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Multi-year assessment of water and energy exchange from an oil sands reclamation cover, Fort McMurray, Canada

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Abstract

The oil sands mining industry in Canada has made a commitment to return disturbed areas to an equivalent capability to that which existed prior to mining. In the landscape reconstruction process, ecosystems are created that bare little similarity to the pre-existing boreal forest at the onset of reclamation. However, certification requires successful reclamation, which can in part be evaluated through long-term ecosystem studies. A reclamation site, informally named South Bison Hill (SBH) has had growing season water and energy balances observed since 2003 utilising the eddy covariance technique. SBH was capped with a 0.2 m peat-glacial till mixture overlying 0.8 m of reworked glacial till soil. The site was seeded to barley cultivar (Hordeum spp.) in the summer of 2002 and later planted to white spruce (Picea glauca) and aspen (Populus spp.) in the summer/fall of 2004. Since 2003, the major species atop SBH has changed dramatically and by 2009, an aspen stand predominated with heights in excess of 2 m. Climatically, mean growing season (June–August) temperatures did not vary more than 2°C for a given month, yet precipitation varied considerably as 2004 had 91 mm of rain during June–August while 2008 had 271 mm during the same period. With the exception of a dry 2004, SBH increasingly partitioned energy into latent heat, on average, year after year. At the onset of the measurement, SBH approximately ~55% of net radiation (June–August average) partitioned into latent heat. 2004 had ~47%, yet the evaporative ratio increased consistently thereafter to values ~70% in 2009. Larger latent heat fluxes cannot be attributed solely to climate as increased leaf area index, interception and a longer leaf-out period have increased total evaporation. In most years, evaporation exceeds summer rainfall, utilising snowmelt recharge to sustain evaporation rates. Using natural aspen stands as a comparison, it is expected that water use from the soil cover will continue to increase as the ecosystem ages.

1 Introduction

Oil sands mining is of significant importance to the Canadian economy and is experiencing large-scale expansion in north-central Alberta. While there are several types of extraction, the majority of current mining involves removal of bitumen from large open pits, resulting in significant landscape disturbances. As part of the Alberta *Environmental Protection and Enhancement Act* (EPEA), mine operators are required to return reclamation areas to a land capability equivalent equal to that which existed prior to mining. The target ecosystem after reclamation and regeneration can take several decades to achieve, and includes ecosystems of the boreal forest that are suitable for use by a range of stakeholders including traditional users and commercial forestry.

In the construction of reclaimed landforms, early successional ecosystems are created that bare little similarity to the undisturbed boreal forest that existed prior to mining. While reclamation sites vary based on parent material and construction strategies, all have a physiography, soil properties and vegetation that have been altered from the pre-mining landscape. Central to the performance of reclaimed soil covers is their water balance. With regards to plant functioning, sufficient moisture must be retained in the soil to support a range of successional species and a mature forest along with supplying water to wetlands and pit lakes. In the oil sands region, the largest loss of water is through evapotranspiration (ET), which is approximately equal to precipitation on an annual basis (Devito et al., 2005) and controls the near-surface movement of salts from oxidised sulphates in the carbonate-rich glacial tills that may result in soil salinisation; and also influences the quantity of deep percolation.

Vegetation productivity, nutrient and water budgets are all influenced by ET. However, during the early stages of reclamation, ecosystems undergo a dramatic shift in species on an inter-annual basis. Unlike mature forests and agricultural crops, little biometeorological information is available for invasive species and juvenile vegetation that thrive on reclamation covers after establishment. However, their influence along with that of soils in partitioning available energy into latent heat (ET) and sensible heat (direct heating of the atmosphere) has important implications for long-term recovery strategies. In the sub-humid climate of northern Alberta, understanding ET losses of water and how this relates to cover evolution is critical in assessing the sustainability of the reclamation process.

In this paper, growing season water and energy balance components are reported from 2003 to 2009 atop an overburden landform located at the Syncrude Canada Ltd., Mildred Lake mine north of Fort McMurray Alberta. During this period, the landform underwent dramatic shifts in vegetation along with considerable differences in growing season precipitation and temperature. The objective of this work is to highlight the necessity of long-term ecosystem studies to assess the trajectory of water use on oil sands reclamation covers and how changes in vegetation through time can have a profound impact on the water and energy balance.

2 Materials and methods

2.1 Site description

The study site (57° 39' N, 111° 13' W), is a saline-sodic clay shale overburden landform informally termed South Bison Hill (SBH). SBH was constructed with overburden from oil sand mining in stages between 1980 and 1996. The area of SBH is ~2 km^2; it rises 60 m above the surrounding landscape and has a large relatively flat top several hundred metres in diameter. Reclamation proceeded in 2 phases, the soil capping study area on the north slope of the landform was reclaimed with variable soil covers in January of 1999. This area was then fertilised and seeded to agronomic barley and planted to white spruce and aspen in the summer of 1999. The top of the structure and the remaining slopes were capped with a 20 cm peat mineral mix overlying 80 cm of till in the winter of 2002. These areas were fertilised and seeded to agronomic barley in the summer of 2002 and then planted to white spruce (*Picea Glauca*) in the summer/fall of 2004. At the beginning of 2003, the major plant species atop SBH was foxtail barley (*Hordeum jubatum*). Minor species included fireweed (*Epilobium angustifolium*), sow thistle (*Sonchus arvense*), and white and yellow sweet clover (*Melilotus alba*, *Melilotus officinalis*). Beginning in 2006, the site has transitioned gradually to an ecosystem dominated by aspen (*Populus tremuloides* Michx.), which has grown as both planted and volunteer (invasive) and by 2009 was on average ~1.5 m in height (Figure 1).

The climate is classified as a sub-humid continental, which is characterised by cold winters and warm summers. Thirty-year climate normals (1971–2000) for Fort McMurray indicate daily temperatures for January and July are -18.8oC and +16.8oC, respectively. Mean annual precipitation is 456 mm, of which 342 mm occurs as rainfall. The majority of rainfall (67 %) occurs from June to August and is delivered largely as convective storms of high intensity and short duration (Devito et al., 2005).

2.2 Continuous measurements

The eddy covariance technique was used to measure fluxes of momentum, sensible heat (H) and latent heat (L_vE) on a continuous basis. A meteorological tower was placed in the approximate centre of SBH in 2003 with several hundred metres of fetch in each direction. The measurement system consisted of a three-dimensional sonic anemometer (CSAT3; Campbell Scientific), an open-path infrared gas analyser (LI-7500; Li-Cor), and a fine-wire thermocouple located in the approximate centre of the sonic head, which was located 2.9 m above the ground from 2003–2008 and was raised to 5.1 m in 2009. Both wind speed and gas concentration measurements and their fluctuations were obtained at a frequency of 20 Hz. LE and H were calculated as the product of the mean covariance of the vertical wind speed fluctuations (w') and the scalar fluctuations in water vapour density (ρ_v') and temperature (T') as described by Webb et al. (1980).

$$L_v E = L_v \overline{w' \rho_v '} \tag{1}$$

$$H = C_a \overline{w'T'} \tag{2}$$

where C_a is the heat capacity of air, and the prime (') denotes the deviation from the mean.

Figure 1 **Site photographs for 2003, 2005, 2007 and 2009. Note that in 2009, the instrumentation tower has been raised compared with other years**

At the tower with the eddy covariance instrumentation, down and up-welling long and short-wave radiation were measured using a CNR1 net radiometer (Kipp and Zonen) mounted 3.1 m above the ground on a boom that projected 3 m horizontally from the tower. Air temperature and relative humidity were measured at 3 m (HMP45C, Vaisala). In addition to the sonic anemometer, wind speed was measured at 3.1 and 1.5 m (MetOne, R.M. Young). Soil heat flux, *G*, was measured using two heat flux plates, buried 0.5 m below the surface. Data was recorded at 1-minute intervals and recorded every 30 minutes on the CR23X datalogger. Supplemental data was collected at a second tower approximately 100 m from the eddy covariance tower, with an event-recording tipping rainfall gauge (TE-525, Texas Instruments). At depths of 0.05, 0.15, 0.25, 0.4, 0.95, 1.15, 1.25 and 1.80 m, soil moisture (CS615, Campbell Scientific), soil suction (229L, Campbell Scientific) and soil temperature were measured every four hours and recorded on a CR10X data-logger (Campbell Scientific).

2.3 Data corrections, gap filling and energy balance closure

The energy budget for SBH can be described as

$$Rn = L_v E + H + G + \varepsilon \tag{3}$$

where Rn is net radiation calculated via the four short and long-wave components and ε is a residual flux density associated with errors. Typically, eddy covariance underestimates scalar fluxes (H and L_vE) resulting in a residual flux density. In this study, H and L_vE were corrected for underestimation by adjusting for energy balance closure (Twine et al., 2000). Additional corrections to the flux measurements and gap-filling were made following the methods outlined in Carey (2008).

2.4 Periodic measurements

To assess the growth of vegetation within and among growing season, leaf area index (LAI) was measured at approximately two-week intervals with an LAI-2000 (Li-Cor) plant canopy analyser. Referenced site-photographs were also made at this time. Stand characteristics (i.e. species height, composition and density) were measured annually at the end of each growing season.

3 Results

Data is reported from 2003 to 2009. For the first three years of study, measurements were made May to August inclusive, and beginning 2006 were extended to the end of September. When comparing averages among years, the May to August period will be reported for consistency.

3.1 Climate

Variation in climate for the 2003–2009 growing seasons (May–August) are summarised in Figure 2. There is considerable difference in growing season rainfall among years, with 2008 having the greatest rainfall at 276 mm, whereas 2003 and 2004 were notably drier with 147 and 131 mm, respectively. The 30 year climate normal (1971–2000) for Fort McMurray is 266 mm for May to August, and only 2008 had greater than normal rainfall. There was some difference in growing season air temperature among the years (Figure 2). 2004 was the coolest growing season (13.2°C) whereas 2006 was the warmest (15.7°C). There was no relationship between precipitation and temperature on a seasonal basis. It is important to note that growing season averages do not express intra-seasonal variability in rainfall. For example, in many years, precipitation was concentrated in one or two months, with distinct wet and dry periods.

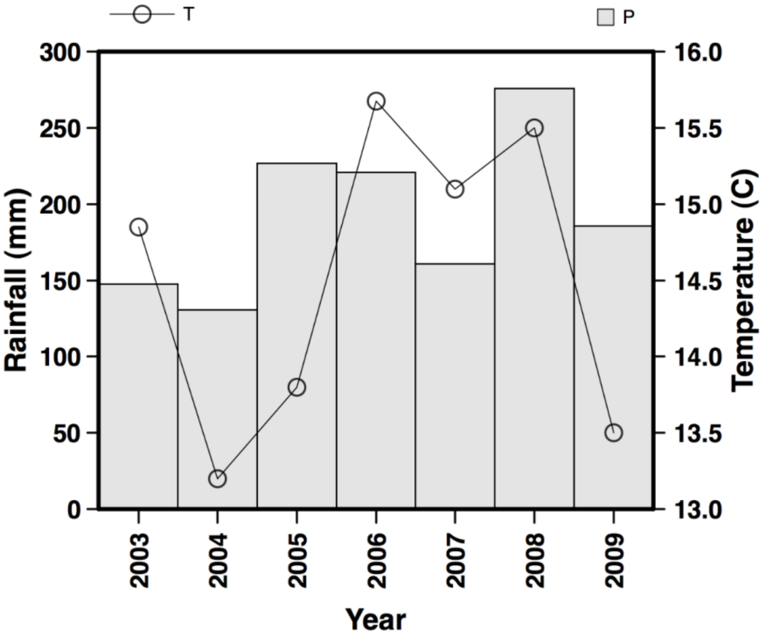

Figure 2 May to August total rainfall (grey bars) and average air temperature (open circles) for the 2003–2009 study period

3.2 Soil moisture and suction

Near surface soil moisture exhibited little variability below 40 cm (data not shown), yet in the upper profile, water content varied both within and among years (Figure 3). Soil moisture was generally greatest at the beginning of May due to snowmelt recharge and declined thereafter due to evaporation with rainfall acting to recharge the soils. Virtually no deep percolation occurs at SBH due to the impermeable nature of the waste rock substrate. 2004 and 2007 were notably dry years with long periods of soil moisture recession. 2005 and 2008 were wet with many mind-summer rainfall events; however, there is a general decrease in soil water at 25 cm from 2003 to 2009 despite changes in annual rainfall.

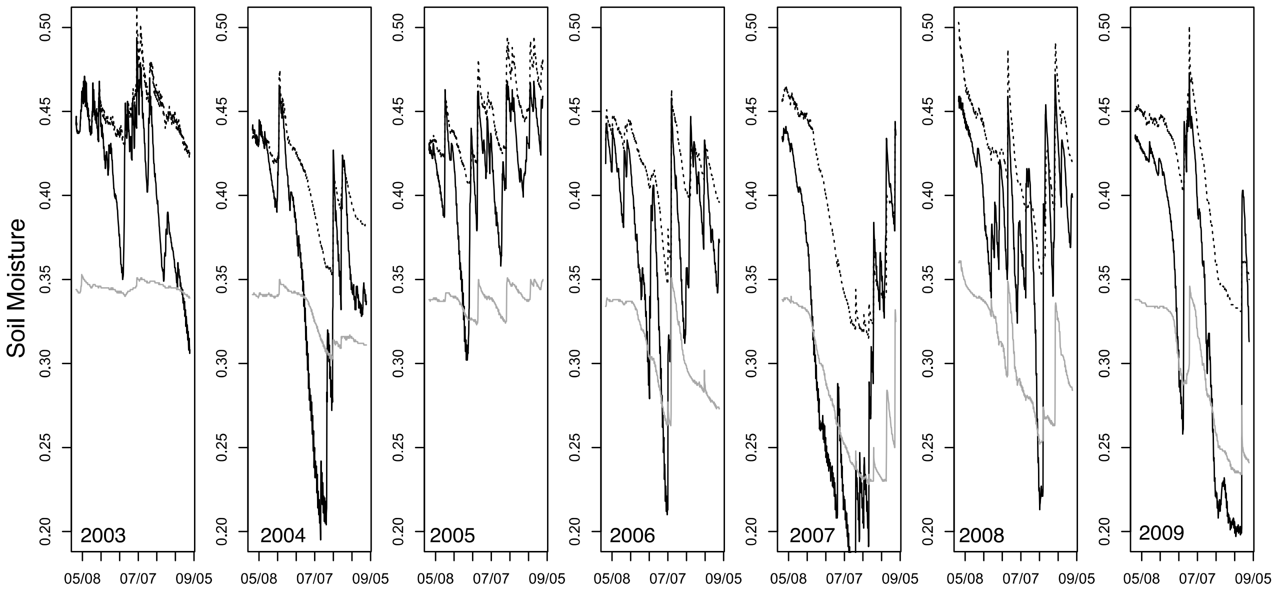

Figure 3 **Soil moisture in the upper 25 cm of the profile from 1 May to 31 August for all years. Solid line is 5 cm, dashed 15 cm and grey solid line 25 cm depth**

Much like soil moisture, suction in the top 25 cm showed the variability within and among seasons (Figure 4). During the first three years of the study, soil suctions did not exceed 400 kPa despite a very dry 2004. Beginning 2007, soil suctions became markedly greater, and in 2007 and 2009 exceeded 500 kPa as soil moisture levels dropped below 0.3. Typically, suction increases by the end of August due to a decline in ET and late-season rain.

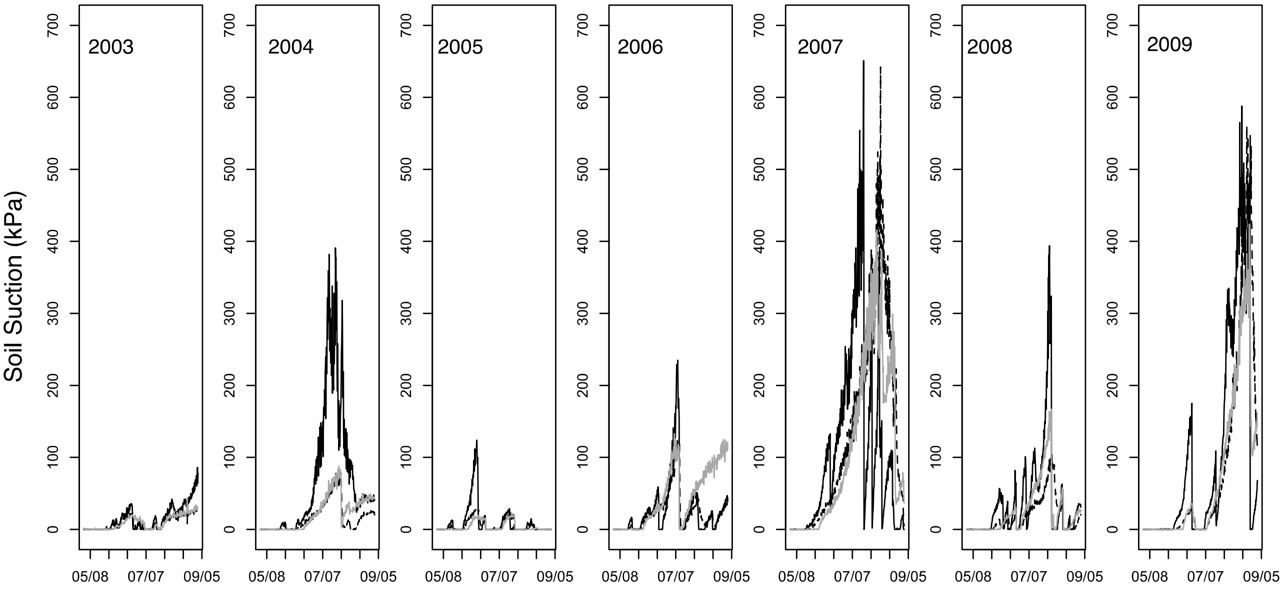

Figure 4 **Soil suction in the upper 25 cm of the profile from 1 May – 31 August for all years. Solid line is 5 cm, dashed 15 cm and grey solid line 25 cm depth**

3.3 Leaf area index and vegetation

Leaf area index (LAI) began increasing rapidly in early June in all years, typically peaked in July and declined gradually thereafter depending upon the vegetation type that predominated the site (Figure 5). Note that September LAI values are reported beginning 2006. At the onset of reclamation in 2003, the dominant species throughout the growing season was foxtail barley, which has a very short growing season and accounted for the rapid rise and fall of LAI by early August. In contrast, peak LAI was greater approximately three weeks later in 2004, and values were sustained by a second flowering of sweet clover that was not apparent on the in 2003. The lowest LAI occurred in 2005, when values increased quickly but slowly declined as no single species was abundant compared with earlier years. Beginning in 2006, there was an increase in plant diversity and aspen. Once established, aspen became the predominant species, increasing in height and in 2008 rapidly increased its folial area (as expressed by LAI). Beginning in 2008, LAI at SBH was largely controlled by the bud-burst and senescence of an aspen stand in its early stages of establishment, and values were approximately 3 times greater than those observed at the beginning of the study in 2003.

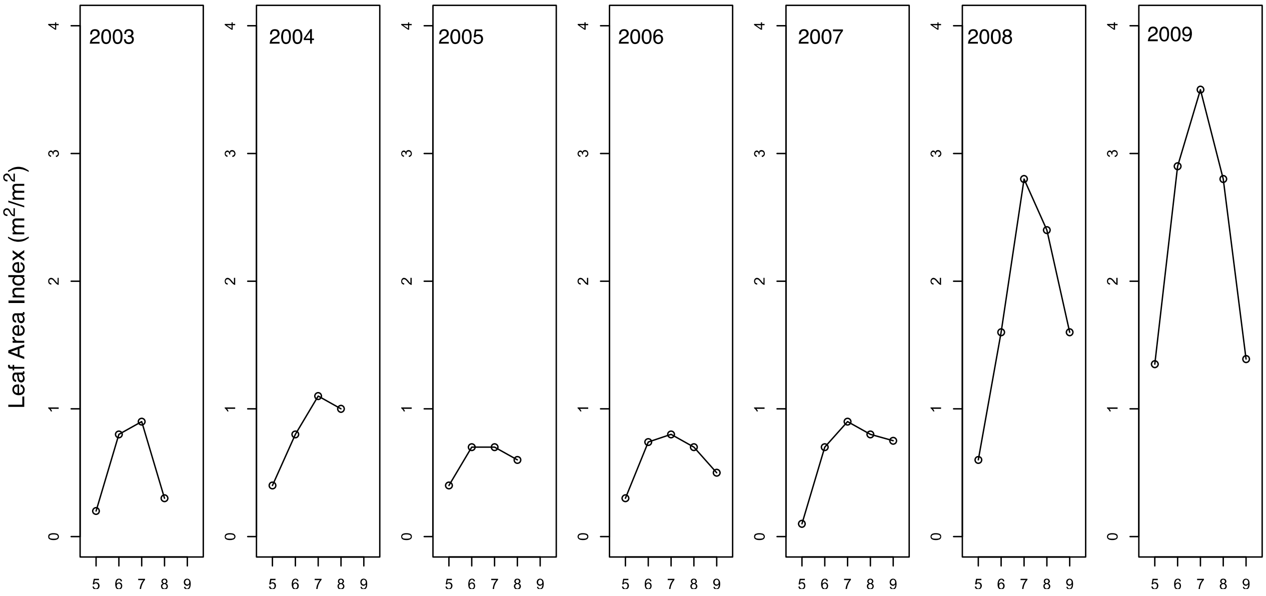

Figure 5 **Growing season leaf area index (LAI) for the 2003–2009 study period. Month of year is on x-axis**

3.4 Surface energy balance

Growing season partitioning of energy showed a strong increase in the fraction on net radiation that was partitioned into latent heat (L_vE) over the course of the study (Figure 6). At the onset of the study, L_vE was either slightly greater (2003, 2005) or slightly less (2004) than sensible heat (H). Low values of L_vE in 2004 are attributed to the dry growing season. The gradual increase in L_vE reflects a weak increase in precipitation, by more strongly an increase in LAI and transpiration contributions by the surface vegetation. Increased LAI of the aspen stand resulted in the potential to transpire considerably more water than early in the study. It is important to note that despite a wet 2008 and a slightly dry 2009, soil suctions (Figure 4) continued to rise on-site, reflecting both the demand of a maturing aspen stand and because of increased interception and reduced throughfall to soils. The subsurface heat flux, G, generally declined as the vegetation established on site and less radiation penetrated to the surface.

3.5 Evapotranspiration

Average monthly ET rates expressed in millimetres per day follow a trend of increasing rates throughout the growing season followed by a steep decline, particularly in September during the years recorded (2006 to 2009). May to August values ranged from ~1.3 to 3.5 mm per day, with monthly and inter-annual differences due to the variability in available energy and climate, vegetation and soil water availability. Peak growing season ET was smallest in 2004 at 2.3 mm and greatest in 2009 at ~3.5 mm. The differences in May to August total actual ET are shown in Figure 8a. In all cases, these are greater than seasonal rainfall, relying on soil water recharge during snowmelt to sustain ET and plant growth.

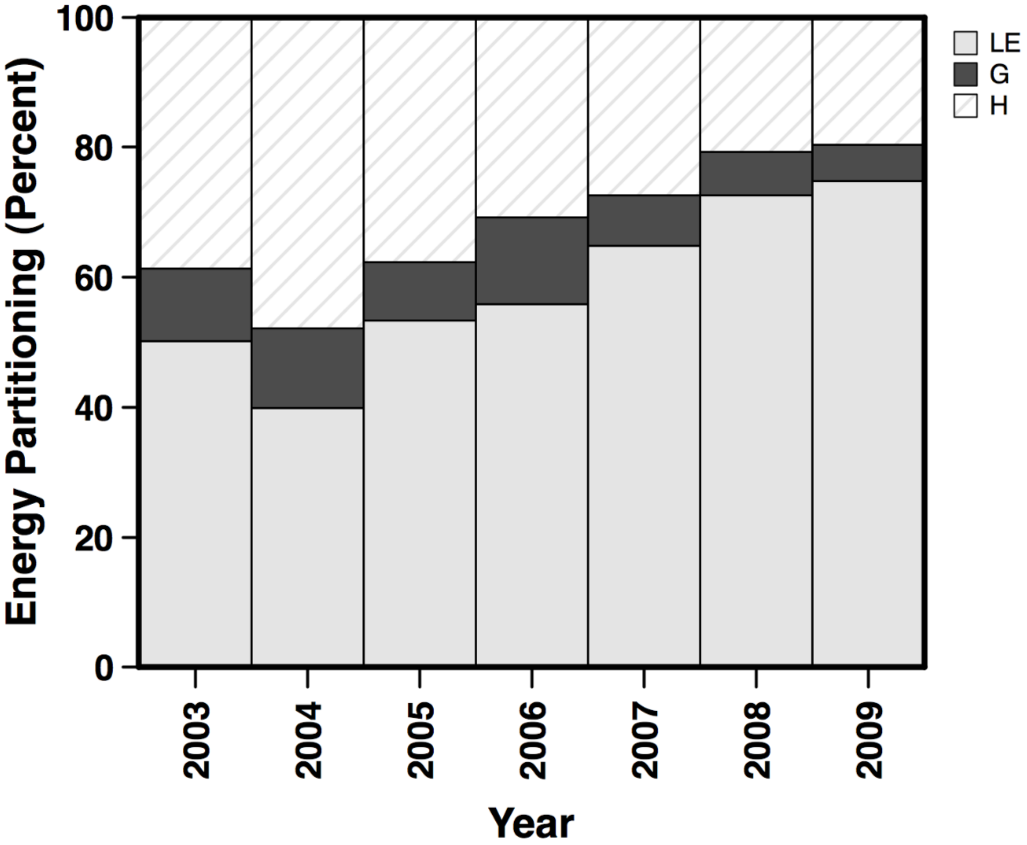

Figure 6 **Annual energy balance partitioning for the May – August growing season. LE is latent heat flux, G is ground heat flux and H is sensible heat flux**

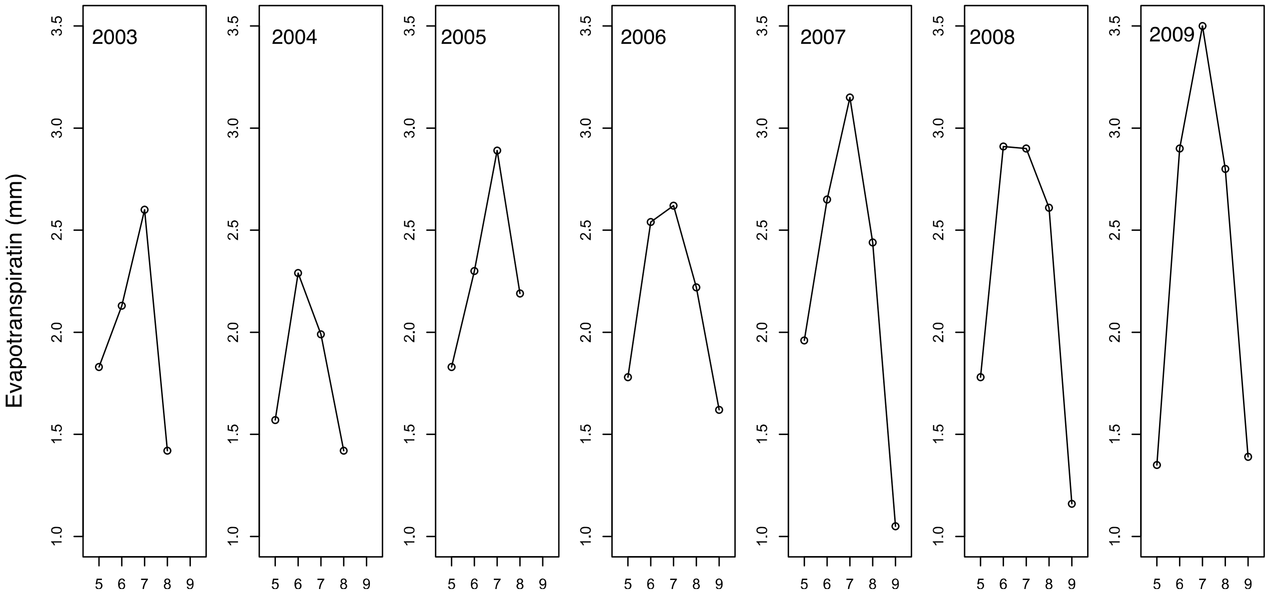

Figure 7 **Monthly evapotranspiration (ET) for the 2003–2009 study period. Month of year is on x-axis**

4 Discussion and conclusions

Evapotranspiration is a complex hydrological process. Atmospheric drivers such as net radiation, windspeed and vapour pressure deficit (VPD) are moderated by plant photosynthetic capacity, stomatal regulation, soil moisture and suction. Multi-year data sets of this nature are rare, and evaluating the relative influence of climate, vegetation and soils for a highly dynamic environment is challenging. To further explore patterns and factors affecting changing ET atop SBH, Figure 8 (a-h) displays various climate and physiological factors on an annual basis as they relate to ET, and also potential evapotranspiration (PET) as determined via the Penman-Monteith equation (Monteith and Unsworth, 1990), which is a commonly used metric for determining actual ET when designing soil covers.

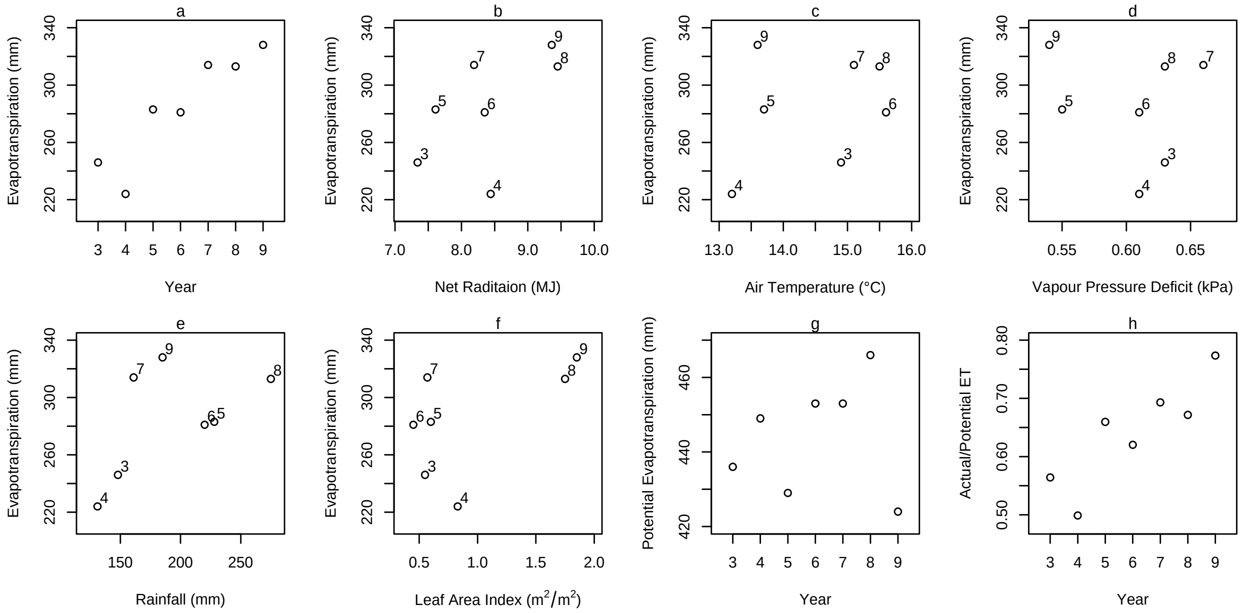

Figure 8 **Panels of (a) year vs. ET, (b) Net Radiation vs. ET, (c) Air Temperature vs. ET, (d) Vapour Pressure Deficit vs. ET, (e) rainfall vs. ET, (f) LAI vs. ET, (g) year vs. PET, and (h) year vs. ET/PET. Number beside open circle indicates the year of observation, i.e. 7 = 2007**

Growing season (May to August) ET atop SBH has gradually increased from 2003 to 2009 (Figure 8a), despite large differences in climate among the study years. The implication of this finding are important as it suggests that water use by this ecosystem increases during early stages of succession, and that water balance data during the first few years of recovery may not be indicative of future cover water use. Net radiation is the meteorological variable that is most closely related to differences in ET among the study years (Figure 8b). 2008 and 2009 were the two highest energy years and also the two years with the highest ET, despite being wet (2008) and moderately dry (2009). However, air temperature and net radiation are not closely correlated on a growing season basis, and temperature index methods to estimate ET must be used with caution (Figure 8c). 2004 had the lowest ET although was moderate in terms of net radiation. Examination of other panels suggests that cool temperatures and low rainfall and soil moisture suppressed ET. There was no obvious relationship between ET and air temperature (Figure 8c), nor ET and VPD (Figure 8d). Vapour pressure deficit is a surrogate for atmospheric humidity, with greater values indicating a dryer atmosphere further saturation and more likely to enhance evaporation. For wet environments, VPD can often be closely related to ET as diffusive processes dominate turbulent transfer. However, for SBH, the surface did not freely evaporate (such as an evaporation pan), and there was no clear relation between VPD and ET. However, ET was high in 2007 despite moderate radiation and low LAI, which may be in part attributed to dry atmospheric conditions. Despite the difficulty in observing a VPD control on ET, years with more rainfall do, on average, evaporate more than dry years as would be expected (Figure 8e). In years with low soil moisture and large suction (Figures 3 and 4), ET was suppressed. The relationship between LAI and ET suggest a strong vegetation influence on ET, however this is complicated by a large jump in LAI from 2007 to 2008 due to the development of the aspen canopy. Prior to 2007, LAI was low, and there was no relation with ET. However, it is very likely that the increase in ET in 2008 and 2009 can be in part attributed to increased transpiration as an ET component.

PET is an easily calculated parameter using various techniques from readily available environmental variables. For most reclamation covers that are not instrumented for direct measurement of ET, calculations of PET with a correction factor are typically used to provide ET estimates. PET varied by less than 50 mm among years, despite ET varying by over 100 mm. The ratio of actual to potential evapotranspiration (ET/PET) is often considered a static parameter obtained for a given environment and/or ecosystem in water balance modelling. However, Figure 8h demonstrates that this ratio has changed by over 25% in the 7 years since regeneration began atop SBH. The implications of this are large as more water is being removed vertically from the cover as a fraction of the "demand" that the atmosphere places on it.

Other factors that may in part explain this increase in ET and related to LAI is the influence of canopy interception. With increased foliage, more precipitation is intercepted by the canopy and directly evaporated from the vegetation surface. In addition, less water is able to reach the surface as throughfall, and soil moisture declines. The lower soil moisture levels and higher soil suctions in 2008, despite this being the wettest year, may be partly attributed to declines in precipitation reaching the soil and increased ET from direct precipitation on the canopy. As the aspen canopy continues to develop, water reaching the soil may continue to decline, lowering soil moisture and increasing suction. If soil water is lowered sufficiently, soil suctions will become large enough to reduce ET and photosynthesis will not occur at an optimal capacity and vegetation will begin to exhibit signs of stress and mortality (Barr et al., 2007; Hogg et al., 2008).

In conclusion, SBH has and continues to undergo dramatic changes in vegetation type and stage of development. Future measurements will determine whether once a target ecosystem is established, if water balance variability is as large as observed during the first stages of reclamation, or whether a more direct and predictable response to climate forcing is observed. There is considerable data from mature boreal forest stands, including aspen, that suggests ET is largely controlled by variations in climate, particularly in relation to spring conditions which determines the length of time the canopy has leaves (Barr et al., 2007). As water use appears to be increasing at SBH, there is a possibility that the soil cover will eventually not be able to supply sufficient soil moisture to sustain a mature aspen forest with peak growing season (July) evaporation of ~ 4 mm per day. Research has shown that modelling the response of SBH and other covers remains a challenge, as accurate parameterisation of changing remains difficult yet critical in soil moisture and water balance assessments (Keshta et al., 2009). Only through long-term research programs can the success of these highly dynamic ecosystems be assessed.

Acknowledgements

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