the moisture deficits that can accumulate above the water table in the absence of precipitation.

Soil moisture in upland duff and margin peat followed a drying trend throughout 2015. Following snowmelt in 2016, water content in the upland duff and margin peat were not sufficiently higher than values observed in fall of 2015 (Fig. 7). These data suggest that there was no net wetting to the organic near surface soils in the upland or margins at Poplar Fen from snowmelt infiltration. This

soil moisture deficit was further enhanced by the lack of spring precipitation and increased evaporative demand (Hayward and Clymo, 1983) driven by the low humidity, high temperatures and winds at the time of the Horse River fire (Fig. 4). This deficit would have increased the available fuels for the wildfire allowing for significant combustion of these organic layers (Table 4).

5.3 Assessing the hydrometeorological conditions preceding the Horse River Fire and burning of Poplar Fen

The historical meteorological and field hydrological data illustrate the susceptibility of regionally-abundant WBP peatland watersheds to wildfire during extended dry periods. Results suggest that the wildfire at Poplar Fen, and the greater Horse River Wildfire, was not simply a consequence of anomalous drought climate conditions, but rather, interconnected hydrometeorological factors not uncommon to the Western Boreal Plain, occurring at least twice in the five-year instrument record. These factors included low autumn soil moisture and water tables, modest snowfall, overwinter drainage, insufficient spring rainfall, and high spring air temperatures and winds. The synchronicity of these factors, occurring in the same hydrological year, combined with mature tree stands with high accumulated fuels ubiquitous to the region, likely contributed to the large magnitude Horse River Wildfire. The similarities of the hydrometeorological events preceding the Horse River Fire with previous years (1968, 1998, 2002, and 2011) of similar burned area in the spring (Hirsch and de Groot, 1999; Tymstra et al., 2005; FTCWRC, 2012) suggest that the mild and/or dry fall, winter and spring conditions conducive for spring fire occur frequently in the region with a recent recurrence interval of

five years. Moreover, conditions favouring spring wildfire may be enhanced by climate change, given the responsiveness of forest fuel moisture to changes in temperature and precipitation (Weber and Flannigan, 1997; Flannigan et al., 2016).

5.5 Differences in burn severity within Poplar Fen

During summer 2015, vertical hydraulic gradients decreased in all fen and margin wells over periods of low precipitation. In lower fen these remained positive throughout the 2015 sampling period (Fig. 6), indicating upward groundwater discharge into the basal peat (water gain to peatland) from the underlying silty sand and outwash layers. In upper fen regions, these values were always lower and eventually became negative over time in the absence of rainfall, suggesting a flow reversal (downward), and loss of water from the basal peat to the underlying silt layer. Margin areas, located at a higher topographic position between fen and upland, exhibited the strongest negative hydraulic gradients, suggesting that these areas were recharging the underlying mineral layers throughout the entire year. These subtle differences in topographic position therefore played a large role in the observed differences in burn severity between these areas (Table 4). Hence, treed headwater moderate-rich fens and fen margin tracts in the WBP may be particularly vulnerable to wildfire.

5.6 Soil moisture: an early indicator of spring wildfire danger

The 2015 moisture conditions observed in the upland duff of Poplar Fen were illustrated reasonably well with the DC. The DC was overwintered for 2016 using a range of startup values from different

methods (Table 3). Scenarios 2 and 3 produced DCs that were lower than the expected DC (scenario 1), since carry-over and wetting-efficiency coefficients overestimated the recharge to the duff layer by 15-21%. These default coefficients may not have accounted for the high sublimation rates caused by low relative humidity and high solar radiation, common to the Western Boreal forests of Canada (Burles and Boon, 2011). The lower recharge values measured at Poplar Fen (35% of melt water) may also be due to moisture deficits that accumulated since the summer of 2015, as a high proportion of the available meltwater went towards recharging the unsaturated mineral soil underlying the duff. The start up DC that was calculated using the directly measured duff recharge (scenario 4) was much closer to the expected DC, suggesting that the overwintering calculation is suitable for the duff layer at Poplar Fen when VWC is directly measured.

Due to differences in soil bulk density and depth of burn, average duff fuel consumption was ~50% less than the consumption observed in margins (Table 4). The observed duff fuel consumption at Poplar Fen (~7.0 kg m^{-2}), along with the VWC-inferred expected (488) and overwintered (452) final duff DC values, were both in line with fuel consumption and DC estimates from interior Alaska (Kane et al., 2007) and are on the higher end of DCs measured from other burned boreal forest fires throughout continental western Canada (de Groot et al., 2009). Thus, the overwintering procedures that were calculated using default wetting efficiency coefficients produced lower final DC values that did not reflect the fuel consumption rates measured at Poplar Fen. The observed range in overwintering DC calculations in Table 3 highlights the difficulties in determining a proper start up DC for watersheds that

experience periods of prolonged drying prior to snowmelt. These overwintering calculations have a substantial impact on DC values calculated for the following growing season, predominantly in the early spring. Estimations based on VWC measurements may therefore produce more accurate and conservative spring DC values, given that the selected coefficients may not properly represent the hydrological and meteorological processes occurring in the Western Boreal Plain during the snowmelt period.

6 Conclusions

This study applies a combination of pre-fire and historical hydrometeorological data from a moderate-rich fen watershed, to contextualize the conditions preceding the 2016 Horse River Wildfire. The fire was manifested by dry hydrometeorological conditions extending back to summer 2015. This included low fall soil moisture, modest snowfall, and no spring rainfall, with above-average spring air temperatures and high winds also prevalent; conditions not uncommon in the sub-humid WBP. It was ultimately the less frequent synchronization of these factors that led to a wildfire of this size and observed depth of burn in boreal forests and wetlands, and the associated fuel losses. These coinciding hydrometeorological conditions share stark similarities with previous years with large burned areas from spring fires, namely 1968, 1998, 2002, and 2011, which may support the notion that fires of this magnitude are a function of WBP climate cycles. However, as natural as these factors may be, spring conditions conducive to wildfire could be enhanced by climate change, given the responsiveness of these boreal watersheds to changes in temperature and precipitation.

Field data from Poplar Fen confirmed that moisture deficits accumulated between summer 2015 and the Horse River fire the following spring. Following a relatively mild winter, the modest 2016 snowmelt did not raise upland duff and margin peat moisture above fall 2015 values. This was in part due to the hydrogeological setting of Poplar Fen, as water tables and hydraulic head decreased in the absence of localized precipitation-driven recharge from adjacent uplands, with no evidence of a regional groundwater connection to supplement discharge during extended dry periods. We propose that headwater peatlands in this region fed by localized flow systems will be particularly susceptible to water table fluctuations under a drying climate, rendering them more vulnerable to burning from wildfire.

The dry conditions and subsequent duff fuel consumption observed at Poplar Fen in the spring of 2016 were difficult to illustrate with the Drought Code (DC) when carry-over and wetting-efficiency coefficients were applied to the overwintering procedure. Closer agreement was found when measured directly measured duff soil moisture recharge was applied to the overwintering procedure in place of the coefficients. In order to better gauge the susceptibility of WBP headwater systems to wildfire in the spring, management strategies could therefore benefit from monitoring soil moisture at different land classes and watersheds. These data would allow for more accurate overwintering DC calculations, and would provide managers more time to prepare for a fire season by considering additional indicators that can be detected earlier.

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9 Figures
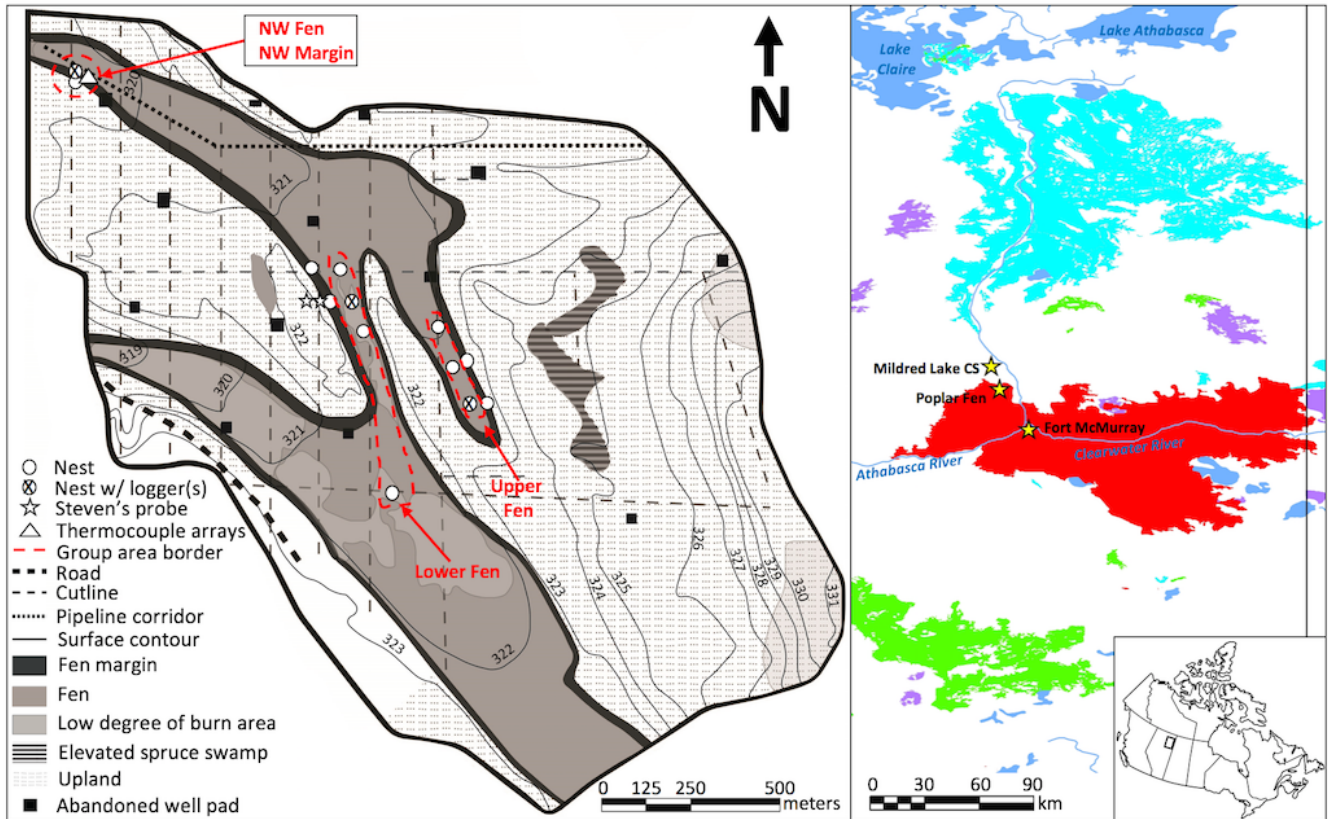
Figure 1: Map of Poplar Fen watershed (left; 56°56'N; 111°32'W). The entire area was burned with the exception of areas highlighted in blue. Included is an inset of northeastern boreal Alberta (right) showing burned area during years of high spring fire frequency, including 1998 (purple), 2002 (green), 2011 (cyan), and 2016 (red).
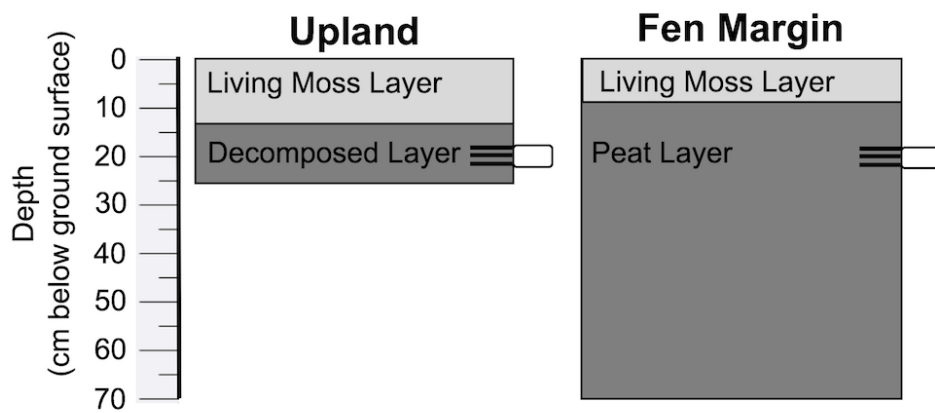
Figure 2: Moisture probe profiles in upland duff and fen margin peat.
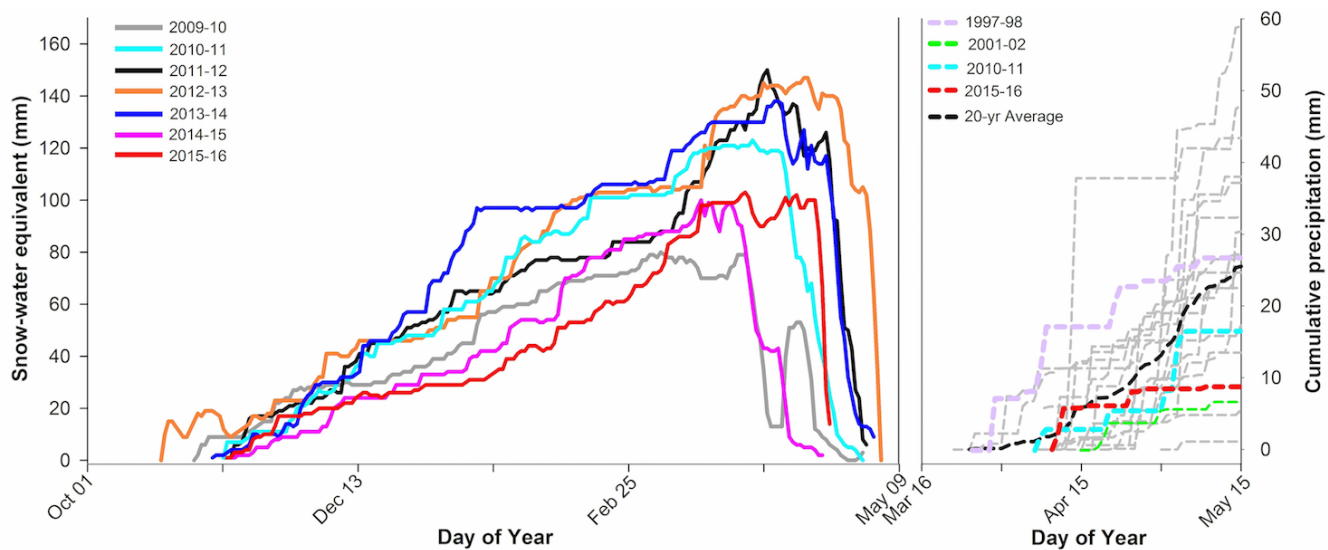
Figure 3: Measured accumulation and ablation of SWE at Gordon Lake snow pillow (left), and interpolated cumulative early spring rainfall from 1996 and 2016 at Poplar Fen (right). Coloured lines in graph b) correspond to years of high burned area in the spring, including 1997-98 (726 968 ha), 2001-02 (496 515 ha), 2010-11 (806 055 ha), and 2015-16 (663 529 ha) (Natural Resources Canada, 2017).
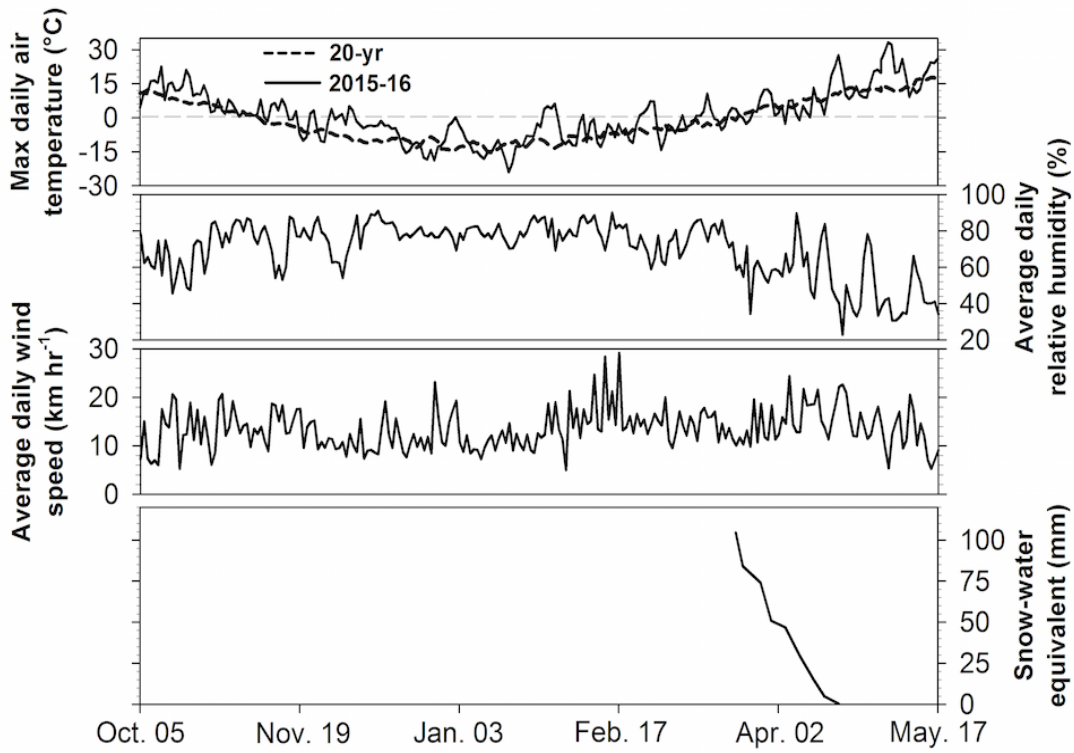
Figure 4: Daily records of a) maximum air temperature (with 20-yr average), b) average daily relative humidity, and c) average daily wind speed at Mildred Lake climate station from Oct 05 2015 to May 17, 2016, and d) measured area-weighted SWE for Poplar Fen in 2016.
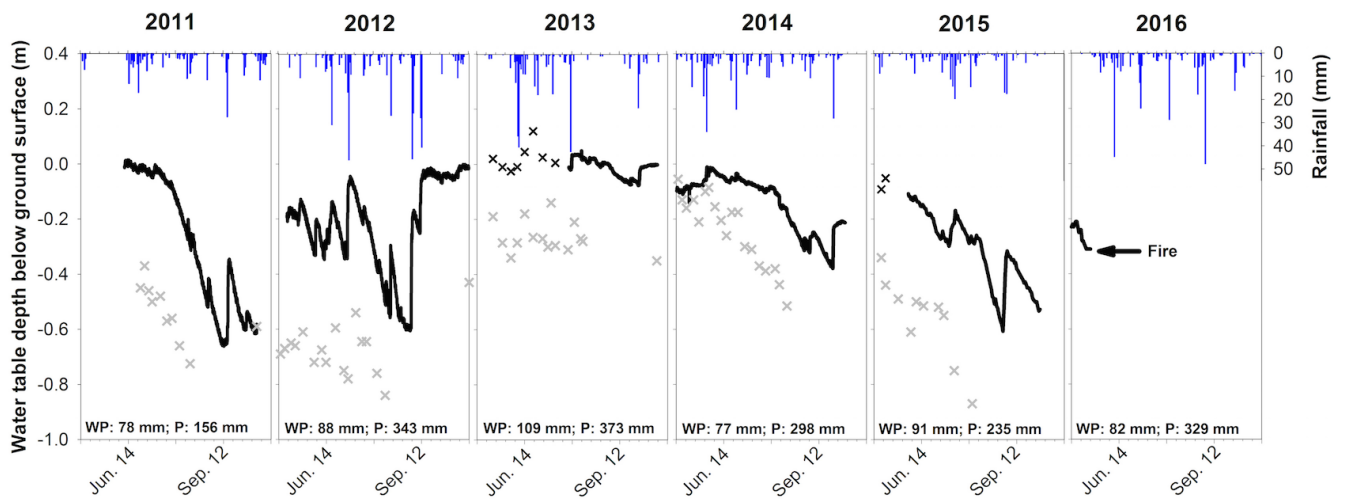
Figure 5: Logged (lines) and manually (x symbols) recorded water table position at NW fen (black) and NW margin (grey) (see Fig. 1), from 2011-2016, with field-measured rainfall (P), and total winter precipitation (WP) interpolated for the Poplar Fen area.
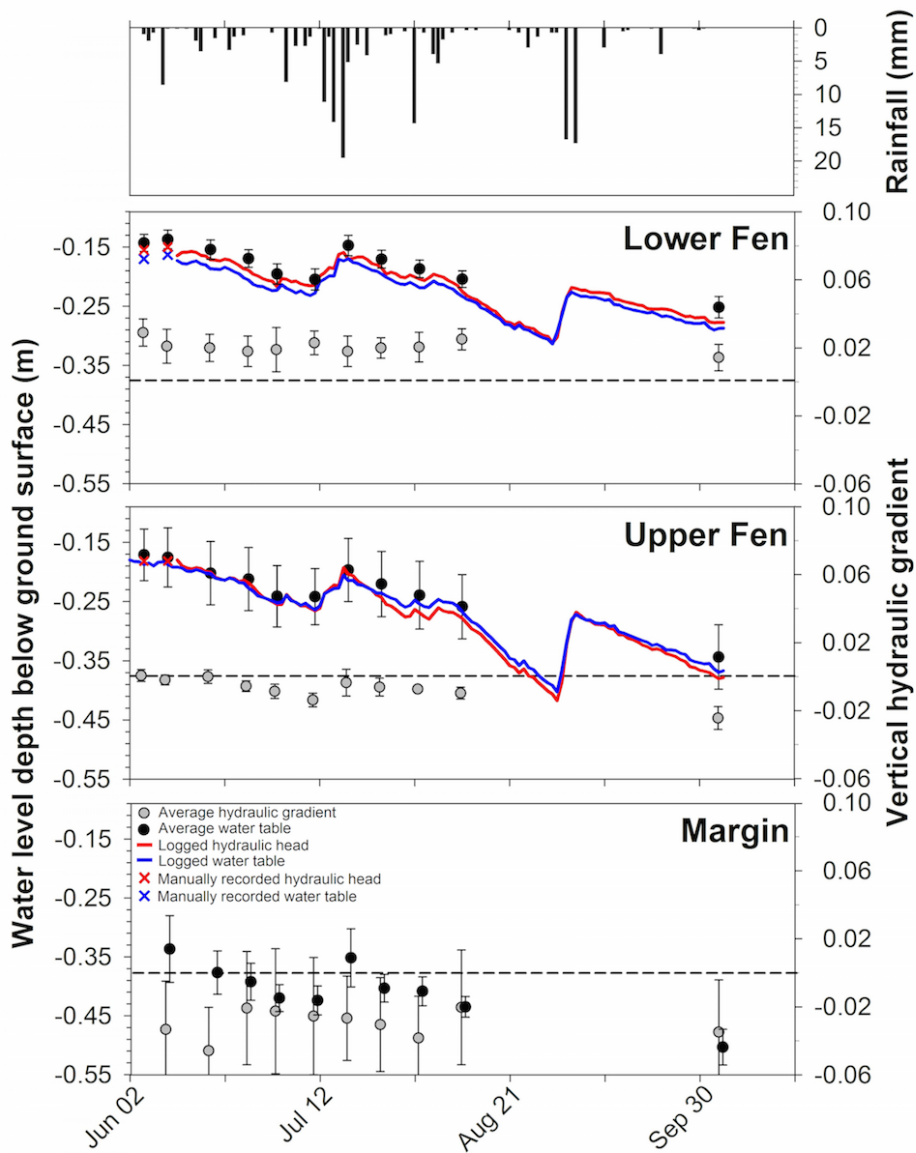
Figure 6: Average (SE) water table (black x-symbol) and vertical hydraulic gradient (grey circle) between water table and underlying mineral for lower and upper fen, and margin areas, along with logged (line) and manually recorded (x-symbol) water table (blue) and hydraulic head (red) for lower and upper fen areas in 2015. A negative hydraulic represents a loss of water from the fen to the underlying mineral substrates. Rainfall is also illustrated.
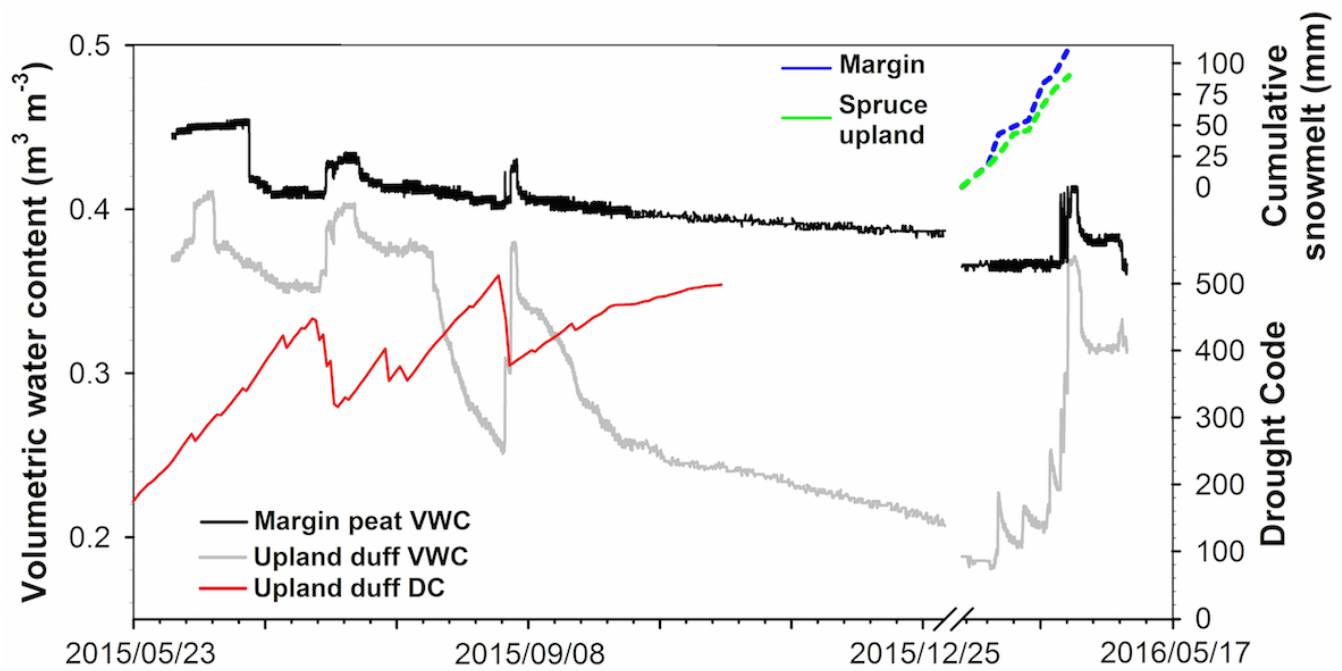
Figure 7: Volumetric water content (m³ m⁻³) for upland duff and margin peat from Jun 02, 2015-May 02, 2016, including with average 2016 snowmelt recharge (mm) for upland and margin, and Drought Code from May-October, 2015.

10 Tables

Table 1: Summary of scenarios used for calculating a starting DC for April 19, 2016.

Scenario #	Carry-over a	Wetting-efficiency b
1) Expected DC values based on observed relationship between 2015 VWC and DC.	N/A	N/A
2) Overwintering procedure with default CFFDRS values (Lawson and Armitage, 2008) using precipitation from Fort McMurray airport.	0.75	0.75
3) Overwintering procedure with Alberta Agriculture and Forestry values with Poplar Fen manual SWE data.	0.5	1
4) Overwintering procedure with upland duff: Using measured 32 mm snowmelt recharge (Oct. 31 – Apr. 19).	1	1

Table 2: Total hydrological year rainfall and snowfall from 1996-2016, interpolated for the Poplar Fen area. Asterisks correspond to years of high burned area in the spring.

Year	Total	Rain	Snow
1996-97	467	354	114
1997-98*	265	156	109
1998-99	280	227	53
1999-20	395	331	64
2000-01	356	277	79
2001-02*	396	322	75
2002-03	424	306	118
2003-04	396	286	110
2004-05	523	385	138
2005-06	409	303	106
2006-07	352	215	137
2007-08	387	235	151
2008-09	269	210	58
2009-10	421	330	90
2010-11*	235	156	78
2011-12	430	343	88
2012-13	481	373	109
2013-14	375	298	77
2014-15	326	235	91
2015-16*	412	329	82

Table 3: April 19, 2016 startup and final May 17 DCs for Poplar Fen using four different scenarios.

Scenario #	Carry-over a	Wetting-efficiency b	Starting DC on April 19, 2016	Final DC on May 17, 2016
1) Expected DC values based on observed relationship between 2015 VWC and DC	N/A	N/A	357	488
2) Overwintering procedure with default CFFDRS values (Lawson and Armitage, 2008) using precipitation from Fort McMurray airport	0.75	0.75	242	373
3) Overwintering procedure with Alberta Agriculture and Forestry values with Poplar Fen manual SWE data	0.5	1	212	344
4) Overwintering procedure with upland duff: Using measured 32 mm snowmelt recharge (Oct. 31 – Apr. 19)	1	1	321	452

Table 4: Average (± SE) surface change and fuel consumption in upland, margin, and fen at Poplar Fen.

Type	Measured Ground Surface Change (m)	Pre-Burn Bulk Density (kg m^{-3})	Estimated Fuel Consumption (kg m^{-2})
Duff	0.10±0.02	70	7.0±1.2
Margin	0.13±0.01	98	13.0±1.2
Fen (burned)	0.02±0.002	70	1.6±0.06
Fen (unburned)	0	70	0