USING ECOSYSTEM WATER AND CARBON FLUXES AS INTEGRATED MEASURES OF RECLAMATION SUCCESS

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ABSTRACT

The cycling of water, energy, and carbon are ecosystem functions that support the overall health and success of vegetated ecosystems. With insufficient water and/or nutrients, water use and carbon uptake are reduced and ecosystems experience stress. In most of western and northern Canada, ecosystems experience growing-season water stresses that limit growth. Understanding the linkages between climate, water availability and use, and carbon assimilation is central to understanding of the magnitude of this limitation, and of key ecosystem functions.

We assembled and synthesized over 15 years of research on water and carbon fluxes and ecosystem development on reclaimed oil-sands mine sites and on non-mine reference sites in the Athabasca Oil Sands Region of northern Alberta. A central premise of this work is that if reclaimed and reference sites with similar moisture and nutrient availability are using water and assimilating carbon at similar rates under the same climate, this suggests that the reclaimed sites are experiencing no greater levels of environmental stress than the reference sites, and no greater limitations to utilizing available site resources. Results of our work indicate similar functional processes of water storage and use, and carbon assimilation, between mine sites reclaimed to boreal-forest communities and non-mine reference sites.

KEY WORDS

oil sands, mine reclamation, water use, water flux, carbon assimilation, eddy covariance.

INTRODUCTION

There is a current lack of certainty and defined process in western Canadian jurisdictions with respect to measurement and demonstration of the success of mine reclamation. Both Alberta and British Columbia rely on multiple mechanisms for regulating reclamation and describing desired outcomes, primarily *Environmental Protection and Enhancement Act* approvals and the *Act*'s associated *Conservation and Reclamation Regulation* in Alberta, and Mining and Reclamation Permits and the B.C. *Mine's Act*'s *Health, Safety and Reclamation Code for Mines in British Columbia* in B.C. This body of regulation covers many requirements in the two jurisdictions (not necessarily common between jurisdictions), such as minimum reclamation-cover depth criteria and quality of materials used, allowable types of plant species and expectations for sustainability, productivity, and metal uptake, and the expectation that land capability on the reclaimed landscape will not be poorer than on the pre-development landscape. However – likely intentionally – there is little guidance on how to acceptably demonstrate the achievement of prescribed outcomes such as sustainable revegetation and equivalent land capability.

The replacement of equivalent land capability relies on the re-establishment of a variety of ecosystem functions such as water, nutrient, and energy cycling. Because it is difficult to directly measure these functions, evaluation of reclamation performance has typically relied on the measurement of a large number of ecosystem variables (e.g., soil chemistry, tree densities, plant community composition, wildlife presence), under the premise that in aggregate these variables will reflect ecosystem function and land capability. However, this approach has limitations, primarily:

- data on a large number of variables can be onerous to collect and impossible to appropriately integrate;
- variables may be poor indicators of actual function;
- variables are often highly correlated, which means that monitoring may be inefficiently measuring many similar responses; and
- it is difficult to know how to address conflicting results over many measured variables.

In our work, we explore the use of eddy covariance measures of water use and carbon assimilation as an alternative approach to evaluation of reclamation success, by more directly assessing ecosystem functions. This approach uses instruments mounted on towers above vegetation canopies to take continuous measurements of the atmospheric products of ecosystem function, specifically water and carbon dioxide exchange. The results are called ‘flux’ measurements, as their sum over a given period equates to the net flux of these constituents into or out of the study site. In addition, we collected information on soils and vegetation properties co-located with eddy covariance measurement fields at all study sites. The goal of this research is to use flux and non-flux indicators of ecosystem function to inform evaluation of equivalent capability on reclaimed sites. This paper provides an update on this research.

KEY RESEARCH PRINCIPLES

Our research proposes an alternate approach to the evaluation of ecosystem function and equivalent capability based on the following principles:

1. Ecosystem water and carbon fluxes are integrative indicators of a suite of supporting ecosystem processes and characteristics. Flux measurements are integrative both spatially and temporally – depending on a number of factors, the measurement field of an eddy covariance installation is approximately 3-4 ha, measuring the atmospheric products of thousands of trees, as well as understory species and soil biota. In addition, during the growing-season period of operation, eddy covariance instruments are sampling 10-20 times per second, continuously. These integrative measurements contrast with typical ground-based ecological sampling, where plots in a 4-ha area might sample 1-10% of that area 1-4 times in a growing season.

2. Identified relationships between water/carbon fluxes and non-flux biometrics will support development of non-flux indicators of ecosystem function, and permit knowledge gained from instrumented research sites to be applied across the non-instrumented landscape.
3. Measurement of both flux and non-flux indicators in juvenile non-mine ecosystems ("reference sites") disturbed through fire or forest harvest can provide ranges of natural variation for study indicators, and thus define expected performance "envelopes" for evaluation of equivalent capability.

METHODS

All sites in this study are upland forests, either reclaimed oil-sands sites, or reference sites naturally regenerating after fire or harvest events. Sites are further categorized into 'Dry' and 'Fresh' soil-moisture-regime groups based on analysis of the plant-available water storage capacity (AWSC) and water-deficit calculations described below. Most study sites are regenerating aspen and white spruce stands, although a few of the drier sites are dominated by jack pine. Site ages range from 4 to 88 years old, with reclaimed sites all 25 years of age or younger. Reference sites are located in the vicinity of the oil-sands mining area north of Fort McMurray, and in the Utikima Research Study Area north of Slave Lake, Alberta.

Flux data collected in the current study and in previous work has produced a database spanning 2003 to 2017 and covering 80 site-years at 15 sites overall, including 64 site-years of flux data at 10 sites1. A key element of our approach in this study was to co-locate flux and non-flux measurements. In the sections below, we describe methods used for both types of data collection.

<u>Water and carbon flux methods</u>

Eddy covariance uses above-canopy infrared gas analyzers to measure water-vapour and carbon-dioxide concentrations simultaneous with three-dimensional tracking of air-mass movements at a frequency of 10-20 times per second, which allows for mass balances of water and CO2 to be tabulated over the course of days and seasons. The results are called 'flux' measurements, as their sum over a given period equates to the net flux of these constituents, either into or out of the study site. The eddy covariance method and the reliability of its hydrometeorological data are well-established in scientific literature over the last 30 years (Wilson et al., 2001; Baldocchi, 2003).

At ten study sites, teams from McMaster University and the University of Waterloo led, respectively, by Dr. Sean Carey and Dr. Rich Petrone, established eddy covariance monitoring stations. Hydrometeorological data were collected at all sites on towers that ensure flux instrumentation are located at a minimum height above the canopy of 1/10th the canopy height (Petrone et al. 2015). Net ecosystem exchange (NEE), latent (Le) and sensible (H) energy exchanges, windspeed and direction, and friction velocity were measured using eddy covariance instrumentation for the snow-free period, coincident with hydrometeorological data.

[1] Five reference sites have been surveyed only for non-flux characteristics.

Instrumentation deployment followed the same protocols for setup and data processing for all sites using the standardized FLUXNET criteria so that measurements among sites would be intercomparable. Instrumentation consisted of either open-path or closed-path infrared gas analyzers (IRGA) (LI-7500 or LI-7000, respectively; LI-COR, Inc., Nebraska, USA) and a three-dimensional sonic anemometer (CSAT3 (Campbell Scientific Inc.) or WindMaster Pro (RM Young)). Fluxes were sampled at a rate of 10 to 20 Hz and averaged over half-hourly periods. NEE correction procedures included filtering for periods of low friction velocity ($<0.35\ m \cdot s^{-1}$) (Petrone et al. 2007) and rotation of vertical and horizontal wind velocities to zero (Kaimal and Finnigan 1994). Gaps within eddy covariance data were filled based on the mean moving windows or site-specific short-term regressions and quality controlled to remove outliers exceeding two standard deviations of the mean (Papale et al. 2006).

<u>Non-flux biometric methods</u>

The non-flux biometric measurements focussed on vegetation leaf-area index (LAI) and soil properties, covering the period 2013-2017. We collected all non-flux data in late July to mid-August, in the middle of the growing season.

Sampling for non-flux parameters consisted of 16 plots spaced 50 m apart on a four-by-four grid centred on the flux tower. The goal of this spacing was to ensure plots fell within the dominant tower measurement areas, which has subsequently been confirmed (Strilesky et al., 2017). We adjusted the layout model to fit plots within one ecosystem and forest-stand type. Vegetation was sampled within a 100-m2 (5.64-m radius) circular plot, with soils data collected outside the plot boundary. LAI was measured at 35 to 40 locations within each 100-m2 plot using LAI-2000 and LAI-2200 Plant Canopy Analyzers (Li-COR Inc. USA), and corrected for canopy clumping, needle-to-shoot, woody-to-total area ratios, and sun-scattering effects (Chen, 1996; Chen et al., 1997; Li-Cor, 2013). Two readings were taken at each measurement location in a plot: one at or near the ground surface, and another above the majority of the understory vegetation. This allows LAI results to be calculated for the understory and canopy layers, as well as the sum total. LAI results from all plots at a site were averaged to arrive at a site LAI for each year. LAI measurements prior to 2013 were made by university research teams, using the same equipment but different methodologies. Efforts were made to homogenize the two approaches using site photos and reclamation histories.

Four 1-m soil pits were dug at each site. These soil pits were located at the four plots nearest to the flux towers, and dug less than 5 m from the outer 100-m2 plot boundary. Soils were surveyed using standard methods (Soil Classification Working Group, 1998; BC Ministry of Environment, 2010) and samples were sent for analysis of soil chemical and physical properties at a certified laboratory (Exova, Edmonton, AB). The data for soil particle-size distribution and organic-matter content were used to calculate plant-available water storage capacity (AWSC). These calculations were made using several peer-reviewed models (Clothier et al., 1977; Arya and Paris, 1981; Arya et al., 1999; Saxton and Rawls, 2005), following from the work outlined in Straker et al. (2015).

Actual Soil Moisture Regime (ASMR) was estimated following Pojar et al. (1987), based on a ratio of estimated maximum actual evapotranspiration (AET) to potential evapotranspiration (PET).[2,3] Study sites span a four-class ASMR gradient from Very Dry to Fresh; for grouping and interpretation, these classes have been aggregated into two broader classes: Dry and Fresh. Nomenclature based on these aggregated ASMR classes and used throughout this report is provided in Table 1.

Table 1. Site grouping nomenclature.

Site type	**ASMR Class**	**ASMR Group**
Reclaimed	Moderately Dry	**Reclaimed – Dry**[4]
	Slightly Dry	**Reclaimed – Fresh**
	Fresh	
Reference	Very Dry	**Reference – Dry**[4]
	Fresh	**Reference – Fresh**

RESULTS

Water storage

We estimated the potential for study-site rooting zones to store and utilize plant-available water using AWSC and ASMR, where ASMR reflects the presence (or lack thereof) and severity of soil water constraints to evapotranspiration and photosynthesis in an average growing season (Pojar et al. 1987). Our data show that the reclaimed study sites have AWSC values of approximately 55-190 mm, and ASMRs from Moderately Dry to Fresh; reference sites have AWSC values of approximately 15-150 mm, and ASMRs from Very Dry to Fresh. A Fresh ASMR implies that in an average growing season, there are periods during which plant demand for water (evapotranspiration, ET) exceeds meteoric supply of water (precipitation, P), and plants need to withdraw soil water to meet this demand, but do not fully deplete the soil storage reservoir. Thus, there is no water deficit under average climatic conditions, and actual ET (AET) approaches potential ET (PET). Recharge of the soil-water reservoir then occurs during other periods of the

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[2] Maximum AET was calculated as AWSC plus mean P in May, June, July, August, and September, and represents maximum AET if a site were capable of capturing and utilizing all growing-season P plus stored soil water. Mean PET for MJJAS was 446 mm for Fort McMurray sites and 371 mm for URSA sites.

[3] This approach for these ASMR classes assumes that no rooting-zone water table is present during the growing season, at least once vegetation has occupied a site.

[4] In reclaimed sites, the Dry ASMR group is comprised of Moderately Dry sites, while in reference sites, the same ASMR group is represented by one Very Dry site. The differences in water limitations in the Very Dry and Moderately Dry sites is likely substantial, but we have insufficient data in this study from the Very Dry reference site to observe these differences.

growing season and during the non-growing season. Dry ASMRs imply varying degrees of water deficit, where growing-season P and stored soil water are not sufficient to meet potential evapotranspiration demand. Matric potential in the soil reach levels that limit plant uptake of water, and ecosystem water use is constrained by water availability.

<u>Water use</u>

This synthesis of study data based on general trends in vertical water-balance components shows that reclaimed sites range from having on average little to no constraint on evapotranspiration (Reclaimed – Fresh sites) to moderate constraints (Reclaimed – Dry sites). The study site with the longest record is very close to the Slightly Dry-Fresh threshold, and in an average climate year experiences a very small water deficit, with relatively little constraint on AET. This interpretation is supported by continuous soil-water-content data from this site, which shows that available soil water contents (AWC, volumetric contents above wilting point) are depleted during all growing seasons, as plants withdraw water to meet transpiration demands. However, at no time during any growing season from 2003 to 2014 – covering a range of wetter and drier years – did AWC approach zero, and critical water deficits did not occur (Strilesky et al. 2017). This behavior is similar to the aspen reference sites, which also have large soil-water storage capacity and ecosystem development relatively unconstrained by lack of soil water in an average climate year. In contrast, the driest reference site, a jack pine-lichen site, has substantially constrained vegetation community composition and growth due to water limitations.

We examined a 64-year climate record (1944-2007) from Environment Canada's Fort McMurray CS station and a 49-year climate record (1958-2007) from Environment Canada's Red Earth Creek station to look at how the central tendencies of seasonal moisture deficits described above change with climatic variation. ASMR classifications are related to the magnitude and frequency of water limitations, with larger and more frequent limitations on Dry sites than on Fresh sites. Water deficits constraining ET occur in roughly 90% of years on the Very Dry reference site, but in only 20-45% of years in the Fresh reclaimed and reference sites. Thus, all sites experience water deficits that constrain ecosystem processes, but these deficits are larger and occur more frequently on the Dry sites than on the Fresh sites. Growing-season water use measured by eddy covariance is similar between reference and reclaimed study sites. These results are supported by broader comparisons between some of the reclaimed sites in this study and a wider range of reference sites, which show that the reclaimed ecosystems are functioning within the range of natural variability with respect to water use (Strilesky et al. 2017). Although there are fluctuations driven by annual and seasonal climate variability, all Reference – Fresh and Reclaimed - Fresh sites have AET that approaches PET for June-July-August in years with adequate growing-season precipitation. Also, despite this substantial variation, AET at reclaimed sites groups well by ASMR classes, with sites in the Reclaimed - Dry class generally having AET values < 300 mm, and the older Reclaimed – Fresh site generally having AET ≥ 300 mm.

<u>Comparison to ranges of natural variation – water storage and use</u>

We used information on water storage and water use on the reference sites in this study to define ranges of natural variation for key indicators, including AWSC, ASMR, and AET. The AWSC range of natural variation is from approximately 15–150 mm, with ASMR from Very Dry to Fresh. In comparison, the reclaimed study sites group more tightly and are generally wetter, with AWSC from 55–190 mm, and ASMR from Moderately Dry to Fresh. The range of natural variation for measured evapotranspiration (in the June-July-August period, or JJA) for older (i.e., not immediately following disturbance) sites in this study is roughly 190–300 mm, while equivalent values for Reclaimed – Fresh sites are roughly 290–360 mm, with Reclaimed – Dry sites roughly 150–290 mm. This synthesis suggests that reclamation has been successful at establishing a range of site conditions in the submesic–mesic (Moderately Dry to Fresh) end of the range of natural variation, having ecosystem water use equivalent to that of reference sites. However, currently approved reclamation practices do not generally support re-creation of sites at the dry end of this range. These practices have generally been designed to minimize constraints on water use and ecosystem processes by mandating use of thick cover systems with large water-storage reservoirs. However, in the western boreal plains, these constraints are a natural part of the heterogeneity of upland ecosystems, and a major determinant of ecosystem diversity. Varying degrees of water storage and resulting deficits are a component of overall ecosystem diversity, and where achievement of equivalent land capability is dependent on the presence of dry reclaimed ecosites within the full range of achieved ecosystem diversity, reclamation success will be partially impeded based on absence of those ecosystems.

Comparison to ranges of natural variation – carbon assimilation

Comparison of net ecosystem production (NEP) on reclaimed and reference study sites shows that older Reclaimed – Fresh sites have June-July-August NEP values (roughly 290–470 g C/m^2) similar to those of Reference – Fresh sites (roughly 320 – 630 g C/m^2), while Reclaimed – Dry sites have lower values (roughly 0–320 g C/m^2). Corroborating the findings discussed above on soil-water constraints on ecosystem development, Strilesky et al. (2017), in a detailed study of the Slightly Dry South Bison Hill study site, report that carbon assimilation at this site is not constrained by soil water availability.

Relationships between fluxes and non-flux biometrics

We explored the relationships between ASMR and water/carbon fluxes and showed that both fluxes are influenced by the ability of soils and reclamation-cover systems to store water and make it available for plant use. A fourth indicator of these processes, and one that does not require measurement of fluxes, is LAI. Like AET and NEP, development of LAI is related to water storage in soil systems, and is both reflective of fluxes – e.g., leaves represent a product of NEP – and influences them, e.g., transpiration and carbon assimilation occur at the surface of or within leaf structures. Thus we expect fluxes to show relationships with LAI.

We evaluated a number of non-flux biometrics for correlation with flux measures and determined that total LAI[5] consistently shows relationships with fluxes, and has the advantage of being capable of application across a wider range of vegetation types than just forest stands. A generalized relationship between LAI and NEP derived from our data is shown in Figure 1 –

[5] Understory and overstory LAI combined.

actual observations vary by approximately ±100 g C/m^2 around the fit line. These data indicate that JJA NEP increases rapidly as the first unit of LAI develops, with declining incremental increase with additional LAI.

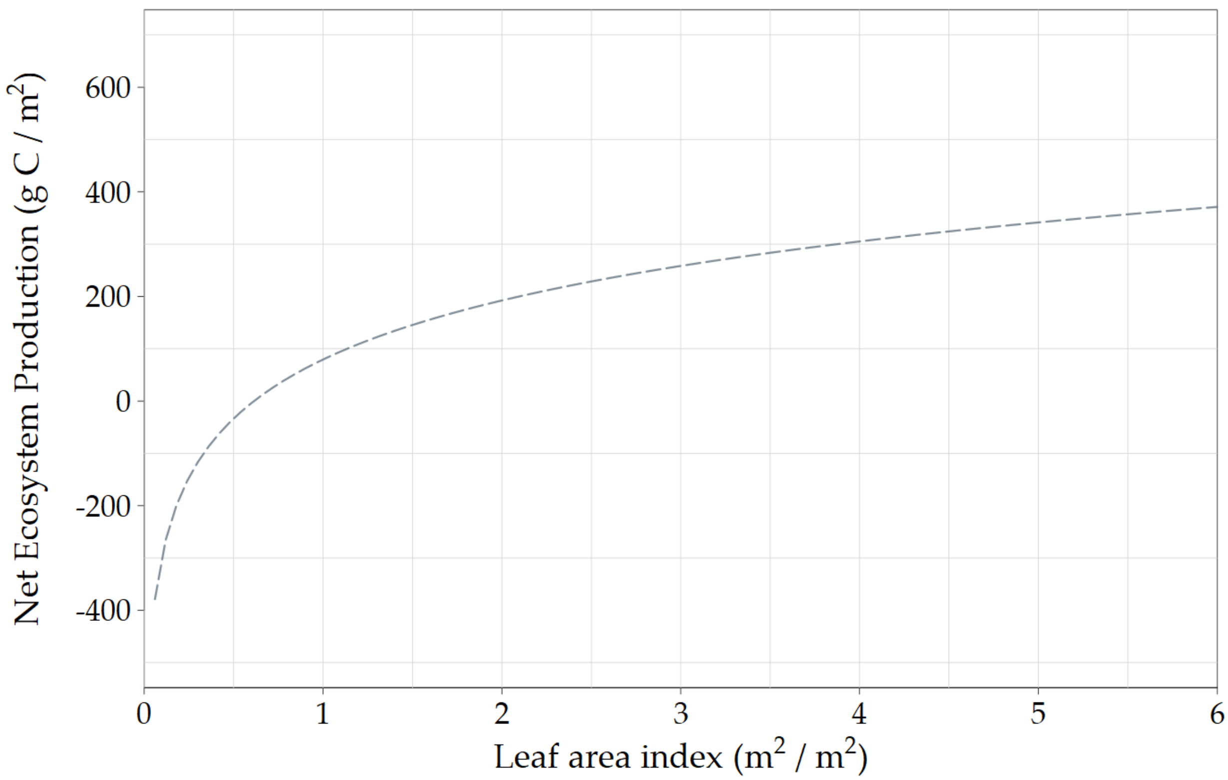

Figure 1. Generalized fit based on study data of June-July-August net ecosystem production by leaf-area index.

CONCLUSION

This research has demonstrated that a small number of metrics can be used to assess functional performance of reclaimed upland ecosystems. On instrumented sites, water and carbon fluxes are integrative indicators of reclaimed ecosystem development. We have shown relationships between these flux indicators and the non-flux indicators of soil moisture regime and plant leaf area, allowing extension of our study findings across the non-instrumented landscape for both reclamation assessment and estimation of water and carbon fluxes. For all these indicators, reclamation success can be measured against performance envelopes observed in natural ecosystems. Our research shows that all indicators reach a climate-mediated quasi-steady state approximately 10-20 years following initial revegetation and can be reliably used within this window to provide information on expected longer-term values.

Our work has also shown that carbon assimilation and water use in reclaimed uplands is equivalent to or exceeds that of natural uplands. Reclamation cover systems appear to generally store more water than natural upland soils in the boreal plain, and resulting ecosystems are using more water than their natural counterparts at similar ages. This high water storage and use suggests that upland reclamation covers and ecosystems generate less surplus water as runoff than natural uplands, resulting in less water available to downstream wetland and aquatic environments.

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