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DEVELOPING A FUNCTIONAL APPROACH TO ASSESSMENT OF LAND CAPABILITY: UTILIZING ECOSYSTEM WATER AND CARBON NUTRIENT FLUXES AS INTEGRATED MEASURES OF RECLAMATION PERFORMANCE

Knowledge Synthesis

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SUMMARY

This report synthesizes over 15 years of research (and 64 site-years of data) on water use, carbon assimilation, and associated ecosystem development on reclaimed oil-sands-mine sites and on non-mine reference sites. A key feature of this research is the use of eddy-covariance methods to make integrative measurements of ecosystem performance. This approach uses instruments mounted on towers above the vegetation canopy 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 land capability on reclaimed sites, where data from reference sites provide envelopes of natural performance for these indicators. All study sites are upland forests; reclamation study sites are located on the Syncrude and Suncor mine sites, while reference sites are located primarily in the Utikuma Research Study Area north of Slave Lake, Alberta.

Our research has demonstrated 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. Our work provides multiple lines of evidence to suggest that upland reclamation covers mandated by operating approvals are too conservative, or “over-built”. These thick covers are designed to support the development of productive forests, but do not provide edaphic conditions to produce the drier end of the expected range of upland ecosystems observed in reference systems, and introduce a risk of not generating sufficient water for down-gradient receiving environments. An applied interpretation of this finding is that for both ecological and hydrological reasons, reclamation cover practice should be encouraged to incorporate greater variation, to allow development of a range of ecosystems and runoff volumes, rather than mandating a uniform and conservative (thick) minimum cover depth that results in excessively high water storage and low runoff. This is the only current reclamation failure mode indicated by our work – on our study sites, we have not observed failure to establish functional upland reclamation ecosystems, and cannot identify mechanisms that would cause failure based on water availability given our knowledge of ecosystem and hydrological processes and current reclamation practice.

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 plant leaf area and soil moisture regime, 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.

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1. INTRODUCTION

The overall health and success of vegetated ecosystems is directly linked to the cycling of water, energy, and carbon. Plant growth is controlled by climate (energy) and mediated by available water and sufficient nutrients in the rooting zone. Ecosystems develop and occur across a range of climates and experience stress when there are limitations to water, nutrients or light. In cases where these limitations occur (both spatially and temporally), carbon uptake and production is reduced. In most of western and northern Canada, the primary limitation on ecosystem productivity is water stress. The climate of western Canada is particularly variable over annual and decadal scales, and 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.

In this report, we synthesize over 15 years of research (and 64 site-years of data) on water and carbon fluxes and associated ecosystem function and development on reclaimed oil-sands-mine sites and on non-mine reference sites initiated through other disturbances (i.e., forest harvest and fire). This research represents a continuation and expansion of an existing long-term ecohydrological research network, and most recently includes studies conducted from 2013 to 2017 as a joint industry project supported by Syncrude Canada Ltd. and Suncor Energy Inc.

1.1 Research rationale

Alberta's regulation of mine reclamation requires the return of land capability similar to that prior to disturbance. This return relies on the re-establishment of a variety of ecosystem functions such as water, nutrient, and energy cycling to support the production of ecosystem services. Because it is difficult to directly measure ecosystem function, evaluation of reclamation performance has typically relied on the measurement of a large number of ecosystem variables (e.g., soil chemistry, tree densities), 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; an alternate focus on fewer factors or on emergent properties that biologically integrate those factors may be more effective;
- there is no clear protocol on how to address conflicting results over many measured variables; and
- measured variables may reflect current site performance, but fail to provide information on site stability under changing conditions, and on broader landscape-level performance.

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

1. ecosystem water and carbon fluxes are integrative indicators of a suite of supporting ecosystem processes and characteristics;
2. assessment of the efficiency of ecosystem water use provides important insight on resiliency to climatic variation and change, and on landscape-level water storage and yield;

3. 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; and
4. measurement of both flux and non-flux indicators in juvenile non-mine ecosystems 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.

2. RESEARCH OBJECTIVES

Our overall applied research goal in this program is to use flux and non-flux indicators of ecosystem function to inform evaluation of land capability on reclaimed oil-sands mine sites. This goal is supported by the following objectives:

- Using state-of-the-art measurements of ecosystem-scale fluxes of water, energy and carbon from a range of reclaimed, natural and disturbed sites provides a mechanistic understanding of how ecosystem site characteristics and age affect water, energy and carbon fluxes. This will demonstrate the sensitivity of evapotranspiration, ecosystem exchange of CO_2, and water use efficiency to soil water limitations, climate, ecosystem type and age, and placement strategy.
- Collecting data on non-flux vegetation characteristics co-located with flux research sites to evaluate relationships with water and carbon fluxes, and to identify non-flux indicators of ecosystem function.

These objectives will support the development of key indicators to evaluate reclamation performance and predict ecosystem development trajectories, and are also intended to provide interpretations to support ongoing refinement of reclamation practices.

3. METHODS

In the subsections below, we summarize information on the sites included in this study, and on the flux and non-flux measurement methods we used at these sites. Appendix A defines all acronyms used in this document. Additional information on each study site is included as site "fact sheets" in Appendix B.

3.1 Study team

The study team consisted of personnel from three primary organizations: McMaster University, the University of Waterloo, and Integral Ecology Group (IEG). McMaster and Waterloo were responsible for instrumentation and collection of all flux data, for flux-data reduction and interpretations, and for all data from study sites collected prior to 2013. IEG was responsible for collection of non-flux biometrics, including soils and vegetation information. Key personnel included principal investigators Drs. Sean Carey (McMaster) and Richard Petrone (Waterloo), and Justin Straker (IEG). Trevor Baker of IEG conducted much of the data compilation, analysis, and interpretations that appear in this report. Doctoral student Stacey Strilesky (Carleton University) contributed to the project through her data compilation, cleaning, and interpretation, and produced a number of the figures that appear in this report.

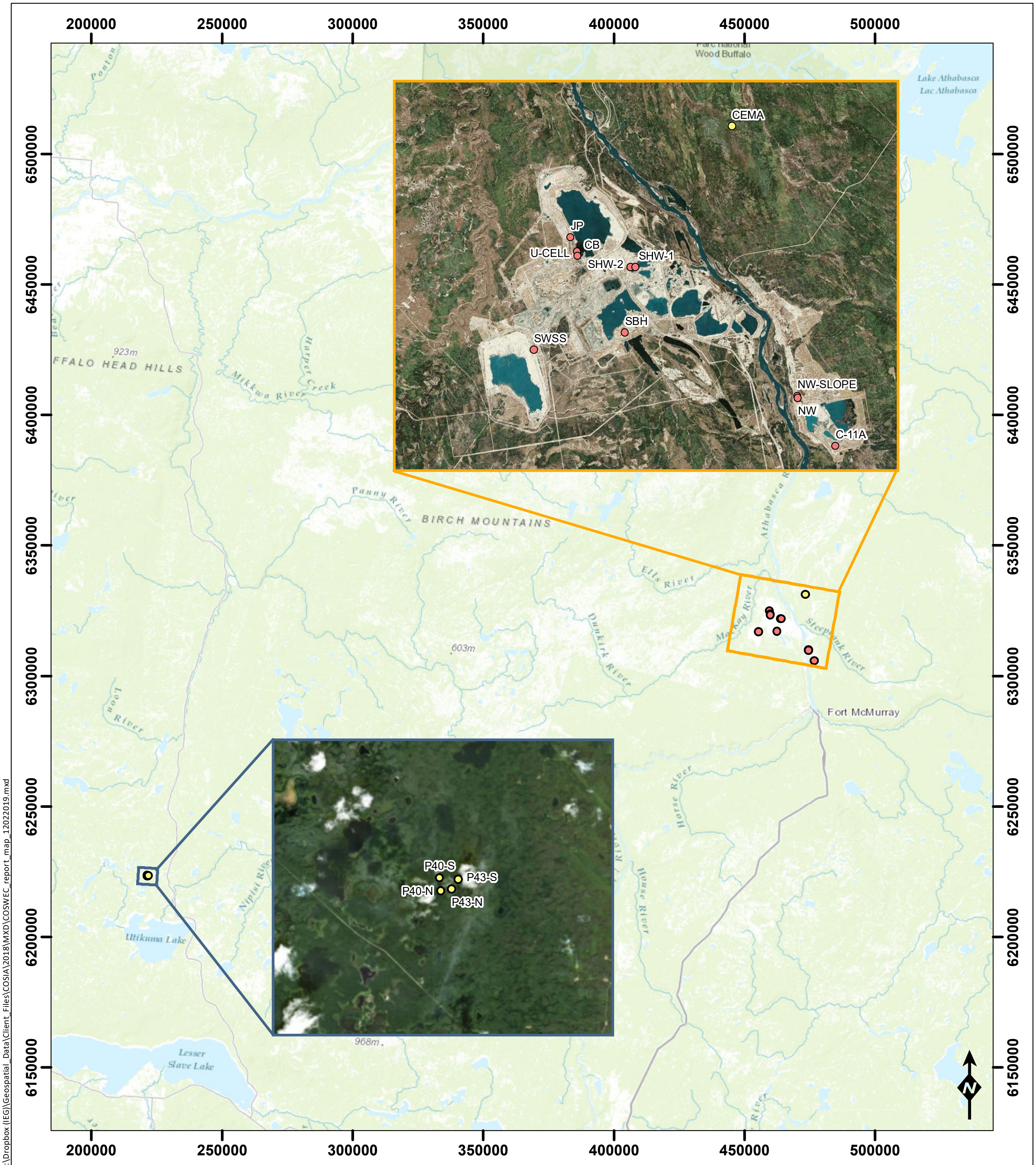
3.2 Study sites

Study sites include both reclaimed and non-mine reference sites (Tables 1 and 2, Figure 1). Reclaimed sites are all located on the Syncrude Base Mine and Suncor Mine north of Fort McMurray, Alberta. Most of the study reference sites are in the Utikuma Region Study Area (URSA) near Utikuma Lake, approximately 260 km southwest of the oil-sands sites. An additional reference site without flux instrumentation is located approximately 40 km northwest of the oil-sands sites. We have used other long-term flux research in the Canadian western boreal forest (the BOREAS and BERMS projects [Barr et al., 2004b; Amiro et al., 2006; Zha et al. 2013]) for comparative purposes, but these data have not been used to develop the models and relationships presented here.

Table 1. Summary of study sites.

Reclaimed / Reference (disturbance)	Area	Site	Site ID	Stand age	Flux years	Dominant tree species	Estimated ecosite[1]	# of plots
Reclaimed	Suncor	Nikanotee Watershed Upland	NW	4	5	Sb, Pj	b / d	16
Reclaimed	Syncrude	Sandhill Watershed Upland	SHW-1	6	5	Aw, Sw	d	12
Reclaimed	Syncrude	Sandhill Watershed Perched Upland	SHW-2	6	2	Aw, Pb	d	10
Reclaimed	Suncor	Nikanotee Watershed Side-Slopes	NW-SLOPE	6, 10	-	Aw, Sw	d	11
Reclaimed	Syncrude	Coke Beach	CB	11	1	Sw	b / d	16
Reclaimed	Suncor	Cell 11A	C-11A	12	6	Pj	b / d	7
Reclaimed	Syncrude	South Bison Hill	SBH	15	15	Aw	d	13
Reclaimed	Syncrude	U-shaped Cell	U-CELL	20	-	Aw	b	1
Reclaimed	Syncrude	Southwest Sand Storage	SWSS	22	4	Aw, Ls	b / d	16
Reclaimed	Syncrude	Jack Pine	JP	25	6	Pj	b / d	12
Reference (harvest)	URSA	P40 Juvenile North-Facing	P40-N[2]	10	2	Aw	d1.5 / d1.6	11
Reference (harvest)	URSA	P40 Juvenile South-Facing	P40-S	11	12	Aw	d1.5 / d1.6	12
Reference (fire)	URSA	P43 Mature North-Facing	P43-N	73	-	Aw	d1.5	4
Reference (fire)	URSA	P43 Mature South-Facing	P43-S	76	-	Aw	d1.5	14
Reference (fire)	Ft McMurray	CEMA Mature Jack Pine	CEMA	89	-	Pj	a1.1 / a1.2	4

[1] Plant community types are provided for reference sites, classification follows Beckingham and Archibald, 1996.
[2] Data from site P40-25m originates from a 25-m tower located at P40-N. The P40-N data record is constructed of data from the 25-m tower pre-harvest, and from the shorter tower post-harvest. The ongoing data record from the 25-m tower is assigned the 'P40-25m' identifier in subsequent years.



D:\Dropbox (IEG)\Geospatial_Data\Client_Files\COSIA\2018\MXD\COSWEC_report_map_12022019.mxd

Figure 1. Site locations.

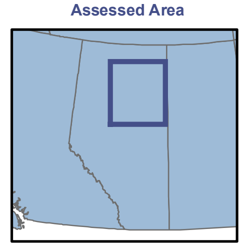
Reclaimed

Reference

Scale:
1:2,000,000

Kilometers
0 25 50 100

Assessed Area



Created by: IEG Integral Ecology Group

Client: cosia

Drawn by: MI

Checked by: TB

Date: 13-Feb-2019

Project: COSWEC-17

Datum/Coordinates: NAD83/UTM Zone 12

Table 2. Site material and reclamation-cover characteristics.

Reclaimed / Reference (disturbance)	Area	Site	Substrate	Reclamation Cover Depth (cm)
Reference (fire)	NE of Suncor	CEMA Jack Pine	Glaciofluvial sand	n/a
Reclaimed	Syncrude	U-shaped Cell	Tailings / coke	0
Reclaimed	Suncor	Nikanotee Watershed Upland	Tailings	30-40
Reclaimed	Syncrude	Southwest Sand Storage	Tailings	45-65
Reclaimed	Syncrude	Coke Beach	Coke	35-70
Reclaimed	Syncrude	Jack Pine	Tailings	45-65
Reclaimed	Suncor	Cell 11A	Tailings	15-35
Reclaimed	Suncor	Nikanotee Watershed Side-Slopes	Tailings / secondary	20-35
Reclaimed	Syncrude	South Bison Hill	Saline-sodic overburden	100+
Reclaimed	Syncrude	Sandhill Watershed Perched Upland	Tailings	60-85
Reclaimed	Syncrude	Sandhill Watershed Upland	Tailings	50-60
Reference (harvest)	URSA	P40 Juvenile North-Facing	Morainal	n/a
Reference (harvest)	URSA	P40 Juvenile South-Facing	Morainal	n/a
Reference (fire)	URSA	P43 Mature South-Facing	Morainal	n/a
Reference (fire)	URSA	P43 Mature North-Facing	Morainal	n/a

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’ groups based on analysis of the plant-available water storage capacity (AWSC) and water-deficit calculations described in Section 3.4.4 below. Most study sites are regenerating aspen and white spruce stands, although a few of the drier sites are dominated by jack pine. The reference sites are d ecosites, while reclaimed sites are estimated as b and d ecosites (Beckingham and Archibald, 1996). Site ages range from 4 to 88 years old, with reclaimed sites all 25 years of age or younger (Table 1). Further, data were collected from multiple sites over a number of years and seasons, when combined consistent patterns and correlations between fluxes and biometric variables can be detected (Harrison, 2011).

Flux data collected in the current study is a continuation of several past projects undertaken by Syncrude, Suncor, and other organizations, yielding a database spanning 2003 to 2017 and covering 80 site-years at 15 sites overall, including 64 site-years of flux data at 10 sites[3]. During this project, from 2013 to 2017, there were 26 site-years of flux data and 45 site-years of vegetation data collected. More detail on study sites is presented in Appendix B. A key element

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

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.

3.3 Water and carbon flux methods

3.3.1 General background

The key feature of this research is the use of eddy-covariance (EC) methods to make integrative measurements of ecosystem performance. This approach uses a suite of instruments mounted on towers above the vegetation canopy to take continuous measurements of the atmospheric products of ecosystem function, specifically water and carbon dioxide (CO_2). Measuring the concentration of these gases using infrared gas analyzers simultaneous with three-dimensional tracking of air-mass movements at a frequency of 10-20 times per second allows for mass balances of water and CO_2 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 EC 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).

3.3.2 Current study

At ten study sites, teams from McMaster University and the University of Waterloo led, respectively, by Dr. Sean Carey and Dr. Rich Petrone, established EC monitoring stations (Table 1).

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). Variability in temporal measurements and inter- or intra-annual climate were examined throughout the year, yet to facilitate inter-site and inter-year comparison we focus on the snow-free period from 1 June to 31 August. Mean half-hourly atmospheric measurements included air temperature (T_a (°C)), relative humidity (RH, %), and above-canopy net and short-wave radiation (Q^*, Sd, $W \cdot m^{-2}$) measured at a height coincident with flux instrumentation. Precipitation (P) was measured using a series of total weighing and tipping bucket gauges located near each tower.

Soil measurements including moisture, temperature, and heat fluxes were conducted at positions adjacent to the meteorological towers. Soil moisture content and temperature were collected using a series of calibrated and corrected water content reflectometers and thermocouples to variable depths in the rooting zone. Groundwater levels were measured using wells adjacent to towers where the water table was within 2 m of the surface. These data were complemented with detailed profile analysis of soil physical properties.

Net ecosystem exchange (NEE), latent (Le) and sensible (H) energy exchanges, windspeed and direction, and friction velocity were measured using EC instrumentation for the snow-free period, coincident with hydrometeorological data. Instrumentation deployment followed the same protocols for setup and data processing for all sites following the standardized FLUXNET criteria (Baldocchi et al., 2001) 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·s^{-1}) (Petrone et al. 2007) and rotation of vertical and horizontal wind velocities to zero (Kaimal and Finnigan 1994). Gaps within EC 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). Gross ecosystem production (GEP) was estimated from half-hourly estimates of net ecosystem production (NEP [4], where NEP = −NEE)), and total ecosystem respiration (R_e). Nighttime NEP was used as a direct estimate of R_e during periods when friction velocity was greater than the minimum threshold. For periods below this threshold, R_e was estimated using an empirical model as a function of within-canopy T_a. Daytime GEP was estimated as the difference between NEP and R_e (GEP = NEP – R_e), where daytime R_e was determined from the same empirical model used for nighttime R_e (Griffis et al. 2003).

A flux footprint parameterization based on a full-scale Lagrangian particle model (Kljun et al. 2002; Kljun et al. 2004) was used to estimate contribution areas for mass fluxes. The footprint is defined as the probability of contribution by CO_2 and water fluxes per unit area upwind of the EC system.

Gap-filled flux data for June 1 - August 31 were summed for each year, and these June-July-August (JJA) fluxes are used for discussion and analysis in this report. We believe the use of JJA sums to compare sites and years is appropriate, because annual totals are highly dependent on dates of bud burst and senescence, and thus vary strongly with annual weather patterns (Huang et al. 2011). JJA data allow us to reduce this variation and focus more on site responses over the majority of the growing season.

3.4 Non-flux biometric methods

The non-flux biometric data can be split into three types: 1) general vegetation (including leaf-area-index [LAI]), 2) forest mensuration, and 3) soil data (Table 2). We began surveys for all three data types using the current project methods in 2013. Prior measurement years, back to 2003, have only LAI measurements to complement the flux measurements, making the 2013-17 period our most extensive dataset. We collected all non-flux data in late July to mid-August, in the middle of the growing season.

3.4.1 Site and plot layout

Our model for plot layout consisted of 16 survey 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. Plot counts by site are presented in Table 1. Summary of study sites. and site layouts are shown in Appendix B.

Each plot-centre was marked permanently with rebar in the year of establishment. Concentric 10-m^2 (1.78-m radius, ‘milhectare’) and 100-m^2 (5.64-m radius) plots were established. The only measurements constrained to the 10-m^2 plots were milhectare tree tallies, as described in Section 0 below.

[4] In this study, NEP is positive when the ecosystem is a sink for atmospheric CO_2 (i.e. C assimilation [GEP] is greater than C loss via respiration [R_e])

3.4.2 Vegetation data

We completed both LAI and vegetation-cover surveys within 100-m^2 plots. Trained botanists conducted the vegetation-cover surveys, estimating percent cover for each species with a cover greater than 1%. We used these data to calculate annual metrics such as total vegetation cover, species diversity and species richness (Table 3).

In our 2013-2017 data set, LAI was measured at 35 to 40 locations within each 100-m^2 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 McMaster and Waterloo research teams, using the same equipment but different methodologies. Efforts were made to normalize pre-2013 and 2013-onward data sets using site photos and reclamation histories (Appendix C), to arrive at a single LAI dataset for all flux years.

Table 3. Summary of non-flux biometric data.

<table>
<tr><th>Data type</th><th>Source data</th><th>Biometric variable</th><th>Units</th></tr>
<tr><td rowspan="7">Vegetation</td><td rowspan="3">Leaf area index</td><td>Understory LAI</td><td>-</td></tr>
<tr><td>Canopy LAI</td><td>-</td></tr>
<tr><td>Total LAI</td><td>-</td></tr>
<tr><td rowspan="4">Vegetation cover</td><td>Total vegetation cover</td><td>%</td></tr>
<tr><td>Vegetation cover by growth form and origin</td><td>%</td></tr>
<tr><td>Species richness</td><td>-</td></tr>
<tr><td>Shannon diversity</td><td>-</td></tr>
<tr><td rowspan="10">Forest</td><td rowspan="7">Tagged tree mensuration</td><td>Total tagged tree density</td><td>stems per hectare</td></tr>
<tr><td>Tree density by species and type</td><td>stems per hectare</td></tr>
<tr><td>Quadratic mean diameter</td><td>cm</td></tr>
<tr><td>Basal area</td><td>m^2/ha</td></tr>
<tr><td>Site index</td><td>estimated height (m) at 50 years</td></tr>
<tr><td>Stand density index</td><td>equivalent number of 10-inch DBH stems per hectare</td></tr>
<tr><td rowspan="2">Wilson's spacing factor</td><td rowspan="2">ratio of mean inter-tree distance to tree height</td></tr>
<tr><td rowspan="3">Milhectare tree tallies</td></tr>
<tr><td>Total tree density</td><td>stems per hectare</td></tr>
<tr><td>Tree density by species and type</td><td>stems per hectare</td></tr>
<tr><td rowspan="8">Soil</td><td rowspan="2">Soil surveys</td><td>Dominant rooting depth</td><td>cm</td></tr>
<tr><td>Depth of organic and litter horizons</td><td>cm</td></tr>
<tr><td rowspan="5">Soil chemistry</td><td>Available N, P, K</td><td>% wt. (upper 50 cm)</td></tr>
<tr><td>pH</td><td>-</td></tr>
<tr><td>EC</td><td>dS/m (upper 50 cm)</td></tr>
<tr><td>Organic matter (OM) content</td><td>% wt. (upper 50 cm)</td></tr>
<tr><td rowspan="3">AWSC (from particle-size, OM content, and topography)</td><td rowspan="3">mm available water in upper metre of soil</td></tr>
<tr><td>Soil physical properties</td></tr>
<tr><td rowspan="2">Site</td><td>Topography</td></tr>
<tr><td>Site history</td><td>Site age</td><td>number of completed growing seasons since disturbance (reference) or planting (reclaimed)</td></tr>
</table>

3.4.3 Forest mensuration data

We tagged all trees greater than 4-cm breast-height diameter (DBH) within the 100-m^2 plots, and measured height and DBH annually. We used the resulting data to calculate tagged densities, basal area, quadratic mean diameter, site index by species (Huang, 1994), as well as stocking metrics such as stand density index (Reineke, 1933) and Wilson's spacing factor (Wilson, 1946) (Table 2). We used the 4-cm-DBH tagging limit because of very high stem densities (e.g., >10 000 stems per hectare) at some younger sites. To facilitate equal density comparison between all sites, milhectare tallies in the 10-m^2 plots were made of all stems taller than 30 cm for conifers and 130 cm for deciduous trees.

3.4.4 Soil data

In the initial survey year of the current project, 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-m^2 plot boundary. Soils were surveyed using standard methods (Soil Classification Working Group, 1998; BC Ministry of Environment, 2015) 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 (PSD) and organic-matter (OM) content were used to calculate plant-available water storage capacity (AWSC). As elaborated upon in Appendix D, these calculations were made using several peer-reviewed models (Clothier et al., 1977; Arya and Paris, 1981; Arya et al., 1999; Saxton, 2005; Saxton and Rawls, 2006), following from the work outlined in Straker et al. (2015).

3.4.5 Available water storage capacity, actual soil moisture regime, and site grouping

We estimated the potential for study-site rooting zones to store and utilize plant-available water using AWSC, which is a covariate with the potential to substantially influence ecosystem flux and leaf-area responses. AWSC results were used to determine actual soil moisture regime (ASMR) – based on a ratio of estimated maximum actual evapotranspiration (AET) to potential evapotranspiration (PET)[5,6] – which 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, defined in Appendix A[7]).

These characteristics are summarized by study site in Table 4 and elaborated upon in Appendix E. They show that the reclaimed study sites have AWSC values of approximately 50-200 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,

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[5] Maximum AET was calculated as AWSC plus mean P in May, June, July, August, and September, and represents maximum AET if a site if a site had fully developed LAI and was 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. This is detailed further in Appendix E.

[6] 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.

[7] On a scale of excessively dry to very wet ecosystems.

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 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.

Table 4. AWSC and ASMR by study site.

Reclaimed / Reference (disturbance)	Area	Site	Substrate	Reclamation Cover Depth (cm)	AWSC (mm in upper 1 m)	Actual SMR (maximum AET[8]/PET)
Reference (fire)	NE of Suncor	CEMA Jack Pine	Glaciofluvial sand	n/a	15	Very Dry (68%)
Reclaimed	Syncrude	U-shaped Cell	Tailings / coke	0	51	Moderately Dry (76%)
Reclaimed	Suncor	Nikanotee Watershed Upland	Tailings	30-40	68	Moderately Dry (80%)
Reclaimed	Syncrude	Southwest Sand Storage	Tailings	45-65	88	Moderately Dry (84%)
Reclaimed	Syncrude	Coke Beach	Coke	35-70	92	Moderately Dry (85%)
Reclaimed	Syncrude	Jack Pine	Tailings	45-65	104	Moderately Dry (88%)
Reclaimed	Suncor	Cell 11A	Tailings	15-35	105	Moderately Dry (88%)
Reclaimed	Suncor	Nikanotee Watershed Side-Slopes	Tailings / secondary	20-35	119	Slightly Dry (91%)
Reclaimed	Syncrude	South Bison Hill	Saline-sodic overburden	100+	150	Slightly Dry (98%)
Reclaimed	Syncrude	Sandhill Watershed Perched Upland	Tailings	60-85	160	Fresh (100%)
Reclaimed	Syncrude	Sandhill Watershed Upland	Tailings	50-60	201	Fresh (100%)
Reference (harvest)	URSA	P40 Juvenile North-Facing	Morainal	n/a	116	Fresh (100%)
Reference (harvest)	URSA	P40 Juvenile South-Facing	Morainal	n/a	132	Fresh (100%)
Reference (fire)	URSA	P43 Mature South-Facing	Morainal	n/a	138	Fresh (100%)
Reference (fire)	URSA	P43 Mature North-Facing	Morainal	n/a	149	Fresh (100%)

[8] 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.

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 as used throughout this report is provided in Table 5.

Table 5. Site grouping nomenclature.

Site type	ASMR Class	ASMR Group
Reclaimed	Moderately Dry	**Reclaimed – Dry**[9]
	Slightly Dry	**Reclaimed – Fresh**
	Fresh	
Reference	Very Dry	**Reference – Dry**[6]
	Fresh	**Reference – Fresh**

We use ASMR in this report to stratify sites and to attribute observed variation to known site characteristics. An initial exploration of implications of these site characteristics for site water balances (e.g., parameters such as site runoff in average climate years, and the proportion of years with the potential to produce runoff) is presented in Appendix E.

3.5 Interpretations of water-balance responses

In this study we examine a key water-balance term, AET, and discuss possible implications of differences in this term to other water-balance terms such as runoff. Because transpiration is a dominant component of AET on well-vegetated sites, AET is dependent not only on climatic factors, but on the state of vegetation development, and the ability of the soil to store and supply water for plant use. Gaining an understanding of longer-term AET behavior thus requires knowledge of site performance with well-developed vegetation, where transpiration is maximized. The ideal way to acquire that knowledge would be empirical, based on data derived from the eddy-covariance instrumentation. This approach would necessitate many study sites (e.g., >10) with multiple years of data acquired under conditions of well-developed vegetation (i.e., on sites ≥10 years old). However, this study is limited at this time in this respect: we only have multiple years of data for four study sites at this age or older. For two more sites, we have a single 10-year-plus data point. In a study that is already limited by the total number and distribution of study sites, it is difficult at this time to draw robust conclusions from this data set alone.

An additional approach to examining AET, and for drawing inferences about these water-balance terms over longer time periods and across a broader reclamation landscape, is to develop models based on covariates that can explain and project responses to non-measured sites and/or ages. In order to do this, in this study we used the concept of "maximum AET", based on

[9] 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.

climate, the ability of a soil or reclamation-cover system to store and release water across a range of plant-available matric potential, and on an assumption of full LAI development. This concept was used to define ASMR and to augment empirical observations – in our results and discussion, we rely both on empirical data and this modelled response.

4. RESULTS

Corresponding with stated research objectives, we present results below for both EC and non-EC metrics included in this study.

4.1 Eddy covariance

We utilized our network of flux tower sites (Table 1) with additional data for the western boreal forests available from the published literature and accessible through the AmeriFlux web portal (ameriflux.lbl.gov) to evaluate how stand age, vegetation type and other edaphic conditions influenced water and carbon dioxide balances at these sites. For comparative analysis, we focus on the June-August growing season.

4.1.1 Evapotranspiration

Total actual June through August evapotranspiration (JJA ET) for the reclamation and reference sites ranges from 130 mm to 360 mm (Figures 2, 3), or on average 1.4 - 3.5 mm/d (Figure 4). The range of this variability is controlled by seasonal weather conditions, vegetation characteristics and edaphic conditions. Reclamation sites had a larger range and value of JJA ET than reference sites, and broadleaf forests had greater JJA ET than conifer stands. Application of a rank-sum statistical test on this data set with grouped analysis indicates that there is no significant difference between groups (Figure 3). Whereas JJA ET is generally low at the onset of reclamation, values rapidly increase once established and temporal trends thereafter are largely governed by seasonal differences in climate. By 10-20 years, JJA ET was similar to rates at the reference forests > 40 year of age. Initial upland reclamation conditions are generally dry enough to limit direct evaporation, requiring root development with vegetation establishment to access this water. Thus, initial JJA ET rates are low until vegetation establishment and associate root development leads to an increase in the transpiration component.

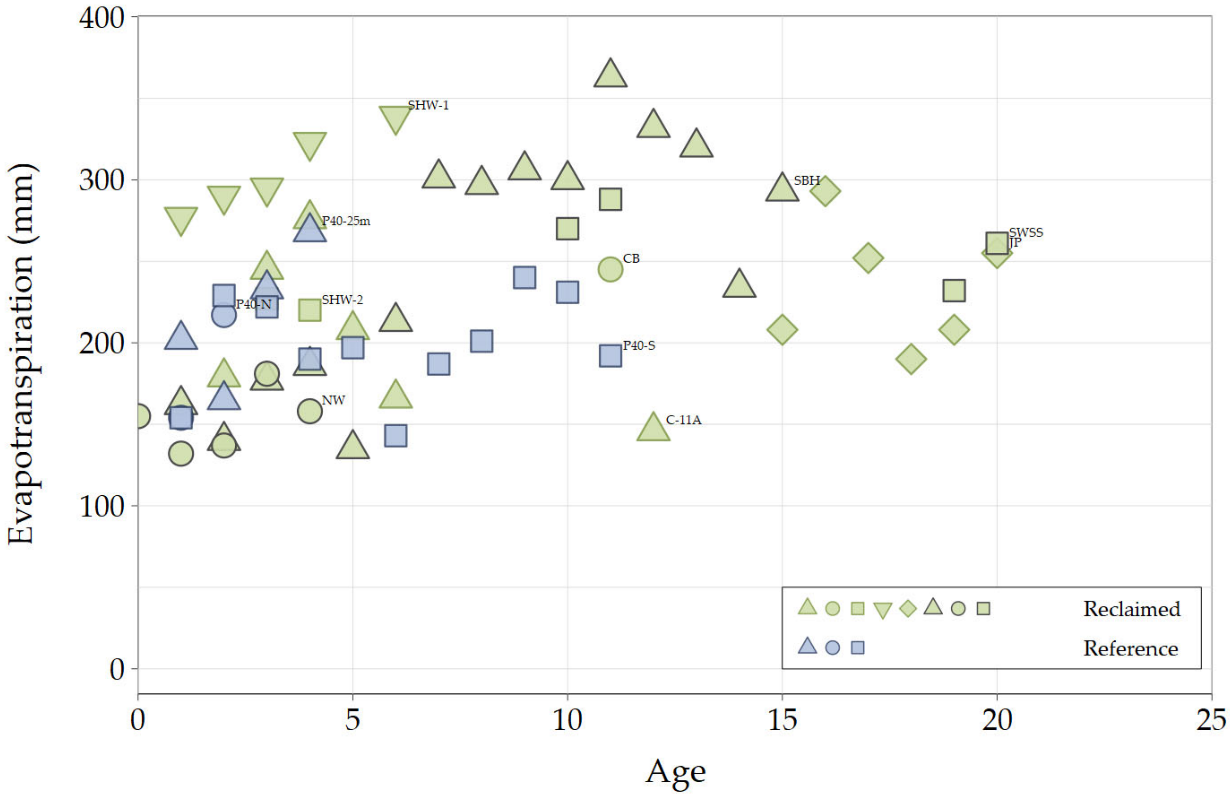

Figure 2. JJA actual evapotranspiration by site age. Sites are identified as reclaimed or reference sites. Short-form site labels are placed next to symbols for the last year of data collection.

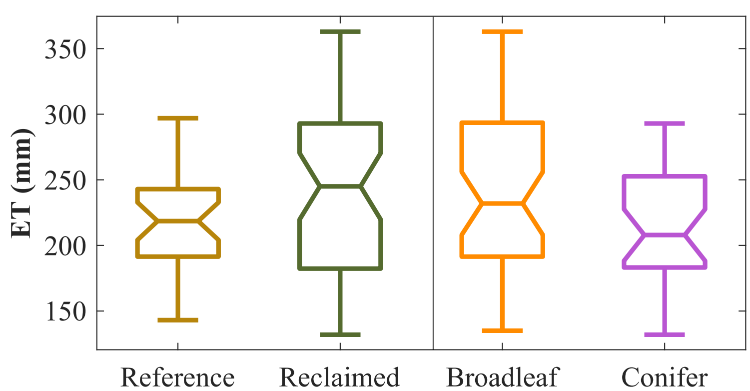

Figure 3. June-August actual evapotranspiration (mm) for reference-reclaimed and broadleaf-conifer paired groupings. The median value horizontally bisects the boxplot, the box edges are the percentiles (upper = 75th and lower = 25th), the whiskers extend to the extreme data points. There was no significant difference between paired groupings (Mann-Whitney U-Test; $p<0.05$).

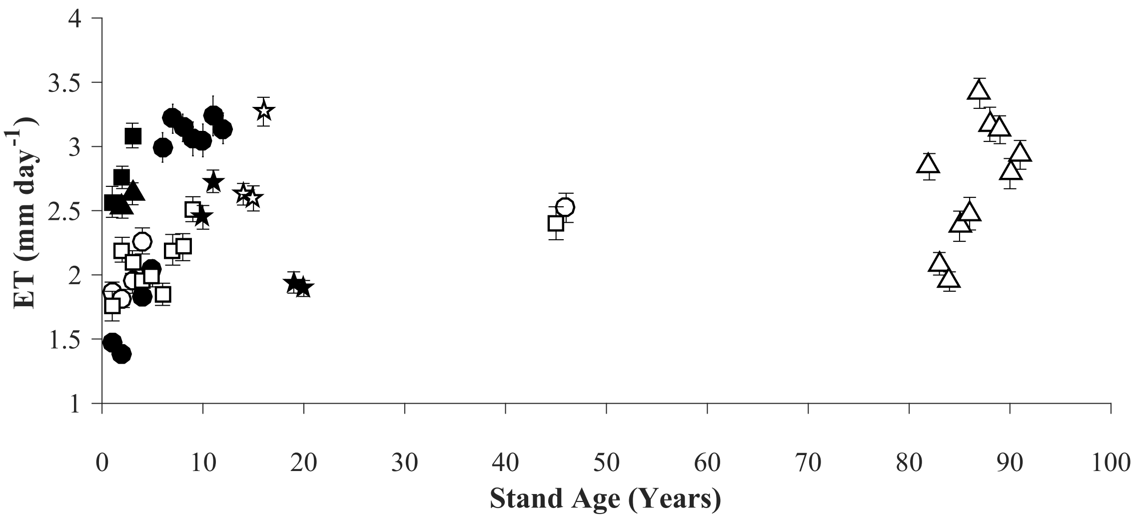

Figure 4. June-August evapotranspiration rate versus stand age. Reclaimed sites in black (SHW-2 – ▲, SHW-1 – ■, SBH – ●, SWSS – ★) while reference sites are grey and open-faced (REC1 – ○, REC2 – □, OA – △, WB – ☆).[10]

5.1.2. Ecosystem productivity

From an ecosystem perspective, productivity and carbon sequestration typically increase as an ecosystem develops, rapidly at first and then reaching a maximum rate with potential decline post maturity. Using the EC-derived GEP and NEP values for reclamation and reference sites, it is evident that both gross and net ecosystem production increase following reclamation in a general logarithmic fashion (Figures 5, 6). As vegetation establishes, primary productivity increases, and JJA NEP becomes positive as photosynthetic production exceeds ecosystem respiration, which is typically high post-disturbance. Note that differences in vegetation and other reclamation practice factors influence the rate at which GEP and NEP increase. Again, within approximately 10 years, reclaimed forests have GEP and NEP within a range of expected productivity during this early growing trajectory (Figures 5, 6).

[10] "OA" and "WB" are the Old Aspen and Western Boreal AmeriFlux sites.

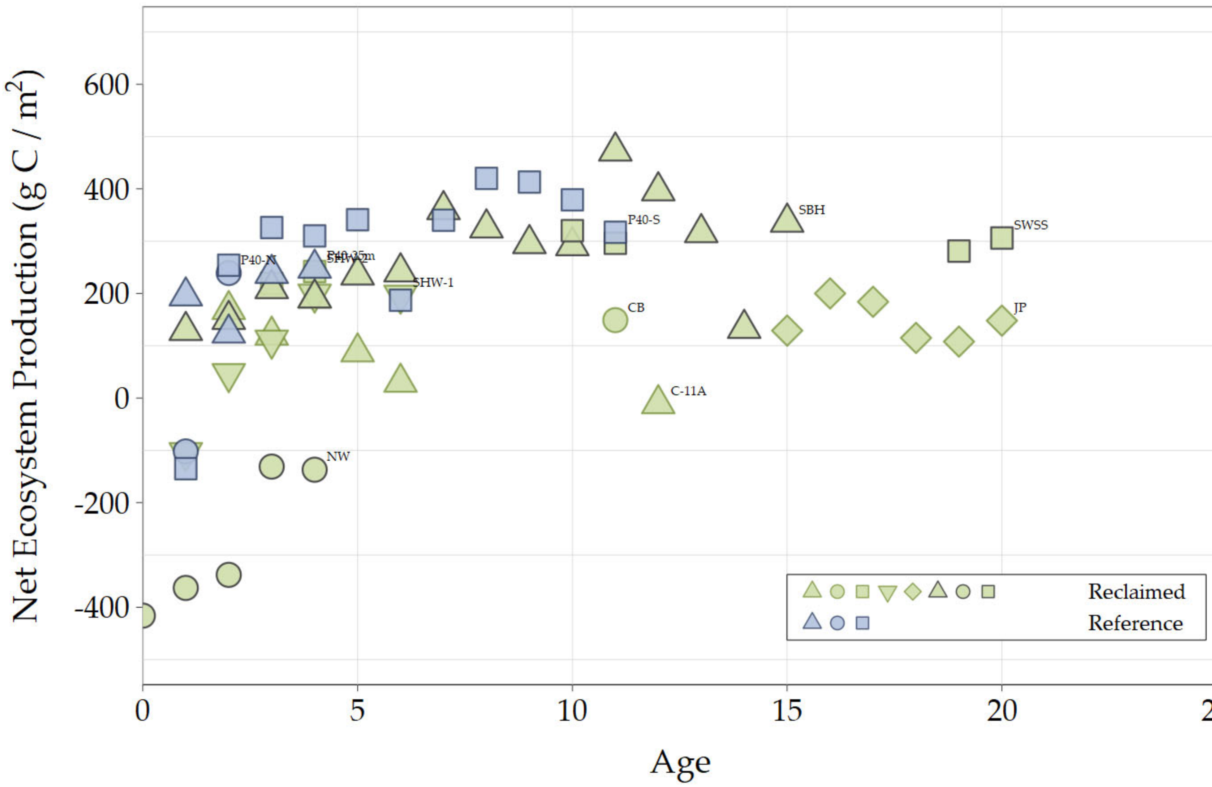

Figure 5. JJA net ecosystem productivity by site age. Sites are identified as reclaimed or reference. Short-form site labels are placed next to symbols for the last year of data collection.

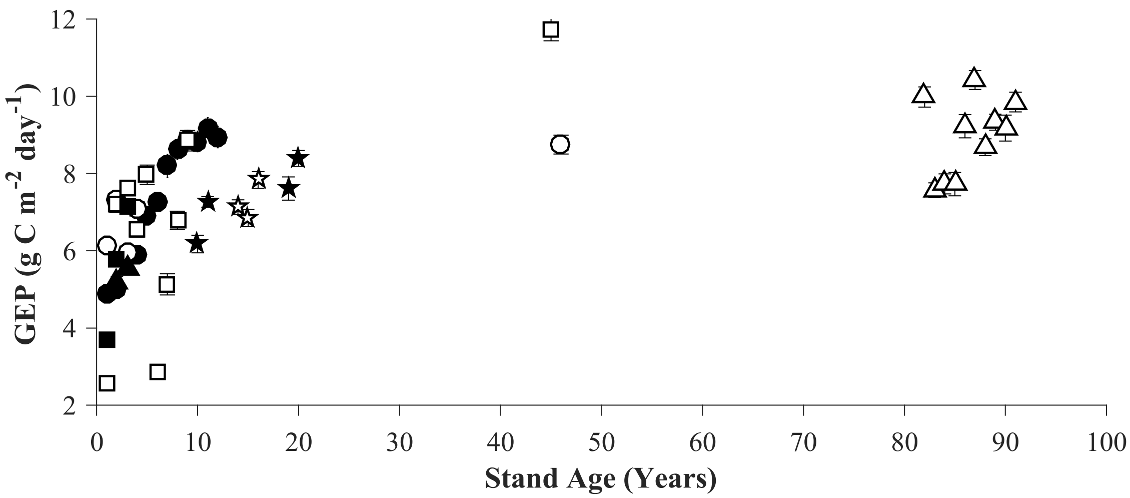

Figure 6. Chronosequence graphs of average daily June-August gross ecosystem productivity (GEP, g C m^{-2} day^{-1}). Symbols are described in Figure 4.

There is a wide range of natural variability of boreal forest sites for GEP and NEP (~ 1000 g C m^{-2} per growing season). Grouping sites by reference versus reclaimed suggests that there is no difference in GEP and NEP between these two data sets, although reference sites have a much greater variability in GEP than reclaimed sites. In contrast, when grouping sites by conifer versus broadleaf, there is a significant difference between groups (Figure 7). Broadleaf forests measured in this study have a greater GEP and NEP than conifers, a finding which has been reported elsewhere in the literature (Brümmer et al., 2012). Interesting differences exist in relative rates of increase in GEP in NEP between broadleaf and conifer reference and reclaimed stands (Figure 8). Reclaimed broadleaf forest GEP continues to increase over the same age range relative to the (regenerating) reference sites, which is due to the fact that the dominant broadleaf species are aspen. Clonal species such as aspen that are harvested and regenerating (as is the case with the young reference sites) do not require the early growth resources for root establishment, which the young reclaimed stands do (Tullus et al. 2007; Rytter, 2006). Further, the higher uptake rates on reclaimed sites are balanced by larger soil respiration leading to NEP values are that are more similar between the reclaimed and reference stands (Figure 8).

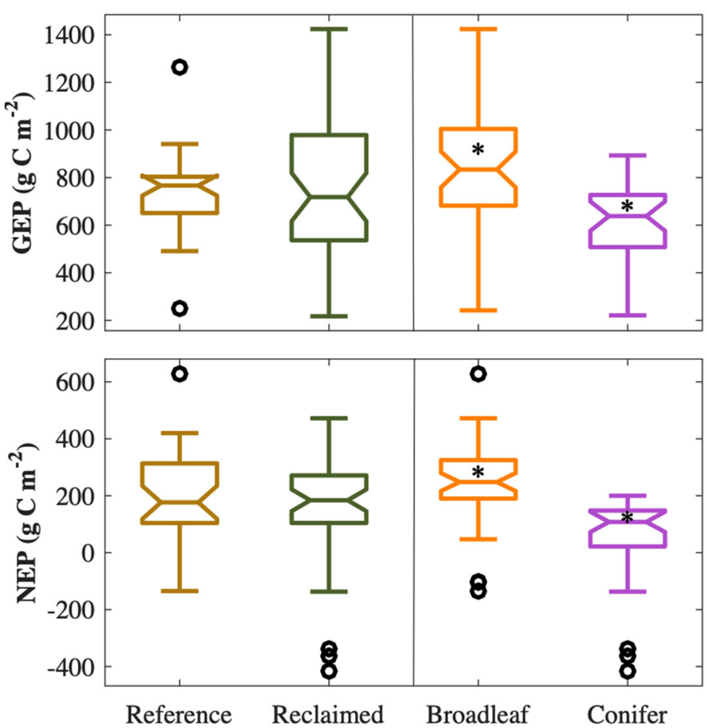

Figure 7. June-August gross ecosystem productivity (GEP, top), and net ecosystem productivity (NEP, bottom) for reference-reclaimed and broadleaf-conifer paired groups from the data set. The median value horizontally bisects the boxplot, the box edges are the percentiles (upper = 75th and lower = 25th), the intervals are the notches, the whiskers are the extreme values and the ◦ are the outliers (determined as more than three scaled median absolute deviations away from the median). Significant differences between the broadleaf and conifer paired groupings for GEP and NEP (Mann-Whitney U-Test; $p < 0.05$) are indicated with an asterisk (*).

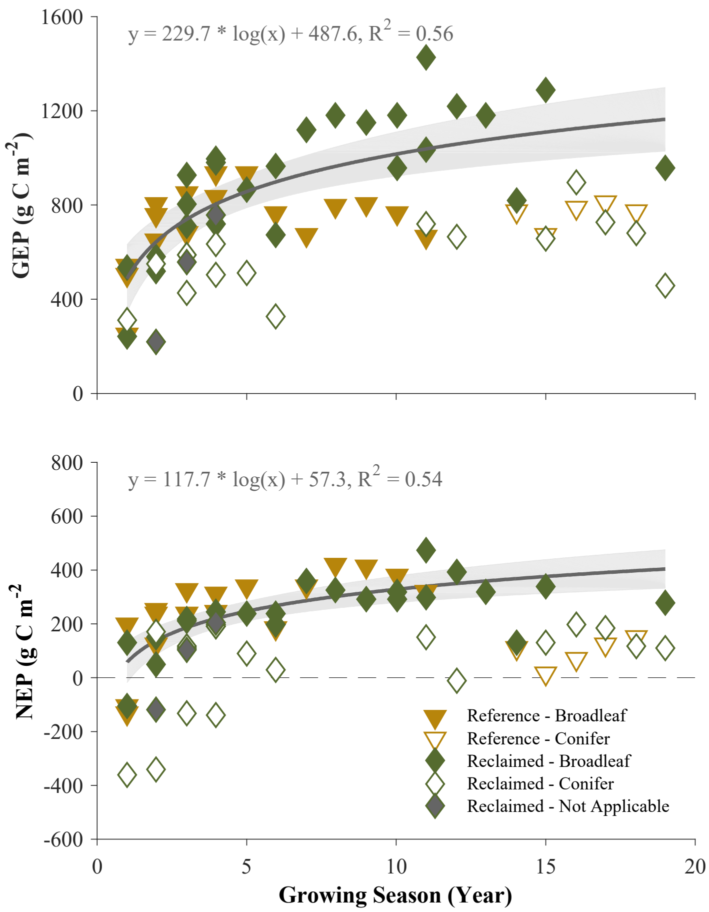

Figure 8. June-August GEP (top) and NEP (bottom) for young reference and reclaimed sites (< 20 years of age). The logarithmic curves (dark grey line), 95% confidence interval ranges for the curves (light grey shaded area), and affiliated equations (grey text) are fit to sites with broadleaf trees (trembling aspen or balsam poplar). The Sandhill Watershed lowland site, which did not have a dominant tree cover identified in the data set, is categorized as "Reclaimed – Not Applicable".

4.2 Non-flux biometrics

4.2.1 LAI

Trajectories of LAI development (a non-flux biometric) are presented in Figure 9. These data show patterns similar to those observed for AET and ecosystem productivity, with a range of LAI values for reclaimed ecosystems, both higher and lower than observed in reference ecosystems. The CEMA reference site, a mature, jack-pine a1 (Beckingham and Archibald, 1996) stand (not in Figure 9) has an LAI of 2.6, which is similar to those measured for the lowest, and younger, reclaimed sites.

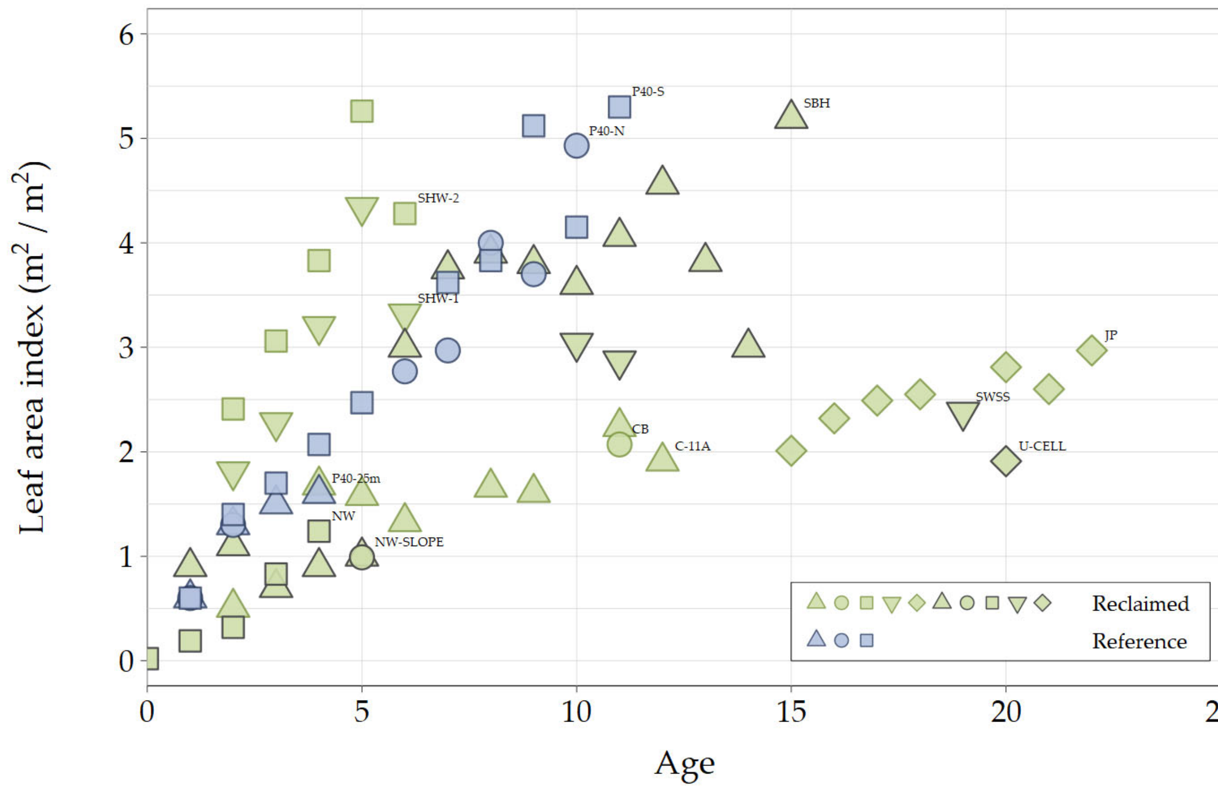

Figure 9. Leaf-area index by study site age. Sites are identified as reclaimed or reference. Short-form site labels are placed next to symbols for the last year of data collection.

4.2.2 Site index

Site-index values for sites of sufficient age to provide a reliable estimate of site index and which have at least one of the major local tree species (Aw, Sw, Pj) are shown in Table 6. fortunately, at this time interpretations based on these data are limited by the small number of sites that are old enough for site-index measurement and have a common species for comparison.

Table 6. Site index values for aspen (Aw), white spruce (Sw) and jack pine (Pj) at all sites with trees of sufficient size and age for assessment.

	Site index (m)		
Site	**Aw**	**Sw**	**Pj**
C-11A	-	-	15.5
CB	-	19.9	-
CEMA	-	-	12.6
JP	-	-	15.6
P43-N	20.3	-	-
P43-S	19.4	-	-
SBH	23.2	22.4	-
SWSS	22.2	-	-

4.3 Relationships between fluxes and non-flux biometrics

We evaluated a number of non-flux biometrics for correlation with flux measures (Appendix F), and found that total LAI[11] consistently shows strong correlations with both carbon and water fluxes using a relatively large sample size among study metrics, and has the advantage of being capable of application across a wider range of vegetation types than just forest stands[12]. These relationships are shown in Figure 10 for AET and Figure 11 for NEP, and show increasing measured fluxes with increasing LAI values. The fitted line indicates that JJA AET increases by approximately 30 mm for each additional unit of LAI. The apparent relationship of NEP to LAI is a more complex curvilinear (logarithmic) fit, with NEP increasing rapidly as the first unit of LAI develops, and declining incremental increase with additional LAI. There is variation around these fit lines, due in part to seasonal climatic variation that is not accounted for in the fit models. Nevertheless, we believe that application of these models (and models of LAI-age trajectories by site type based on data in Table 4) to estimation of water and carbon fluxes on the reclaimed landscape would enable relatively accurate annual carbon and water flux estimates to be made with minimal data inputs, which should be obtainable from LAI measurements (potentially including remote estimates of LAI), and from soil data from standard reclamation surveys (e.g., post-construction soil surveys).

[11] LAI measurements taken at or near ground-height. Strong relationships with fluxes were seen using both IEG's total LAI values and the broader dataset of standardized LAI values (Appendix C).

[12] Other non-flux variables also show relationships with flux measures, or have the potential to (as detailed in Appendix F). For instance, both Wilson's Spacing Factor (a variable related to the ratio of stand density and stand height) and total vegetation cover (estimated by a botanist) show significant relationships with NEP. However, these relationships are based on substantially fewer data points than the LAI relationships, and thus are not as robustly tested, and are subject to leverage from a relatively small number of data points at either extreme of a data range. In addition, we expect that site index, a measure of the potential tree productivity of a site, will show relationships with the 'plateau' flux measures for sites having reached maximum LAI. However, at this time, because (i) site index requires a minimum tree age for reliable estimation and (ii) few sites have reached a point where plateau fluxes can be estimated, there are not enough site-index data points in this study to meaningfully evaluate these relationships.

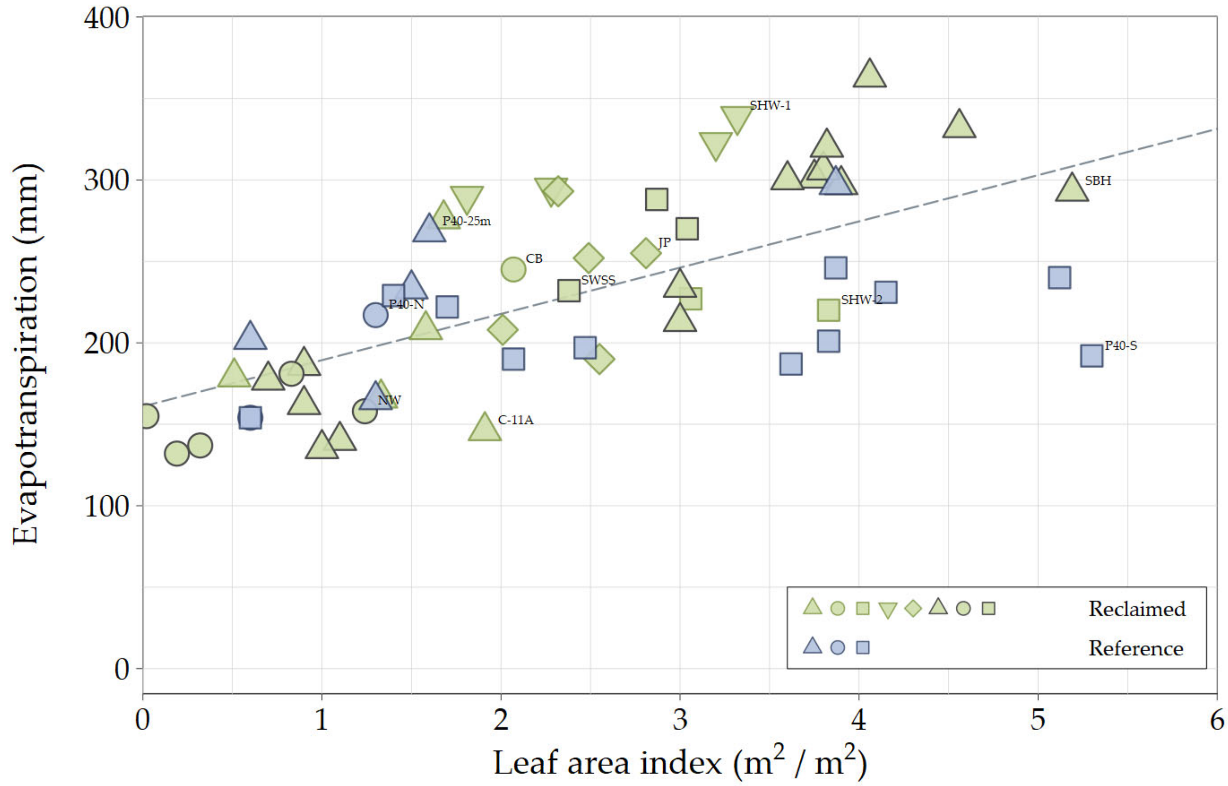

Figure 10. JJA actual evapotranspiration by leaf-area index for study sites. Sites are identified as reclaimed or reference. Short-form site labels are placed next to symbols for the last year of data collection. Dashed line shows the linear fit between variables.

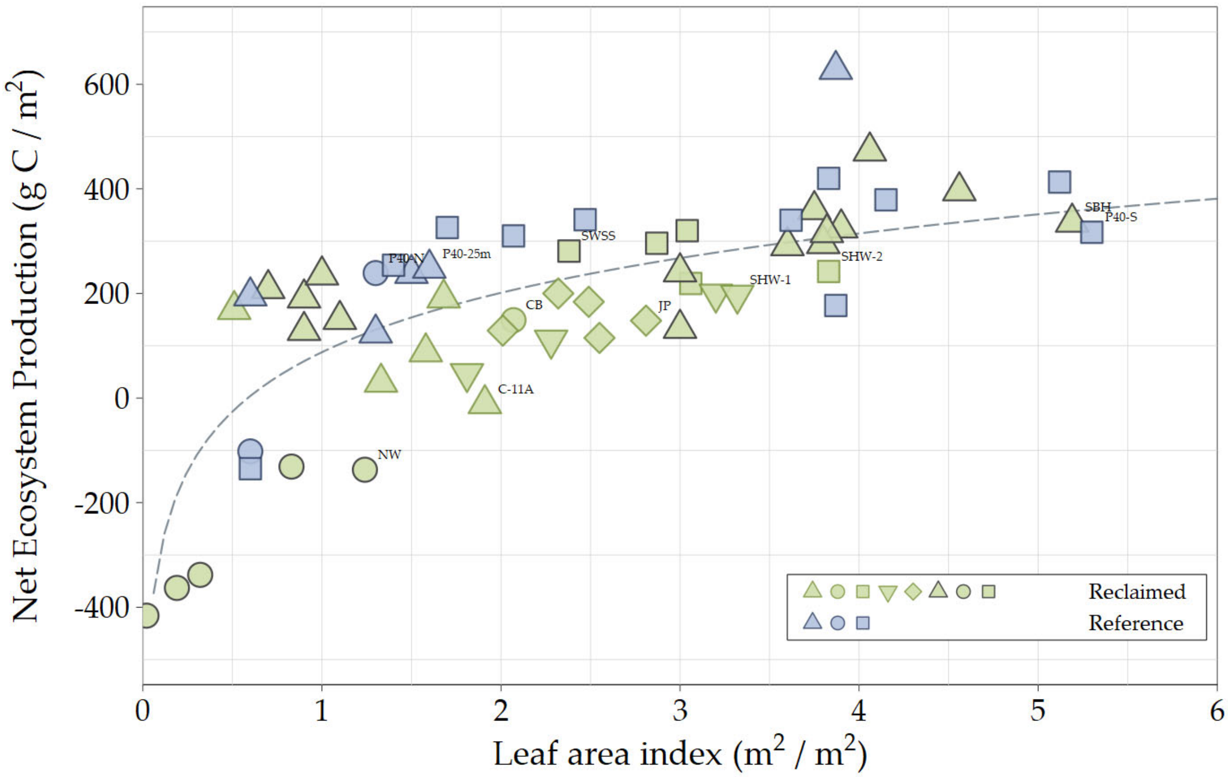

Figure 11. JJA net ecosystem production by leaf-area index for study sites. Sites are identified as reclaimed or reference. Short-form site labels are placed next to symbols for the last year of data collection. Dashed line shows the curvilinear (logarithmic) fit between variables.

5. DISCUSSION OF KEY QUESTIONS AND FINDINGS

We synthesized findings from the current research program and previous related work to address three key issues:

1. equivalency between reclaimed and reference sites of water storage and water use, and carbon assimilation;
2. temporal aspects of ecosystem recovery trajectories from mining and forestry disturbances; and
3. relationships between water/carbon fluxes and non-flux biometrics.

We discuss these topics below, highlight their importance to industry, and provide ideas for next steps in this program.

5.1 Equivalency of water storage and use, and carbon assimilation

Synthesis:

- **Water storage and use in sampled reclaimed uplands is equivalent to or exceeds that of sampled reference-site uplands.**

- **Net carbon assimilation in sampled reclaimed uplands is equivalent to or exceeds that of reference-site uplands.**
- **Equivalency in ecosystem function as indicated by water use and carbon assimilation can be measured using a small number of metrics.**
- **Amount of measured evapotranspiration and carbon assimilation in sampled reclaimed ecosystems is related to the capacity of reclamation cover systems to store water and release it for ecosystem use, as well as to climatic variation.**
- **Due to high water-storage capacity in sampled reclamation cover systems with high organic-matter contents and finer mineral-fraction textures, resulting upland forests are only moderately constrained to unconstrained in their use of water and assimilation of carbon in average years.**
- **Storage and use of large amounts of water by reclaimed upland ecosystems with typical reclamation cover systems suggests that the potential for generation of runoff in these systems is very low. Empirical evidence here supports previous simulations that these systems release little water for use by downstream ecosystems.**
- **Generation of surplus water from reclaimed uplands for landscape-scale ecosystem function would require deviation from current reclamation practice.**
- **We have not observed "reclamation failures" in this research, and cannot identify plausible edaphic mechanisms that would cause failure based on water availability and given current reclamation practice. The only currently identified failure mode relates to lack of achievement of ecosystem diversity based on inadequate replacement of xeric ecosystems and associated generation of runoff (P – ET > 0).**

Limitations:

- **Although the number of site-years of data in this study is unprecedented in research of this kind, the number of sites in the study is low. We have not fully described ranges of natural variation, particularly for drier sites, and have not studied existing sites over the full range of climate variability.**

Our synthesis of study data (fluxes and cover characteristics) based on general trends in vertical water-balance components and the ASMR classification reported by Pojar et al. (1987) shows that reclaimed sites range from having on average little to no constraint on evapotranspiration (Syncrude's Sandhill upland sites and South Bison Hill, and Suncor's Nikanotee side slopes) to moderate constraints (Syncrude's Coke Beach, U-Cell, Southwest Sand Storage, and Jack Pine sites, and Suncor's Cell 11A and Nikanotee upland). The South Bison Hill site is very close to the Slightly Dry-Fresh threshold (Table 4), and in an average climate year experiences a very small water deficit, with relatively little constraint on AET (i.e., mean JJA AET for SBH over the period 2009-2017 is 305 mm, while PET is 316 mm). 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 URSA 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, the CEMA jack pine-lichen a ecosite, has substantially constrained vegetation community composition and growth due to water limitations.

An initial exploration of implications of these site characteristics for site water balances (e.g., parameters such as site runoff in average climate years, and the proportion of years with the potential to produce runoff) is presented in Appendix E.

All study 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, as shown in Figure 12 (same data as Figure 2 but with sites identified by ASMR). 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 JJA 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 South Bison Hill site generally having AET ≥ 300 mm (Figure 12).

Our data suggest that water use by Reclaimed – Fresh ecosystems in this study is equal to or exceeds that of Reference – Fresh ecosystems in the study, with growing-season AET approximately 50 mm higher on reclaimed sites than on reference sites at equivalent ages and stand types. This observation is consistent with the interpretation that Reclaimed – Fresh study sites generally have higher AWSC than the Reference – Fresh study sites, due largely to the high water-storage of peat-mineral mixes in reclamation (Appendix D).

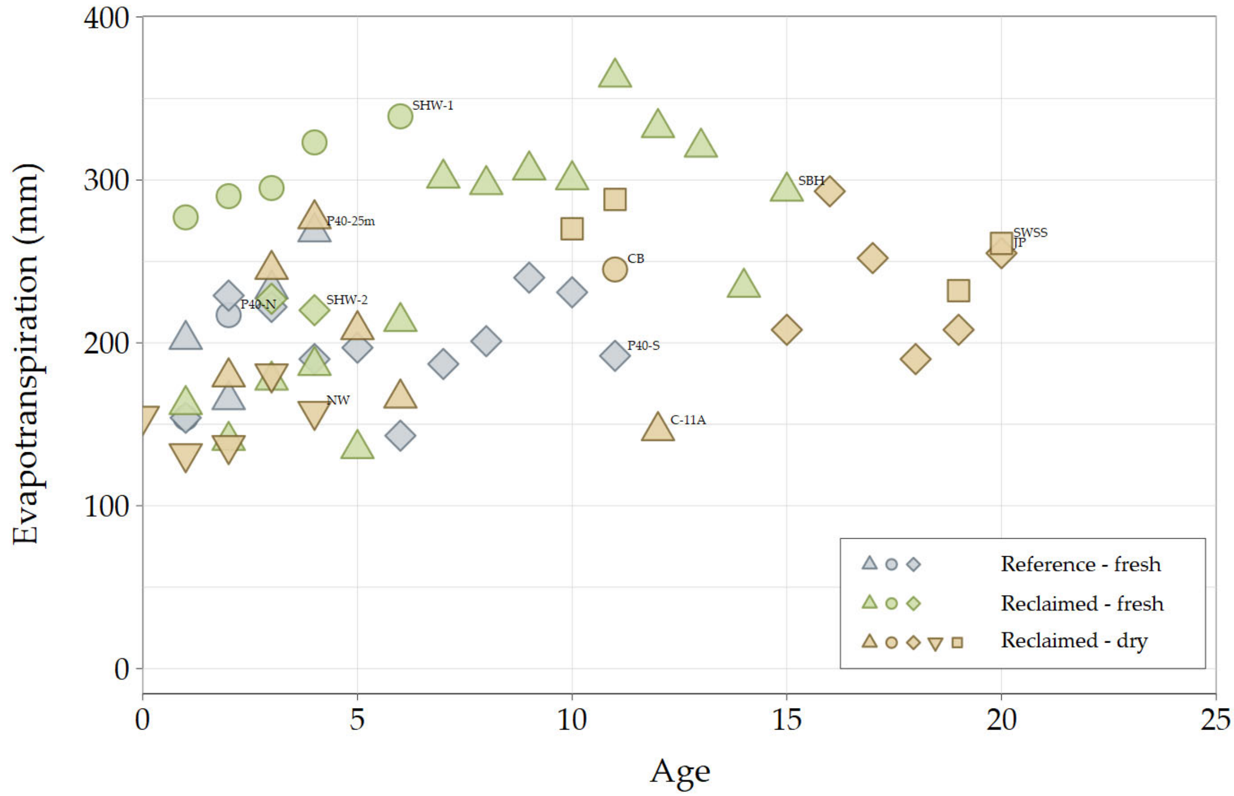

Figure 12. JJA actual evapotranspiration by site age. Sites are grouped by category (Table 5), with each site identified by a different symbol in its category. Short-form site labels are placed next to symbols for the last year of data collection.

5.1.1 Comparisons to natural ranges of variation: water storage and use

We used information on water storage and water use on the reference sites in this study to define preliminary 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 JJA period) for older (i.e., not immediately following disturbance) sites in this study is roughly 190–300 mm[13], 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 (Appendix D). 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.

Extending this analysis to representing the full range of conditions observed in reclamation sites is still preliminary. Data thus far suggests that we have adequately described the natural range of AWSC through inclusion of the Reference - Dry, non-instrumented CEMA Jack Pine site. However, we have not described a similar range of water use, as Reference - Dry sites are expected to have lower AET (Amiro et al., 2006) but are without flux measurements in the current study.

5.1.2 Comparisons to natural ranges of variation: carbon assimilation

Comparison of NEP on reclaimed and reference study sites is provided in Figure 13 (same data as Figure 5 but stratified by ASMR class). These data show that older Reclaimed – Fresh sites have JJA 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.

[13] Data from the older (pre-harvest) P40 reference site at URSA, not shown in Figure 2.

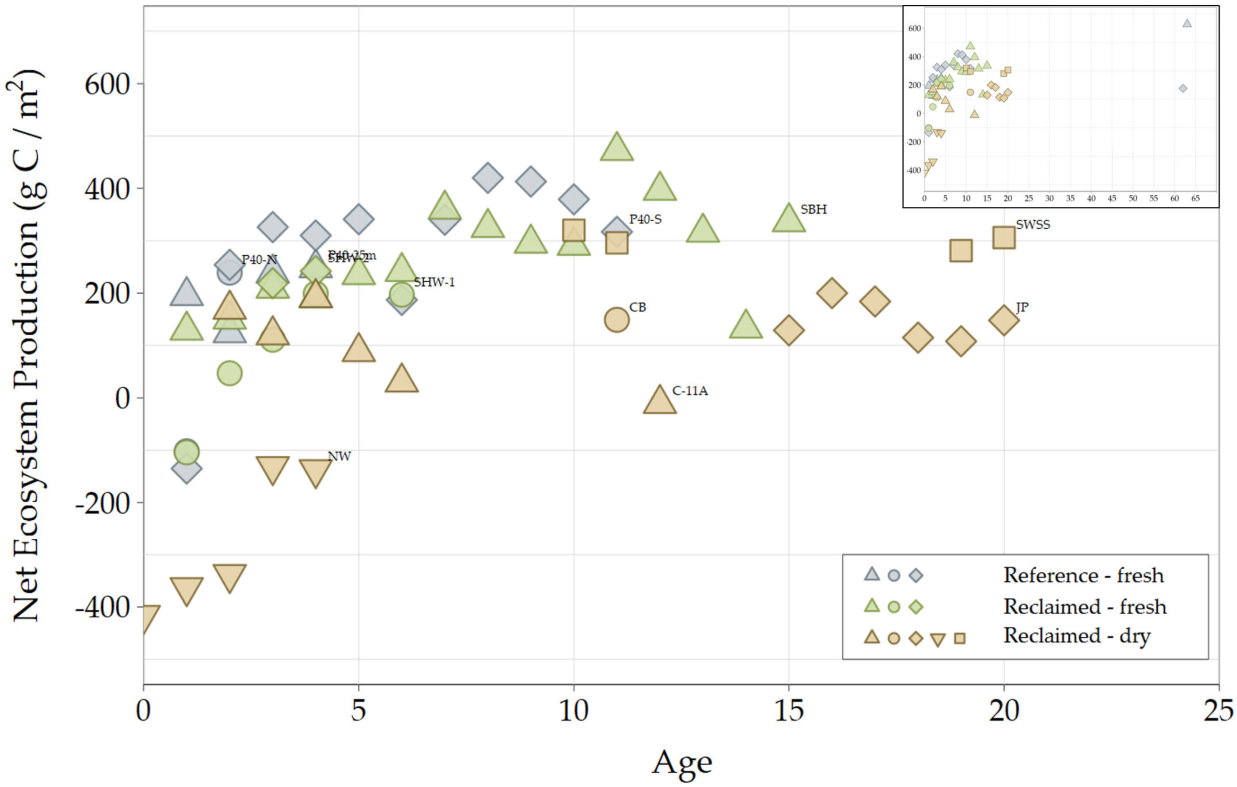

Figure 13. JJA net ecosystem production (total) by site age. Sites under 25 years are on the main graph; the inset also includes data from pre-harvest years at P40. Sites are grouped by category (Table 5), with each site identified by a different symbol in its category. Short-form site labels are placed next to symbols for the last year of data collection.

5.1.3 Possibility of reclamation failure, or creation of non-equivalent conditions

Reclamation failure could be broadly defined as a failure to establish functioning vegetated ecosystems on reclaimed sites capable of supporting one or more desired end land uses. There is no evidence in our research of any edaphic conditions or ecosystem processes that could plausibly lead to this kind of failure given current reclamation practices. Historic reclamation practices and operating-approval conditions have resulted in the construction of reclamation covers that store ample water for ecosystem use, and do not approach the dry end of the range of natural variation for storage (see Appendix D for detailed discussion). It would not be possible given current practices and approvals to create a site as dry as the Very Dry CEMA reference site, without the use of a cover consisting primarily of salvaged coarse glaciofluvial sands. All mine wastes (even separated coarser tailings, which are dominated by medium and fine sand[14]) and cover materials store substantially more plant-available water than these glaciofluvial sands; construction of a cover with ≤ 20 mm of storage (like the CEMA reference site) would require placement of approximately 25 cm of tailings or 15 cm of mineral secondary materials over an impermeable, root-restricting layer or coke. To our knowledge, practices like this are not currently contemplated by any operators.

The only possible failure mode suggested by our research is the "failure" of reclamation covers – as mandated by operating approvals and currently used – to support development of xeric ecosystems within the range of natural variation of the boreal forest. This may not be important in itself, as these ecosystems are relatively rare, but it has implications for broader landscape-scale reclamation. These low-storage, xeric uplands are the only ecosystems capable of consistently generating substantial runoff and groundwater recharge, while the higher-storage mesic ecosystems utilize the majority of the water balance in an internal storage-and-evapotranspiration cycle, making little water available for downstream ecosystems. Reconstruction of low-storage uplands as a component of reclamation would require either placement of thinner cover systems than are currently used by operators or permitted by operating approvals, or use of coarser-textured reclamation covers (e.g. glaciofluvial deposits) than were present at sampled sites.

5.2 Reclamation recovery trajectories

Synthesis:

- **AET, NEP, and LAI are key indicators used in this study of performance and developmental trajectories of reclaimed ecosystems.**
- **Our research shows that these indicators reach a climate-mediated quasi-steady state by approximately 10-20 years following initial revegetation, and can be reliably used within this window to provide information on expected longer-term values.**
- **This assessment window is consistent with other mandated evaluation approaches such as the Alberta Regeneration Standards for the Mineable Oil Sands.**
- **There is no evidence nor are there hypothesized processes that would suggest that longer monitoring periods are necessary on a routine basis to provide reliable**

[14] A further discussion on sand size and soil water storage for tailings and natural soils is presented in Appendix D.

information on the functional processes of water use, carbon assimilation, and plant-cover development.

Development trajectories of AET and NEP were presented in Figure 12 and Figure 13. These data show that both AET and NEP in reclaimed systems – based primarily on trajectories from the Syncrude South Bison Hill and Jack Pine sites – reach quasi-steady states by approximately year 10. Differences after this age are largely or wholly due to climatic variation. Strilesky et al. (2017) report that the South Bison Hill reclaimed site after approximately 10 years of growth has water-use and carbon dynamics that have stabilized to values comparable to those observed in other boreal-forest landscapes across a range of ages. For AET, it is not possible that the Slightly Dry and Fresh sites could move towards significantly higher values over time, as these sites are already using almost all available water (AWSC plus growing-season P) in an average climate year, and have already evolved to the climatic limits of the regional bioclimate system.

Trajectories of LAI development are presented in Figure 14 (same data as Figure 9 but stratified by ASMR class). These data show patterns similar to those observed for AET and NEP, with LAI values similar between Reference – Fresh and Reclaimed – Fresh ecosystems, and lower values for Reclaimed – Dry ecosystems. The Very Dry CEMA reference site, a mature, xeric RSMR, jack-pine a1 stand (not in Figure 14) has an LAI of 2.6, which is similar to those measured for the younger Reclaimed – Dry sites.

LAI for the Reclaimed – Dry sites appears to have reached a quasi-steady state of roughly 2.4–3.2 after age 10, while values for the Reclaimed – Fresh (South Bison Hill) site after this age are roughly 3.0–5.2. It is difficult to determine whether in fact the Reference - Fresh sites have reached a quasi-steady state for LAI after age 10, as the 2017 value for the P40S site (the oldest young reference site) is very early in this age range, and was the highest LAI observed to date on this site, at 5.3. The mature URSA reference sites range from 3.7–3.9, suggesting that LAI values decline in Reference – Fresh aspen stands as these stands age, which is consistent with literature showing Alberta aspen stand LAI values plateau between roughly 18 and 45 years of age and decline thereafter (Huang et al., 2013).

Data for all key study metrics – AET, NEP, and LAI – strongly suggest that data representative of longer-term conditions in these stands can be reliably collected within the 11-20-year period following revegetation window. This timeframe is consistent with the provincial performance-survey assessment window for re-establishment of forest stands on reclaimed sites (AESRD, 2013a). There is no evidence to support the conjecture that longer time periods may be needed to evaluate ecosystem function and performance on these sites with respect to water use, carbon assimilation, and development of plant cover.

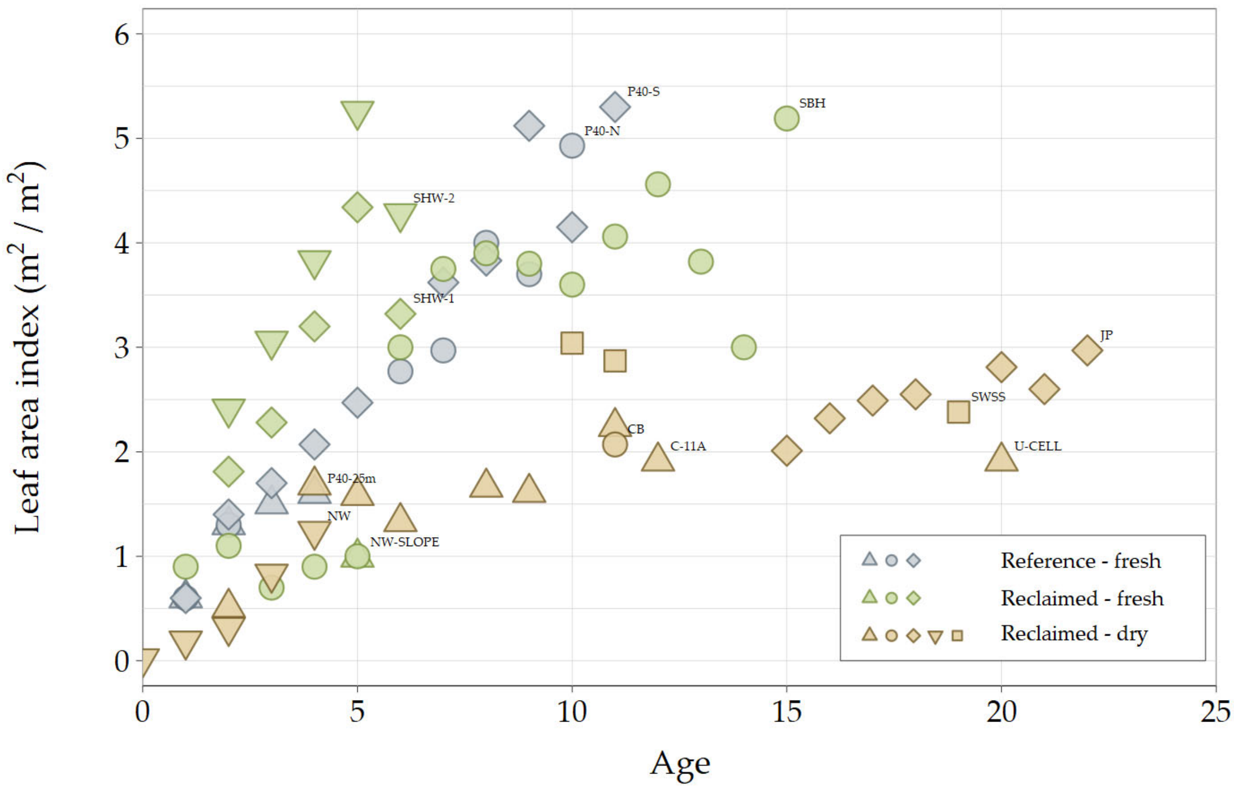

Figure 14. Leaf-area index by study site age. Sites are grouped by category (Table 3), with each site identified by a different symbol in its category. Short-form site labels are placed next to symbols for the last year of data collection.

5.3 Relationships between fluxes and non-flux biometrics

Synthesis:

- **AET and NEP show positive relationships to LAI.**
- **These relationships provide the basis for a quantified estimation of fluxes on non-instrumented sites, given measurements or projections of LAI.**

In Section 6.1, we explored the relationships between ASMR and water/carbon fluxes, and showed that both fluxes appear to be influenced by the ability of soils and reclamation-cover systems to store water and make it available for plant use. A fourth indicator variable in 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.

Our approach to using LAI as an indicator of water and carbon fluxes is supported in other scientific literature. Across 18 Canadian forests representing 80 site-years of flux data, LAI was found to be the best stand characteristic to predict NEP and GEP, accounting for 66% and 80% of variation, respectively (Zha et al., 2013). This is similar to Reich's (2012) finding that 75% of NEP variation in northern USA (MN, WI) conifer and deciduous stands can be explained by LAI. Other significant C flux correlates identified by that study were mean annual air temperature, mean annual precipitation, and total soil nitrogen in the upper 10-cm of mineral soil. The lack of correlation seen with these variables in our study can be attributed to the greater geographic range among Zha et al.'s study sites (i.e., coastal BC to northern boreal), while our study contains too narrow a range of conditions to detect similar effects. Canopy LAI was found to be the dominant control on annual NEP in a boreal aspen stand (Barr et al., 2004a). Huang et al. (2011) link the concept of 'maximum sustainable LAI' for oilsands reclamation sites to soil water balances and relies upon equations that use LAI to estimate NEP and AET (see Appendix F for a graphical comparison with our dataset). LAI is frequently used to estimate AET in remote-sensing modelling (e.g., Lui et al., 2013), but recent research indicates that species traits and site conditions (e.g. tree canopy cover) should be considered to increase modelling accuracy (Lauiainen et al., 2016). Another important factor for predicting annual water and C fluxes is growing-season length (Barr et al., 2004a; Ueyama et al., 2013), which is partly controlled for in the current study by confining measurements to the JJA period.

6. NEXT STEPS

Synthesis:

- **The current research was designed as a "proof of concept" study, and has demonstrated that ecosystem fluxes can be linked to non-flux biometrics, and that these indicators can be used to provide key information on ecosystem function and reclamation performance.**
- **We believe that this work can be further developed to improve our core understanding, to address landscape-scale water and carbon balances for reclaimed mine sites, and to reliably apply findings to non-instrumented sites through the use of non-flux biometrics and reclamation-cover characteristics. Specifically, we believe**

our research can be further developed to generate water-balance information (P-E runoff envelopes) and carbon-balance estimates for all representative landscape units in the Fort McMurray region.

In this research, we used a range of reclaimed, natural and disturbed forested sites to develop initial approaches for linking ecosystem fluxes to other biometric measurements. To date, we have provided preliminary evidence that EC measurements of water and carbon flux coupled with simple measurements (e.g., soil water characteristics, LAI, vegetation species and age) can effectively fingerprint a system and where it is located on a trajectory of water use and carbon allocation. While we have discussed much of this research in this report, the results and implications of it are nascent. Fully realized, we believe that this research will enable industry to effectively scale the detailed hydrological and flux measurements conducted at the intensive sites outlined in this report to other reclaimed systems without such measurements, using more widely deployable biometric measurements.

Below we outline areas for further development of this research.

6.1 Develop methods to apply study findings across the reclaimed landscape

Our work to date has demonstrated that LAI has an initially linear asymptotic relationship with AET, and that LAI determines ranges of possible AET that are ultimately influenced by annual climatic variation. Trajectories of LAI and flux development are also partially controlled by the ability of reclamation-cover systems to store and release water for ecosystem use, which can be approximated by an ASMR approach. Use of LAI and ASMR support the following approaches to landscape-level assessment and design/modelling:

i. LAI is more readily widely measured – potentially through remote-sensing techniques – than eddy-covariance fluxes. Use of LAI-flux relationships thus allows flux terms to be assigned to any area for which LAI can be measured or estimated/projected.

ii. ASMR can be determined for a built or planned reclamation landscape, given information on topography and cover characteristics. LAI trajectories can then be assigned based on ASMR (e.g., Figure 14), to allow modelling of LAI development on both existing and planned reclamation areas. This approach, linked with the LAI-flux relationships, is the basis of a site-wide model for water and carbon balances.

Based on this approach, there is strong potential to further develop relationships between LAI, ASMR, and fluxes to extrapolate learnings from a small number of relatively expensive instrumented sites to all reclaimed upland sites using either (i) simple, relatively inexpensive and repeatable field measures or (ii) remote sensing data such as that from LiDAR programs. The goals of this work would be to support the ability to assign defensible water and carbon balance values to every existing or planned reclamation polygon, and to discuss how resulting values can be applied for closure landscape design, site-wide water-balance modeling (e.g., Huang et al., 2011), site-wide carbon-balance modeling, and potentially other applications.

6.2 Refine functional assessment framework and expand network

Our work in this study has allowed us to define trajectories for evapotranspiration and NEP within a broad envelope based on moisture class, stand age and type. However, the lack of representation of certain ecosystem types (e.g. dry jack pine, white spruce, wet lowland forests) in a variable climate presents limitations. It is evident that to test the robustness of our approach, additional sites are required in the analysis, and particularly sites that are: (i) more representative of drier, less productive ecosystems; and (ii) influenced by the presence of growing-season groundwater in wet lowland positions. For example, Cell 11A and Coke Beach, which were (re)instrumented in 2017, provided important information for drier soils and conifer species. Installation of additional sites would further extend our studied range in site conditions, and allow us to derive relationships that are as robust as possible for the range in potential conditions encountered in reclamation.

In addition to the new instrumented sites, it would be beneficial to also expand studies on non-instrumented sites to allow further definition of the trajectories of LAI development over time on sites with a wide range of AWSC values and ASMR. We believe these attributes exert a strong influence on developmental trajectories of LAI, AET and NEP over time (Figures 12, 13, and 14), and quantifying these effects would be useful for predicting AET and NEP in a closure planning context where vegetation does not yet exist but generalized soil attributes can be reasonably inferred .

6.3 Fingerprint ecosystem water use along environmental gradients

The long-term success of ecosystems along an environmental gradient requires an understanding of the landscape-scale water balance. While there is considerable knowledge of natural analogue systems from HEAD (Hydrology, Ecology And Disturbance) and other programs, the vertical versus lateral partitioning of water in reclaimed landscapes requires careful consideration of all hydrological fluxes combined with a knowledge as to how these fluxes will change with ecosystem development and a variable climate. Considering that the greatest variability in water balance is the difference between precipitation (in both rain and snow) and evapotranspiration (based on species type, stage of growth and moisture stress), ongoing and expanded networks of eddy covariance stations targeting representative ecosystems would provide the necessary data for landscape-scale planning and assessment throughout the closure lifecycle.[15] The single largest unknown in driving closure water-balance/groundwater models is the "upper boundary" (P-E), which in turn governs water yield from ecosystems, as future weather/climate can be adequately represented in predictive models. Another way of stating this is that:

1. water yield from terrestrial ecosystems is the difference between P and AET;
2. estimates of AET in water models are typically modelled from climate data rather than based on empirical measurements, and insensitive to soil and vegetation types and stages of vegetation development; and
3. given that water yield is a relatively small number relative to P, a large uncertainty in AET leads to a large uncertainty in water yield.

We believe that our approach has the potential to substantially reduce this uncertainty.

Our research to date has focused on uplands, yet lowlands (wetlands and end-pit lakes) rely in part on delivery of water from up-gradient systems, and during dry periods may supply water to upland landscapes. There are eddy covariance sites at several wetlands both on and off-site in Fort McMurray and one end pit lake. It would be beneficial to bring all of these sites together to provide water balance information (P-E envelopes) for all representative landscape units in the Fort McMurray region. This work would provide time-varying envelopes, which will allow an

[15] Including the potential implications of changing climate.

empirically-driven estimate of water available for recharge/runoff. It is recognized that runoff is poorly characterized across the landscape, so it is recommended that this information be coupled with existing soil-cover data and data from regionalization studies to estimate the storage/runoff partitioning. This information will be of critical value to reclamation planning on several fronts, as it will: 1) establish differences in P-E among and within landscapes around Fort McMurray; 2) provide P-E for landscapes where this data does not exist and estimates for closure planning have high uncertainty; and 3) supply data for hydrologic models of landscape closure. To date, it is clear that this P-E upper boundary is the single greatest uncertainty in site hydrology modelling, as this modelling is largely driven by subsurface and topographic characterization and the upper boundary is 'tuned' to support hydraulic head data from piezometers and standing water. We believe that this approach has considerable risk by not explicitly treating storage and unsaturated moisture dynamics as influenced by vegetation, and direct measures of vertical fluxes and their accurate representation will dramatically improve the certainty of estimation.

6.4 Provide first-order estimates of annual CO_2 balances and their variability

Eddy covariance provides an estimate of net ecosystem production (or net ecosystem exchange, [NEE] or net primary productivity [NPP]), the difference between ecosystem productivity and respiration. While there are numerous mechanisms to measure carbon stocks in the landscape, only eddy covariance provides integrated measures of carbon loss and allocation on sub-annual timescales and can separate both the processes of respiration from photosynthetic uptake. There is considerable variability in carbon fluxes both among sites and inter-annually. To date, we have not attempted to estimate annual carbon balances, but it is a reasonably straight-forward process. There is value in providing carbon-balance estimates for different representative landscapes in the Fort McMurray region. Data from the flux towers will allow companies to more accurately account for their carbon footprint. This will also act to refute some of the misconception with respect to the carbon life cycle of oil sands mining operations.

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Appendix A. Glossary of terms

AET - actual evapotranspiration. The amount of water lost by an ecosystem via evaporation and transpiration. All AET values in this report are measured directly by EC towers, except where the maximum AET concept is explored in Section 5.1.

AWSC - plant-available water-storage capacity. The amount of water available to plants (i.e. stored between field capacity and wilting point. This is estimated in this report using methods outlined in Appendix D.

EC - eddy-covariance. The method used for making carbon and water flux measurements in this study, involving high-frequency measurements of gas concentrations and three-dimensional air movement.

GEP - gross ecosystem production. This is the total carbon assimilation for a site before loss by respiration. Respiration (R) is the difference between GEP and NEP (GEP = NEP + R), and requires an estimated value for R based on factors such as soil temperature and moisture. Due to uncertainty in the R component of GEP, NEP has been preferred for comparisons between sites.

JJA - June-July-August. The common period of analysis used for all site-years. From June 1 to August 31, inclusive.

LAI - leaf area index, one-sided leaf area per unit ground area (unitless ratio). An objective, repeatable measure of vegetation cover on a site. Suffixes are used to indicate various types of LAI measurements. If no suffix is used, then total LAI is being referred to.

LAItot - total LAI - measured at or near ground-height.

LAIc - canopy LAI - measured above most understory vegetation, approximately hip-height.

LAIu - understory LAI - calculated as the difference between LAItot and LAIc.

LAI.lab - LAI values measured by the Petrone and Carey labs, which are discussed further in Appendix C.

MJJAS - May-June-July-August-September. This period of analysis is used for some water balance analyses, such as mean soil water deficit. From May 1 to September 30, inclusive.

NEE - net ecosystem exchange. The net difference in carbon exchange between primary production (photosynthesis, fixing of carbon) and respiration (metabolism, loss of carbon). NEE is C-flux described relative to the atmosphere (positive NEE indicates carbon gained by atmosphere, lost by ecosystem). Measured directly by EC towers.

NEP - net ecosystem production. Equivalent to NEE (NEP = -NEE) but described relative to the ecosystem (positive NEP indicates a gain of carbon fixed from the atmosphere). Measured directly by EC towers.

P - precipitation.

PET - potential evapotranspiration. This is the amount of water that would be evaporated and transpired from a homogeneous vegetated surface with unlimited soil water. This is calculated using data from the EC towers.

SMR - soil moisture regime. This is a classification concept to describe the moisture supply of sites. There are two ways that the SMR concept is applied in this report:

> **RSMR** - relative soil moisture regime. Sites are classified with respect to their soil properties, slope locations, and groundwater supplies, on a relative scale uninformed by climate. In this sense, most areas should have representation in all upland RSMR classes. Upland sites can range from very xeric on soils that store little water and are located in water-shedding locations, to mesic on soils that store water well and are located in neutral to water-receiving locations. Sites with groundwater influence are classified as 'subhygric' (intermittent seeps) to 'hydric' (near-permanent saturation).
>
> **ASMR** - actual soil moisture regime. Sites are classified with reference to climate-driven water deficits and surpluses. Since climatic water deficits and surpluses are usually much larger than rooting-zone soil-water reserves, ASMR can differ greatly from region to region.

Table A-1. Classification of Actual Soil Moisture Regime, following Pojar et al., 1987.

Differentia	**Class**
Rooting-zone groundwater absent during the growing season *Water deficit occurs (soil-stored reserve water is used up and drought begins if current precipitation is insufficient for plant needs)*	
Deficit > 5 months (AET/PET ≤ 55%)	Excessively dry
Deficit > 3 months but ≤ 5 months (AET/PET ≤ 75 but > 55%)	Very dry
Deficit > 1.5 months but ≤ 3 months (AET/PET ≤ 90 but > 75%)	Moderately dry
Deficit > 0 but ≤ 1.5 month (AET/PET > 90%)	Slightly dry
No water deficit occurs	
Utilization (and recharge) occurs (current need for water exceeds supply and soil-stored water is used)	Fresh
No utilization (current need for water does not exceed supply, temporary groundwater table may present)	Moist
Rooting-zone groundwater present during the growing season (water supply exceeds demand)	
Groundwater table > 30 cm deep	Very moist
Groundwater table > 0 but ≤ 30 cm deep	Wet
Groundwater table at or above the ground surface	Very wet

Appendix B. Study-site fact sheets

Site	Location	Substrate	SMR Grouping
Cell 11A (C-11A)	Suncor	Tailings	Reclaimed - Dry

SITE DESCRIPTION

C-11A is a young, reclaimed jack pine stand on the south slopes of Suncor's Dyke 11A. It had a flux tower from 2007 to 2011, and was re-instrumented in spring 2017. It represents a dry reclaimed site with a thin reclamation cover overlying tailings.

SITE INFORMATION

Age (total growing seasons)	12
Planting date(s)	Spring 2006

Planting details

Pj (1565 sph), Aw (400 sph), Bw (200 sph). 1+0 stock.

Cover/substrate

Peat-mineral mix (49% peat, 13-38 cm) covering tailings.

Ecosite phase	b1
Est. AWSC (mm/m)	103
Slope (˚)	6
Aspect	169

DATA RECORDS

Number of plots	7
Tower location	12V 6305658 476809

Years of data, by type

Flux	6
LAI	8
Vegetation	2
Mensuration/Site index	3

Plants with highest cover (2014)

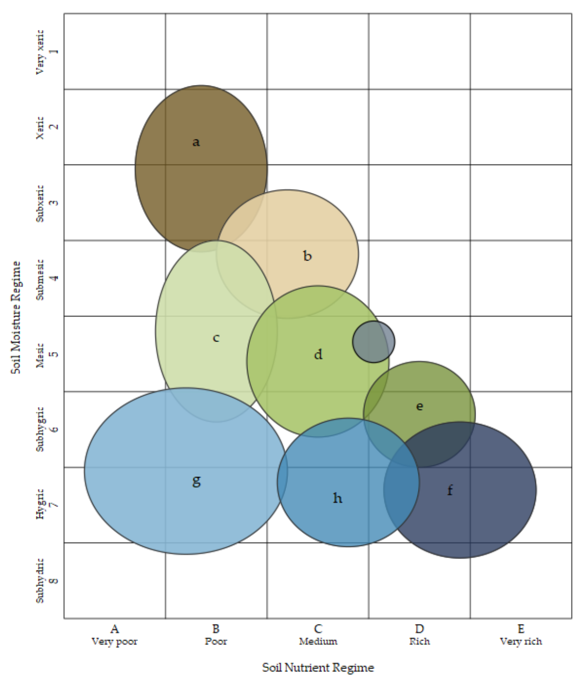
- Jack pine (14%)
- Sow-thistle (10%)
- Wild strawberry (7%)
- Fowl bluegrass (6%)
- Fireweed (5%)

RECENT DATA

LAI	1.91	(2017)	**milha density (sph)**	2571	(2014)
Total vegetation cover (%)	93	(2014)	**QMD, tagged stems (cm)**	1.9	(2014)
Native species cover (%)	80	(2014)	**Site index**	18.0 (Pj)	(2016)

PHOTO (2016)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
Sandhill Perched Fen (FEN-PERCH)	Syncrude	Tailings	Reclaimed - Fresh

SITE DESCRIPTION

The Syncrude perched fen was designed to maintain a shallow water table, but much of the site is currently drier than this and is developing into treed uplands. Fluxes have been measured here since 2014.

SITE INFORMATION

Age (total growing seasons): 6

Planting date(s): Spring 2012

Planting details

Aw, Pb

Cover/substrate

Cover over tailings is 45-115 cm deep; made of either PMM (90% peat) over fine-textured mineral subsoil, or PMM (90% peat) over tailings over fine-textured mineral subsoil.

Ecosite phase: d2

Est. AWSC (mm/m): 173

Slope (˚): Level

Aspect: -

DATA RECORDS

Number of plots	10
Tower location	12V 6321823 463867

Years of data, by type

Flux	2
LAI	5
Vegetation	3
Mensuration/Site index	3

Plants with highest cover (2015)

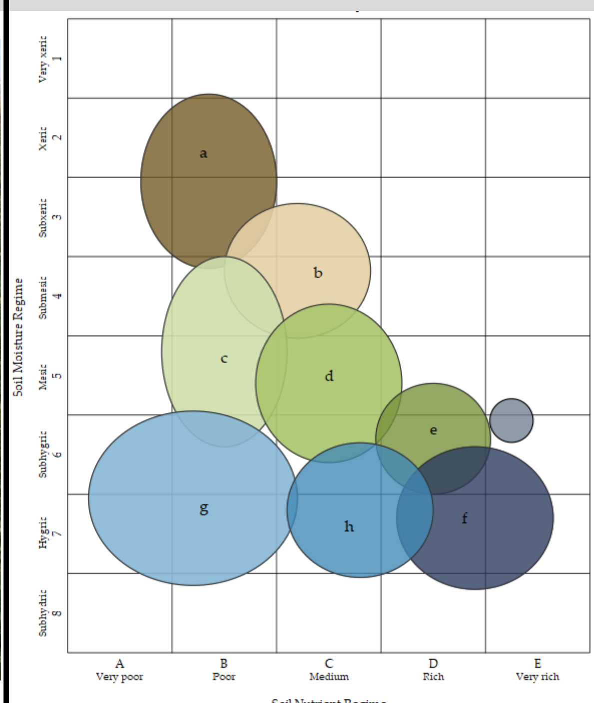
Bluejoint reedgrass (55%)
Red raspberry (8%)
Willow sp. (5%)
Sow-thistle (5%)
Wild strawberry (3%)

RECENT DATA

LAI	4.3	(2017)	**milha density (sph)**	1100	(2013)
Total vegetation cover (%)	96	(2015)	**QMD, tagged stems (cm)**	0.65	(2015)
Native species cover (%)	87	(2015)	**Site index**	-	

PHOTO (2017)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
Sandhill Fen upland (FEN-UP)	Syncrude	Tailings	Reclaimed - Fresh

SITE DESCRIPTION

This upland site in Syncrude's Sandhill fen area has undergone rapid revegetation since planting in 2012. Aspen and white spruce are establishing themselves above the herbaceous layer. Flux measurements have been done here since the site's first growing season in 2012.

SITE INFORMATION

Age (total growing seasons)	6
Planting date(s)	Spring 2012

Planting details

Aw and Sw planted into naturally-regenerating Aw that originated with material placement in

Cover/substrate

Peat-mineral mix (90% peat, 51-63 cm) placed over fine-textured mineral subsoil, covering tailings to a depth > 125 cm.

Ecosite phase	d2
Est. AWSC (mm/m)	205
Slope (˚)	< 5
Aspect	-

Plants with highest cover (2015)

- Bluejoint reedgrass (22%)
- Sow-thistle (9%)
- Fowl bluegrass (5%)
- Slender wheatgrass (4%)
- Pin cherry (3%)

DATA RECORDS

Number of plots	12
Tower location	12V 6321769 464225

Years of data, by type

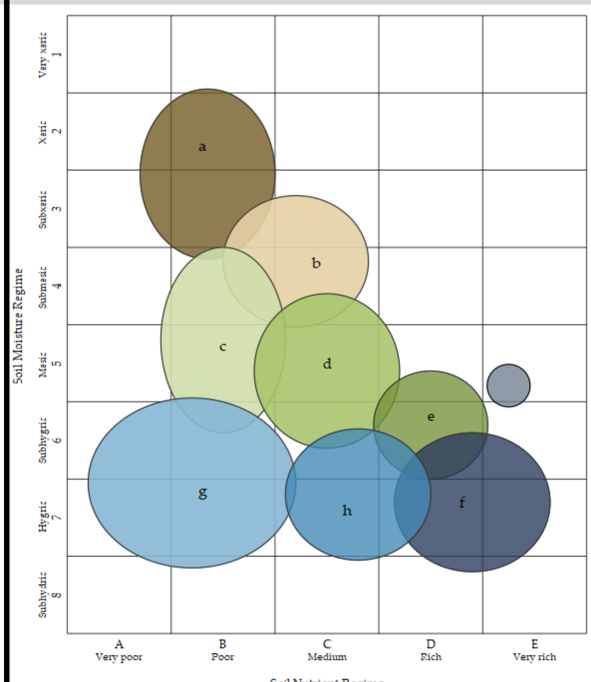
Flux	5
LAI	5
Vegetation	3
Mensuration/Site index	3

RECENT DATA

LAI	3.3	(2017)
Total vegetation cover (%)	81	(2015)
Native species cover (%)	60	(2015)
milha density (sph)	1983	(2015)
QMD, tagged stems (cm)	0.6	(2015)
Site index	-	

PHOTO (2017)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
Reclaimed jack pine (JP)	Syncrude	Tailings	Reclaimed - Dry

SITE DESCRIPTION

This reclaimed jack pine stand had a flux tower in its 15th through 20th growing seasons (2007-2012) and, along with C-11A, represents maturing jack pine reclamation in this study, although with more water-storage capacity than C-11A.

SITE INFORMATION

Age (total growing seasons)	25
Planting date(s)	Fall 1992

Planting details

Pj planted at 2900 sph.

Cover/substrate

Peat (5-10% by volume) mixed with fine-textured glaciolacustrine sediment, covering tailings to a depth of 45-60 cm.

Ecosite phase	b1
Est. AWSC (mm/m)	101
Slope (°)	< 5
Aspect	-

DATA RECORDS

Number of plots	12
Tower location	12V 6324844 459755

Years of data, by type

Flux	6
LAI	7
Vegetation	2
Mensuration/Site index	2

Plants with highest cover (2014)

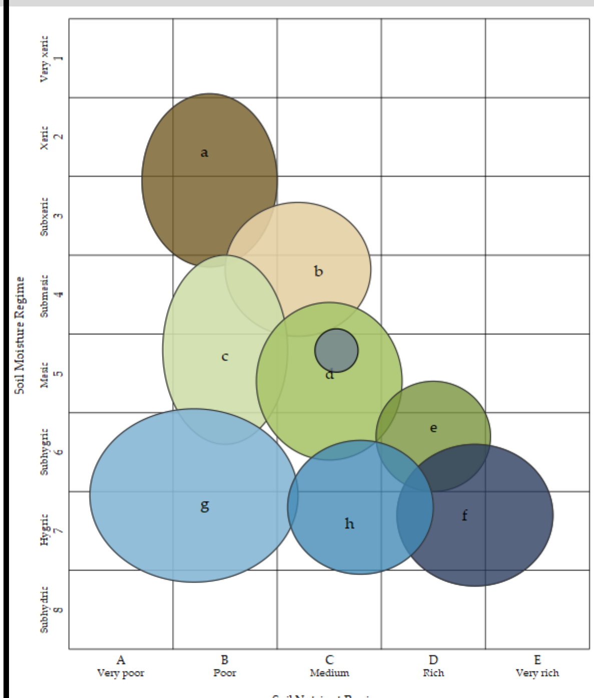
Jack pine (38%)
Chickpea milkvetch (11%)
Prickly rose (7%)
Wild strawberry (6%)
Bluejoint reedgrass (6%)

RECENT DATA

LAI	3	(2014)	**milha density (sph)**	3083	(2014)
Total vegetation cover (%)	89	(2014)	**QMD, tagged stems (cm)**	8.8	(2014)
Native species cover (%)	73	(2014)	**Site index**	15.6 (Pj)	(2014)

PHOTO (2014)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
South Bison Hill (SBH)	Syncrude	SSOB	Reclaimed - Fresh

SITE DESCRIPTION

South Bison Hill is a flagship sentinel site with the longest continuous dataset for flux and LAI, which began in the first growing season in 2003 and is ongoing. It is currently a mixed forest composed of aspen and white spruce, and is expected to gradually transition to a white spruce forest.

SITE INFORMATION

Age (total growing seasons)	15
Planting date(s)	Spring 2003

Planting details

Sw planted (1944 sph) into naturally-established Aw.

Cover/substrate

Peat-mineral mix (80% peat, 16-34 cm) over mineral subsoil (total cover > 100 cm deep), covering saline-sodic overburden

Ecosite phase	d2
Est. AWSC (mm/m)	151
Slope (˚)	< 5
Aspect	-

DATA RECORDS

Number of plots	14
Tower location	12V 6316956 462566

Years of data, by type

Flux	15
LAI	15
Vegetation	3
Mensuration/Site index	4

Plants with highest cover (2015)

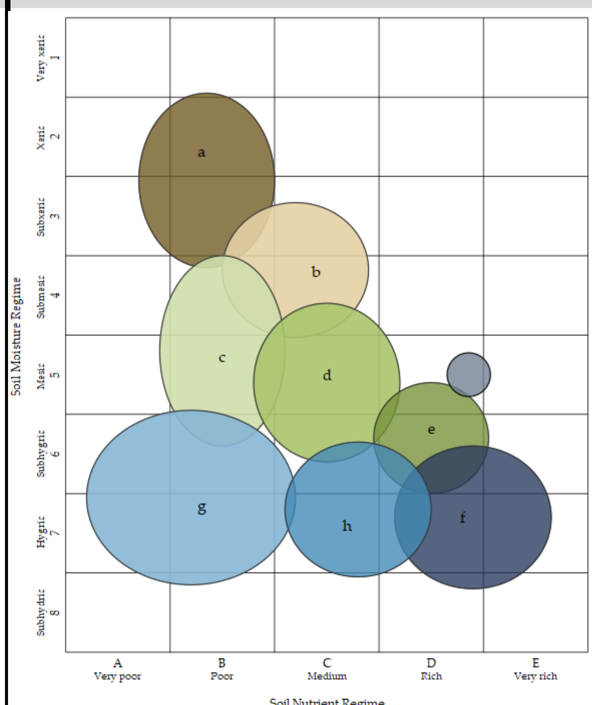
Trembling aspen (28%)
Sow-thistle (12%)
Bebb's willow (10%)
White spruce (9%)
Water sedge (8%)

RECENT DATA

LAI	5.2	(2017)	**milha density (sph)**	14533	(2015)
Total vegetation cover (%)	99	(2015)	**QMD, tagged stems (cm)**	4.4	(2015)
Native species cover (%)	80	(2015)	**Site index**	23.2 (Aw), 22.0 (Sw)	(2016)

PHOTO (2017)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
Nikanotee Fen upland (SUN-FEN)	Suncor	Tailings	Reclaimed - Dry

SITE DESCRIPTION

The upland site in the Suncor fen area sits adjacent to the wetland. Here tailings are covered with a coarser, less rich surface-soil cover and its revegetation has been slower than similar peat-mineral-mix-covered sites. Black spruce, jack pine, and mixed deciduous trees are establishing among a developing herbaceous layer. Flux measurements have been made since the growing season before planting in 2013 and are ongoing.

SITE INFORMATION

Age (total growing seasons)	4
Planting date(s)	Fall 2013

Planting details

Sb (900 sph), Pj (572 sph) and shrubs planted.

Cover/substrate

Mineral 'LFH' cover (32-41 cm) over tailings

Ecosite	b / d
Est. AWSC (mm/m)	70
Slope (˚)	< 5
Aspect	-

DATA RECORDS

Number of plots	16
Tower location	12V 6309786 474628

Years of data, by type

Flux	5
LAI	5
Vegetation	3
Mensuration/Site index	3

Plants with highest cover (2015)

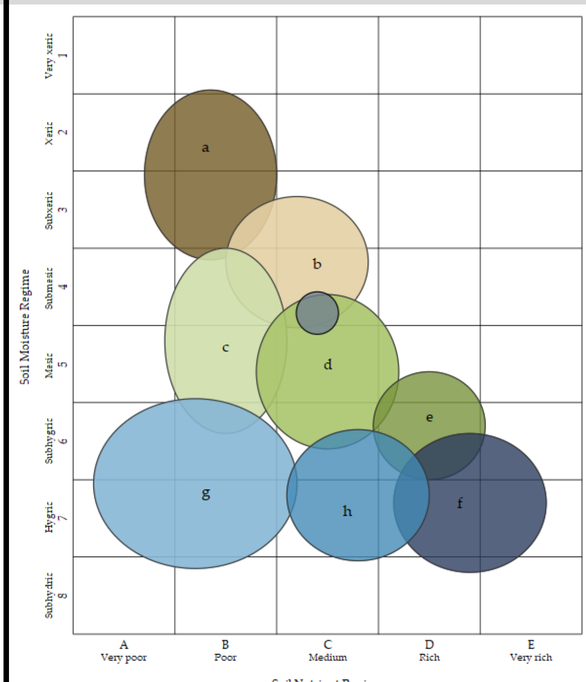
Sow-thistle (4%)
Foxtail barley (4%)
Russian thistle (3%)
Narrow-leaf hawksbeard (1%)
Rough bentgrass (1%)

RECENT DATA

LAI	1.3	(2017)
Total vegetation cover (%)	25	(2015)
Native species cover (%)	13	(2015)
milha density (sph)	563	(2015)
QMD, tagged stems (cm)	-	
Site index	-	

PHOTO (2016)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
Nikanotee Fen slopes (SUN-EDGE)	Suncor	SSOB	Reclaimed - Fresh

SITE DESCRIPTION

This collection of plots are located on the slopes surrounding the Suncor fen upland. They are of mixed age (6 and 10 years old) and target ecosystem (d1, d3, b1) but all are built of peat-mineral mix over tailings covering overburden. These plots were established to characterize juvenile upland reclamation areas surrounding the Suncor research fen.

SITE INFORMATION

Age (total growing seasons)	6, 10
Planting date(s)	June 2008, June 2012

Planting details

Aw (1930 sph), Sw (300 sph), Pj (180 sph), Bp (210 sph) and shrubs planted.

Cover/substrate

Peat-mineral mix (20% peat, 20-56 cm), some overlying mineral soil, covering tailings or overburden to depths of 56-

Ecosite phase	d1 / b1 / d3
Est. AWSC (mm/m)	119
Slope (˚)	11, 13
Aspect	83, 280

DATA RECORDS

Number of plots	11
Site location plot #1 (no tower)	12 V 6309637 474823

Years of data, by type

Flux	0
LAI	1
Vegetation	1
Mensuration/Site index	1

Plants with highest cover (2015)

Sow-thistle (10%)
Common oat (7%)
Balsam polar (5%)
Bluejoint reedgrass (4%)
Trembling aspen (3%)

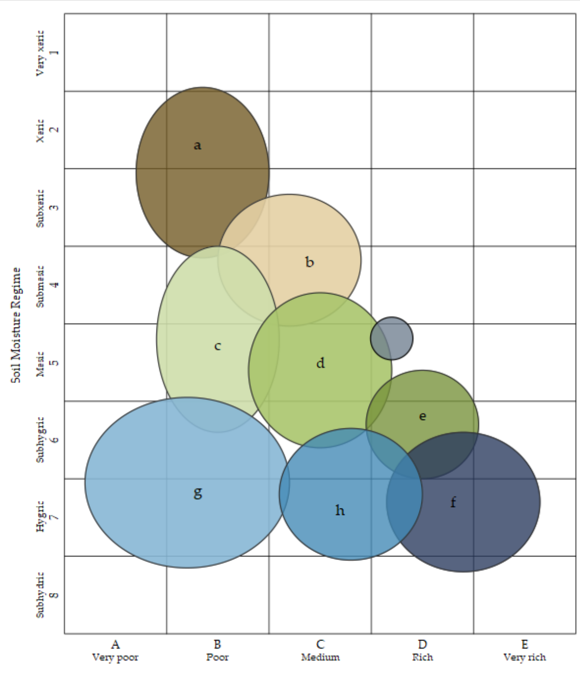
RECENT DATA

LAI	1.0	(2015)
Total vegetation cover (%)	48	(2015)
Native species cover (%)	26	(2015)

milha density (sph)	3909	(2015)
QMD, tagged stems (cm)	0.9	
Site index	-	

PHOTO (2015)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
Southwest Sand Storage (SWSS)	Syncrude	Tailings	Reclaimed - Dry

SITE DESCRIPTION

The footprint of the Southwest Sand Storage tower encompassed stands of Siberian larch and aspen. Flux measurements were made at this site in 2005-06 and 2014-15.

SITE INFORMATION

Age (total growing seasons)	22
Planting date(s)	Spring 1996

Planting details

Aw/Pb/Sw/Pj or Ls/Pb, at a combined density of 2000 sph.

Cover/substrate

Mineral soil with minor peat inclusions (5%) over tailings to depths of 46-66 cm.

Ecosite	b / d
Est. AWSC (mm/m)	90
Slope (°)	< 5
Aspect	-

DATA RECORDS

Number of plots	16
Tower location	12V 6316898 455488

Years of data, by type

Flux	4
LAI	3
Vegetation	1
Mensuration/Site index	1

Plants with highest cover (2014)

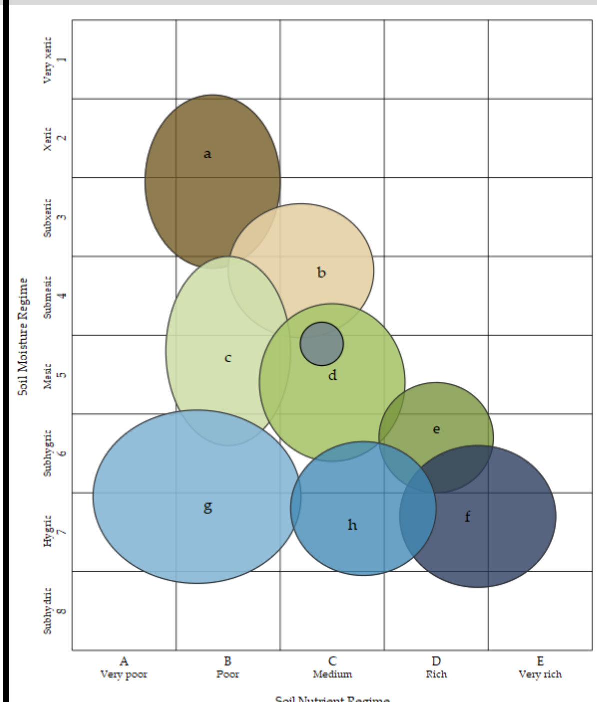
Siberian larch (11%)
Trembling aspen (7%)
Balsam polar (6%)
Smooth brome (6%)
Alfalfa (6%)

RECENT DATA

LAI	2.4	(2014)
Total vegetation cover (%)	84	(2014)
Native species cover (%)	43	(2014)
milha density (sph)	3938	(2014)
QMD, tagged stems (cm)	7	(2014)
Site index	26.8 (Ls), 22.2 (Aw), 17.6 (Pb)	(2014)

PHOTO (2017)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
CEMA jack pine site	Ft. McMurray	Natural soil	Reference - Dry

SITE DESCRIPTION

CEMA is a mature a ecosite consisting of a pure jack pine stand with a reindeer lichen-bearberry-blueberry understory. It has never had flux measurements taken but was measured in 2015 to represent the driest ecosystems of the oilsands region.

SITE INFORMATION

Age (total growing seasons)	90
Disturbance date:	Fire, ~1927

Planting details

Not planted. Natural regeneration of pure Pj stand.

Soils/surficial materials

Orthic Eutric Brunisols on coarse-textured glaciofluvial deposits.

Plant community type	a1.1 / a1.2
Est. AWSC (mm/m)	16
Slope (°)	< 5
Aspect	-

DATA RECORDS

Number of plots	4
Site location plot #1 (no tower)	12V 6331029 473324

Years of data, by type

Flux	0
LAI	1
Vegetation	1
Mensuration/Site index	1

Plants with highest cover, no % recorded (2015)

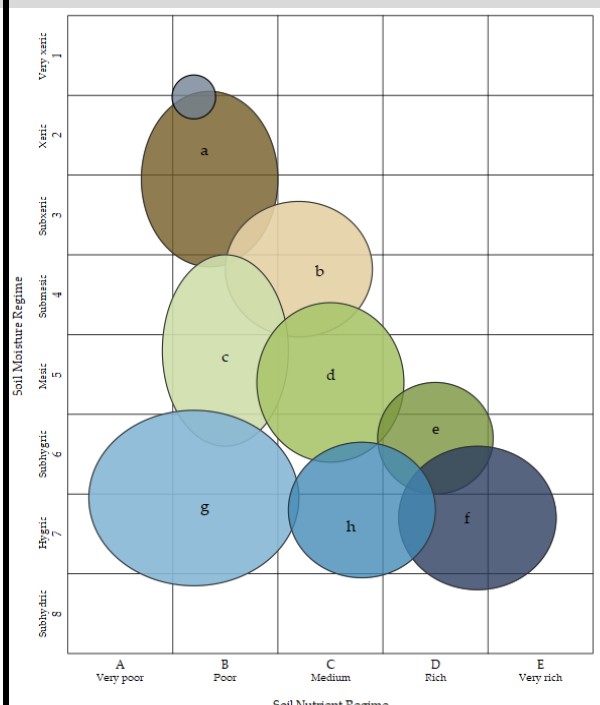
Jack pine
Cladonia sp.
Feathermoss
Bearberry
Blueberry

RECENT DATA

LAI	2.6	(2016)
Total vegetation cover (%)	-	
Native species cover (%)	-	
milha density (sph)	500	(2015)
QMD, tagged stems (cm)	5.2	(2015)
Site index	12.7 (Pj)	(2015)

PHOTO (2015)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
South-facing juvenile aspen (P40-S)	URSA	Natural soil	Reference - Fresh

SITE DESCRIPTION

P40-S is the older of the two regenerating aspen stands at URSA. It was logged in the winter of 2006-07. Flux measurements include 1 pre-harvest year beginning in 2006 and are ongoing.

SITE INFORMATION

Age (total growing seasons) 11

Disturbance date: Harvested, winter 2006-07

Planting details

Not planted. Natural regeneration of Aw-dominated deciduous forest.

Soils/surficial materials

Orthic Gray Luvisols on moderately fine-textured moraine.

Plant community type

d1.5 / d1.6

Est. AWSC (mm/m)

122

Slope (˚) 5

Aspect 160

DATA RECORDS

Number of plots	12
Tower location	12V 6223502 221469

Years of data, by type

Flux	12
LAI	10 (+1 estimated pre-harvest year)
Vegetation	3 (+1 estimate pre-harvest year)
Mensuration/Site index	3 (+1 estimate pre-harvest year)

Plants with highest cover (2015)

Trembling aspen (32%)

Balsam polar (8%)

Bluejoint reedgrass (7%)

Fireweed (7%)

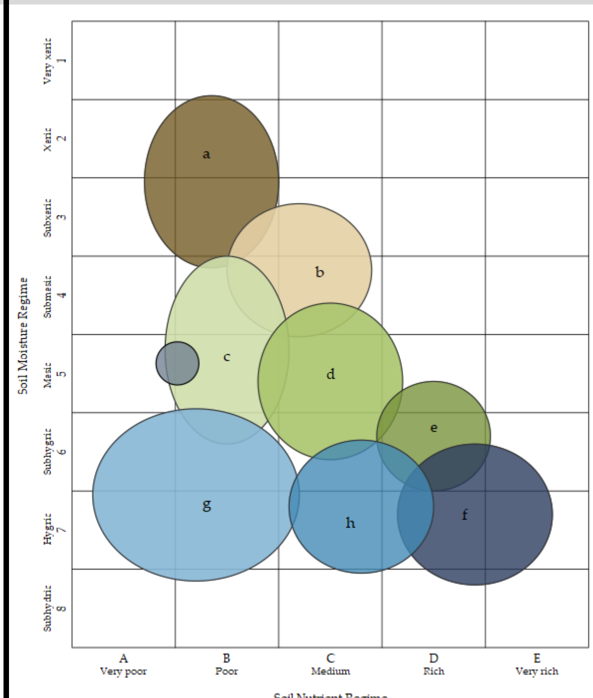
Prickly rose (6%)

RECENT DATA

LAI	5.3	(2017)	**milha density (sph)**	26333	(2015)
Total vegetation cover (%)	91	(2015)	**QMD, tagged stems (cm)**	4.3	(2015)
Native species cover (%)	90	(2015)	**Site index**	-	

PHOTO (2017)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
North-facing juvenile aspen (P40-N)	URSA	Natural soil	Reference - Fresh

SITE DESCRIPTION

P40-N is the younger of the two regenerating aspen stands at URSA. It was logged in the winter of 2007-08. Flux measurements were taken in the first two growing seasons after harvest. LAI measurements were resumed by IEG in 2013.

SITE INFORMATION

Age (total growing seasons)	10
Disturbance date:	Harvested, winter 2007-08

Planting details

Not planted. Natural regeneration of Aw-dominated deciduous forest.

Soils/surficial materials

Orthic Gray Luvisols and Eluviated Eutric Brunisols on moderately fine-textured till.

Plant community type	d1.5 / d1.6
Est. AWSC (mm/m)	125
Slope (˚)	7
Aspect	340

DATA RECORDS

Number of plots	11
Tower location	12V 6223223 221484

Years of data, by type

Flux	2
LAI	7
Vegetation	3
Mensuration/Site index	3

Plants with highest cover (2015)

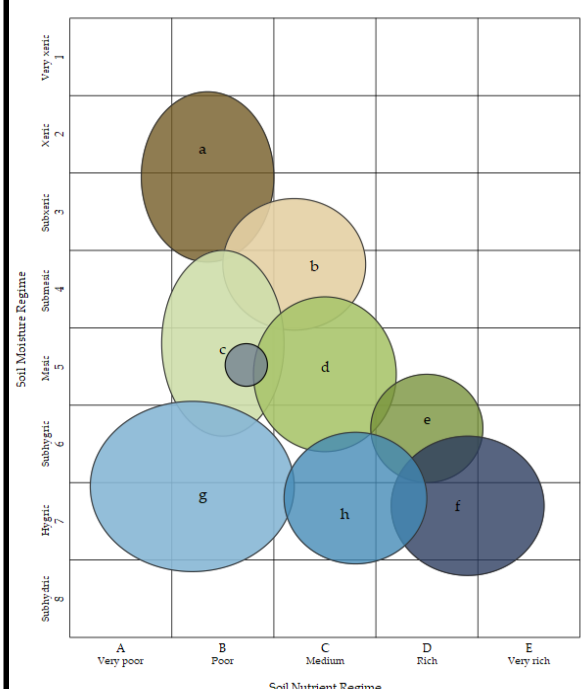
Trembling aspen (20%)
Downy ryegrass (13%)
Fireweed (10%)
Bebb's willow (9%)
Prickly rose (5%)

RECENT DATA

LAI	4.9	(2017)
Total vegetation cover (%)	83	(2015)
Native species cover (%)	83	(2015)
milha density (sph)	19455	(2015)
QMD, tagged stems (cm)	-	
Site index	-	

PHOTO (2017)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
South-facing mature aspen (P43-S)	URSA	Natural soil	Reference - Fresh

SITE DESCRIPTION

P43-S is part of an unharvested aspen upland adjacent to the regenerating P40 stands. It has never had flux instrumentation, but it has been measured to understand the characteristics of mature aspen uplands in the region, including the pre-harvest P40 stands.

SITE INFORMATION

Age (from max. core age)	74
Disturbance date:	Fire, ~ 1941

Planting details

Not planted. Natural regeneration of Aw-dominated deciduous forest.

Soils/surficial materials

Orthic Gray Luvisols and Gleyed Grey Luvisols on medium to moderately fine-textured morainal deposits.

Plant community type	d1.5
Est. AWSC (mm/m)	133
Slope (˚)	8
Aspect	182

DATA RECORDS

Number of plots	14
Site location location plot #1	12V 6223415 221841

Years of data, by type

Flux	0
LAI	2
Vegetation	2
Mensuration/Site index	2

Plants with highest cover (2014)

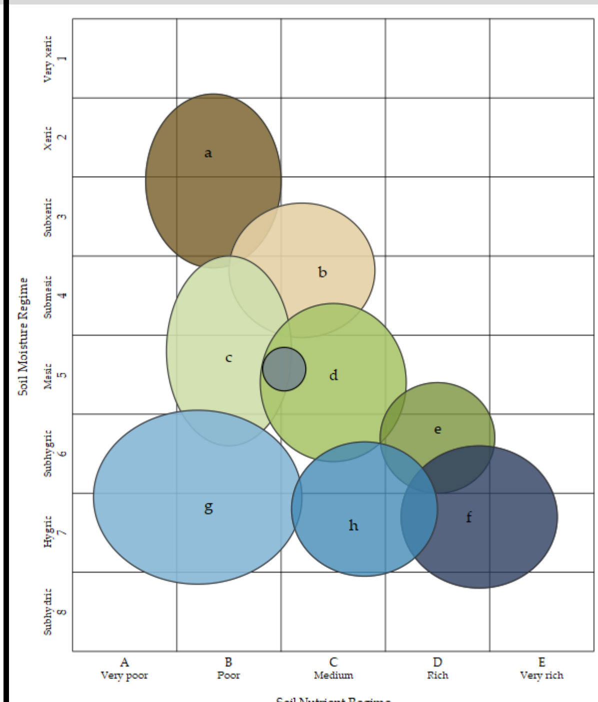
- Trembling aspen (27%)
- Highbush cranberry (8%)
- Prickly rose (6%)
- Balsam poplar (6%)
- Wild sarsaparilla (5%)

RECENT DATA

LAI	3.7	(2014)	**milha density (sph)**	2000	(2014)
Total vegetation cover (%)	77	(2014)	**QMD, tagged stems (cm)**	15.9	(2014)
Native species cover (%)	77	(2014)	**Site index**	19.4 (Aw)	(2014)

PHOTO (2014)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
North-facing mature aspen (P43-N)	URSA	Natural soil	Reference - Fresh

SITE DESCRIPTION

P43-N is part of an unharvested aspen upland adjacent to the regenerating P40 stands. It has never had flux instrumentation, but it has been measured to understand the characteristics of mature aspen uplands in the region, including the pre-harvest P40 stands.

SITE INFORMATION

Age (from max. core age)	73
Disturbance date:	Fire, ~ 1941

Planting details

Not planted. Natural regeneration of Aw-dominated deciduous forest.

Soils/surficial materials

Orthic Gray Luvisols and Gleyed Grey Luvisols on medium to moderately fine-textured morainal deposits.

Plant community type	d1.5
Est. AWSC (mm/m)	150
Slope (˚)	< 5
Aspect	-

DATA RECORDS

Number of plots	4
Site location location plot #1	12V 6223267 221657

Years of data, by type

Flux	0
LAI	2
Vegetation	2
Mensuration/Site index	2

Plants with highest cover (2014)

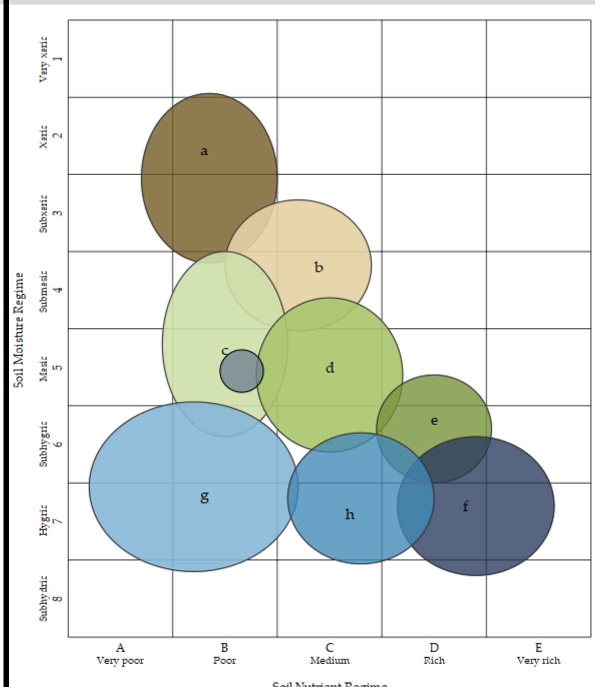
Trembling aspen (24%)
Highbush cranberry (11%)
Balsam poplar (6%)
Prickly rose (5%)
Fireweed (4%)

RECENT DATA

LAI	3.9	(2014)	**milha density (sph)**	1500	(2014)
Total vegetation cover (%)	76	(2014)	**QMD, tagged stems (cm)**	14.5	(2014)
Native species cover (%)	76	(2014)	**Site index**	20.3 (Aw)	(2014)

PHOTO (2014)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
Coke Beach (CB)	Syncrude	Coke	Reclaimed - Dry

SITE DESCRIPTION

Coke Beach is a newly established flux site representing some of the thinner covers on the reclaimed landscape, in this case roughly 50 cm of PMM over coke. Only one year of flux and biometric data is in this study.

SITE INFORMATION

Age (total growing seasons)	11
Planting date(s)	Fall 2006

Planting details

Sw

Cover/substrate

PMM (9% peat, 45-60 cm deep) over coke.

Ecosite phase	b1
Est. AWSC (mm/m)	97
Slope (˚)	< 5
Aspect	-

DATA RECORDS

Number of plots	16
Tower location	12V 6323710 460054

Years of data, by type

Flux	1
LAI	1
Vegetation	1
Mensuration/Site index	1

Plants with highest cover (2017)

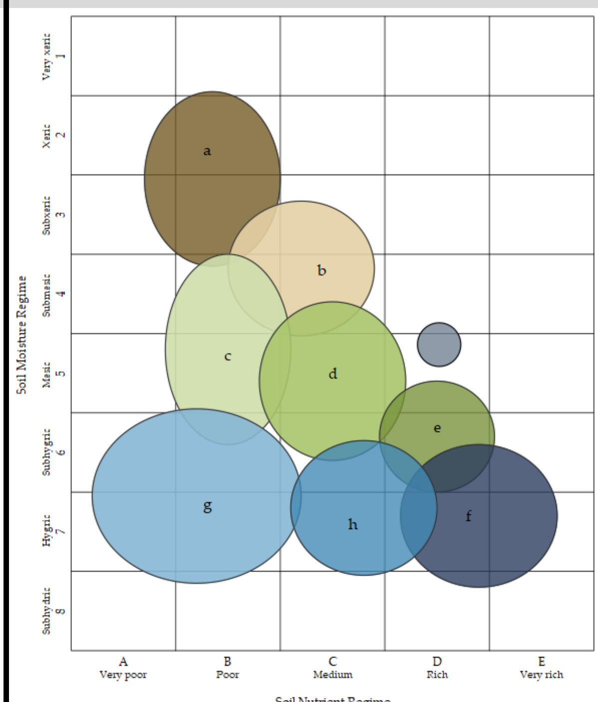
White spruce (10%)
Alfalfa (10%)
Redshank (9%)
Creeping bentgrass (4%)
Wild strawberry (4%)

RECENT DATA

LAI	2.1	(2017)	**milha density (sph)**	2188	2017
Total vegetation cover (%)	61.8	(2017)	**QMD, tagged stems (cm)**	-	2017
Native species cover (%)	40.5	(2017)	**Site index**	19.7 (Sw)	2017

PHOTO (2017)

EDATOPIC GRID



Site	Location	Substrate	SMR Grouping
U-shaped Cell (U-CELL)	Syncrude	Tailings	Reclaimed - Dry

SITE DESCRIPTION

This is a small site that represents the driest end of reclamation covers at Syncrude, with a cover consisting mostly of coke with some tailings. It is too small for flux measurements but was included in this study for AWSC and LAI context. Despite the poor soil materials, this site has developed a moderate vegetation cover including aspen stems.

SITE INFORMATION

Age (total growing seasons)	20
Planting date(s)	Fall 1997
Planting details	-

Cover/substrate

A mixture of coke and tailings (70% coke, 34 cm deep) over tailings.

Ecosite phase	b1
Est. AWSC (mm/m)	51
Slope (˚)	< 5
Aspect	-

DATA RECORDS

Number of plots	1
Site location	12V 6323352 460006

Years of data, by type

Flux	-
LAI	1
Vegetation	1
Mensuration/Site index	-

Plants with highest cover (2017)

Alfalfa (15%)
Trembeling aspen (12%)
Green alder (8%)
Creeping bentrass (3%)
Redshank (2%)

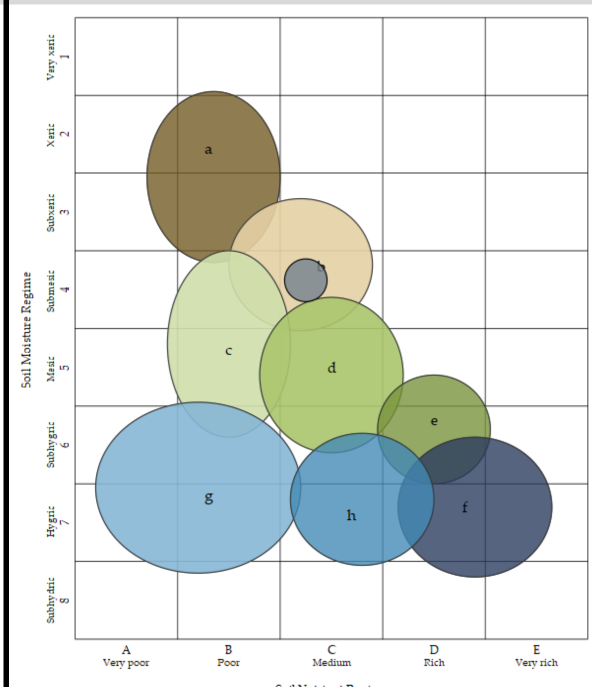
RECENT DATA

LAI	1.91	(2017)
Total vegetation cover (%)	44.6	(2017)
Native species cover (%)	25.1	(2017)

milha density (sph)	-	2017
QMD, tagged stems (cm)	-	2017
Site index	-	2017

PHOTO (2017)

EDATOPIC GRID



Appendix C. LAI processing and detailed results

As described in Section 2.2, there were differences in methodology between research teams, which required further processing before assembling a standardized LAI dataset for all flux years. These differences mostly relate to height of measurement, which is a very influential factor in LAI measurements that has no universal standard, and is often omitted in published research. Researchers in mature forest stands often measure LAI at roughly hip height, above most of the understory, as this is the height that gives the most consistent measurements (due to greater distance between the sensor and its nearest leaves), and this is the vegetation component that largely dictates a site's energy balance and biometeorological properties (Barr et al., 2004; Chen et al., 2005). This is the measurement referred to here as canopy LAI (LAIc). On the other hand, researchers working in grasslands and agronomy must characterize the understory and make measurements at the lowest feasible height that maintains recommended sensor-leaf distances (i.e., roughly 4 times leaf width), which is roughly 2-10 cm above the ground surface. This is the measurement referred to as total LAI (LAItot) as nearly all vegetation is captured. The difference between LAItot and LAIc (LAItot = LAIc + LAIu) is referred to as understory LAI (LAIu).

The primary issue in relating measurements by biometric field crews since 2013 to previous measurements by the EC field crews (LAI.lab) is that there was apparent inconsistency in measurement heights at some sites. While grass and forb-dominated communities seem to have been measured near the ground, and are considered equivalent to the LAItot measurements of the biometric crews, treed sites seem to have been measured more similarly to the biometric crews' LAIc measurements. Sites that progressed from grass-dominated to treed, such as P40-S and SBH, appear to have had their LAI.lab measurement height increased or varied over time. Secondary issues with data compatibility include the lack of sun-scattering and conifer corrections[16] in the older dataset. Neither correction has been applied to older data due to insufficient data[17], which should generally lead to underestimation of LAI.

On a site-by-site basis, best efforts were made to standardize past measurements into LAItot-equivalents using site photos, site ages, and co-measured LAI years. This process is described below by site. The younger sites without mention in this section were not edited or cleaned; their LAI.lab values were used directly to represent LAItot.

In the tables below, numerous parameters are split into measured and estimated values. Measured LAIc, LAIu, and LAItot values (i.e. the biometric crew measurements) were used for the final analysis dataset when available, and values estimated from LAI.lab were used in other years.

[16] A correction is applied to the LAI attributed to conifer species due to assumptions in uncorrected LAI measures regarding needle and stem architecture. Attributing LAI measures to vegetation type is not reliable without vegetation survey data, so pre-IEG measurements were generally not conifer-corrected.
[17] With the exception of the uniform jack pine stand at JP, which was possible to conifer-correct due to its consistent composition (i.e., dominated by large jack pine) in all measured years.

Cell-11A (C-11A)

LAI was measured by EC teams in 2007 and 2009-2011, a period covering growing seasons 2 through 6. Site photos indicated that woody stems were a minor component of vegetation cover in early years. By 2013, jack pine were the dominant vegetation component and that appeared to have been the case for several years. The 2007 LAI.lab values were assumed to be taken near ground height (LAItot), and are used as a pure understory measurement (i.e., LAIc=0, LAItot=LAI.lab). In later years, the ratio of LAIc:LAItot measured in 2013 was used as the end point in estimating LAIc- and LAIu-equivalents from the lab data (Table C-1).

Table C-1. Summary of C-11A LAI data standardization process.

Year	Age	LAI.lab	LAIc:LAItot ratio		LAIc		LAIu		LAItot		Notes
			est.	meas.	est.	meas.	est.	meas.	est.	meas.	
2007	2	0.51	0	-	0	-	0.51	-	0.51	-	LAIc estimated to be 0. LAI.lab = LAItot
2008	3	-	-	-	-	-	-	-	-	-	No LAI record.
2009	4	1.68	0.23	-	0.35	-	1.33	-	1.68	-	Used half of 2013 LAIc:LAItot ratio
2010	5	1.58	0.23	-	0.33	-	1.25	-	1.58	-	
2011	6	1.33	0.44	-	0.58	-	0.75	-	1.33	-	Used 2013 LAIc:LAItot ratio
2012	7	-	-	-	-	-	-	-	-	-	No LAI record.
2013	8	-	-	0.44	-	0.7	-	0.96	-	1.66	2013 values measured by biometric crews, not estimated.

Jack Pine (JP)

LAI of the JP site was measured by EC teams in 2007-2010 and 2012. The 2007-2010 period should have been relatively stable in terms of vegetation as these were growing seasons 19 through 22. The 2007-2010 LAI.lab values are in line with the biometric crews' 2013-2017 LAIc measurements, and have been used as such.

In 2012, there was a notable increase in LAI.lab. If this LAI.lab value was used as an LAIc value, it would have been nearly 40% higher than any other JP LAIc value measured before or since, and there is no mechanism in a pine stand to produce a single-year LAIc spike of that magnitude. Therefore, it appears that the 2012 LAI.lab value is at least partially a product of the measurement height being lowered (i.e. moving closer to LAItot), or another unknown measurement error. This left the choice to discard the measurement altogether, use it as-is as an anomalous LAIc value, or assume it was taken at or near ground level and use it as an LAItot value fitting the expected trend. There was no direct evidence to support that the measurement differences were caused by a change in wand height, but (i) this hypothesis represents one of the key sources of LAI measurement variability, (ii) is more likely than single-year LAI spikes in pine stands, and (iii) allows inclusion of another site-year in the database. Therefore, the 2012 LAI.lab value was used as an LAItot value.

Since JP was only ever measured as a relatively stable conifer stand, it is straightforward to apply corrections retroactively. The conifer correction estimated for 2013-2017 decreases canopy LAI by 17%, which was applied to the estimated LAIc component of the LAI.lab values, which were then included in a conifer-corrected estimate of LAItot.

In summary, the 2007-2010 LAI.lab values were treated as canopy LAI values, and the 2012 LAI.lab value was treated as a total LAI value. Conversion between LAItot, LAIc, and LAIu components was done using the mean LAIc:LAItot ratio (0.68) from the biometric crew's 2013 and 2014 measurements.

Table C-2. Summary of JP LAI data standardization process.

Year	Age	LAI lab	LAIc:LAItot ratio		LAIc		LAIu		LAItot		Notes
			est.	meas.	est.	meas.	est.	meas.	est.	meas.	
2007	15	1.65	0.68	-	1.37	-	0.64	-	2.01	-	Assumed LAI.lab taken at canopy level. Used 0.83 conifer correction factor to downscale this estimated LAIc. Used 2013-2014 LAIc:LAItot ratio to estimate LAIu and LAItot from corrected LAIc value. e.g. 2007: LAI.lab = 1.65 LAIc = LAI.lab * 0.83 = 1.37 LAItot = LAIc * (1/0.68) = 2.01 LAIu = LAItot - LAIc = 0.64
2008	16	1.91	0.68	-	1.59	-	0.74	-	2.32	-	
2009	17	2.05	0.68	-	1.70	-	0.79	-	2.49	-	
2010	18	2.1	0.68	-	1.74	-	0.81	-	2.55	-	
2011	19	-	-	-	-	-	-	-	-	-	No LAI record.
2012	20	3.2	0.68	-	1.91	-	0.89	-	2.81	-	LAI.lab used as a total LAI value requiring conifer-correction adjustment.
2013	21	-	-	0.68	-	1.77	-	0.84	-	2.60	Measured by biometric crews, basis for previous year corrections.

2014	22	-	-	0.69	-	2.04	-	0.93	-	2.97	

URSA P40 sites

The approach to data standardization at P40 varied according to site age. In growing seasons up to and including the 3rd growing season, canopy LAI was assumed to be zero and all LAI.lab values are used as LAItot values. LAI for later growing seasons has been standardized based on co-measured values by the EC and biometric crews in 2013, 2015, and 2016.

The LAI.lab values for 2015 and 2016 were nearly identical to the LAIc values from biometric surveys. This demonstrates that there was a shift in measurement height since the initial three post-harvest years (2007-2009), when there would have been little to no canopy and all measurements would necessarily have been made near ground-height (i.e. LAI.lab ≈ LAItot). It appears that 2013 was a transitional year, in which LAI.lab was measured somewhere between the LAIc and LAItot heights, as shown by LAI.lab being more than double the biometric crew's LAIc, but roughly 25% less than their LAItot. The hypothesis underpinning the standardization here was that increasing amounts of understory vegetation were omitted as the measurement height was gradually raised between the fourth and seventh growing seasons (2010 through 2013) before reaching the LAIc height in 2015 and 2016. Therefore, standardization involved two parts: (i) apportioning an increasing part of LAI.lab to LAIc; and (ii) adding an increasing amount of LAIu estimated to have been missed. A linear trajectory was used to interpolate between the 2009 assumptions of LAIc=0 and LAI.lab=LAItot and the 2013 co-measured ratios that estimate LAIc and LAItot at 36% and 145% of LAI.lab, respectively (Table C-3). Conversion ratios of LAI.lab:LAItot in excess of 1 is the mechanism by which the 'missing' LAIu is added.

Table C-3. Summary of P40-S LAI data standardization process.

Year	Age	Lab LAI	LAI.lab: LAIc		LAI.lab: LAItot		LAIc		LAIu		LAItot		Notes
			est.	meas.	est.	meas.	est.	meas.	est.	meas.	est.	meas.	
2006	62	2.2	1	-	1.85	-	2.2	-	1.87	-	4.07	-	Pre-harvest LAI. Assumed to be canopy level only, as it is quite similar to canopy LAI measured at neighbouring unharvested P43. Use the P43 LAIc: LAItot ratio to estimate this pre-harvest LAItot.
2007	1	0.6	0	-	1	-	0	-	0.6	-	0.6	-	Post-harvest. Assume LAI measured from ground-level.
2008	2	1.4	0	-	1	-	0	-	1.4	-	1.4	-	
2009	3	1.7	0	-	1	-	0	-	1.7	-	1.7	-	
2010	4	1.8	0.12	-	1.15	-	0.22	-	1.85	-	2.07	-	LAI.lab assumed to be middle height between canopy and ground. LAI ratios are scaled backwards from the co-measured 2013 year to the assumed last year without canopy LAI (2009).
2011	5	1.9	0.24	-	1.3	-	0.46	-	2.01	-	2.47	-	
2012	6	-	-	-	-	-	-	-	-	-	-	-	No LAI record.
2013	7	2.5	-	0.36		1.45	-	0.9	-	2.73	-	3.63	The biometric crew’s data was used for 2013, and the ratios between co-measured EC and biometric LAI values are used to estimate LAI.lab components for 2010 and 2011.
2014	8	-	-	-	-	-	-	-	-	-	-	-	No LAI record.
2015	9	1.8	-	1.09		2.84	-	1.96	-	3.16	-	5.11	EC LAI values are much lower than biometric LAItot, very similar to biometric LAIc.
2016	10	1.7	-	1.0		2.44	-	1.7	-	2.44	-	4.15	

Table C-4. Summary of P40-N LAI data standardization process.

Year	Age	Lab LAI	LAIc: LAItot		LAIc		LAIu		LAItot		Notes
			est.	meas.	est.	meas.	est.	meas.	est.	meas.	
2008	1	0.6	0	-	0	-	0.6	-	0.6	-	Post-harvest. Assume LAI measured from ground-level.
2009	2	1.3	0	-	0	-	1.3	-	1.3	-	

Table C-5. Summary of P40-25m LAI data standardization process.

Year	Age	Lab LAI	LAIc: LAItot		LAIc		LAIu		LAItot		Notes
			est.	meas.	est.	meas.	est.	meas.	est.	meas.	
2007	63	-	-	-	1.6	-	2.27	-	3.87	-	Using 2013-14 LAI values from unharvested P43 as no data collected.
2008	1	0.6	0	-	0	-	0.6	-	0.6	-	Post-harvest. Assume LAI measured from ground-level.
2009	2	1.3	0	-	0	-	1.3	-	1.3	-	
2010	3	1.5	0	-	0	-	1.5	-	1.5	-	
2011	4	1.6	0	-	0	-	1.6	-	1.6	-	

South Bison Hill (SBH)

The approach to data standardization at SBH varied according to site age, similar to the process for P40-S. In growing seasons up to and including the 3th growing season, canopy LAI was assumed to be zero and all values measured by the EC team are used as-is for LAItot values. LAI for later growing seasons have been standardized based on co-measured values by EC and biometric crews in 2013 and 2014.

The EC LAI values for 2013 and 2014 are 0.6 to 0.9 units lower than the biometric measurements, suggesting a difference in measurement height that we have accounted for by adding small LAI corrections to the LAI.lab values (Table C-6). These corrections start at 0.1 LAI units in 2006 and increase to 0.6 in 2012, working under the assumption that the measurement height was gradually raised as the understory filled in. The biometric crew's canopy LAI in 2013 and 2014 was roughly 70% of total LAI, so this value was used as the basis for splitting LAI.lab into estimated LAIc and LAItot components, starting at 10% in 2006, the assumed first year with a measurable canopy, and increasing to 70% in 2012.

Table C-6. Summary of SBH LAI data standardization process.

Year	Age	Lab LAI	LAIc: LAItot		Missing LAI		LAIc		LAIu		LAItot		Notes
			est.	meas.	est.	meas.	est.	meas.	est.	meas.	est.	meas.	
2003	1	0.9	0	-	0	-	0	-	0.9	-	0.9	-	Assume LAI measured from ground-level, all captured.
2004	2	1.1	0	-	0	-	0	-	1.1	-	1.1	-	
2005	3	0.7	0	-	0	-	0	-	0.7	-	0.7	-	
2006	4	0.8	0.1	-	0.1	-	0.08	-	0.82	-	0.9	-	Understory LAI est. = LAI.lab * (1-[LAIc:LAItot]) + LAI.missing Canopy LAI est. = LAI.lab * [LAIc:LAItot] Total LAI est. = LAI.lab + LAI.missing
2007	5	0.9	0.2	-	0.1	-	0.18	-	0.82	-	1	-	
2008	6	2.8	0.3	-	0.2	-	0.84	-	2.16	-	3	-	
2009	7	3.45	0.4	-	0.3	-	1.38	-	2.37	-	3.75	-	
2010	8	3.5	0.5	-	0.4	-	1.75	-	2.15	-	3.9	-	
2011	9	3.3	0.6	-	0.5	-	1.98	-	1.82	-	3.8	-	
2012	10	3	0.7	-	0.6	-	2.1	-	1.5	-	3.6	-	
2013	11	3.2	-	0.69	-	0.86	-	2.79	-	1.27	-	4.06	Biometric LAI values used for these years. Corrections for prior years derived from these years.
2014	12	3.4	-	0.75	-	0.56	-	3.41	-	1.15	-	4.56	

Southwest Sand Storage (SWSS)

There were two years of flux measurements (2005 and 2006) taken at this site prior to biometric crew surveys. Photos and typical developmental trajectories indicate that by ages 10 to 11 in 2005 and 2006, the measured LAI values (1.7 and 1.8) were closer to canopy LAI values than total LAI values. Therefore, these values were used directly as canopy LAI, and total LAI was then estimated using the LAIc:LAItot ratio of 0.59 eddy-cmeasured in 2014.

Table C-7. Summary of SWSS LAI data standardization process.

Year	Age	Lab LAI	LAIc: LAItot		LAIc		LAIu		LAItot		Notes
			est.	meas.	est.	meas.	est.	meas.	est.	meas.	
2005	10	1.8	0.59	-	1.8	-	1.24	-	3.04	-	Assume LAI.lab=LAIc, and estimate LAItot using 2014 LAIc:LAItot ratio.
2006	11	1.7	0.59	-	1.7	-	1.17	-	2.87	-	
2007-2013	12-18	-	-	-	-	-	-	-	-	-	No flux.
2014	19	-	-	0.59	-	1.41	-	0.97	-	2.38	The only year of biometric crew measurements.
2015	20	-	-	-	1.41	-	0.97	-	2.38	-	LAI intentionally not measured by either crew, therefore used 2014 values.

Appendix D. AWSC methods and detailed results

A standardized method of estimating plant-available water-storage capacity (AWSC) from soil survey data using adaptations of peer-reviewed models has been employed (Straker et al., 2015a, 2015b). The primary inputs to this model are soil particle-size distribution (PSD), organic-matter (OM) content, soil depth, and topographical data, as well as layering arrangements within the soil profile. Each study site's reported AWSC is a mean result from one to seven soil pits surveyed at each site[18]. Two AWSC models are central to this approach: Arya and Paris (1981; Arya et al., 1999) and Saxton and Rawls (2006; Saxton, 2005).

The Arya and Paris (A&P) approach is a physical model based on the capillary equation and uses only PSD and bulk density as inputs. The PSD-centric approach ignores the benefit of OM and soil structure on AWSC, and thus appears better suited to poorly-developed low-OM soils. To adjust for this omission, we adjust the A&P value by the percent increase in AWSC attributable to OM according to the Saxton and Rawls (S&R) model.

The S&R approach is an empirical model built on regressions of soil survey data (PSD, OM content, and bulk density) against pressure-plate AWSC results to determine a best-fit prediction of AWSC. Since it is based on agricultural soil samples, we believe this model better-suited to higher-OM, better-aggregated soils.

The A&P model is quite sensitive to size distributions of sand particles because fine (0.1 - 0.25 mm) and very fine (0.053 - 0.1 mm) sand contribute water-storage to their modelled profile but coarser sands do not. Oilsands reclamation research has explored similar concepts in understanding soil moisture on tailings sites (Macyk, 2006; see *Results and discussion* section below). We do not have sand-size breakdowns from lab data for most of our study sites so have estimated using best available data. Actual lab data by layer is used for CEMA, Coke Beach, and U-Cell. Site-specific data from another study was used for Cell-11A (Macyk, 2006). All other sites had their sand breakdowns estimated based off of their silt contents, which is correlated to very fine sand contents (unpublished data[19]).

Both the S&R and A&P equations allow the estimation of water-retention curves (WRC, volumetric water content vs. tension) for each material. In the A&P model, which does not specify the field capacity tension (Tfc) for calculating AWSC from the WRC, Tfc is estimated between 5 and 33 kPa for each sample based on fine-fraction sand content, with coarser samples receiving a lower Tfc. This Tfc value is used in the profile layering corrections described below.

In recognition of the different applicability of the two models (A&P for unstructured vs. S&R for structured, natural soils), the final AWSC value for each layer is calculated as a weighted mean between the A&P and S&R results, with weighting derived from total-soil (as opposed to fine-fraction) OM and clay contents, which are used as proxies for aggregation. Litter layers are assigned an AWSC value of 185 mm/m based on relevant literature (Heineman, 1998).

Novel reclamation materials, coke, coke-tailings (CT), and peat-mineral mixes (PMM), are assigned AWSC values using volume-weighted calculations that combines mineral-soil AWSC

[18] Pit counts by site are variable but the ratio of vegetation plots to soil pits does not exceed 4:1.

[19] While silt and very fine sand contents are significantly correlated, other sand size-fractions do not correlate well to other PSD values. Therefore, the mean ratio of fine to medium-and-coarser sand is used to apportion the remaining sand fractions after VF sand is estimated from silt contents. This is done separately for each material.

values with peat (290 mm/m[20]) and coke (28 mm/m[20]), based on volume estimates from survey notes and photos.

The material AWSC values for each layer in a soil pit are depth-weighted and summed across the upper metre to give a pit AWSC. As layers are compiled, the effects of layering on AWSC are estimated using Clothier et al.'s (1977) model, again based on the capillary equation. This model does not account for AWSC effects of coarse-over-fine layering situations, which is a shortcoming of the current approach. However, most layering observed in this project was of the fine-over-coarse type (e.g. mineral subsoil over tailings), so are therefore covered. Layering adjustments were not applied to high-peat PMM samples as hydraulic continuity between mineral layers is an assumption of the Clothier model.

Once layers are adjusted, they are summed into a profile AWSC for the upper metre. The final step is to adjust the profile AWSC for the topographical effects of slope and aspect. Modelled solar-radiation differences across latitudes, slopes and aspects are used to produce modifiers (additions or deductions) to the energy-neutral profile AWSC estimate. These modifiers are intended not to imply actual reductions or additions to AWSC on different slopes and aspects, but as surrogate modifiers to AWSC to reflect increased or decreased evapotranspirative demand driven by varying energy regimes. Short-wave radiation was calculated for different slopes, aspects and latitudes as the sum of the direct- and diffuse-beam components. The theoretical direct-beam component of solar radiation was determined after Garnier and Ohmura (1968, 1970). Diffuse clear-sky radiation was calculated assuming a standard atmosphere after Iqbal (1983). These modelled values were then converted to additions or deductions to AWSC (in mm water per m material depth) by indexing to a neutral energy regime defined by radiation received on flat ground at a given latitude. Energy correction values are calculated as percent increases or decreases based on percent difference of radiation values for a given slope-aspect position from the mean neutral radiation value. Thus, positions receiving higher radiation receive a proportional decrease to their profile AWSC, and vice versa.

Application of this energy-correction approach to the 15 study sites resulted in 8 sites being assigned a neutral energy correction, 6 sites being assigned AWSC deductions (ranging from -1 to -8 mm/m), and 1 site being assigned an addition (+2 mm/m). These are relatively small effects, which do not influence our RSMR or ASMR classifications, due to muted topography at study sites.

[20] Calculated from water-retention curves and bulk density from Wolter (2012). Alternate values of 0 to 25 mm/m, depending on coke texture, have been reported (MDH, 2005).

Table D-1. Soil properties and AWSC calculations for one representative profile per site. Among the layer AWSC columns at right, the PMM or CT value takes precedence over the weighted mean when both are present. The profile AWSC is calculated by multiplying the depth interval by the layer AWSC.

Site	n	Material type	cm		Compaction	% of whole soil		% of sub-2 mm fraction			OM (% wt)	Sand VC-M / F / VF	Sand breakdown origin	Material AWSC, mm/m				Notes
			Upper depth, mean	Lower depth, range		Peat or coke (% vol)	CF % wt)	Sand	Silt	Clay				A&P	S&R	Wtd. mean	LFH, PMM or CT re-calc.	
CEM A	4	Litter	-2	0	-	-	-	-	-	-	-	-	-	-	-	-	185	
		Glaciofluv.	0	100	None	-	2.4	97.4	1.2	1.4	0.4	89 / 11 / 1	tested 2017	10.1	33.4	12.2	-	
U-CELL	1	Coke-Tailings	0	34	None	70	-	-	-	-	-	-	-	64	61.6	62.8	38.4	
		Tailings	34	100	Slight	-	2.2	83.4	12	4.6	2.3	19 / 75 / 6	tested 2017	62.4	53.9	58.1	-	
NW	4	Mineral soil	0	32-41	Slight	-	25.6	49.7	33.6	16.7	3.9	43 / 42 / 15	est. - 2017 results	89.5	104.4	102.6	-	
		Tailings	38	100	Slight	-	0	94.4	4.2	1.4	0.4	52 / 44 / 4	est. - literature	70.9	29.4	50.2	-	
SWSS	4	PMM	0	46-66	None	5	12.6	31.7	27.2	41.1	3.5	45 / 43 / 12	est. - 2017 results	86.5	124.2	120.4	129.3	
		Tailings	52	100	None	-	0	88.6	6.8	4.6	0.5	50 / 43 / 7	est. - literature	49.1	46.5	47.8	-	
JP	4	Litter	-2	0	-	-	-	-	-	-	-	-	-	-	-	-	185	
		PMM	0	45-60	Slight	9	2.8	32.4	26.2	41.4	3.4	45 / 44 / 11	est. - 2017 results	84.7	116.7	113.3	129.4	
		Tailings	55	100	None	-	0	92	7	1	0.3	50 / 43 / 7	est. - literature	76.5	43.6	60.1	-	
CB	3	PMM	0	36-68	Slight	29	10.6	36.6	32.3	31.1	9.7	42 / 43 / 15	tested 2017	118	119.9	125.1	171.5	
		Coke	49	100	Loose	-	-	-	-	-	-	-	-	-	-	-	28	
C-11A	4	PMM	0	13-38	None	49	11.3	60.8	23.5	15.7	8.4	46 / 44 / 10	est. - 2017 results	111.8	121.5	122.4	205.7	
		Tailings	28	100	None	-	0	96.6	1.9	1.5	0.4	47 / 44 / 9	from Macyk (1996)	90.4	36	63.2	-	
NW-SLOPE	7	PMM	0	20-56	None	20	18.3	42.6	28.8	28.6	13.4	44 / 43 / 13	est. - 2017 results	107.6	137.6	137.5	164.8	Site spans several polygons. Most had low-peat PMM over mineral subsoil (secondary). Tailings sampled at one site
		Mineral (6 pits)	31	100	Loose	-	15.8	41.5	29.8	28.7	5	44 / 43 / 13	est. - 2017 results	76.9	101.2	98.9	-	
		Tailings (1 pit)	56	100	None	-	1.1	97.4	1.8	0.8	0.4	53 / 45 / 1	est. - literature	65.1	32	48.5	-	
SBH	4	Litter	-2	0	-	-	-	-	-	-	-	-	-	-	-	-	185	SSOB is beyond modelled profile
		PMM	0	16-34	None	81	7.7	33.1	32.5	34.3	28.4	43 / 42 / 15	est. - 2017 results	123.9	143.9	143.9	262.5	
		Mineral soil	22	100	Slight	-	0	38.6	25.1	36.4	1	45 / 44 / 11	est. - 2017 results	95.9	123.5	114.4	-	
		SSOB	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
SHW-2	2	PMM	0	31-34	None	90	0	42.7	36.6	20.6	43.5	42 / 41 / 17	est. - 2017 results	243.2	164.9	204	281.4	There are two profile designs at this site, with two pits in each.
		Tailings	33	62-100	None	-	0	99.6	0.3	0.1	0.3	54 / 45 / 1	est. - literature	78.5	23.2	50.9	-	
		Mineral	84	100	None	-	4	47.1	26.7	26.1	14.1	45 / 44 / 12	est. - 2017 results	131.7	125.2	128.6	-	
	2	PMM	0	45-72	None	90	0	42.7	36.6	20.6	43.5	42 / 41 / 17	est. - 2017 results	243.2	164.9	204	281.4	
		Mineral	59	100	None	-	4	47.1	26.7	26.1	14.1	45 / 44 / 12	est. - 2017 results	131.7	125.2	128.6	-	
SHW-1	4	PMM	0	51-63	None	91	0	49.4	35.1	15.5	41.7	43 / 41 / 16	est. - 2017 results	258.3	161.8	210	283	
		Mineral soil	58	100	None	-	4.1	45.7	25	29.3	0	45 / 44 / 11	est. - 2017 results	89.1	110.4	100.8	-	

Table D-1 (continued). Soil properties and AWSC calculations for one representative profile per site. Among the layer AWSC columns at right, the PMM or CT value takes precedence over the weighted mean when both are present. The profile AWSC is calculated by multiplying the depth interval by the layer AWSC.

Site	n	Material type	cm		Compaction	% of whole soil		% of sub-2 mm fraction			OM (% wt)	Sand VC-M / F / VF	Sand breakdown origin	Material AWSC, mm/m			
			Upper depth, mean	Lower depth, range		Peat or coke (% vol)	Peat or coke (% vol)	Sand	Silt	Clay				A&P	S&R	Wtd. mean	LFH, PMM or CT re-calc.
P40-N	4	Litter	-7	0	-	-	-	-	-	-	-	-	-	-	-	-	185
		Morainal	0	100	Slight	-	5.8	44.1	34	22	0.4	65 / 25 / 10	est. - 2017 results	111.6	111.8	111.9	-
P40-S	4	Litter	-8	0	-	-	-	-	-	-	-	-	-	-	-	-	185
		Morainal	0	100	Slight	-	1.6	50.2	31.7	18	0.1	65 / 25 / 10	est. - 2017 results	111.1	102.2	106.7	-
P43-N	4	Litter	-8	0	-	-	-	-	-	-	-	-	-	-	-	-	185
		Morainal	0	100	Slight	-	2	38.1	42.7	19.1	0.3	65 / 25 / 10	est. - 2017 results	146.3	127.2	136.7	-
P43-S	4	Litter	-7	0	-	-	-	-	-	-	-	-	-	-	-	-	185
		Morainal	0	100	Slight	-	1.5	38.5	37.1	24.4	0.6	65 / 25 / 10	est. - 2017 results	128.2	123.1	126.3	-

Table D-2. Summary of energy corrections and AWSC results using four energy-adjusted approaches (our final weighted mean; Saxton & Rawls, 2006; Arya & Paris, 1981; the LCCS). Results are ordered roughly from driest to wettest, but Reference - Fresh sites are placed together at the bottom of the table.

Site	Slope, %	Aspect	Energy correction, % adjustment	AWSC, mm/m			
				Final, energy-corrected	Saxton & Rawls, energy-corrected	Arya & Paris, energy-corrected	LCCS
CEMA	0	-	0	16	38	14	80
U-CELL	0	-	0	51	56	63	83
NW	0	-	0	70	63	83	118
SWSS	10	250	-0.5	90	92	72	138
CB	1	-	0	97	85	100	98
JP	2	-	0	101	91	88	139
C-11A	10	169	-1	103	64	99	118
NW-SLOPE	23	234	1.7	119	112	90	153
SBH	1	-	0	151	133	107	170
SHW-2	0	-	0	173	111	167	134
SHW-1	4	-	0	205	140	186	162
P40-S	9	160	-0.3	122	117	126	140
P40-N	11	200	-2.4	122	122	122	166
P43-S	15	196	-5.6	133	130	135	151
P43-N	8	113	0	150	141	160	151

AWSC Results and discussion

Soil survey data and model results are presented in two tables above. Table D-1 lays out the contributing AWSC calculations by layer at each site and allows the site summaries in Table D-2 to be interpreted. The range of profile AWSC results from our approach (16-205 mm) is wider than the LCCS range (80-170 mm) (Table D-2). We believe that these differences are meaningful because the wider range of AWSC values is reflective of the literature and expected results from theory. Our assertion applies to two of the major reclamation materials, tailings and PMM, and seems important for further consideration towards the goal of reclaiming dry ecosystems.

The considerable range of particle sizes (and associated surface areas and pore sizes) that comprise the sand fraction (0.053-2 mm) indicate that there should be meaningful differences between sand subclasses in their propensity to retain plant-available water. This is not reflected in the LCCS, which assigns the same AWSC value to all tailings sand. The relationship of sand-size breakdown and AWSC is backed up by the data of Macyk (2006), which shows strong positive correlation between pressure-plate AWSC and depth-weighted very-fine sand (VFS), silt (Si), and clay (Cl) contents of tailings sands and coarse Brunisols[21]. In other studies[22], the AWSC of oilsands coarse tailings has been reported between 13 and 125 mm/m (n=20, mean=47, median=37), as compared to our modelled values of 43-68 mm/m (n=29, mean=54, median=53). The standard LCCS value of 100 mm/m is higher than both approaches.

The LCCS distinguishes between AWSC values for coarse- and fine-textured PMM (120 and 170 mm/m, respectively), but is without reference to peat content. We believe peat content to be the most important AWSC determinant of PMM because of the discrepancy in water storage between peat and mineral materials. Peat AWSC values have been reported from 50 to 490 mm/m (n=17, mean=288, median=300)[23]. This overlaps with but overall is greater than the AWSC of most mineral soils, which are typically between 30 and 200 mm/m, rarely exceeding 300 mm/m.

Our surveys found PMM peat contents ranging from 5% (SWSS, JP) to 90% (SHW-1, SHW-2), and our modelled AWSC values were between 112 and 286 mm/m (n=73, mean=203, median=194). This is in good agreement with PMM AWSC values in other studies[24] (n=5, range=116-240, mean=184). All approaches support a low-end AWSC estimate of about 120 mm/m but the LCCS apparently underestimates the high-end of PMM AWSC.

We believe that further development of AWSC approaches for tailings and PMM would allow more accurate better water balance calculations, which can facilitate understanding of the role water deficits play in shaping revegetation outcomes, as well as the function of xeric sites for yielding water within landscape-level water balances.

[21] From IEG's reanalysis of Macyk's (2006) published survey and AWSC data.
[22] All but one of these are pressure-plate results, the other is a field assessment. Only coarse tailings, such as those identified as beach sands, dyke materials were used, not fine tailings. Sources: Moskal and Leskiw, 1999; M.D. Haug & Associates, 2001; MDH Engineered Solutions, 2005; Macyk, 2006.
[23] All are apparently laboratory results. All peat AWSC values were used with the exception of live sphagnum samples. Sources: Boelter, 1968; Moskal, 1999; Moskal and Leskiw, 1999; Letts et al., 2000; MDH Engineered Solutions, 2005; Dimitre et al., 2010, 2014; O'Kane Consultants, 2018.
[24] One of five samples is a field result. Sources: Moskal, 1999; Moskal and Leskiw, 1999.

Appendix E. Water-balance analyses

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 (see ASMR definition in Appendix A). Based on our preliminary work, water deficits constraining ET would be projected to occur in roughly 90% of years on the Very Dry CEMA reference site, in roughly 70–90% of years in the Moderately Dry reclaimed sites, in 55–65% of years in the Slightly Dry reclaimed sites, and in 20-40% of years in the Fresh reclaimed and URSA reference sites (Table E-1).

Analysis integrating long-term Environment Canada climate records and water balance parameters derived from our AWSC and PET values (Table E-1) is helpful to place AWSC values within their climatic context. 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 the Red Earth Creek station in order to estimate the mean soil water deficit and the percent of years in which a soil water deficit would have taken place. This soil water deficit is defined in relation to PET and AWSC over the JJA and MJJAS periods.

PET values for the JJA period are derived from our dataset mean for the Fort McMurray and URSA sites. For the MJJAS period, May and September are not covered by our PET dataset and have been estimated using values for Ft. McMurray and Slave Lake from a provincial dataset (AESRD, 2013b). Due to incompatibilities in PET calculation methodologies, we cannot use the AESRD values directly; rather, the mean ratio of our monthly PET to ESRD PET in each study area was determined for the JJA period and used to scale the May and September AESRD values into reasonable equivalents for our study.

The difference between PET and AWSC (using a simplifying assumption of fixed PET for all years) for each site is the precipitation (P) deficit (pDef), which is the required P in a mean PET year to prevent water deficit in the JJA or MJJAS period. The shortfall (or surplus) in actual P for each of the long-term record years is the soil water deficit (sDef). The percent of years in the long-term record in which a soil water deficit occurred (sDef.pc) is a parallel metric. These soil water deficit metrics were also included in flux correlation analysis and ranked highly among covariates, particularly for explaining AET (Appendix F).

$pDef = PET\text{-}AWSC$; simplified as constant value for all years.

$sDef = pDef\text{-}P_{annual}$; variable for each year of the data record.

$sDef.pc = [\#\ of\ years\ with\ positive\ sDef]\ /\ [\#\ of\ years\ in\ data\ record]$

Table E-1. Summary of water balance analyses by site.

Reclaimed / Reference (disturbance)	Area	Site	Substrate	Reclamation Cover Depth (cm)	AWSC (mm in upper 1 m)	Actual SMR (maximum AET[25]/PET)	Percent of Years with MJJAS Water Deficit[26]	Mean Annual Yield (mm)[27]	Proportion of Years with Water Yield[9]
Reference (fire)	NE of Suncor	CEMA Jack Pine	Glaciofluvial sand	n/a	16	Very Dry (68%)	98%	95	95%
Reclaimed	Syncrude	U-shaped Cell	Tailings / coke	0	51	Moderately Dry (76%)	90%	60	90%
Reclaimed	Suncor	Nikanotee Watershed Upland	Tailings	30-40	70	Moderately Dry (80%)	85%	45	80%
Reclaimed	Syncrude	Southwest Sand Storage	Tailings	45-65	90	Moderately Dry (84%)	75%	25	75%
Reclaimed	Syncrude	Coke Beach	Coke	35-70	97	Moderately Dry (85%)	75%	20	70%
Reclaimed	Syncrude	Jack Pine	Tailings	45-60	101	Moderately Dry (88%)	70%	10	65%
Reclaimed	Suncor	Cell 11A	Tailings	15-40	103	Moderately Dry (88%)	70%	5	65%
Reclaimed	Suncor	Nikanotee Watershed Side-Slopes	Tailings / secondary	20-55	119	Slightly Dry (91%)	65%	~0	55%
Reclaimed	Syncrude	South Bison Hill	Saline-sodic overburden	100+	151	Slightly Dry (98%)	55%	~0	45%
Reclaimed	Syncrude	Sandhill Watershed Perched Upland	Tailings	30-70	174	Fresh (100%)	40%	~0	45%
Reclaimed	Syncrude	Sandhill Watershed Upland	Tailings	50-65	205	Fresh (100%)	20%	~0	30%
Reference (harvest)	URSA	P40 Juvenile North-Facing	Morainal	n/a	122	Fresh (100%)	30%	~0	50%
Reference (harvest)	URSA	P40 Juvenile South-Facing	Morainal	n/a	122	Fresh (100%)	25%	~0	45%
Reference (fire)	URSA	P43 Mature South-Facing	Morainal	n/a	133	Fresh (100%)	25%	~0	45%
Reference (fire)	URSA	P43 Mature North-Facing	Morainal	n/a	150	Fresh (100%)	20%	~0	40%

[25] 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.

[26] Calculated based on a 64-year climate record from Fort McMurray (1944-2007) and a 49-year climate record from Red Earth Creek (1959-2007), where a deficit is defined as a year in which May-Sept. P + AWSC is less than PET.

[27] Calculated as the average annual difference between P and maximum AET.

Appendix F. Relationships between flux and non-flux metrics

Flux-LAI relationships in literature

The equations relating LAI to AET and NEP used by Huang et al. (2011) are quite similar to the results from this study. The slope of the LAI-AET relationships from the two studies are very similar but the y-intercept of the Huang equation is much lower (Figure F-1).[28] Their LAI-NEP equation is nearly identical to the linear fit through our data (Figure F-2), although the logarithmic fit for our data is actually stronger (Figure 11).

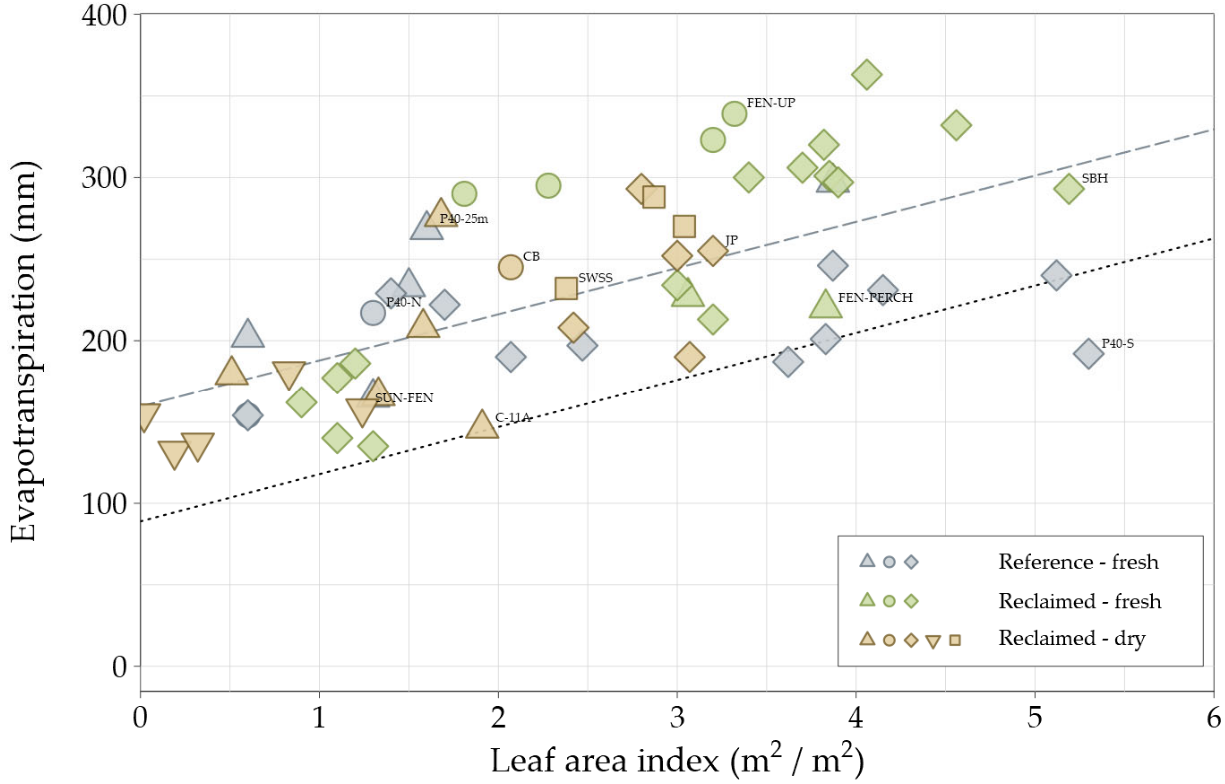


Figure F-1. The relationship between LAI and AET in our dataset with a linear fit (dashed line), plotted in comparison to the LAI-AET equation from Huang et al. (2011) (dotted line).

[28] The discrepancy between y-intercepts may be related to the fact that Huang et al.'s LAI-AET relationship is a two-step process requiring conversion of LAI to NEP and then NEP to AET. While their LAI-NEP relationship compares well to our data (Figure F-2), their NEP-AET relationship is from a global review paper and may not represent boreal ecosystems well.

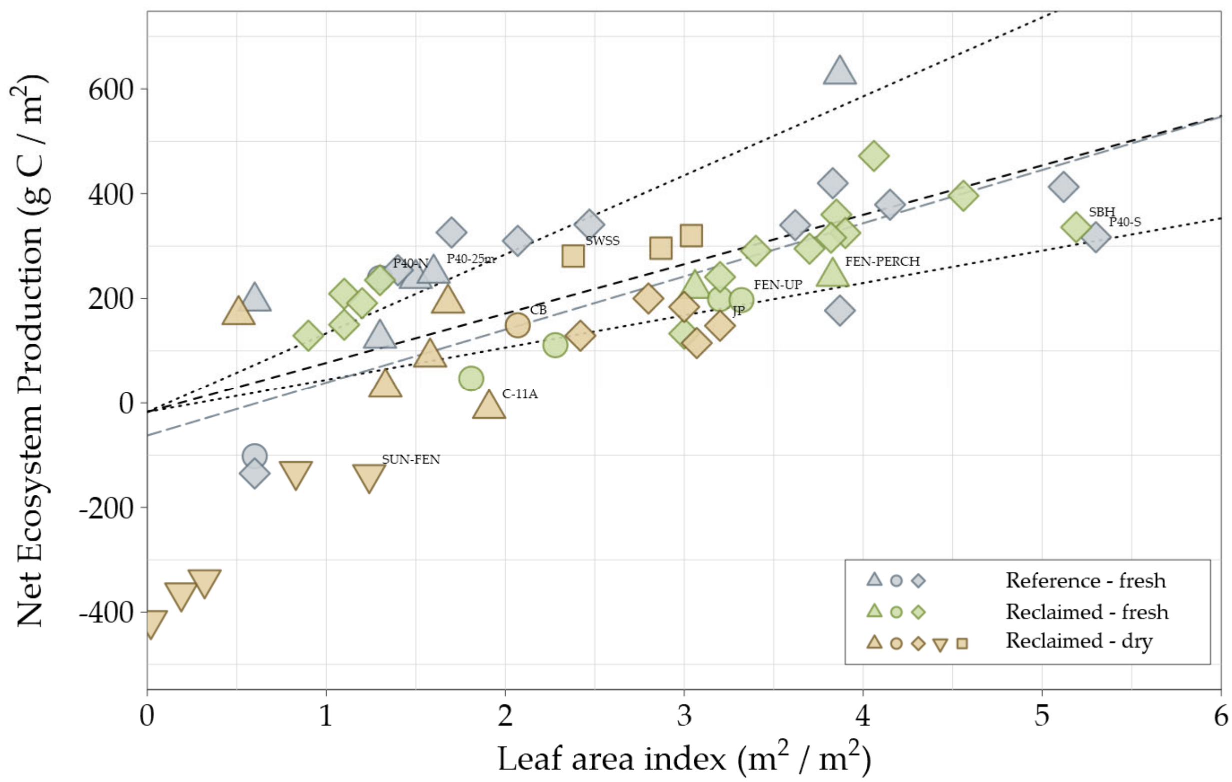


Figure F-2. The relationship between LAI and NEP with linear fit (long-dashed line) plotted with Huang et al.'s (2011) prediction of mean (short-dashed line), minimum and maximum NEP values (dotted lines).

Flux-biometric relationships in the current study

In the first step to identify the non-flux metrics that have the strongest correlation with flux measurements, we ran linear, polynomial (2nd order), and logarithmic regressions for all possible pair combinations of flux and non-flux metrics. The regression results for all non-flux correlates with linear R^2 values greater than 0.1 and sample number equal to or greater than 12 are presented below. In many cases, polynomial fits had high R^2 but the relationship was not theoretically sound, which was identified in subsequent screening steps.

Table F-1. Summary of regression results for non-flux measurements versus AET.

AET covariate	n	Linear R^2	Best regression type	Best R^2	n, reclaimed only	Linear R^2, reclaimed only
LAI (lab original)	38	0.592	polynomial	0.593	23	0.643
Percent of years with MJJAS soil water deficit	24	0.525	linear	0.533	19	0.617
Mean MJJAS soil water deficit	24	0.502	linear	0.51	19	0.635
Total LAI (all)	58	0.416	polynomial	0.494	40	0.642
Vegetation cover, percent	18	0.407	polynomial	0.43	13	0.62
Percent of years with JJA soil water deficit	24	0.378	polynomial	0.428	19	0.631
Total LAI (IEG)	24	0.306	polynomial	0.422	19	0.624
Potential evapotranspiration	63	0.293	polynomial	0.362	44	0.323
Canopy LAI (all)	58	0.291	polynomial	0.299	40	0.304
Wilson's spacing factor	17	0.286	polynomial	0.291	12	0.486
Mean JJA soil water deficit	24	0.281	polynomial	0.492	19	0.635
AWSC	63	0.209	polynomial	0.214	44	0.235
Tree cover, percent	17	0.183	log	0.333	12	0.458
Canopy LAI (IEG)	24	0.165	polynomial	0.201	19	0.217

Table F-2. Summary of regression results for non-flux measurements versus NEP.

NEP covariate	n	Linear R^2	Best regression type	Best R^2	n, reclaimed only	Linear R^2, reclaimed only
Total LAI (IEG)	24	0.853	polynomial	0.937	19	0.872
Vegetation cover, percent	18	0.812	polynomial	0.825	13	0.934
Wilson's spacing factor	17	0.747	polynomial	0.768	12	0.792
Mean JJA soil water deficit	24	0.524	polynomial	0.701	19	0.407
Total LAI (all)	58	0.512	log	0.642	40	0.595
Percent of years with JJA soil water deficit	24	0.495	polynomial	0.697	19	0.403
Tree cover, percent	17	0.486	log	0.658	12	0.454
Mean MJJAS soil water deficit	24	0.42	polynomial	0.799	19	0.407
Canopy LAI (IEG)	24	0.37	log	0.446	19	0.373
Percent of years with MJJAS soil water deficit	24	0.36	polynomial	0.77	19	0.379
LAI (lab original)	38	0.326	log	0.364	23	0.401
Understory LAI (all)	26	0.308	polynomial	0.576	19	0.248
Canopy LAI (all)	58	0.26	polynomial	0.273	40	0.357
Quadratic mean diameter	12	0.254	log	0.437	-	-
Stand density index	12	0.171	log	0.448	-	-
Basal area	12	0.144	log	0.45	-	-
Age	63	0.131	log	0.38	44	0.194
AWSC	63	0.109	polynomial	0.459	44	0.157

Table F-3. Summary of regression results for non-flux measurements versus GEP.

GEP covariate	n	Linear R^2	Best regression type	Best R^2	n, reclaimed only	Linear R^2, reclaimed only
Vegetation cover, percent	18	0.694	linear	0.694	13	0.889
Total LAI (IEG)	24	0.581	polynomial	0.68	19	0.926
Total LAI (all)	58	0.544	polynomial	0.611	40	0.784
Wilson's spacing factor	17	0.544	polynomial	0.573	12	0.675
LAI (lab original)	38	0.493	linear	0.493	23	0.474
Canopy LAI (IEG)	24	0.427	polynomial	0.436	19	0.492
Canopy LAI (all)	58	0.413	polynomial	0.42	40	0.485
Tree cover, percent	17	0.343	log	0.426	12	0.55
Mean MJJAS soil water deficit	24	0.333	polynomial	0.554	19	0.375
Percent of years with MJJAS soil water deficit	24	0.329	polynomial	0.538	19	0.352
Percent of years with JJA soil water deficit	24	0.278	polynomial	0.644	19	0.388
Mean JJA soil water deficit	24	0.211	polynomial	0.746	19	0.375
Age	63	0.153	log	0.298	44	0.171
AWSC	63	0.136	polynomial	0.253	44	0.145
Stand density index	12	0.122	polynomial	0.452	-	-
Quadratic mean diameter	12	0.121	log	0.263	-	-
Potential evapotranspiration	63	0.106	polynomial	0.148	44	0.172

Each of the relationships identified in the Tables F-1 to F-3 was screened in detail. Covariates were assessed by regression strength, sample count and distribution, and fit to expected theoretical relationships. Multiple regressions combining top-ranked covariates were tentatively explored for all fluxes, but none provided statistically significant results that strongly improved upon single regressions.

- Biometric correlations to AET were relatively weak compared to those of C fluxes with all linear R^2 values below 0.6. The strongest of AET correlations are from soil water deficit and vegetation cover (including LAI) metrics (Table F-1, Figures F-3 to F-5).
- Much stronger correlations were found with NEP (Table F-2, Figures F-6 and F-7), where three covariates have linear R^2 values over 70%: total LAI (IEG measurements only), vegetation cover, and Wilson's spacing factor (Wsf). Of these, the LAItot.IEG relationship has the highest sample number, the most even distribution of points, and the advantage of being annually variable as compared to Wsf.
- The top-ranked covariates for GEP are similar to those for NEP but with generally weaker correlations. This might be expected at least in part because GEP is not directly measured but dependent on estimated respiration fluxes.
- The rightmost columns in Tables F-1 to F-3 show that there were often stronger correlations within the reclaimed site data than the larger dataset. However, it is likely that differences in climate (slightly wetter and lower PET at URSA) and stand type (pure aspen at URSA) contribute to this variation as much or more than any functional differences between reclaimed and reference sites.

Scatterplot matrices of biometric-flux regressions

The following figures summarize flux regression performance of a wider array of biometric variables than are discussed in the text above. In these figures, the R^2 and p-values in the upper section correspond to the mirror-image scatterplot (i.e. upper-right values correspond to lower-left plot). The trend lines and the regression summary statistics are for linear relationships with R^2 values greater than 0.4 and p-values less than 0.05 flagged by text colour.

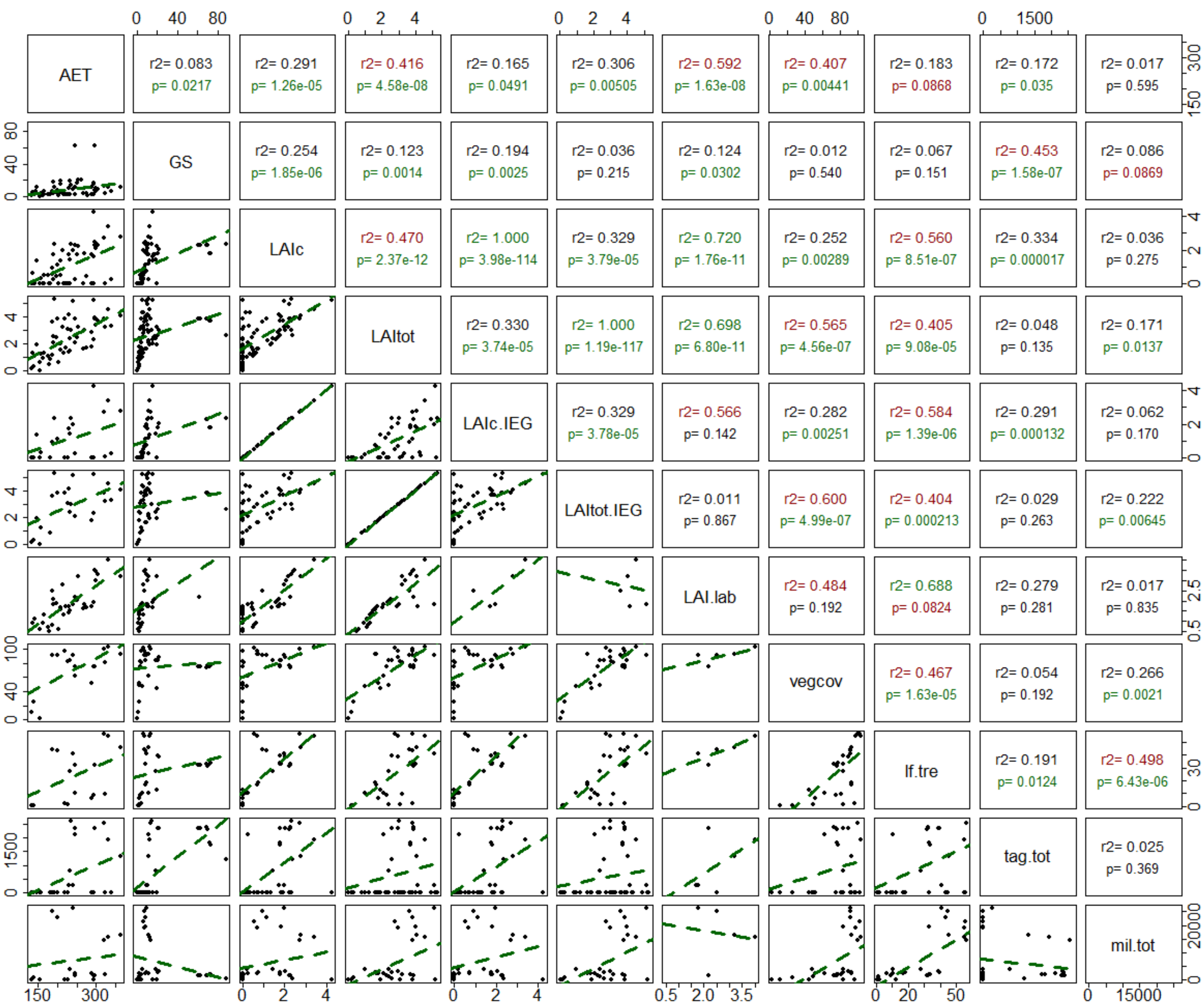


Figure F-3. Scatterplot matrix showing regression strength of AET versus age, vegetation cover, and tree density metrics - age (GS), canopy LAI from all sources (LAIc), total LAI from all sources (LAItot), canopy LAI by IEG (LAIc.IEG), total LAI by IEG (LAItot.IEG), original Carey/Petrone LAI (LAI.lab), percent vegetation cover (vegcov), percent tree cover (lf.tre), tagged tree density (tag.tot), milhectare stem density (mil.tot).

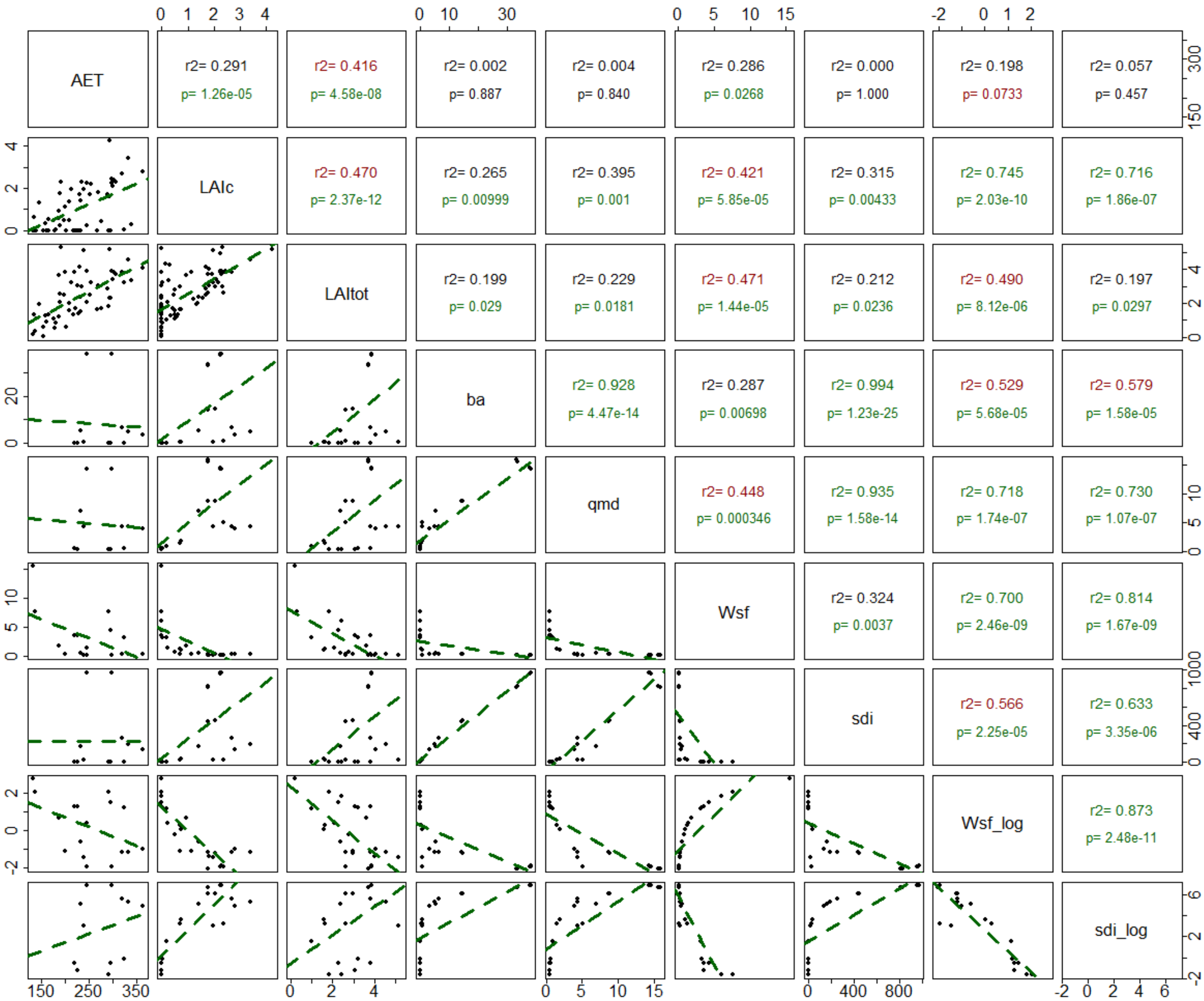


Figure F-4. Scatterplot matrix showing regression strength of AET versus LAI and forestry metrics - basal area (ba), quadratic mean diameter (qmd), Wilson's spacing factor (Wsf), stand density index (sdi), and logs of Wsf and sdi.

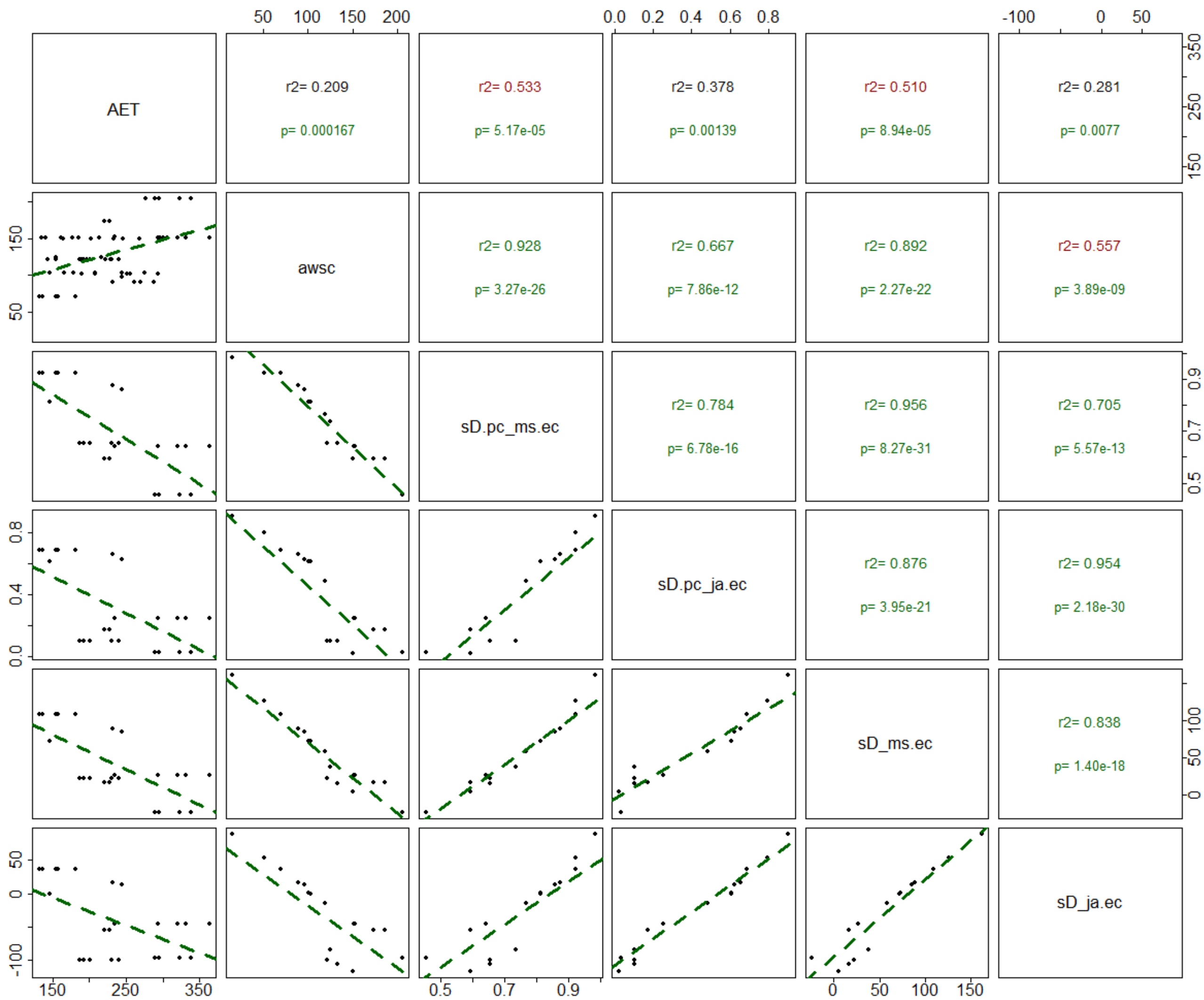


Figure F-5. Scatterplot matrix showing regression strength of AET versus AWSC and soil water deficit metrics. Percent of years with MJJAS soil water deficit (sD.pc_ms.ec), percent of years with MJJAS soil water deficit (sD.pc_ja.ec), mean MJJAS soil water deficit (sD_ms.ec), mean JJA soil water deficit (sD_ja.ec).

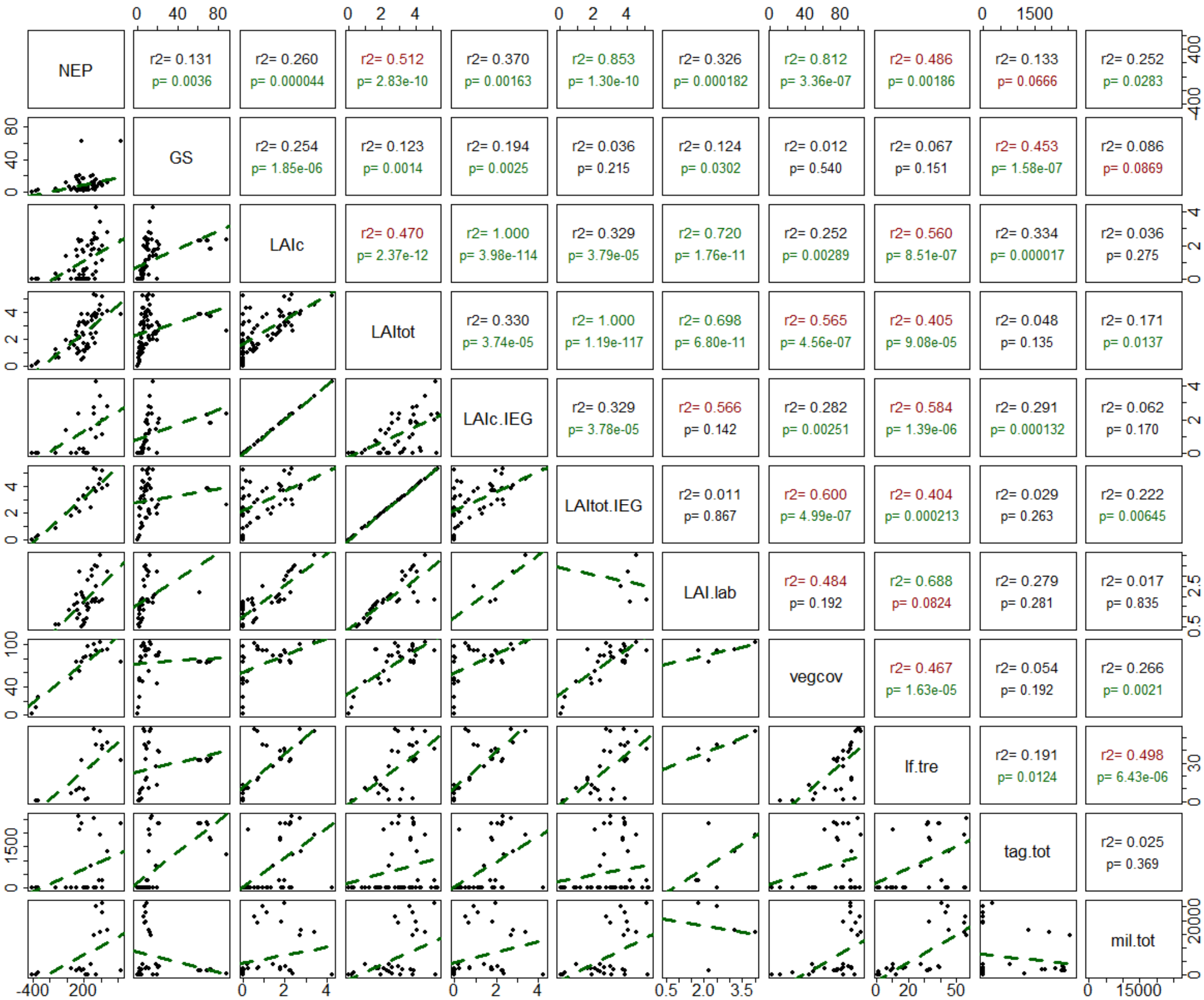


Figure F-6. Scatterplot matrix showing regression strength of NEP versus age, vegetation cover, and tree density metrics - age (GS), canopy LAI from all sources (LAIc), total LAI from all sources (LAItot), canopy LAI by IEG (LAIc.IEG), total LAI by IEG (LAItot.IEG), original Carey/Petrone LAI (LAI.lab), percent vegetation cover (vegcov), percent tree cover (lf.tre), tagged tree density (tag.tot), milhectare stem density (mil.tot).

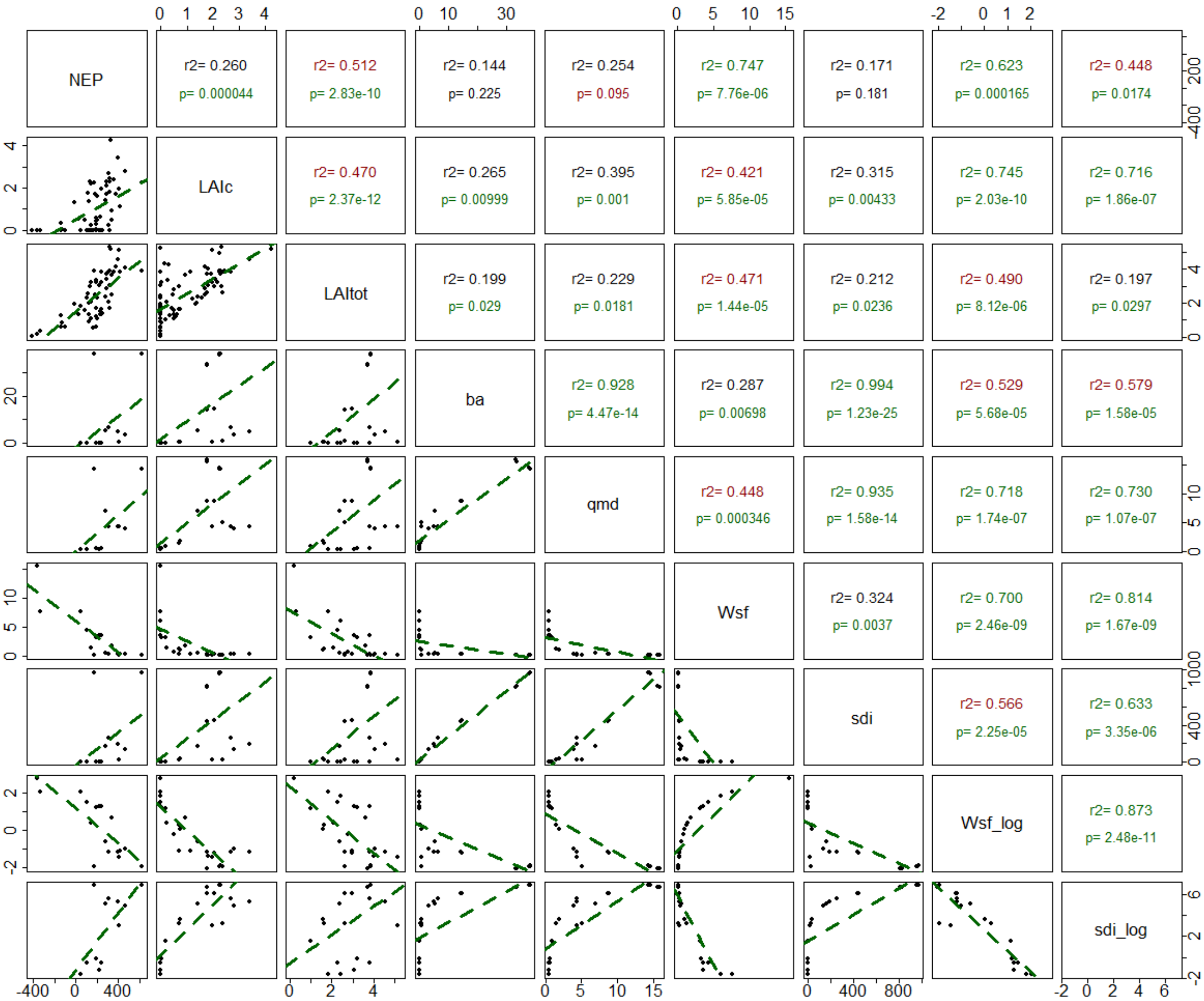


Figure F-7. Scatterplot matrix showing regression strength of NEP versus LAI and forestry metrics - basal area (ba), quadratic mean diameter (qmd), Wilson's spacing factor (Wsf), stand density index (sdi), and logs of Wsf and sdi.

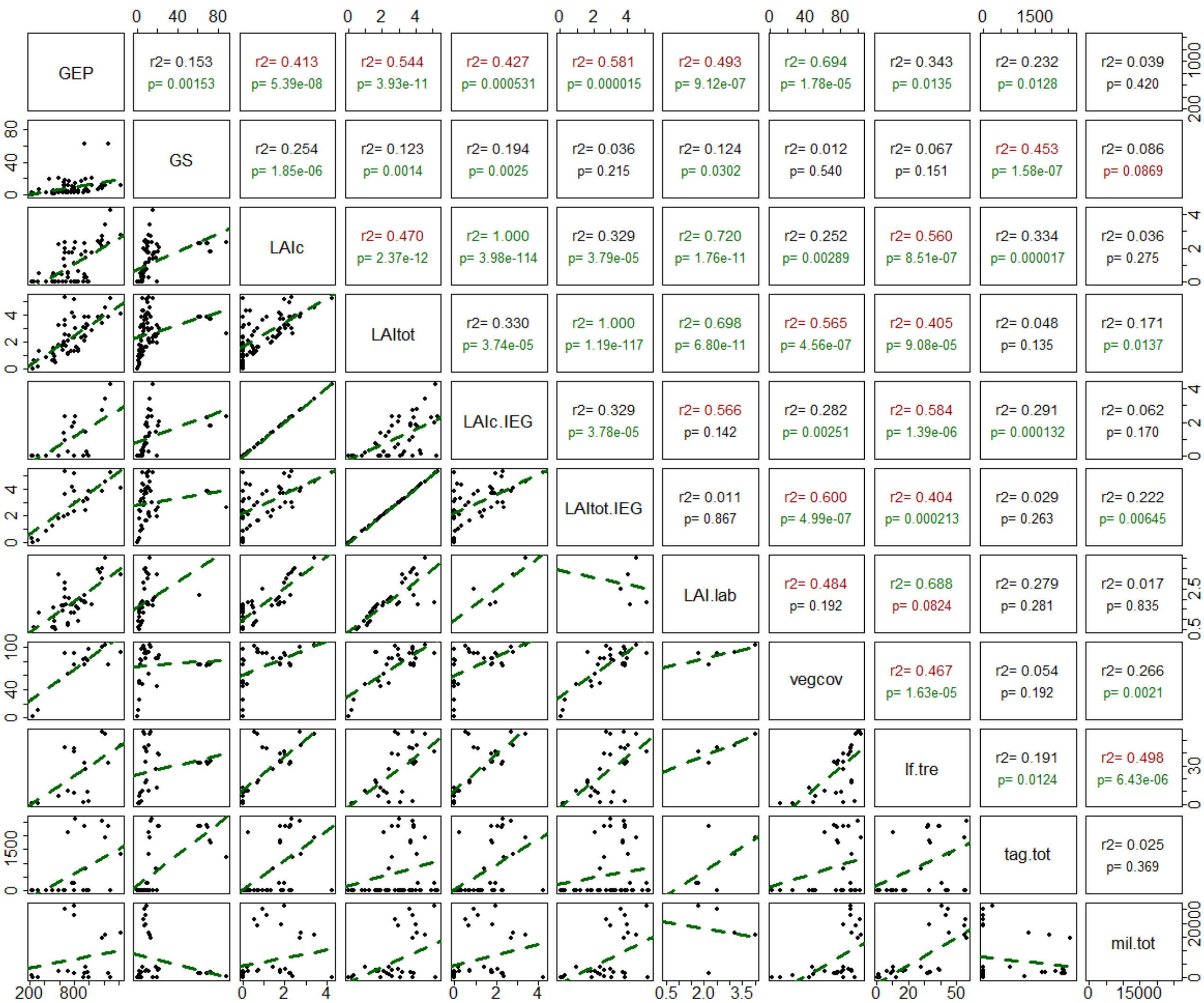


Figure F-8. Scatterplot matrix showing regression strength of GEP versus age, vegetation cover, and tree density metrics - age (GS), canopy LAI from all sources (LAIc), total LAI from all sources (LAItot), canopy LAI by IEG (LAIc.IEG), total LAI by IEG (LAItot.IEG), original Carey/Petrone LAI (LAI.lab), percent vegetation cover (vegcov), percent tree cover (lf.tre), tagged tree density (tag.tot), milhectare stem density (mil.tot).

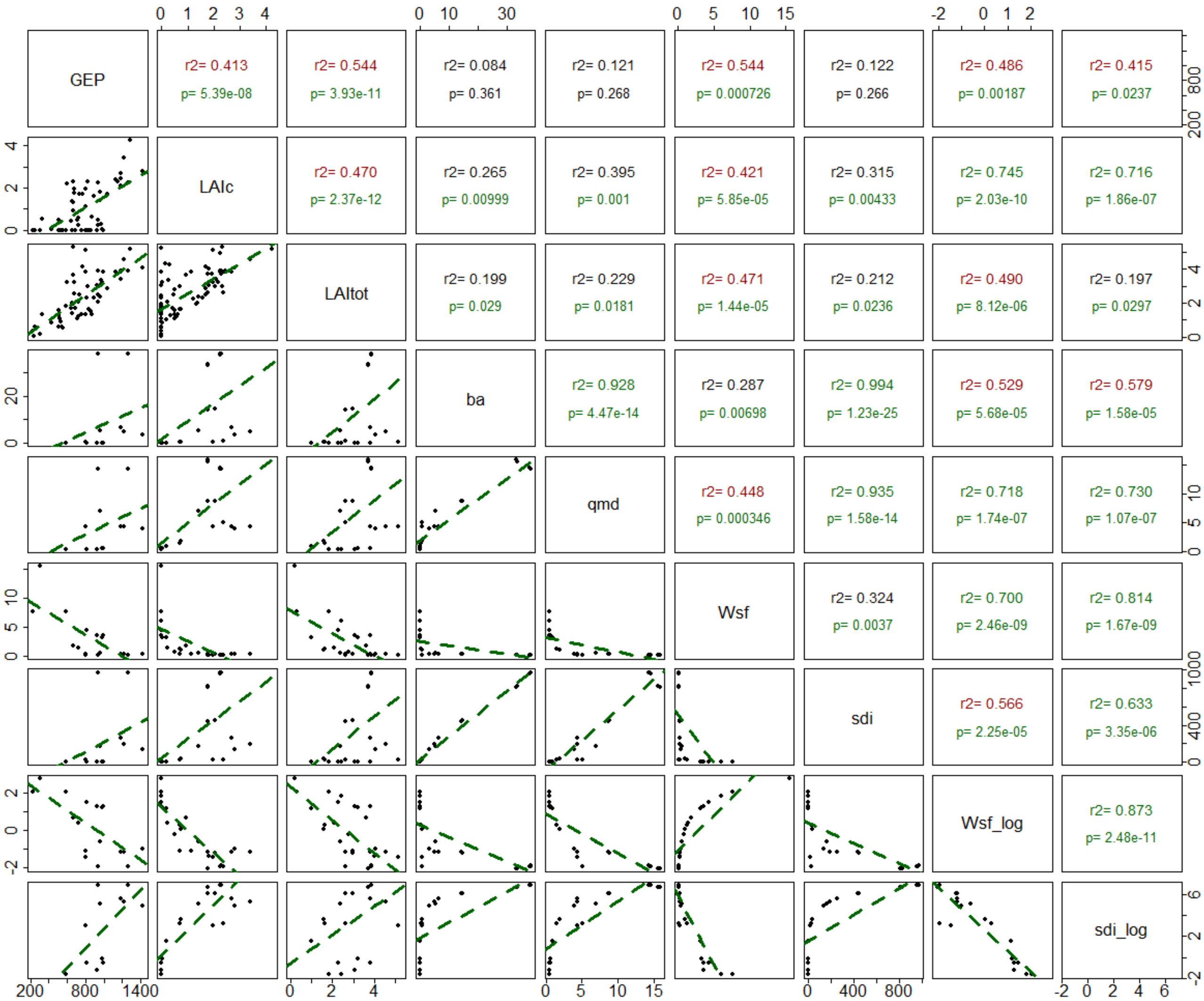


Figure F-9. Scatterplot matrix showing regression strength of GEP versus LAI and forestry metrics - basal area (ba), quadratic mean diameter (qmd), Wilson's spacing factor (Wsf), stand density index (sdi), and logs of Wsf and sdi.