Functioning of reclaimed oil sands ecosystems and the
implications for reclamation certification

by

Stacey Lynne Strilesky

A thesis submitted to the Faculty of Graduate and Postdoctoral
Affairs in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Geography

Carleton University
Ottawa, Ontario

© 2019, Stacey Lynne Strilesky

PREFACE

This dissertation integrated one published article and two manuscripts to address the research goal of identifying water use criteria and indicators for reclamation of forested upland oil sands landscapes in the Canadian boreal forest. The initial study, “Forest water use in the initial stages of reclamation in the Athabasca Oil Sands Region” (Chapter 3), examined a single reclaimed ecosystem with a focus on determining whether or not water balance issues such as a trend of sharply increasing water use were present. This chapter was published in the journal *Hydrological Processes* and was reproduced here with the permission of the publisher and co-authors (Strilesky *et al.*, 2017)¹. Formatting was adjusted to comply with the dissertation guidelines but content was not altered. Specific adaptations included: 1) Removal of the abstract and keywords, 2) single column page layout, 3) size 12 and Times New Roman font for all text, 4) re-numbering of headings to integrate with the flow of other headings in the document and inclusion of the headings in the overall “Table of Contents”, 5) re-numbering of figures and equations to integrate with the flow of other figures and equations in the thesis and inclusion of figure captions in an overall “List of Figures”, and 6) reformatting of references to integrate with the format of other references and transferring of the references to an overall “References” section. Material from this chapter should be referenced from the original journal publication.

¹ Strilesky, S. L., Humphreys, E. R., & Carey, S. K. (2017). Forest water use in the initial stages of reclamation in the Athabasca Oil Sands Region. *Hydrological Processes*, 31(15), 2781–2792. <https://doi.org/10.1002/hyp.11220>

As the primary author of the article and manuscripts integrated into this dissertation, I was responsible for envisioning and executing a research project within the framework of a multi-institutional research program. The program, “Developing a functional approach to assessment of equivalent capability: Utilizing ecosystem water, carbon and nutrient fluxes as integrated measures of reclamation performance”, was led by Drs. Sean Carey and Richard Petrone. I was responsible for acquiring and processing data sets, analysing and presenting the data, and writing the content of the thesis. This involved choosing the study sites, obtaining data from researchers and industry personnel, becoming familiar with the data collection methods and data sets themselves, processing raw eddy covariance data where required, and re-processing data obtained from other sources to address quality concerns or to facilitate comparison among data sets collected by different groups at different times at different sites. To become familiar with the reclaimed study sites and the techniques used to collect site data, I conducted two visits to these sites in 2015. During these trips, I visited the study sites at Syncrude’s Base Mine and assisted with forest inventory measurements (*e.g.*, leaf area index, tree density, diameter at breast height), which were used in this thesis. The following year, I visited the provincial government facilities in Edmonton to review the reclamation certification application for Gateway Hill. During these trips, I also spoke with individuals familiar with the sites (*e.g.*, researchers from academia as well as employees from industry and consulting companies) to gather information on past data collection practices and site development. Familiarity with reference sites was gained from a combination of reading published literature and speaking with researchers familiar with the sites themselves and

data collection practices. The contributions of Drs. Elyn Humphreys and Sean Carey (co-authors of Chapter 3) included sharing data sets, providing feedback on research activities including methods and outcomes, and editing.

ABSTRACT

Water use indicators of evapotranspiration, water use efficiency, and gross ecosystem productivity were derived using eddy covariance (EC) measurements of surface-atmosphere exchanges of water, carbon, and energy. They were examined with the goal of identifying potential indicators for assessment and certification of reclaimed landscapes in the Athabasca Oil Sands Region (AOSR). The research outcomes suggest that these indicators provide meaningful assessments of reclaimed AOSR upland and wetland landscapes, thus improving our understanding of ecosystem function, reclamation practices, and certification guidelines. An initial study using a 12-year EC data record for a single reclaimed upland forest dominated by aspen suggested that following approximately 10 years of post-construction variability, the water use characteristics of the site were within the range of variability of natural upland forests in the region. The second study of this thesis expanded the scope of the research to include seven additional EC data records with four AOSR reclaimed sites and four western boreal reference sites. By ~ 20 years of age, the post-disturbance sites' water use indicators were within the range of natural variability. The initial post-disturbance water use variability was related to disturbance type, vegetation cover, moisture, and temperature. The final study examined annual growing season EC-derived water use indicators for 21 upland reference and reclaimed sites, which provided > 100 site years for assessing the potential of these data sets to contribute to assessment and certification in additional ways beyond what can be provided by other ecosystem assessment techniques such as biometrics (including soil and vegetation surveys) and remote sensing. The integrated

assessments of ecosystem functioning derived from EC measurements of water and carbon fluxes may be used to situate reclaimed landscapes in relation to the range of variability and along development trajectories for upland boreal sites.

ACKNOWLEDGEMENTS

Guidance and financial support for the execution of this doctoral research project were kindly provided by co-supervisors Drs. Elyn R. Humphreys and Sean K. Carey. Site access and archived data for reclaimed sites were provided by Syncrude Canada Ltd. (SCL) while research funds were provided by SCL and Suncor Energy. The Watershed Hydrology Group, field technician Dr. Mike Treberg, and data technician Dr. Gordon Drewitt of McMaster University conducted site setup, maintenance, and data management for reclaimed sites. Botanical site data for the reclaimed and some reference sites were collected and analyzed by Integral Ecology Group with special thanks going to Justin Straker, Jeff Anderson, Trevor Baker, and Meghan Laidlaw. The Hydrometeorology Research Group under Dr. Richard Petrone at the University of Waterloo, including data technicians George Sutherland and Adam Green, conducted site setup, maintenance, and data management for the Red Earth Creek reference sites. Data for two of the reference sites were obtained from the Ameriflux Network online data-sharing portal with special thanks going to principal investigators Drs. Brian Amiro and Andrew Black.

TABLE OF CONTENTS

Preface -----	ii
Abstract -----	v
Acknowledgements -----	vii
Table of Contents-----	viii
List of Tables -----	xi
List of Figures -----	xii
List of Abbreviations and Symbols-----	xvii
1 Introduction-----	1
2 Background and Methodology-----	5
2.1 Introduction -----	5
2.2 Study Region-----	5
2.2.1 Physiographic Region and Geology-----	6
2.2.2 Climate -----	8
2.2.3 Boreal Zone-----	8
2.3 Oil Sands Mining Industry of Western Canada-----	10
2.3.1 Overview of the Origin and Current Status -----	10
2.3.2 Stakeholders in Oil Sands Mining Reclamation Activities -----	11
2.3.3 Challenges of Reclaiming Disturbed Oil Sands Landscapes -----	16
2.4 Fundamentals of the Research Approach-----	19
2.4.1 Earth System Science and Ecosystem Analysis -----	19
2.4.2 Water and Carbon Balance and Complexity -----	21
2.4.3 Eddy Covariance Technique -----	23
2.4.4 Chronosequences and Natural Analogues-----	27
2.5 Conclusion -----	28
3 Forest water use in the initial stages of reclamation in the Athabasca Oil Sands Region -----	30
3.1 Introduction -----	30
3.2 Methodology-----	33
3.2.1 Site Description -----	33

3.2.2	Eddy Covariance -----	36
3.3	Results -----	42
3.4	Discussion -----	50
3.4.1	Implications for Oil Sands Reclamation -----	55
3.5	Conclusion -----	57
	Acknowledgements -----	58
4	Filling in a forest patchwork: A multi-site analysis of reclaimed and reference patches of the Canadian boreal forest -----	59
4.1	Introduction -----	59
4.2	Methodology -----	61
4.2.1	Study Locations -----	61
4.2.1.1	Reference and Reclaimed Sites -----	61
4.2.1.2	Regional Climate -----	65
4.2.2	Flux Measurements and Derived Variables -----	66
4.3	Results -----	70
4.3.1	Climate -----	70
4.3.2	Variations in Water, Carbon, and Energy Fluxes -----	71
4.3.2.1	Annual Variation -----	71
4.3.2.2	Monthly Variation -----	75
4.3.3	Flux Relationships with Site and Environmental Variables -----	77
4.4	Discussion -----	80
4.5	Conclusion -----	87
5	The eddy covariance method for assessing reclaimed ecosystems in the Athabasca Oil Sands Region -----	89
5.1	Introduction -----	89
5.2	Overview of the Criteria and Indicators for AOSR Landscapes -----	90
5.3	Forest Inventories -----	95
5.4	Remote Sensing -----	98
5.5	Overview of the EC technique -----	101
5.6	The use of the EC technique for assessment of reclaimed AOSR landscapes --	104
5.6.1.1	Integrative Measures of Ecosystem Functioning -----	105
5.6.1.2	Using Available Data Sets To Compare With Other Ecosystems ----	114
5.6.1.3	Applicability To A Variety of Ecosystem Types -----	115
5.6.1.4	Integration With Other Assessment Practices And Regulatory Frameworks -----	115

5.6.1.5	Considerations-----	121
5.7	Conclusion -----	122
6	Conclusion-----	124
7	References -----	130
8	Appendices -----	151
8.1	Appendix I -----	151
8.2	Appendix II -----	152
8.3	Appendix III -----	153

LIST OF TABLES

Table 4-1. Selected historical information and structural characteristics for the reclaimed and reference study sites. -----	63
Table 4-2. List of EC tower locations, instrumentation, and sampling rates. All data were processed to half-hour averages. -----	69
Table 4-3. Table of median values for the period June through August along with lower (25%) and upper (75%) quartiles for comparative groupings of daily-averaged EC flux variables. β values were for mid-day. An asterisk (*) indicates the significantly different paired groupings (Mann-Whitney U-Test; $p < 0.05$). -----	76
Table 4-4. Comparison of ranges and values for selected sites from the literature and the young sites (< 20 years old) presented here. Additional information regarding type and period of measurement as well as vegetation type for the literature values are included in the footnotes for the table. -----	87
Table 5-1. List of terrestrial and aquatic indicators recommended for reclamation certification in the Athabasca Oil Sands Region (AOSR) by the Cumulative Environmental Association's (CEMA) Reclamation Working Group (RWG). The Energy Resources Conservation Board (ERCB) referred to in the comments was subsequently incorporated into the Alberta Energy Regulator. Adapted from Table 3 in Poscente and Charette (2012: 22–24). -----	93
Table 5-2. Measurement periods and descriptions for the EC sites provided in the data set with appropriate eddy covariance (EC) data: Evapotranspiration (ET); net ecosystem productivity (NEP); and gross ecosystem productivity (GEP). -----	106

LIST OF FIGURES

Figure 2-1. The location of the mined and untapped oil sands deposits within Alberta (left) and Alberta within Canada (upper right) (Government of Alberta, 2010). -----	12
Figure 2-2. View of Syncrude Canada Ltd.'s active Base Mine site located north of Fort McMurray, Alberta. -----	18
Figure 2-3. Tower setup at the SBH reclamation site in 2003. EC equipment includes a sonic anemometer (CSAT3, Campbell Scientific Inc., USA (CSI)), an infrared gas analyzer (LI-7500, LI-COR, USA), and a data logger. Complementary meteorological equipment includes a net radiometer (CNR1, Kipp and Zonen, Delft, Netherlands) and a temperature and relative humidity probe (HMP45C, Vaisala Oyj, Finland). Batteries, charged by solar panels, are used to power the equipment. Black swirls represent turbulent air flow (eddies) while orange clouds and blue water droplets represent the entities of carbon dioxide (CO ₂) and water vapour (H ₂ O), respectively, transported by the eddies and measured at this tower. -----	25
Figure 3-1. Map of Alberta (left) with an inset map of the region around Fort McMurray (right) showing the location of the SBH study site within the active oil sands project boundaries. Data are courtesy of Alberta Environment and Parks (2015), DMTI Spatial Inc. (2014a, 2014b), and Statistics Canada (2016). Reprinted with permission of John Wiley and Sons. -----	34
Figure 3-2. Photographs of the eddy covariance tower at SBH in 2003 (left) and 2014 (right). The flux equipment measurement height was 2.9 m in 2003 and 8.25 m in 2014. Reprinted with permission of John Wiley and Sons. -----	35
Figure 3-3. (Top) Average daily growing season soil water content (SWC) at 25 (light grey), 40 (black), and 115 (dark grey) cm depths; (middle) average daily growing season available water content (AWC), and (bottom) total monthly P during the growing season for June (light grey), July (dark grey), and August (black). Reprinted with permission of John Wiley and Sons. -----	43
Figure 3-4. Growing season leaf area index (LAI) measurements for SBH from 2003 through 2014. Reprinted with permission of John Wiley and Sons. -----	44
Figure 3-5. Annual growing season midday (June-August; 11:00 h - 14:00 h) Bowen's ratio (β) (top) and friction velocity (u_*) (bottom) values for SBH for the 12-year study period (2003-2014). Error bars represent ± 1 SE. Reprinted with permission of John Wiley and Sons. -----	44

Figure 3-6. Growing season (June-August) gross ecosystem productivity (GEP) during the 12-year measurement period (2003-2014). Error bars represent ± 1 SE. Reprinted with permission of John Wiley and Sons. -----	46
Figure 3-7. Growing season (June-August) evapotranspiration (ET) from 2003 - 2014. Error bars represent ± 1 SE. Reprinted with permission of John Wiley and Sons. -----	46
Figure 3-8. Diurnal monthly growing season evapotranspiration (ET) grouped by early successional species vegetation years (2003-2007) and later forest vegetation years (2008-2014). Reprinted with permission of John Wiley and Sons. -----	47
Figure 3-9. Annual growing season canopy conductance (g_c) expressed per unit ground area (top) and expressed per unit leaf area after normalizing by leaf area index (LAI) (bottom). Error bars represent ± 1 SE. Reprinted with permission of John Wiley and Sons. -----	48
Figure 3-10. Total rainfall (bars), evapotranspiration (ET, black circles), potential evapotranspiration (PET, open grey squares), and reference crop evapotranspiration (ET_{REF} , open grey diamonds) for the 2003-2014 growing seasons (June-August). Reprinted with permission of John Wiley and Sons. -----	49
Figure 3-11. Growing season (June-August) water use efficiency (WUE). Error bars represent ± 1 SE. Reprinted with permission of John Wiley and Sons. -----	49
Figure 4-1. Map of Alberta and Saskatchewan (left) showing the locations of the reference boreal forest sites with an inset map of the region around Fort McMurray (right) showing the locations of the reclaimed sites. Data from Alberta Environment and Parks (2015), Brandt and Natural Resources Canada (Brandt, 2009), DMTI Spatial Inc. (2014a, 2014b), and Statistics Canada (2016). ----	62
Figure 4-2. Monthly (June-July-August) average daily temperatures ($^{\circ}C$, right) and total P (mm, left) for the northern Alberta (top) and central Saskatchewan (bottom) regions. For northern Alberta, P is from the Mildred Lake Climate Station (top, left). For central Saskatchewan, P is from the OA study site (bottom, left). Reclaimed site temperature records are black and solid (SF1 – ▲, SF2 – ■, SBH – ●, SWSS – ★) while reference sites are grey and open-faced (REC1 – ○, REC2 – □, OA – △, WB – ☆). Shaded columns delineate years while the dashed horizontal lines represent either the June-August climate normal daily average temperature (right) or monthly average P (left) for the Environment Canada weather stations in Fort McMurray, Alberta (top) or Prince Albert, Saskatchewan (bottom). -----	72

Figure 4-3. Average daily temperature vs. total P for the peak period of the growing season (June through August) for the years shown in Figure 4-2. Symbols are described in Figure 4-2. -----	73
Figure 4-4. Chronosequence graphs of average daily June-August evapotranspiration (ET, mm day ⁻¹ , top), water use efficiency (WUE, CO ₂ mol ⁻¹ H ₂ O, middle), and gross ecosystem productivity (GEP, g C m ⁻² day ⁻¹ , bottom). Symbols are described in Figure 4-2.-----	74
Figure 4-5. July through August midday Bowen's ratio (β) for sites with data available for 2003-2010. Symbols are described in Figure 4-2. -----	75
Figure 4-6. Daily average ET for June through August versus midday (11:00 h – 14:00 h) g _c . Symbols are described in Figure 4-2. -----	77
Figure 4-7. Total evapotranspiration (ET), water use efficiency (WUE), and gross ecosystem productivity (GEP) for July versus June through August. Symbols are described in Figure 4-2. The black lines and equations represent the least squares linear regression models for all of the sites. Note the different y- and x-axis scales for each plot. -----	78
Figure 4-8. Median monthly (June – white, July – light grey, and August – dark grey) values of average ET, WUE, GEP, H, β , and R _n for the site type (reclaimed; reference), tree type (fewer conifers; more conifers), and age (< 20 years old; > 20 years old) groupings. Error bars represent lower (25%) and upper (75%) quartiles. Note the different y-axis scale for each plot. -----	79
Figure 4-9. Total June through August ET, WUE, GEP, H, β , and R _n regression tree model predictor importance estimates for site type (reference/reclaimed), P, T _{air} , K _↓ , tree type (fewer conifers/more conifers), age (< 20 years old/> 20 years old), g _c , and vapour pressure deficit (D) predictors for reclaimed and reference sites. Note the different y-axis scale for each plot. -----	80
Figure 5-1. June-August gross ecosystem productivity (GEP, top), net ecosystem productivity (NEP, middle), and evapotranspiration (ET, 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, and the ° are the outliers. 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 (*).-----	109

Figure 5-2. June-August GEP for young reference and reclaimed sites. The grey shaded area represents the range of variability for the reference sites. The Sandhill Fen 3 lowland site, which did not have a dominant tree cover identified in the data set, is categorized as “Reclaimed – Not Applicable”. ----- 110

Figure 5-3. 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 Fen 3 lowland site, which did not have a dominant tree cover identified in the data set, is categorized as “Reclaimed – Not Applicable”. ----- 111

Figure 5-4. Conceptual diagram of spatial and temporal coverage associated with three methods to measure ecosystem productivity in an aspen-dominated boreal forest: Micrometeorological techniques (*e.g.*, EC), satellite remote sensing (RS), and forest inventory (FI). Spatial coverage: EC data represent the tower ‘footprint’ (see main text), which varies due to surface cover and atmospheric conditions and ranges from a few metres to hundreds of metres (Aubinet *et al.*, 2012); RS pixels represent an area of ground whose size depends on sensor and platform (*e.g.*, satellite-based sensors: 0.3 m for SPOT, 10 m for LANDSAT, 250 to 1000 m for MODIS) (Lillesand *et al.*, 2004); and FI which may provide single tree to plot-scale assessments of specific ecosystem structure components (*e.g.*, trees that have reached a minimum height) but do not necessarily integrate all ecosystem components nor their functions with many measurements only suitable for forest ecosystems. Temporal coverage: EC towers may be placed at suitable sites regardless of the age of the vegetation cover and data sets > 10 years are available (Aubinet *et al.*, 2012); RS depends on sensor and platform with limitations in image frequency (*e.g.*, revisit period: 5 for SPOT, 16 days for LANDSAT, 1 to 2 days for MODIS) an important factor (National Aeronautics and Space Administration, 2018; USGS, 2018) while long-term monitoring using some indices may be ineffective once reflectance data is no longer sensitive to increasing forest LAI at a certain growth stage (Huete *et al.*, 1997b; Chasmer *et al.*, 2018); and FI requires person time to revisit measurement plots with a number of metrics unsuited for young sites (Vasiliauskas and Chen, 2002).----- 117

Figure 5-5. Peak of growing season leaf area index (LAI) against total growing season gross ecosystem productivity (GEP) for reference and reclaimed sites. The lines and models represent respective least squares linear regressions for reference sites (brown), reclaimed sites (green), and the total data set (grey). The Sandhill Fen 3 lowland site, which did not have a dominant tree cover identified in the data set, is categorized as “Reclaimed – Not Applicable”. ----- 118

Figure 5-6. Peak of growing season leaf area index (LAI) against total growing season net ecosystem productivity (NEP) for reference and reclaimed sites. The logarithmic curve (dark grey line), 95% confidence interval range for the curve (light grey shaded area), and affiliated equation (grey text) are fit to the entire data set. The Sandhill Fen 3 lowland site, which did not have a dominant tree cover identified in the data set, is categorized as “Reclaimed – Not Applicable”. --- 119

LIST OF ABBREVIATIONS AND SYMBOLS

%	percent	ESI	evaporative stress index
°	degree	ET	evapotranspiration
°C	degrees Celsius	ET _{REF}	reference evapotranspiration
<	less than	EVI	enhanced vegetation index
>	greater than	f	dry mole fraction of carbon dioxide
~	approximately	F _c	carbon dioxide flux
▼, ▽	reference sites (broadleaf trees, conifer trees)	FI	forest inventory
◆, ◇	reclaimed sites (broadleaf trees, conifer trees)	g	gram
AET	actual evapotranspiration	g _c	canopy conductance
AOSR	Athabasca Oil Sands Region	GEP	gross ecosystem productivity
AWC	available water content	Gill	Gill Instruments (company)
BERMS	Boreal Ecosystem Research and Monitoring Sites	H	sensible heat flux
BOREAS	Boreal Ecosystem-Atmosphere Study	h	hour
CEMA	Cumulative Environmental Management Association	H ₂ O	water
cm	centimetre	ha	hectare
CO ₂	carbon dioxide	IRGA	infrared gas analyzer
COSIA	Canada's Oil Sands Innovation Alliance	K↓	incoming solar radiation
c _p	specific heat of air	km	kilometre
C _p	specific heat capacity of air	kPa	kilopascal
CRT	Closure and Reclamation Team, Syncrude Canada Ltd.	LAI	leaf area index
CSI	Campbell Scientific Ltd. (company)	LCCS	Land Capability Classification System for Forest Ecosystems in the Oil Sands (working manual and 3 rd Edition)
CVI	chlorophyll vegetation index	LE	latent heat flux
D	vapour density deficit of air	LI-COR	LI-COR Inc. (company)
DBH	diameter at breast height	L _v , λ	latent heat of vapourization
Dfb	Climate classification for snowy (D) and humid (f) areas with warm summers (b).	m	metre
Dfc	Climate classification for snowy (D) and humid (f) areas with cool summers (c).	M	million
e	vapour pressure of air	M _a	molecular weight of air
EC	eddy covariance	mm	millimetre
ER	ecosystem respiration	mmol	millimole
		mol	mole
		M _w	molecular weight of water
		NDVI	normalized difference vegetation index
		NEE	net ecosystem exchange
		NEP	net ecosystem productivity
		NIR	near infrared
		OA, △	Old Aspen (study site)

p	probability value	z_o	roughness length
P	precipitation	β	Bowen's Ratio
PET	potential evapotranspiration	θ_v	soil volumetric water content
QA/QC	quality assurance/quality checks	μm	micrometre
κ	von Karman's constant	μmol	micromole
R	respiration	ρ	density of air
r	correlation coefficient	ρ_d	density of dry air
R	red		
R^2	coefficient of determination		
R_a	available energy		
r_a	aerodynamic resistance		
R_{aut}	autotrophic respiration		
r_c	canopy resistance		
REC1, ○	Red Earth Creek 1 (study site)		
REC2, □	Red Earth Creek 2 (study site)		
R_{het}	heterotrophic respiration		
R_n	net radiation		
RS	remote sensing		
s	change in saturation vapour pressure with temperature		
s	second		
S	storage		
SBH, ●	South Bison Hill (study site)		
SF2, ■	Sandhill Fen 2 (study site)		
SFI, ▲	Sandhill Fen 1 (study site)		
SI	site index		
spp	species		
SWC	soil water content		
SWSS, ★	Southwest Sands Storage (study site)		
u	wind speed in the horizontal direction		
u_*	friction velocity		
USDE	United States Department of Energy		
USGS	United States Geological Survey		
W	watt		
w	vertical wind velocity		
WB, ☆	Western Boreal (study site)		
WUE	water use efficiency		
z	height of measurement		

1 INTRODUCTION

Existing oil sands mining practices and regulations for the Athabasca Oil Sands Region (AOSR) in western Canada are resulting in the removal and subsequent reclamation of large tracts of land in the western Canadian boreal zone (Alberta Environment, 2010; Gosselin *et al.*, 2010). This region of the boreal forest is characterized by a mixture of upland forests, wetlands, and waterways with a short growing season, a water deficit, and recurring droughts and fire (Brandt, 2009). Reclamation, as maintained by the Government of Alberta, is the transition of a disturbed landscape to one with equivalent (pre-disturbance) land capability and which has a net benefit to stakeholders rather than a duplication of the pre-disturbance landscape (Powter *et al.*, 2012). Reclaimed landscapes should exhibit resilience, which represents the ability of an ecosystem to recover following a disturbance (Walker *et al.*, 2004).

A patchwork of certified reclaimed landscapes is a legally mandated outcome of large-scale extraction operations in the AOSR (Richardson, 2007; Gosselin *et al.*, 2010). However, the management practices and assessment frameworks that will provide a path to reclamation certification are still being discussed and developed (Gosselin *et al.*, 2010; Poscente and Charette, 2012). There are societal and industrial needs for scientific research related to the construction and assessment of landscapes reclaimed subsequent to mining activities. For example, what soil and vegetation characteristics or ecosystem processes should be targeted for reclaimed landscapes and which reclamation practices would foster their successful growth and development? However, despite intensive research activities in these areas (Purdy *et al.*, 2005; Richardson, 2007; Lilles *et al.*, 2012;

Poscente and Charette, 2012), there is a notable gap in the literature related to long-term assessment of these ecosystems (Pinno and Hawkes, 2015). Although a set of indicators has been proposed for reclaimed ecosystem assessment in the AOSR, many indicators focus on structural ecosystem characteristics such as the presence of weeds or have yet to have thresholds and methodology assigned to them (Poscente and Charette, 2012). This thesis examines the functioning of reclaimed upland forest ecosystems using eddy covariance (EC) measurements of water, energy, and carbon exchange between the surface and the atmosphere to gauge ecosystem development. It argues that EC-derived indicators are appropriate for inclusion in certification frameworks.

The water use of ecosystems describes the flow amounts and pathways of water through the environment. It is important because the overall balance and partitioning of water per unit time indicate the long-term survival potential of an ecosystem and its resilience. For example, if more water is consistently used by vegetation than is available, this indicates a potential for drought conditions accompanied by water stress on the vegetation and the subsequent decline of an ecosystem (Aber *et al.*, 2001; Nelson *et al.*, 2018). There is an established body of literature on the application of the EC technique to assess the water use of ecosystems (Mkhabela *et al.*, 2009; Ewers *et al.*, 2011; Brümmer *et al.*, 2012; Cammalleri *et al.*, 2013), but there are few studies of reclaimed landscapes within the AOSR (Carey, 2008; Nicholls *et al.*, 2016; Ketcheson *et al.*, 2017; Strilesky *et al.*, 2017).

The primary goal of this thesis is to examine the water use functioning of reclaimed upland ecosystems in the AOSR and identify indicators that could be used to

assess these ecosystems. A secondary goal is to translate these research outcomes into a format conducive to developing regulatory and certification protocols for reclaimed AOSR landscapes. Applying the EC technique to understand the water use dynamics of reclaimed upland ecosystems is the link among the three research chapters forming the core of this thesis (Chapters 3, 4, and 5). In combination, the three research chapters form a novel research arc with a focus on basic research examining the ecosystem function first of a single site and then multiple sites in order to interpret these research results for reclamation managers and regulators. The initial study (Chapter 3) examines the water use of a single reclaimed aspen-dominated upland ecosystem, the South Bison Hill (SBH) site, over the first 12 years of its development. To my knowledge, this is the first study to directly examine the development of a reclaimed site from its initial planting to a stage of tree growth approaching crown closure. The focus of this study is to observe and interpret evapotranspiration (ET) trends over time in order to evaluate if water balance deficits have or will limit the successful reclamation of this site. The second study (Chapter 4) compares the water use of four reclaimed and four reference aspen-dominated forest ecosystems within the AOSR and similar boreal regions. As with the previous study, the water use indicators are evaluated against the natural range of variability for other boreal aspen forests. The influence of disturbance type, forest species composition, age, and weather and climate variables on water use indicators are examined to better understand the factors influencing this variability in water use function among both reclaimed and reference boreal forests. Finally, the third study (Chapter 5) provides an overview of the realized and potential contributions of the EC

technique for monitoring and certification of reclaimed AOSR landscapes. It focuses on a broader data set (15 sites with 79 site years of EC data) of growing season totals of actual evapotranspiration (AET), net ecosystem productivity (NEP), gross ecosystem productivity (GEP), and others to demonstrate development trajectories, evaluate the potential for complementary relationships with forest inventory (FI) and remote sensing (RS) ecosystem assessment techniques, and recommend EC-derived indicators for inclusion in AOSR assessment and certification frameworks.

Overall, this thesis aims to make meaningful contributions to both the body of scientific research on reclaimed forest landscapes and the development of methods for meaningful regulatory assessment and certification of reclaimed lands. The use of the EC technique to measure fluxes of carbon, water, and energy in reclaimed upland ecosystems in the AOSR is a novel approach to understanding and assessing these ecosystems. I argue that in addition to traditional ecosystem metrics related to forest and soil characteristics (such as species composition, tree density and volume, soil characteristics, *etc.*), ecosystem function with regard to carbon and water cycling is an important ecosystem characteristic to monitor. This is especially important as shifts in climate and regulatory protocols increase the prominence of drought and carbon sequestration issues related to the reclaimed landscapes in the AOSR.

2 BACKGROUND AND METHODOLOGY

2.1 Introduction

This chapter provides an overview of the western Canadian region within which the study sites are located (Section 2.2), introduces the western Canadian oil sands mining industry (Section 2.3), and outlines the research approach (Section 2.4). A basic understanding of the physical landscape provides context for the target reclamation landscapes as well as the reclamation management and assessment issues that are faced by reclamation practitioners. Understanding the oils sands mining industry is essential for placing reclamation and regulatory activities within a broader societal and scientific context as well as identifying further assessment issues. Finally, understanding the research approach provides the foundation for pursuing this project within the environmental science research paradigm fostered within the field of geography and provides context and justification for choosing the EC technique for assessment of ecosystem functioning.

2.2 Study Region

The physical environment within which reclaimed oil sands ecosystems are constructed, including the pre-disturbance land surface cover, are integral to developing targets for and understanding the issues faced by reclamation practitioners. For example, soil and vegetation properties interact with weather and climate characteristics of a region to determine the changing water use characteristics of growing forest ecosystems.

2.2.1 Physiographic Region and Geology

The interior plains physiographic region stretches from the Arctic Ocean coastline of the Northwest Territories to the southern borders of the provinces of Alberta, Saskatchewan, and Manitoba (Pojar, 1996; Bostock, 2014). The region is underlain by marine-sourced limestones and shales while the surface cover varies with grassland vegetation interspersed with mixed-wood forests transitioning to aspen parkland and then dominantly coniferous boreal forest towards the north and the east (Bostock, 1970; Pojar, 1996). In between are varying sedimentary layers formed from fluvial sand and marine mud during different geological periods (Bostock, 1970).

The Athabasca oil sands (Figure 2-1) are primarily formed by the Wabiskaw-McMurray deposit (Hein and Cotterill, 2006). The base of this deposit is a Paleozoic era limestone deposited during the Devonian period (~ 419-358 million years ago) upon which are layered Mesozoic era mud and then sand deposited during the middle of the Barremian age of the Cretaceous period (~ 129-125 million years ago) (Hein and Cotterill, 2006). The Wabiskaw-McMurray formation itself was deposited starting in the Aptian age and ending in the middle of Albion age of the Cretaceous period (~ 125-109 million years ago) and is made up of alternating layers of mud, sand, and shale with an upper mudstone capstone ~ 5 m thick known as the Clearwater Formation (Hein and Cotterill, 2006). The alternating layers are associated with fluvial depositions as well as alternating cycles of inland sea encroachment and retreat related to continental subsidence (Mossop, 1980; Hein and Cotterill, 2006). Overlying the deposit is glacial till

placed during the Pleistocene epoch glaciations of the Quaternary period (~ 2.5 million years ago to 11.8 thousand years ago) (Mossop, 1980).

The oil sand material itself is predominately fine-grained (~ 62.5-200 μm) and is reported to have a film of water surrounding the sand grains that keeps the bitumen in the pore spaces between the grains from adhering to the grains themselves (Mossop, 1980; Czarnecki *et al.*, 2005). The existence of the water film was noted as unproven by Czarnecki *et al.* (2005); however, it is the theoretical basis for the hot water extraction process that was developed specifically for use in this region (Mossop, 1980; Ferguson, 1986; Czarnecki *et al.*, 2005). The sand grains are comprised of quartz (~ 95%), feldspar (~ 2-3%), mica and clay (~ 2-3%), and trace minerals with the sand material 18% bitumen by weight due to the presence of bitumen within the pore spaces between the grains (Mossop, 1980). The bitumen formed in a similar manner to other fossil fuel deposits (*e.g.*, coal, natural gas, conventional oil) in that ancient organic matter died, was covered by sediment, and was subsequently subjected to heat and pressure so that the organic matter was transformed into petroleum (Tissot and Welte, 1984). However, the bitumen is heavier and less viscous than conventional crude oil (Mossop, 1980). Since estuarine-sourced sediments have the highest concentration of bitumen, it likely originated within estuarine environments and later migrated within permeable sediments until it was vertically trapped in the Wabiskaw-McMurray formation by the Clearwater capstone (Mossop, 1980; Czarnecki *et al.*, 2005).

2.2.2 Climate

Köppen-Geiger climate classifications of Dfb and Dfc for the interior plains physiographic region include cool-to-warm moist summers and cold moist-to-dry winters (Kottek *et al.*, 2006). The climate classifications refer to snowy (D) and humid (f) climates but differ with one having warm summers with at least four months of the year $> 10^{\circ}\text{C}$ (b) and the other cool summers (c). The seasonal temperature range in northern Alberta is large with an average of -24°C in January and 16°C in July accompanied by limited precipitation (P) of 40-45 cm per year on average along with 1900 hours of sunshine (Government of Alberta, 2014). For comparison, southern Alberta has 2,300 hours of sunshine along with an average January temperature of -8°C and an average July temperature of 20°C (Government of Alberta, 2014).

2.2.3 Boreal Zone

Northern Alberta and central Saskatchewan are located within the boreal zone of western Canada. Boreal ecosystems are estimated to cover 362 M ha of the North American continent (Brandt, 2009). Definitions and delimitations of the boreal zone, a globally significant biome, vary depending upon discipline and methodologies used. Brandt (2009) provides the following definition upon which the official map of the boreal zone for Natural Resources Canada is defined:

*The boreal zone is defined as the broad, circumpolar vegetation zone of high northern latitudes covered principally with forests and other wooded land consisting of cold-tolerant trees [sic] species primarily within the genera *Abies* [fir], *Larix* [larch], *Picea* [spruce], or *Pinus* [pine] but also *Populus* [aspen] and *Betula* [birch]; the zone also includes lakes, rivers, and*

wetlands, and naturally treeless areas such as alpine areas on mountains, heathlands in areas influenced by oceanic climatic conditions, and some grasslands in drier areas.

The broad scope of this definition represents the landscape variability that is encompassed within the boreal zone. These many landscape types are integrated with the wetland areas viewed as sources of water and the upland forests viewed as sinks (Devito *et al.*, 2012). The focus of this project is on the forested portion of the boreal region that is the target of reclamation activities for the AOSR sites examined in this thesis.

As a result of the dominance of the boreal land cover type in the Northern Hemisphere, the feedbacks on global systems such as climate in response to environmental and physical changes are globally significant. The massive and severe disturbance associated with large-scale surface resource extraction operations has raised concerns about how boreal ecosystems will react including impacts on environmental systems (Chen *et al.*, 1999; Alberta Environment, 2010). Disturbance is integral to boreal forest functioning, especially fire, which is sporadic through space and time (Weber and Flannigan, 1997; Weber and Stocks, 1998; Kimmins, 2011). Hence, fires serve to increase biodiversity and create the forest mosaic of stands varying in species composition and at different stages of their respective life cycles. For example, species such as jack pine are dependent upon the heat (for seed release from the scales of their resinous cones) and destruction (to remove a shade inducing overstory and provide a mineral seedbed for germination) furnished by fire in order to reproduce (Weber and Stocks, 1998). Additional types of disturbance include afforestation, massive erosion (*e.g.*, rockslides), construction of road and rail beds, draining of wetlands, insect

infestation, wind blow down, tree harvesting, and surface mining. Post-surface mining forests are the focus of this project with post-fire and post-harvest boreal reference sites being used for comparison. Reference sites are located within reference ecosystems, which are defined in the reclamation literature as ecosystems either present prior to disturbance or representing a model for a specific land use outcome (Gosselin *et al.*, 2010).

2.3 Oil Sands Mining Industry of Western Canada

The extensive footprint of the western Canadian oil sands mining industry and its position within local, national, and global climate change and landscape disturbance discourses provide the backdrop against which scientific research covering this topic takes place (Richardson, 2007; Gosselin *et al.*, 2010; Nikiforuk, 2010; Levant, 2011). The current status of uncertain reclamation success parameters is the result of the development and status of the mining industry to date, the ongoing intense interplay of the various stakeholders, and the daunting challenges to achieve consensus or at least workable compromises in the face of competing and all too often inflexible stakeholder endgame strategies and priorities. Each of these areas are discussed in order to demonstrate the potential for this thesis to contribute to the development of criteria and indicators for reclamation success on mined oil sands landscapes.

2.3.1 Overview of the Origin and Current Status

While the bitumen-containing western Canadian oil sands were officially observed as early as 1875 when John Macoun led the first geological survey of the Athabaskan region, commercial utilization of the resource commenced in 1930 with

Robert Fitzsimmons' Bitumount plant (Ferguson, 1986; Hein, 2016). A transition from perceiving the region as an inhospitable wasteland to a valuable resource-laden landscape coincided with the development of technology that facilitated separation of the bitumen from the sand and processing of the bitumen into petroleum-based products (Ferguson, 1986). The following era of intensive and large-scale operations marked a change from previous private or government activities (*e.g.*, proposing to use unrefined bitumen as fuel or to pave roads) to large commercial enterprises. For example, the Great Canada Oil Sands consortium, established in 1953, led to the construction of a \$250 M processing plant for isolating bitumen from the oil sands in 1967 (Hein, 2016). Within Alberta, where many active oil sands mining projects are situated, there are approximately 142,200 km² of oil sands deposits with a subset of 4,800 km² currently designated as mineable (Figure 2-1). The three main deposits are affiliated with the Athabasca, Peace River, and Cold Lake regions. Figure 2-1 provides an overview of the Canadian oil sands region in relation to territorial borders and the boreal zone, and provides a breakdown of mined and currently untapped areas.

2.3.2 Stakeholders in Oil Sands Mining Reclamation Activities

Government regulations require a commitment to reclamation before a company is permitted to mine oil sands (Richardson, 2007). The purpose of reclamation is to construct a landscape cover that is sustained by the geological aspects of the landscape and retains essential aspects – not yet definitively determined – of the precursor boreal forest ecosystems (Alberta Environment, 2010; Poscente and Charette, 2012). Federal

Note: 1 km² = 1 square kilometre = 0.39 square miles

Figure 2-1. The location of the mined and untapped oil sands deposits within Alberta (left) and Alberta within Canada (upper right) (Government of Alberta, 2010).

and provincial government departments are responsible for the regulations. The Government of Alberta administers the Athabasca Sands, which includes granting mining leases and reclamation certificates, on behalf of its citizens. Meanwhile the primary involvement of the Government of Canada is in the areas of environmental issues and

inter-provincial / international trade and commerce as well as First Nations lands (Richardson, 2007). As stakeholders with particular concerns regarding environmental issues, First Nations and municipal governments may be involved in consultations and complaints for planning and outcomes but regulatory responsibilities for the oil sands are currently handled by the provincial and federal governments (Richardson, 2007; Powter *et al.*, 2012).

Canada's Oil Sands Innovation Alliance (COSIA) was created in 2012 when 13 of the major oil sands operators came together with a commitment to pooling information and technology to improve environmental protection and reclamation in the oil sands (Canada's Oil Sands Innovation Alliance (COSIA), 2016). Prior to 2012, companies pursued individual reclamation research programs with Syncrude Canada Ltd. obtaining the first (and only as of August 2018) reclamation certification for their Gateway Hill reclamation area in 2008 (Unknown, 2008; Government of Alberta, 2010). This application for reclamation was submitted in 2003 to Alberta Environment (currently Alberta Environment and Parks) and subsequently amended in 2007 before being approved in March of 2008 (Closure and Reclamation Team, Syncrude Canada Ltd. (CRT), 2003). Criteria for approval were based on pre-disturbance landscape conditions and functions (CRT, 2003). Specific required landscape performance goals based upon the time period in which the site was reclaimed include ensuring equivalent land capability, addressing roads, revegetation for land use, ensuring a minimum soil depth, ensuring acceptable soils, managing P, ensuring geotechnically stable slope angles, and conforming to the closure plan for the site. At the time of application for reclamation

certification in 2003, vegetation at Gateway Hill included a mixture of native (*e.g.*, trembling aspen [*Populus tremuloides* Michx.] and poplar [*Populus balsamifera* L.]) and non-native (*e.g.*, Siberian larch [*Larix siberica* Ledeb.] and caragana [*Caragana* spp.]) plant species including trees, shrubs, and grasses.

It is worth mentioning that a primary reason for the amendment submitted in 2007 was related to issues with calculating and reporting soil survey results as per the working manual version of the *Land Capability Classification System for Forest Ecosystems in the Oil Sands* (LCCS) available at that time (CRT, 2003). Alberta Environment requested a re-evaluation of the land capability classes for the site. During the process of doing the evaluation, data and calculation anomalies were identified and addressed by Syncrude Canada Ltd. This process demonstrates the complexity of the data collection and management for reclamation certification and reliance upon soil structural characteristics for reclamation criteria. The practice of seeding with non-native plant species is now absent from currently proposed certification criteria, which instead focus on the establishment of native vegetation (Poscente and Charette, 2012). As a result, despite the existence of a certified reclaimed site, certification protocols should be viewed as “living documents” which evolve alongside reclamation best practices. This view is noted in the preamble content for the LCCS as well as other reclamation related documents such as *Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region* (CRT, 2003; Alberta Environment, 2010). In the 10 years since this approval, there have been no further reclamation certificates issued despite the existence of several reclaimed

sites and, as covered in Section 5.2, criteria for reclamation and certification are still being formulated.

The goal of a social license to operate is a dominant feature within oil sands discourses with proponents from government, industry, and media highlighting aspects such as economic benefits (Richardson, 2007), reclamation practices (Government of Alberta, 2010; McDermott, 2013), and ethical status (Levant, 2011). These exhaustive efforts are being made by applicable stakeholders (*e.g.*, oil sands industry and provincial and federal governments) to develop public trust in local, provincial, national, and global arenas that Canadian oil sands regulations, processes, and results are credible and realistic (Richardson, 2007; Alberta Environment, 2010; Gosselin *et al.*, 2010; Powter *et al.*, 2012; Audet *et al.*, 2014). The term social license to operate refers to a positive label resulting from a value judgement based upon selected criteria and it is a tenet of currently acceptable industrial practice in Canada (Dare, 2014). The foundation for a social license to operate is a dichotomy between a focus on the utility of the region and a focus on the need to preserve the landscape (Davidson and Gismondi, 2011). Scientific research results from many fields contribute to the value judgement in several ways. For example, research projects provide information regarding the preparation for and outcomes of mining and reclamation activities from environmental (Tetreault *et al.*, 2003; Audet *et al.*, 2014), economic (Atkins and MacFadyen, 2008; Heyes *et al.*, 2018), and societal perspectives (Baker and Westman, 2018). This information is often used by others to support arguments both for and against utilization of this resource. Examples include a Government of Canada parliamentary committee report which argued for the economic

benefit of using oil sands resources (Richardson, 2007) while a journalist noted irreversible damage to overlying ecosystems and nearby waterways (Weber, 2012).

2.3.3 Challenges of Reclaiming Disturbed Oil Sands Landscapes

The challenges of reclaiming disturbed oil sands landscapes include fundamental concerns with what conceptual framework should be used for addressing the disturbed landscapes and this is represented in the quagmire of terminology describing the options available (Cullinane Thomas *et al.*, 2012; Powter *et al.*, 2012; McDonald *et al.*, 2016). Reclamation has been noted by the Government of Alberta and the United States Department of the Interior as the practice of improving the structure and function of a disturbed ecosystem as compared to the original, *i.e.*, not an exact replica of the pre-disturbance ecosystem (Cullinane Thomas *et al.*, 2012; Powter *et al.*, 2012). Essentially, the focus is on producing landscapes that are perceived to be of benefit to various stakeholders. Since “restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (McDonald *et al.*, 2016: 9), reclamation falls under the umbrella of restoration as defined by the Society for Ecological Restoration. The methods used to shape a new landscape, which is not consistent with the topography that was previously present, are categorized as construction (McDonald *et al.*, 2016). With regard to the oil sands, the focus on improved ecosystems touches upon diverse uses such as forestry and traditional indigenous activities such as hunting and fishing (CRT, 2003; Alberta Environment, 2010). While issues have been raised about reclamation activities in the oil sands that include the need for and benefit of targeted ecosystems and criteria as well as the potential for a natural recovery to produce better

diversity than an engineered one (Burton and Macdonald, 2011), reclamation is the current standard for addressing mined oil sands.

Surface mining involves removing the surface material (*e.g.*, overburden), which includes all vegetation, soil, and underlying substrate to depths of approximately 70 m to 150 m (Gosselin *et al.*, 2010). Surface materials are often stored for future reclamation, while the underlying material is transferred to a processing plant where the bitumen is extracted via physical and chemical processes (Gosselin *et al.*, 2010). The method for bitumen extraction is water-based and involves agitating a mixture of hot water, chemicals, and oil sand material to aid with the separation and liberation of the bitumen contained within the ground material (Masliyah *et al.*, 2004). The physical manipulation of surface materials results in a loss of heterogeneity as topography is erased and geological layers (*i.e.*, subsurface structure) and soils are mixed during overburden removal (Figure 2-2).

Tailings and water remaining after the separation process are stored on site with tailings used to fill open pits or piled into hills and water pumped into reservoirs forming lakes (Gosselin *et al.*, 2010). These leftover materials have high salinity, a residual oil content (from the naturally occurring bitumen) ranging from 2-6%, and lack viable seeds for the establishment of native (pre-disturbance) vegetation. In addition, they are susceptible to sediment settling and erosion by factors such as physical disturbance and thermal expansion and contraction. Despite the existence of naturally saline landscapes supporting boreal forest cover in the region (Lilles *et al.*, 2012), the salinity of tailings has been noted as the most significant challenge related to reclamation in the oil sands

(Gosselin *et al.*, 2010). This is because the naturally occurring salt ions leached from the ore accumulate in the recycled processing water and impact the ground material that the water comes in contact with (Renault *et al.*, 1998). Subsequently, there is potential for salts to migrate upward from the overburden into the cover layer and increase the salinity of the plant rooting zone (Gosselin *et al.*, 2010).

Supporting productive forestry has been a focus of reclamation activities in the oil sands region (Cumulative Environmental Management Association (CEMA), 2006; Alberta Environment, 2010; Straker and Donald, 2011). Although tree stands suitable for the forest industry are important components of the boreal landscape, the boreal landscape is highly diverse and characterized by a mixture of forested uplands, wetlands, and water bodies (Section 2.2.3). The increasing recognition of the importance of reclaiming to varying terrain types is reflected in the literature. A basic search in Web of

Figure 2-2. View of Syncrude Canada Ltd.'s active Base Mine site located north of Fort McMurray, Alberta.

Science for reclamation activities in the oil sands for the year spans of 2004-2007 and 2014-2017 revealed that there was an increase from 15 % (4 out of a total of 27) to 35 % (30 out of a total of 88) in the proportion of articles focused on wetlands. The targeted outcomes for reclamation have shifted to establishing equivalent and connected landscapes similar to those within the boreal zone that surrounds the area (Audet *et al.*, 2014; Nwaishi *et al.*, 2015; Dompierre *et al.*, 2017).

2.4 Fundamentals of the Research Approach

2.4.1 *Earth System Science and Ecosystem Analysis*

The research approach for this doctoral project is based on the conceptual framework of earth system science. Earth system science has been referred to as a "super discipline" and defined "as a single, integrated physical and social system" (Pitman, 2005). Since the coining of the term "ecosystem" in 1935 (Tansley, 1935), it has become the dominant paradigm within which most of the current earth system and global change research is developed (Golley, 1993; Müller, 1997).

The ecosystem concept developed within the field of ecology as a theoretical foundation and discretely refers to a philosophy (*e.g.*, holistic approach to studying and understanding the earth), an object (*e.g.*, a lake), and a scientific paradigm (*e.g.*, systems theory) (Golley, 1993). Initially, in line with its derivation within mechanistic and reductionist scientific paradigms, the focus was on studying an ecosystem by looking at its mechanisms and components separately rather than trying to study the object as a whole (Golley, 1993). This is indicated by the separation of an ecosystem into its structural (*e.g.*, soil or plants) and functional (*e.g.*, water or carbon cycling) components.

In practice, the focus was on the structural aspects (*i.e.*, biological) of an ecosystem with little understanding of the functional ones (*i.e.*, interactions within and between systems and their components) and this led to criticism of the use and value of the concept (Golley, 1993). More recently, as indicated by Müller (1997), ecosystem theory forms the basis for the modern view of environments with flows of energy and cycles of materials within and between well-defined systems drawing from disciplines such as biogeochemistry, resource economy, and landscape ecology.

As with the ecosystem concept, there are a variety of meanings associated with the terms function, functions, and functioning even when limiting the scope to ecological ecosystem studies (Jax and Setälä, 2005). The role of functioning as a proxy for biodiversity and issues with such a view are particularly dominant themes within the literature (Goldstein, 1999; Loreau *et al.*, 2001; Hooper *et al.*, 2005). Jax and Setälä (2005) identified four different meanings of function within the study of ecology that they deemed the most important: 1) Interactions or processes between two structural components, 2) processes among multiple structural components (*i.e.*, functioning of an ecosystem), 3) role that a structural component or group of components play within a system, and 4) processes of an ecosystem that are of practical use from a human perspective. The second definition (*i.e.*, ecosystem functioning) incorporates water and carbon cycling (the focus in this thesis) and is flexible enough to include queries related to pathways, budgets, and influence of structural assemblages (*e.g.*, vegetation). Goldstein (1999) pointed out that characterizing ecosystems solely upon structure or functioning is problematic. For example, it is important to understand the effects of a

particular management treatment on more than one identified structural component (Goldstein, 1999). This conceptual understanding of an ecosystem highlights the need to expand the integrated certification framework in the AOSR to one that incorporates ecosystem functioning in addition to its current focus on structural ecosystem components.

2.4.2 *Water and Carbon Balance and Complexity*

Biogeochemical cycles describe flows and transformations of elements through the Earth's living (biotic) and non-living (abiotic) components (Christopherson, 2003). As a simplistic overview of the water cycle, water evaporates into the atmosphere from sources such as oceans and snowpacks or through vegetation, falls as P in the form of rain or snow, and then flows through the ground (Schlesinger and Bernhardt, 2013). Storage may be short or long, such as glacier ice or groundwater, which typically exhibit time scales of hundreds or thousands of years for circulation. Devito *et al.* (2012) summarized that the water cycle in the boreal zone is marked by spatial and temporal variability. Forested areas behave as water sinks, where water is transpired by vegetation, and wetland areas behave as water sources, where water is collected and redistributed via various underground and overland pathways (Devito *et al.*, 2012). In the western Canadian boreal region, there is a general climatic water deficit characterised by annual and decadal periods of water losses to the atmosphere exceeding water inputs and thus a small decrease in stored water reserves in soils, water bodies, and groundwater (Devito *et al.*, 2012). Devito *et al.* (2012) also argued that traditional water balance models, which focus on P as the dominant input and runoff as the dominant output, should be retired in

favour of updated models that focus on soil moisture storage change, ET, and groundwater recharge. These are identified as the dominant hydrologic processes in boreal forest regions and are important to consider in ecosystem assessment, management, and reconstruction activities. A surplus of water suggests that an ecosystem is operating within its available water limits and has a high survival potential while a deficit indicates an ecosystem is using more water than is available and may become water stressed (Aber *et al.*, 2001; Nelson *et al.*, 2018).

A simplified overview of the carbon cycle involves the cycling of carbon from the atmosphere by plant photosynthesis or into the ocean by biological and solubility pumps and then back again through decomposition and combustion (Christopherson, 2003). The boreal zone is an important component of the global climate system because of the role forests and wetlands play in accumulating (via live biomass or peat) and releasing (via respiration (R)) carbon (Brandt, 2009) as well as through its role in surface-atmosphere energy exchange (Zhang *et al.*, 2018). Rising concentrations of atmospheric greenhouse gases including carbon-containing carbon dioxide and methane are linked to anthropogenic activities such as combustion of fossil fuels and land use change resulting in the reduction of organic matter stores (Schlesinger and Bernhardt, 2013). Although there is evidence that global terrestrial sinks including the boreal zone have been keeping pace with increasing rates of CO₂ emissions through a variety of proposed mechanisms (*i.e.*, CO₂ fertilization, longer growing seasons, and nutrient fertilization), the future sink strength of boreal forest ecosystems experiencing an ever-changing climate and disturbance regime is uncertain (Malhi *et al.*, 1999; Zhu *et al.*, 2018).

The complexity of these cycles makes it difficult to fully analyse all components at once so studies often focus on a particular flow/flux, storage, or transformation process in boreal ecosystems. For example, Blanken and Black (2004) examined seasonal change in canopy conductance of an aspen forest in Saskatchewan and its relationship to fluxes of water and carbon, Carey (2008) studied the partitioning of energy in a recently reclaimed aspen forest in the AOSR, while Lilles *et al.* (2012) assessed aspen and white spruce trees at naturally saline sites in northern Alberta to draw implications for long-term potential of tree stands on reclaimed landscapes with saline soils. A number of meta-analyses of these component fluxes and processes have improved our understanding of boreal ecosystem water cycling (Law *et al.*, 2002; Amiro *et al.*, 2010; Brümmer *et al.*, 2012).

2.4.3 Eddy Covariance Technique

The EC technique is the key method used in this thesis to evaluate water use characteristics of the AOSR reclaimed sites. A large body of research examining carbon and water fluxes in boreal forests has made use of the EC technique to observe these fluxes at the ecosystem scale (Barr *et al.*, 2001; Law *et al.*, 2002; Coursolle *et al.*, 2006; Amiro *et al.*, 2010; Brümmer *et al.*, 2012). Many of these studies were part of larger research initiatives and networks including the Canadian Carbon Program (CCP), the Boreal Ecosystem-Atmosphere Study (BOREAS), the Boreal Ecosystem Research and Monitoring Sites (BERMS), and the Ameriflux network. A central component of these initiatives was monitoring carbon, water, and energy fluxes above boreal forest (and

other) ecosystems using ‘flux towers’ with EC instrumentation at multiple study sites on a quasi-continuous basis over multiple years (Baldocchi *et al.*, 2001).

The EC technique is a micrometeorological method that measures fluctuations of entities exchanged at the surface of the earth (*e.g.*, CO₂ and H₂O) as they are transported by turbulent air flow (*i.e.*, eddies) (Oke, 1987). Turbulent eddy updrafts and downdrafts are measured using high frequency (usually 10 to 20 Hz) measurements of vertical wind velocity. The covariance of fluctuations of these entities and vertical wind velocity is used to calculate fluxes of the entity over a set time period, usually 30 minutes (Burba, 2013). For example, plants remove CO₂ from the atmosphere during the photosynthetic process while CO₂ is added to the atmosphere by heterotrophic (R_{het}) and autotrophic respiration (R_{aut}). If over the measurement period there is a tendency for parcels of air moving upwards to be depleted in CO₂, this indicates a net uptake of CO₂ by the ecosystem. With regard to warm and moist updrafts, these indicate that sensible heat (H) and (latent heat) LE are directed away from the surface and there is a net transfer of heat into the atmosphere in the form of sensible and latent heat (*e.g.*, ET). This method works best over flat and homogenous terrain when the atmosphere is well mixed (Burba, 2013).

The instruments needed for the EC method and the measurement of CO₂ fluxes, H , and LE include a H₂O/CO₂ gas analyzer (open or closed path), a sonic anemometer thermometer, and a datalogger (Figure 2-3). Important ancillary measurements include meteorological sensors to measure atmospheric pressure (P_b), temperature (air and ground), and net radiation (R_n), for example. Instruments require a power source (solar panels, generator, or hook up to the electrical grid) and a physical structure to support the

Figure 2-3. Tower setup at the SBH reclamation site in 2003. EC equipment includes a sonic anemometer (CSAT3, Campbell Scientific Inc., USA (CSI)), an infrared gas analyzer (LI-7500, LI-COR, USA), and a data logger. Complementary meteorological equipment includes a net radiometer (CNR1, Kipp and Zonen, Delft, Netherlands) and a temperature and relative humidity probe (HMP45C, Vaisala Oyj, Finland). Batteries, charged by solar panels, are used to power the equipment. Black swirls represent turbulent air flow (eddies) while orange clouds and blue water droplets represent the entities of carbon dioxide (CO_2) and water vapour (H_2O), respectively, transported by the eddies and measured at this tower.

instrumentation above the surface (*e.g.*, tripod or tower) (Aubinet *et al.*, 2012; Burba, 2013). This means that conducting EC measurements may involve substantial financial and time investments, which need to be taken into consideration when evaluating its potential use for research within academic or industrial applications.

LE, H, and CO_2 (F_c) fluxes are calculated as follows:

$$LE = L_v \frac{M_w/M_a}{\bar{P}} \rho_d \overline{w'e'} \quad [2-1]$$

$$H = \bar{\rho} C_p \overline{w' T_{air}'} \quad [2-2]$$

$$F_c = \overline{\rho_d w' f'} \quad [2-3]$$

where L_v is the latent heat of vapourization, M_w is the molecular weight of water, M_a is the molecular weight of air, P is the pressure of air, ρ_d is the density of dry air, w is vertical velocity, e is the vapour pressure of air, ρ is the density of air, C_p is the specific heat capacity of air, T_{air} is the temperature of air, and f is the dry mole fraction of carbon dioxide where primes denote fluctuations from the mean and overbars denote the covariance (Burba, 2013).

Together LE and H provide information about the energy balance and energy partitioning at the surface. ET rates are calculated from LE ($ET = LE/L_v$). Ecosystem productivity reflects the flow of both energy and mass through the ecosystem and is sensitive to disturbance or other environmental change (Amiro *et al.*, 2000). NEP of CO_2 during the day represents GEP minus R ($NEP = GEP - R$) and is taken in this thesis as the inverse of net ecosystem exchange of CO_2 (NEE) computed as F_c plus the rate of change in stored CO_2 within the air below the EC sensor ($NEE = F_c + S$). GEP is the total uptake of CO_2 by the vegetation via photosynthesis whereas R includes both heterotrophic (*e.g.*, bacteria) and autotrophic (*i.e.*, plant) respiration. Thus, at night NEP is equivalent to negative R due to an absence of photosynthesis. The sign convention used here is that NEP and GEP represent CO_2 uptake when positive while R is positive when the ecosystem is a source of CO_2 to the atmosphere. The reverse sign convention is used for NEE. The ratio of GEP to ET is useful for evaluating water use efficiency (WUE) of an ecosystem. At the leaf level, WUE is an indication of biomass accumulated

per amount of H₂O transpired but can also be examined at the ecosystem scale and is a critical factor in ecosystem success in the relatively dry AOSR environment with potentially saline substrates (Purdy *et al.*, 2005; Kessler *et al.*, 2010; Lilles *et al.*, 2012).

2.4.4 Chronosequences and Natural Analogues

Water-use characteristics of boreal ecosystems differ over time and space (Chapin *et al.*, 2000). To understand if reclaimed ecosystems are comparable with non-reclaimed ecosystems and thus likely to survive and develop similarly, both chronosequences and comparison with natural analogues may be carried out. Comparing post-disturbance areas with natural analogues is a common approach to study ecosystem development and characteristics such as the recovery of North American boreal forests from fire with regard to carbon dynamics (Litvak *et al.*, 2003), the type and diversity of vegetation communities anticipated in reclaimed saline wetlands in the AOSR (Trites and Bayley, 2009), and the effects of management practices on the diversity of bryophytes in Finnish boreal springs (Lehosmaa *et al.*, 2017). In this type of study, a reference site is used as a control or model so that diverging development or variations in status, respectively, for a study site may be assessed. Quideau *et al.* (2013) asserted that these comparative studies need to account for the range of values associated with natural systems, suggesting that paired studies with one post-disturbance site and one natural analogue may not be as informative as desired. For example, their paper noted that previous studies showed differences between reclaimed and reference soils but noted that their study took into account the range of natural variability and identified areas of overlap with regard to nutrients and microbial communities. Chronosequences are referred to as “space-for-

time” substitution studies in which spatial and temporal variations in a region are assumed to be equivalent (Pickett, 1987). Although continuous monitoring of a given ecosystem is ideal, forests are slow growing and take decades to reach maturity depending on forest species, climate, and the definition of maturity. Thus, many researchers examine forests at different stages of development but with otherwise similar management and other characteristics. Despite the difficulty in controlling for all other potential variables that might affect ecosystem functioning, age trends, or trajectories of NEE, GEP, ET, *etc.* have been created (Litvak *et al.*, 2003; Goulden *et al.*, 2011). Another issue with these studies occurs when measurements are not concurrent or located close to one another and forests experience different weather conditions. However, Bergeron *et al.* (2008) concluded that forest developmental stage is more important than climate based upon the finding that inter-site differences were greater than inter-year differences (wet and dry) in a post-harvest mature black spruce (*Picea mariana* Mill.) forest. These studies are also useful for testing and validating process-based models of forest growth and function (Pretzsch, 2009).

2.5 Conclusion

A greater understanding of how reclaimed ecosystems function and develop with regard to water use is crucial to developing reasonable and defensible regulatory practices and protocols. The challenge of assessment and certification of reclaimed landscapes is a timely topic with gaps in available knowledge. However, with 81,300 ha of land disturbed as of 2013 (Government of Alberta, 2010), there is an intensive effort to investigate and address these gaps via numerous research projects since petroleum

extraction from the oil sands reserves will continue into the foreseeable future (Gosselin *et al.*, 2010). This project contributes to that effort by examining numerous long-term and short-term EC studies of water use functioning at reclaimed sites including chronosequence studies and comparisons with natural analogues.

3 FOREST WATER USE IN THE INITIAL STAGES OF RECLAMATION IN THE ATHABASCA OIL SANDS REGION²

3.1 Introduction

Considerable scientific, management, and regulatory challenges exist related to 1) the extraction of bitumen from the 4,800 km² of land currently designated as mineable and 2) the reclamation of the post-extraction landscape required of companies granted permission to mine oil sands deposits in the Athabasca Oil Sands Region (AOSR) (Richardson, 2007; Gosselin *et al.*, 2010; Powter *et al.*, 2012). A central component of the landscape reclamation strategy is the overall approach and feasibility of constructing heterogeneous boreal landscapes of lowland wetlands and upland forests on previously mined sites (Alberta Environment, 2010; Devito *et al.*, 2012). Although a focus of recent reclamation research efforts has been on the creation of wetlands (Mollard *et al.*, 2015; Borkenhagen and Cooper, 2016; Ketcheson *et al.*, 2016; Nicholls *et al.*, 2016), earlier and ongoing reclamation activities have focussed on forests and aspects of forest establishment including soil water dynamics (Carrera-Hernández *et al.*, 2012; Huang *et al.*, 2015), vegetation cover (Rowland *et al.*, 2009; Pinno and Hawkes, 2015), soil bacteria (Quideau *et al.*, 2013), nutrient fixation (Yan *et al.*, 2012; Kwak *et al.*, 2015), and saline toxicity (Kelln *et al.*, 2008; Lilles *et al.*, 2012).

For upland forests, ecosystem water use is an important factor to consider during construction and ongoing assessment of reclaimed landscapes. Soil covers must be constructed that provide adequate moisture supply for vegetation and are of sufficient

² Refer to the Preface for information on the published status for the content of this chapter and the appropriate source to reference.

thickness to limit the upward migration of saline water that typically occurs beneath constructed covers (Purdy *et al.*, 2005; Rowland *et al.*, 2009; Gosselin *et al.*, 2010). High rates of evapotranspiration (ET) can deplete near-surface available moisture if total water storage in the soil cover is limited, thereby reducing plant growth and drawing saline water up into the rooting zone. In this regard, understanding and anticipating ET for reclaimed ecosystems over time is critical to ensure appropriate reclamation capping strategies.

In the sub-humid western boreal region, ET is the dominant hydrological flux (far surpassing runoff) and varies temporally and spatially with climate and surface cover which exert strong controls on evaporation and transpiration (Amiro *et al.*, 2006a; Ewers *et al.*, 2011; Brümmer *et al.*, 2012; Brown *et al.*, 2014). Terrestrial ecosystem ET is enhanced with adequate soil moisture supply, moderate atmospheric vapour pressure deficit, and increases in available energy. Afforestation and reforestation around the world have been shown to reduce water yield as grasslands or shrublands are replaced with trees through their impacts on transpiration, interception, and evaporation (Farley *et al.*, 2005). There has also been considerable research in Canada's western boreal forest across a range of stand types and ages (Barr *et al.*, 2006). Among boreal tree species, middle-aged forests dominated by deciduous aspen have higher ET than recently disturbed, mature, or conifer dominated stands (Amiro *et al.*, 2006a; Ewers *et al.*, 2011; Brümmer *et al.*, 2012; Brown *et al.*, 2014). Studies suggest that boreal forests have a range of ET variability based on long-term climate cycles (Bonan, 2008), yet the range of ET largely corresponds with species (Barr *et al.*, 2001; Coursolle *et al.*, 2006).

The western Canadian boreal forest is subject to a range of disturbances that influence ecosystem water use such as fire, harvest, and removal for resource extraction activities (cut lines, drill pads, surface mining, *etc.*). Following disturbance, forest hydrological and biogeochemical cycles recover within 10-20 years (Litvak *et al.*, 2003; Amiro *et al.*, 2006b; Goulden *et al.*, 2011), yet the rate of this recovery is dependent upon the type of disturbance, the ecosystem that emerges post-disturbance, and whether it is managed or left to recover naturally. How ecosystems store and use water on constructed soils, and how this compares to other disturbed and undisturbed boreal landscapes, is largely unknown (Amiro *et al.*, 2006a; Ewers *et al.*, 2011; Brümmer *et al.*, 2012; Brown *et al.*, 2014). Long-term information on upland water use is critical in landscape design, as companies must construct a mosaic of linked upland-lowland systems that rely on sufficient moisture availability and redistribution among landscape units. The change in water use with time in uplands will have strong implications for sustainability of the wetlands downslope. Furthermore, it is through detailed observations and long-term measurements that information will emerge to guide regulators in the assessment of reclamation success.

The objective of this paper is to evaluate the ecosystem-scale water use of an upland forest during the first 12 years post-reclamation (2003-2014) using the eddy covariance technique. The study site, South Bison Hill (SBH), is a long-term research site used to evaluate capping soils and forest reclamation practice that has undergone considerable change over this time (Kessler *et al.*, 2010; Huang *et al.*, 2015). By linking changes in water use to ecosystem development, important information on expected

changes to ET will be evaluated along with the functional controls. This information will help fill critical knowledge gaps with regards to ecosystem recovery and water use on oil sands mining landscapes.

3.2 Methodology

3.2.1 Site Description

The SBH study site is located north of Fort McMurray, Alberta within Syncrude Canada Ltd.'s Base Mine (Figure 3-1). Descriptions of the construction and development of SBH are described by Carey (2008) and Huang *et al.* (2015). In summary, SBH is a saline-sodic clay shale overburden deposit formed into a shallow sloped hill (~ 60 m elevation) with a broad plateau approximately 14 ha large. Reclamation soils were placed on the slopes in 1999 and on the plateau in 2001. The hilltop soil profile is shale covered with 100 cm of glacial till soil and 20 cm of peat mineral mix. In 2003, the plateau was fertilized and seeded with barley (*Hordeum* spp.) to reduce erosion of the soil cover while aspen (*Populus tremuloides* Michx.) and spruce (*Picea glauca* (Moench) Voss) were planted in 2004 to promote afforestation of native plant species.

The vegetation cover at the beginning of the study period was dominated by barley (*Hordeum* spp.) with fireweed (*Epilobium angustifolium* L.), sow thistle (*Sonchus arvensis* L.), and sweet clover (*Melilotus alba* Medik., *Melilotus officinalis* L.) also present (Carey, 2008) (Figure 3-2). Vegetation surveys and forest mensuration measurements were conducted mid-growing season in 2013 and 2014. After 10 years since establishment, a mix of trees (coniferous and broadleaf), shrubs (evergreen and deciduous), ferns, graminoids, and forbs are present at the site with trace amounts of

Figure 3-1. Map of Alberta (left) with an inset map of the region around Fort McMurray (right) showing the location of the SBH study site within the active oil sands project boundaries. Data are courtesy of Alberta Environment and Parks (2015), DMTI Spatial Inc. (2014a, 2014b), and Statistics Canada (2016). Reprinted with permission of John Wiley and Sons.

mosses and shrubs (Figure 3-2). Coniferous and broadleaf tree covers are estimated at 8.8 % and 33.8% per 100 m², respectively. The dominant tree species are trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss) while balsam poplar (*Populus balsamifera* L.) and black spruce (*Picea mariana* Mill.) are also present. The density, diameter at breast height, and site index for aspen are 1753 stems ha⁻¹, 5.2 cm, and 24.1, respectively, while comparable data for white spruce are 147 stems ha⁻¹, 2.8 cm, and 21.9. Site index refers to the estimated height in m of the

Figure 3-2. Photographs of the eddy covariance tower at SBH in 2003 (left) and 2014 (right). The flux equipment measurement height was 2.9 m in 2003 and 8.25 m in 2014. Reprinted with permission of John Wiley and Sons.

dominant tree species at an age of 50 years and was calculated using the GYPSY model of Huang *et al.* (2009b).

The northern region of Alberta is classified as sub-humid and cycles through wet and dry periods over both seasonal (*e.g.*, increased precipitation in spring and dry period in late summer) and longer-term (*e.g.*, drought years) time periods (Devito *et al.*, 2012). The nearest Environment Canada weather station is the airport in Fort McMurray (56° 39' 12" N and 111° 13' 24" W). Temperature climate normals (1981-2010) reflect the region's cold winters and warm summers with daily average temperatures ranging from -12.2 °C to -22.5 °C in January and 10.5 °C to 23.7 °C in July (Environment Canada, 2013). From 1981-2010, annual average temperature was 1.0 °C and total precipitation was 418.6 mm (Environment Canada, 2013). Through the growing season (June, July, and August), the climate normal average temperature was 15.7 °C and total precipitation was 211.1 mm. The daily precipitation record for the 12-year study period

was taken from a weather station at Syncrude's Mildred Lake study site (57° 02' 28" N and 111° 33' 32" W).

Leaf area index (LAI) was monitored at SBH using a LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE (LI-COR)) from 2003 until 2012 and then a LAI-2200 Plant Canopy Analyzer (LI-COR) for 2013 and 2014. LAI measurements were carried out 4 to 5 times per season at 3 locations within 30 m of the flux tower and were not corrected for leaf arrangement, which varied over the years. This practice typically results in an underestimation of actual leaf area because overlapping of needles clumped together on a shoot is not taken into account when calculating LAI (Stenberg, 1996). A peak LAI of 4.0 was recorded using the LAI-2200 in mid-July 2014 followed by a value of 3.2 in August that year. A separate survey of the forest in August 2014 resulted in an LAI of 4.56 after correcting for needle leaf arrangement.

3.2.2 Eddy Covariance

The tower where observations were made is on the SBH plateau at 56° 59' 40.6" N and 111° 36' 58.2" W. The initial eddy covariance instrumentation setup for the period between May 2003 and mid-September 2008 is described by Carey (2008). A CSAT3 sonic anemometer (Campbell Scientific Ltd., Logan, UT (CSI)) and an open-path infrared gas analyzer (IRGA) (LI-7500, LI-COR) were mounted 2.9 m above the surface and logged at 10 Hz to a CR23X datalogger (CSI). Calculations of friction velocity (u_*), sensible and latent heat fluxes (H and LE), and CO_2 flux (F_c) were carried out on the logger using ambient air temperature and pressure measurements. In the fall of 2008, a

CR3000 data logger (CSI) was installed on a triangular tower to record and retain the 10 Hz measurements from the eddy covariance instrumentation at half hour intervals.

High frequency data collected by the CR3000 were processed by means of Eddy Pro software (v 5.2.1, LI-COR) using 30-min bulk averaging, the maximization of the covariance with a default time delay, Moncrief spectral corrections, coordinate rotation in two dimensions, no self-heating correction on the LI-7500, and de-spiking. Datalogger-computed fluxes and Eddy Pro fluxes were compared for 2008 and 2009. Calibration factors of $0.935H - 4.305 \text{ W m}^{-2}$, $1.079LE - 0.084 \text{ W m}^{-2}$, $1.099F_c - 0.048 \mu\text{mol m}^{-2} \text{ s}^{-1}$ were applied to the respective datalogger computed H, LE, and CO₂ fluxes from 2003 through 2008 to improve comparability with later years when high frequency data were available for post-processing. All data underwent a QA/QC procedure using Matlab (v 8.6, Mathworks, USA). Measurements were removed when they were associated with equipment malfunction, rain events which obstructed the open-path gas analyzer windows, statistics of eddy covariance input variables were outside of a reasonable value range, or when computed fluxes were greater than three standard deviations from the monthly daytime or nighttime average for a trace.

The rapid growth of vegetation at the site required adjustment of the equipment height at the beginning of several growing seasons: 2.90 m (2003), 2.96 m (2007), 4.63 m (2009), 7.10 m (2011), and 8.25 m (2014) (see Figure 3-2 for an example). The midday growing season flux footprint (Kljun *et al.*, 2004) representing 90 % of the flux source area for 2014 is on average $100.8 \pm 1.2 \text{ m}$ ($\pm 1 \text{ SE}$). The predominant wind direction is southwest ($180^\circ - 210^\circ$). Data were not excluded based upon the flux footprint or wind

direction analyses. The surrounding terrain in the predominant wind direction is similar to the study site and in 2014 less than 1.5 % of measurements retained for analyses are associated with a flux footprint distance beyond the ~130 m site boundary.

Where possible, gaps in the weather data were filled using regression-based relationships with comparable or related traces available from nearby measurement sites. Remaining gaps of up to two half-hour measurements of weather variables were filled with a linear interpolation. Longer gaps in these variables were filled using a mean diurnal variation algorithm with a window of 5 days.

Small gaps (up to two half-hour measurements) in the LE and H energy fluxes were filled using linear interpolation. Larger gaps were filled using a linear relationship between LE and Rn. On average, 20.4 % of the 30-minute June-August LE data were gap-filled with similar amounts of gaps filled during the day (10.3 %) and night (10.1 %).

Net ecosystem exchange (NEE) is the sum of CO₂ fluxes and the rate of change in CO₂ concentration at the height of the eddy covariance instrumentation. Net ecosystem productivity (NEP) was estimated as -NEE after removal of fluxes associated with low nighttime u_* values. Respiration (R) was measured directly as nighttime NEP. An exponential temperature response model was fit to the summer nighttime R measurements adjusted for seasonal variability using data windows of 200 half-hour measurements incremented in steps of 40 half-hour measurements. Modelled values were used to estimate daytime R and fill gaps at night. The difference between measured daytime NEP and modelled R was gross ecosystem productivity (GEP). A rectangular hyperbolic model fit to summer GEP data was adjusted for seasonality using 200 half-

hour windows and increments of 40 half-hours on the GEP values. Modelled GEP was used to fill gaps in daytime GEP while NEP gaps were filled using the difference in modelled GEP and R values. On average, 11 % of the 30-minute June-August GEP data were gap-filled. Growing season flux measurements were not available in 2005 due to instrumentation problems.

Complementary weather variables were measured using a CNR1 net radiometer (Kipp and Zonen, Delft, Netherlands) and a temperature and relative humidity (RH) probe (HMP45C, Vaisala Oyj, Finland). Soil temperature from 0 - 0.05 m depth was measured using TCAV-L thermocouples (CSI) and soil moisture was measured using CS615 probes (CSI) at 0.05, 0.15, 0.25, 0.40, 1.15 and 1.25 m depths with the upper two sensors situated within a peat mineral mix top layer (0-20 cm depth) and the lower sensors within a glacial till soil (20-120 cm depth). Available water content in the top 1 m of soil was calculated as the weighted average of these readings. Field capacity and wilting point of the overlying peat mineral mix were determined to be ~ 0.46 and $\sim 0.20 \text{ m}^3 \text{ m}^{-3}$, respectively, by Huang *et al.* (2015). Comparative values for the underlying glacial till soil were also reported by Huang *et al.* (2015) as ~ 0.36 and $\sim 0.18 \text{ m}^3 \text{ m}^{-3}$.

ET was calculated from latent heat fluxes and the latent heat of vaporization using measured air temperature. Additional derived variables include Bowen's ratio ($\beta = H/LE$), canopy conductance (g_c), and water use efficiency (WUE). For analysis, average not gap-filled midday values of Bowen's ratio and g_c for the period from 11:00 am to 2:00 pm during the growing season were calculated while gap-filled data were used to compute daily values of ET and WUE. Differences in data processing and analysis

resulted in differences in ET and β reported for SBH for 2003 through 2005 (Carey, 2008). These included energy balance closure corrections and differences in integration periods (daily vs. midday, for example).

Canopy conductance (g_c in units of m s^{-1} converted to mm s^{-1}) was calculated as the inverse of canopy resistance (r_c , s m^{-1}) using a rearranged form of the Penman-Monteith equation,

$$LE = \frac{sR_a + \rho c_p D / r_a}{s + \gamma (1 + r_c / r_a)} \quad [3-1]$$

where s is the change in saturation vapour pressure with temperature ($\text{kg m}^{-3} \text{ } ^\circ\text{C}^{-1}$), γ is the psychrometric constant ($\text{kg m}^{-3} \text{ } ^\circ\text{C}^{-1}$), R_a is the available energy flux density (net radiation minus soil heat flux and the rate of change in energy storage) approximated by the sum of H and LE (W m^{-2}), r_a is the aerodynamic resistance (s m^{-1}) calculated as u/u_*^2 , ρ is the density of dry air (kg m^{-3}), c_p is the specific heat of air ($\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), and D is the vapour density deficit of air (kg m^{-3}) all measured at SB30 (Monteith and Unsworth, 2008).

Potential evapotranspiration (PET in units of W m^{-2}) was calculated using a variation of the Penman-Monteith Combination equation presented by Campbell (1977) for evaporation from a wet surface and then converted into mm day^{-1} ,

$$PET = \frac{s}{s + \gamma} \times R_n + \frac{\rho c_p (D / r_a)}{s + \gamma} \quad [3-2]$$

where the terms are as defined above and R_n is the net radiation at the site ($\text{J m}^{-2} \text{ s}^{-1}$).

Reference crop evapotranspiration (ET_{REF}) for the airport in Fort McMurray in units of mm day^{-1} was calculated using an application of the Penman-Monteith

Combination equation currently used by the Food and Agricultural Organization (FAO) of the United Nations (Allen *et al.*, 1998):

$$ET_{REF} = \frac{0.408 \times s \times (R_n) + \gamma \times \left(\frac{900}{T+273.2} \right) \times u \times (D)}{s + \gamma \times (1 + 0.34 \times u)} \quad [3-3]$$

where the terms are as defined above. In addition, R_n is net radiation calculated from incoming solar radiation using a linear regression relationship with R_n at SBH for 2004 when SBH represented a field of early successional species ($\text{MJ m}^{-2} \text{ day}^{-1}$), T is air temperature ($^{\circ}\text{C}$), u is wind speed at a height of 2 m (m s^{-1}). To estimate u at 2 m from the 10 m measurement at the airport, it is calculated as $u = (u_*/\kappa)\ln(z/z_o)$ with u_* (m s^{-1}) derived from a linear regression between wind speed at 10 m height for the airport and u_* at SBH for 2004 when SBH was a field, while κ = von Karman's constant (0.4), z = height of measurement (2 m), and z_o = roughness length (0.01 m). The association between measured ET and these reference measures were assessed using Pearson correlation coefficients (r). The significance level was set to 0.05.

The relative importance of changes in r_c ($=1/g_c$), r_a , and R_a on LE as the forest grew was examined using the partial derivatives of the Penman Monteith equation with respect to these variables following the framework described by Winter and Eltahir (2010). Seasonal estimates of $\delta LE / \delta r_c$, $\delta LE / \delta r_a$, and $\delta LE / \delta R_a$ represented the theoretical sensitivity of midday LE to these driving variables and were computed using daily average midday periods with relatively clear conditions (solar radiation exceeding 400 W m^{-2}) in 2004 and 2013, two years when soil moisture remained relatively high all season. Water use efficiency ($\text{WUE} = \text{GEP}/\text{ET}$ in units of $\text{g CO}_2/\text{kg H}_2\text{O}$) was calculated

using the molecular weights for CO₂ (44 g mol⁻¹) and water (18 g mol⁻¹) along with the density of water.

3.3 Results

From 2003 through 2014, average growing season (June through August) temperatures were higher than the 30-year normal (15.7 °C), ranging between 18.3 °C (2008) and 20.7 °C (2012). Rainfall during the growing season was below the Fort McMurray airport 30-year normal (211.1 mm), ranging from 61.8 mm (2011) to 288.6 mm (2005) with 10 years below normal and two above (Figure 3-3). Annual precipitation varied from 188.5 mm (2011) to 503.9 mm (2005). Within the top 1 m of soil, volumetric water content at the surface typically decreased through the growing season but only lowered to the wilting point of 0.22 m³ m⁻³ for the surficial peat mineral mix for short periods of two to three weeks in August of 2010, 2011, 2012, and 2014. Soil water content did not go below the wilting point of 0.18 m³ m⁻³ identified by Huang *et al.* (2015) for the underlying glacial till soil at any time (Figure 3-3). In all years, growing season available water content remained above 68.9 mm m⁻¹ soil (Figure 3-3). Drier soil conditions appeared with the transition to a forested canopy cover 4 years after establishment (2006). However, growing season rainfall was not significantly different for these two periods ($p < 0.05$). After the development of the tree canopy, soils were never as wet as in the early years except for 2013. This year had the second highest growing season rainfall in the 12-year record.

Figure 3-3. (Top) Average daily growing season soil water content (SWC) at 25 (light grey), 40 (black), and 115 (dark grey) cm depths; (middle) average daily growing season available water content (AWC), and (bottom) total monthly P during the growing season for June (light grey), July (dark grey), and August (black). Reprinted with permission of John Wiley and Sons.

Over the 12-year period, LAI increases coincided with changes in the dominant vegetation (Figure 3-4). Photographs confirm that tree growth began in earnest by 2008 and that canopy closure had not yet occurred by 2014 (Figure 3-2).

Average growing season midday u_* and β reflected the changing nature of the vegetation. Friction velocity increased during the initial portion of the study period from 0.31 m s^{-1} in the early successional species phase to 0.50 m s^{-1} in the ninth year (2011) and remained relatively constant (Figure 3-5), reflecting the increase in momentum

Figure 3-4. Growing season leaf area index (LAI) measurements for SBH from 2003 through 2014. Reprinted with permission of John Wiley and Sons.

Figure 3-5. Annual growing season midday (June-August; 11:00 h - 14:00 h) Bowen's ratio (β) (top) and friction velocity (u_*) (bottom) values for SBH for the 12-year study period (2003-2014). Error bars represent ± 1 SE. Reprinted with permission of John Wiley and Sons.

absorption as canopy height and roughness increased. Energy partitioning of LE relative to H increased over time as illustrated by the decrease in β (Figure 3-5). The sum of LE and H increased by 54 % over the 12-year period, reflecting an increase in available energy. During this time, LE increased by 134 % and H decreased by 23 %. The year-to-year changes in midday β were more gradual and variable than the year-to-year changes in LAI (Figure 3-4), potentially reflecting the combined influence of vegetation change as well as soil moisture (Figure 3-3) and other variations in weather. For example, the lowest midday β occurred in 2013 and coincided with high LAI but also with the greatest growing season rainfall and soil moisture (Figure 3-3, Figure 3-4, Figure 3-5).

Total daily growing season GEP and ET also changed considerably with time. GEP steadily increased over the study period from 4.9 ± 0.14 to 8.9 ± 0.28 g C m⁻² d⁻¹ (± 1 SE) with little variation in the last 4 years (Figure 3-6). Average daily growing season ET increased from 1.6 ± 0.1 to 3.4 ± 0.1 mm d⁻¹ (± 1 SE) since 2003 (Figure 3-7). Seasonally, ET and LAI peaked in July with relatively larger seasonal variations in the later years (Figure 3-8, Figure 3-4). Over the last 6 years (2009-2014), the total growing season ET rate was 3.4 ± 0.05 mm day⁻¹ (± 1 SE). There was an increase in g_c from 5.7 ± 0.9 to 12.1 ± 0.4 mm s⁻¹ over the 12-year period but once normalized by LAI effective leaf-level conductance decreased from a high of 7.8 ± 0.6 to 3.5 ± 0.1 mm s⁻¹ on a leaf area basis or 225.9 ± 4.9 to 131.4 ± 2.9 mmol m⁻² leaf area s⁻¹ (± 1 SE) (Figure 3-9). These trends relate to the shift of dominant plant type from early successional

Figure 3-6. Growing season (June-August) gross ecosystem productivity (GEP) during the 12-year measurement period (2003-2014). Error bars represent ± 1 SE. Reprinted with permission of John Wiley and Sons.

Figure 3-7. Growing season (June-August) evapotranspiration (ET) from 2003 -2014. Error bars represent ± 1 SE. Reprinted with permission of John Wiley and Sons.

species to trees during the study period (Figure 3-2). The low normalized g_c in 2004 is associated with a relatively high LAI and low ET.

ET_{REF} was calculated using meteorological data from the Fort McMurray airport weather station to investigate the influence of weather in the overall ET and PET trends (Figure 3-10). ET_{REF} only varied by 64.6 mm or 16 % from the mean during the 12-year study period (compared to the 200.4 mm and 47 % difference in ET or the 244.2 mm and 31 % difference in PET). Between 2007 and 2008, ET_{REF} dropped by 5.9 mm while PET and ET increased by 195.8 and 97.7 mm, respectively. ET and ET_{REF} did not significantly correlate ($r = -0.11$, $p = 0.75$) while PET and ET did ($r = 0.91$, $p < 0.001$) which suggests that variations in ET over the 12 years were not largely driven by changes in weather.

In 2004, the sensitivity of LE to $r_c (=1/g_c)$ and to r_a under clear midday conditions was similar in magnitude but opposite in sign ($-0.24 \text{ W m}^{-2} / \text{s m}^{-1}$ and $0.35 \text{ W m}^{-2} / \text{s m}^{-1}$,

Figure 3-8. Diurnal monthly growing season evapotranspiration (ET) grouped by early successional species vegetation years (2003-2007) and later forest vegetation years (2008-2014). Reprinted with permission of John Wiley and Sons.

Figure 3-9. Annual growing season canopy conductance (g_c) expressed per unit ground area (top) and expressed per unit leaf area after normalizing by leaf area index (LAI) (bottom). Error bars represent ± 1 SE. Reprinted with permission of John Wiley and Sons.

respectively). In 2013, the sensitivity of LE to r_c increased in magnitude to $-2.12 \text{ W m}^{-2} / \text{s m}^{-1}$ while the sensitivity to r_a changed in sign and magnitude to $-0.77 \text{ W m}^{-2} / \text{s m}^{-1}$. In contrast, there was only a small increase in the sensitivity of LE to R_a between the two years, 0.26 and 0.37 $\text{W m}^{-2} / \text{s m}^{-1}$ in 2004 and 2013, respectively. For the midday periods in this analysis, average r_c decreased by 285 s m^{-1} , r_a decreased by 42 s m^{-1} , and R_a increased by 150 W m^{-2} between 2004 and 2013. Note that there was negligible change in D. These changes all had the effect of increasing midday LE but with the reduction in physiological limitations (increase in g_c /reduction in r_c) likely having the greatest impact.

Figure 3-10. Total rainfall (bars), evapotranspiration (ET, black circles), potential evapotranspiration (PET, open grey squares), and reference crop evapotranspiration (ET_{REF}, open grey diamonds) for the 2003-2014 growing seasons (June-August). Reprinted with permission of John Wiley and Sons.

Figure 3-11. Growing season (June-August) water use efficiency (WUE). Error bars represent ± 1 SE. Reprinted with permission of John Wiley and Sons.

Water use efficiency (WUE) decreased with the shift to a tree-dominated ecosystem but has slightly increased from a low of $7.53 \pm 0.32 \text{ g CO}_2 \text{ kg}^{-1} \text{ H}_2\text{O}$ ($\pm 1 \text{ SE}$) since 2009 (Figure 3-11). This early pattern corresponded to the relatively more rapid increase in ET than GEP with the early transition from early successional species ground cover to forest vegetation. Beginning in 2009, there are continued gains in GEP while ET has levelled off to a greater extent.

3.4 Discussion

Over the 12-year period since reclamation, the metrics that evaluate the hydrological functioning of SBH have changed substantially. ET increased by 62 % as the tree cover established and was accompanied by increases in canopy height, density, LAI, u^* , and canopy-level conductance while leaf-level conductance decreased. These factors along with R_a and D are all inter-related in their effects on the energy availability, water vapour demand, and turbulent transport that drives ET. Our analysis suggests that increases in ET were a result of changes in many of these factors but in particular it was a result of the increase in vegetation cover and increasing g_c .

Over the last 6 years, ET rates were similar to those reported at other undisturbed and post-disturbance boreal forest ecosystems. For example, Mkhabela *et al.* (2009) evaluated six jack pine forest sites between 3 and 30 years post-disturbance (harvest and fire) and found growing season ET was least for the youngest stands. June through August ET ranged from 117 mm to 313 mm (1.2 and 3.4 mm day^{-1}) among the post-disturbance sites in their study with differences in ET attributed to differences in initial site soil conditions but also on species diversity, which was greater post-fire. The authors

noted that post-fire sites had higher ET than post-harvest sites due to higher soil water content associated with finer textured soils and greater organic matter content, while higher levels of available nutrients from the decomposition of woody debris facilitates the regeneration of remaining vegetation. In oil sands landscapes, construction and management decisions determine many of these features including soil physical characteristics, nutrient availability, and vegetation species diversity (Quideau *et al.* 2013), which in turn will influence ET. Amiro *et al.* (2006a) reported peak growing season weekly July average ET rates of $\sim 3 \text{ mm d}^{-1}$ (385 and 328 mm year^{-1}) for a ~ 100 -year-old black spruce forest and $\sim 4 \text{ mm day}^{-1}$ (441 and 323 mm y^{-1}) for a > 80 year old aspen forest in central Saskatchewan, closely corresponding with June-August results for the aspen-dominated SBH site ($3.4 \pm 0.1 \text{ mm day}^{-1}$). Also in Saskatchewan, Barr *et al.* (2001) reported that among forests types, aspen had the highest peak daytime May to September growing season g_c ($\sim 15 \text{ mm s}^{-1}$), whereas coniferous sites had a greater control over transpiration water losses ($\sim 5\text{-}10 \text{ mm s}^{-1}$) in part reducing overall ET. While SBH is much younger than the forests examined by Amiro *et al.* (2006a) and Barr *et al.* (2001), it had a very similar growing season peak midday g_c as it transitioned to a forest after 2008 (June to August average $14.7 \pm 0.8 \text{ mm s}^{-1}$ from 2009 through 2014).

Interannual variability in ET post-2008 was associated with variations in seasonal weather and soil moisture, with increased soil moisture during the traditionally dry period of the growing season (*i.e.*, August) having a strong positive influence on the overall growing season ET. Growing seasons with sustained soil moisture from large precipitation events (2013) or evenly distributed precipitation and lower temperatures

(2009) had the highest non-normalized g_c and high ET. During 2013, ET ($\sim 3.4 \text{ mm d}^{-1}$) approached PET and monthly midday β was between 0.22 and 0.26 over the 3-month period because of sustained wet soils. 2009 was the other year in which ET ($\sim 3.4 \text{ mm day}^{-1}$) approached PET. Despite being cooler than the preceding years, soil water content at depth (25 cm) increased throughout August rather than decreased as in most years. Non-normalized g_c for 2013 and 2009 at $16.2 \pm 1.0 \text{ mm s}^{-1}$ and $15.4 \pm 0.6 \text{ mm s}^{-1}$, respectively, were highest out of the 12-year study period. The positive influence of precipitation and soil moisture on canopy conductance and latent heat exchange has been reported for another boreal forest site (Baldocchi *et al.*, 2000) as well as for the surface conductance of a temperate grassland (Wever *et al.*, 2002). Comparatively, ET was 67 % of calculated PET during the driest year (2011) and g_c was $14.4 \pm 1.1 \text{ mm s}^{-1}$. Although soil moisture did not drop below the estimated wilting point of the glacial till subsoil ($0.18 \text{ m}^3 \text{ m}^{-3}$), soil moisture was below the $0.22 \text{ m}^3 \text{ m}^{-3}$ wilting point for the peat mineral mix topsoil at 25 cm depth for 5.4% of the time in July and 8.4% of the time in August.. In contrast, 2014 had 8.5% of the season at or below $0.22 \text{ m}^3 \text{ m}^{-3}$ with $< 0.07\%$ falling outside the month of August. It is important to note that AWC remained above 74.9 mm m^{-1} soil during these August periods. The similar ET for 2013 and 2014 despite the latter year being drier than the former one is likely related to the high early season soil moisture content.

Compared with other regenerating and mature aspen forests, SBH has similar water use dynamics despite a range in LAI: SBH LAI increased from 0.9 to 4.0 during the study period while multi-site studies reported ranges of 1.0 – 5.8 (Amiro *et al.*,

2006a), 0.8 – 3.1 (Goulden *et al.*, 2011), and ~ 1.0 – ~ 4.0 (Law *et al.*, 2002). As LAI increases beyond a certain threshold, ET does not tend to respond to further increases in LAI. At a higher LAI, ET becomes largely controlled by canopy transpiration with a concomitant reduction in soil evaporation and understory transpiration due to shading and cooling (Blanken *et al.*, 1997; Baldocchi *et al.*, 2000). Another process that limits the influence of leaf area differences is competition for light, nutrients, and water among different species within an ecosystem (Law *et al.*, 2002). This competition results in changing vegetation composition and has been suggested as a reason why ET in deciduous boreal forest stands remains similar as a stand ages followed by a decline in cases where conifers become the dominant tree type (Law *et al.*, 2002; Goulden *et al.*, 2011). At SBH, there is the likelihood of a decline in water use as the forest transitions from an aspen-dominated forest to a spruce forest over the next several decades because of the reduced canopy conductance and ET associated with conifers (Margolis and Ryan, 1997; Amiro *et al.*, 2006b; Ewers *et al.*, 2011; Kimmins, 2011). The studies by Law *et al.* (2002) and Goulden *et al.* (2011) reported similarities in ET or other indicators of ecosystem functioning (*e.g.*, GEP) for different ages of forests with similar growth forms and climate. These results indicate that regardless of the disturbance type, post-disturbance landscapes are capable of reaching a steady water use state within the range of natural variability. At SBH, peak water demand plateaued around the 7-year mark (2009), the year after the large increase in LAI and development of a tree overstory. However, the effect of increasing LAI on ET is likely being mitigated to some extent by decreases in soil and understory ET as previously described.

Recently reclaimed and regenerating sites have been noted as less efficient with regard to water use than intermediate- or mature-aged sites due to increased evaporation coupled with minimal carbon uptake by vegetation (Coursolle *et al.*, 2006; Mkhabela *et al.*, 2009). The relatively high WUE at SBH from 2003 to 2007 is likely due to the presence of both early successional species (including grasses) and young trees, which increased the uptake of carbon relative to recently harvested or burned jack pine sites with WUE as low as 1.9 and 4.8 g CO₂ kg⁻¹ H₂O, respectively (Mkhabela *et al.*, 2009). The 2014 WUE of 9.7 ± 0.3 g CO₂ kg⁻¹ H₂O at SBH is similar to the growing season WUE of mature jack pine and intermediate jack pine forests (ranging from 7.3 to 9.5 g CO₂ kg⁻¹ H₂O) (Mkhabela *et al.*, 2009) and August values of ~ 11.0 g CO₂ kg⁻¹ H₂O reported for a mature northern black spruce forest at ~ 170 years of age but higher than the ~ 5.0 g CO₂ kg⁻¹ H₂O reported for a mature old aspen forest at ~ 80 years of age (Coursolle *et al.*, 2006). The very low WUE of the aspen forest was due to the third year of drought conditions impacting both ET and GEP (Coursolle *et al.*, 2006). Over the last five years of measurements at SBH, year-to-year variations in growing season WUE were less than ~ 2 g CO₂ kg⁻¹ H₂O reflecting relatively constant GEP and ET. This consistency in SBH WUE among the later years is likely due to only relatively short periods with low soil moisture at the end of the growing seasons. The largest change in WUE is in 2013 and is likely due to a very wet summer and higher ET than neighbouring years.

With regards to growing season carbon uptake, the increasing trend in GEP plateaued around 2012 at ~ 9 g C m⁻² day⁻¹. The last 4 years (2011-2014) include the second wettest on record (2013) and two relatively dry years (2011 and 2014), and given

only small differences in LAI normalized g_c values during that period, it is likely that GEP is not being constrained by moisture availability. Mkhabela *et al.* (2009) found that June to August GEP varied at a range of boreal sites following disturbance from $\sim 1 \text{ g C m}^{-2} \text{ day}^{-1}$ at a harvested jack pine site < 5-years-old to $\sim 10 \text{ g C m}^{-2} \text{ day}^{-1}$ at a mixed deciduous-coniferous fire site ~ 15 -years-old. Two jack pine stands 19 years apart had very similar GEP ($\sim 4 \text{ g C m}^{-2} \text{ day}^{-1}$ vs. $\sim 3 \text{ g C m}^{-2} \text{ day}^{-1}$ for 20- and 39-year-old stands) (Mkhabela *et al.*, 2009). Several studies have shown that growing forests of various types in various climates transition from a net CO_2 source to the atmosphere to a net CO_2 sink around the age of 10 years (Litvak *et al.*, 2003; Amiro *et al.*, 2010). It is important to note that these studies are usually examining sites after fire or harvest disturbances as opposed to looking at ecosystems constructed after resource extraction in the oil sands. Gross primary productivity initially increases rapidly following disturbance, levels off, and then declines slightly as a forest matures (Goulden *et al.*, 2011). Although SBH has yet to reach full canopy closure, the GEP trajectory indicates it is entering a phase of relatively high and stable carbon dynamics, as has been reported for other post-disturbance boreal forest chronosequences (Amiro *et al.*, 2010). It is worthwhile to emphasize that findings on boreal forest carbon dynamics are based predominantly on chronosequence studies in which data comes from distinct stands at different ages since disturbance while the findings at SBH are based on data from one site since disturbance.

3.4.1 Implications for Oil Sands Reclamation

Across the Athabasca Oil Sands Region, upland forest reclamation activities are well underway. However, to date there has been limited long-term published research on

post-mining landscapes (Pinno and Hawkes, 2015). Of the 4,800 km² currently estimated as mineable, only 1.04 km² has received a reclamation certificate from the provincial government. This certificate, issued in 2008, was based on an ecosystem assessment after 25 years and as the first application it served as a test of the approvals process at that time (Unknown, 2008). Nevertheless, there exists considerable ongoing uncertainty with the process, including the methods and metrics of evaluation for certification. At present, assessment criteria for reclaimed oil sands landscapes have been proposed to focus on structural components, notably soil and vegetation characteristics of a site (Alberta Environment, 2010; Poscente and Charette, 2012). However, there is ample rationale to further explore functional aspects of recovering ecosystems, particularly as they can be used to test the appropriateness of structural indicators. For upland forests, water use is an informative integrated ecosystem metric, bringing together several ecosystem variables into a succinct set of indicators (Kramer and Boyer, 1995; Mkhabela *et al.*, 2009).

In this study, we utilized the eddy covariance technique along with simple ecosystem metrics (LAI and vegetation characterization) to monitor water and carbon dynamics of an oil sands reclamation site called South Bison Hill over a 12-year period. Results suggest that after ~ 10 years, water use metrics such as ET, and g_c stabilize to values comparable to those observed in other boreal forest landscapes across a range of ages (Litvak *et al.*, 2003; Amiro *et al.*, 2006b; Coursolle *et al.*, 2006; Goulden *et al.*, 2011). This provides valuable information well in advance of 25 years that SBH is utilizing water and functioning in a fashion analogous to a non-oil sands aspen dominated

boreal forest. Although eddy covariance requires specialized instrumentation, it is possible that water use metrics can be directly related to other biometric traditional forestry indices. In addition, the possibility of upscaling these metrics using remotely sensed data should be explored. Finally, it must be noted that this study is based on only one long-term site, and that future research will focus on relating water use to species, reclamation practice, and forest age to improve our characterization of ecosystem success. In this way, results from such long-term research will benefit stakeholders and their efforts developing reclamation practices and reclamation assessment criteria and protocols (Burton and Macdonald, 2011; Poscente and Charette, 2012; Powter *et al.*, 2012).

3.5 Conclusion

This study presents growing season water use characteristics at a reclaimed oil sands site near Fort McMurray called South Bison Hill, and provides the first long-term ecosystem-scale perspective of a constructed upland boreal forest. Based upon the results, we conclude that vegetation development is the dominant control of early water use at reclaimed oil sands sites under non-drought conditions and that regardless of disturbance type, post-disturbance boreal forest landscapes are capable of similar water use. The water use indicators (*i.e.*, WUE, ET, β , and g_c) were noticeably different during the early successional species and forest stages at this site with a clear change associated with the emergence of the trees as the dominant vegetation type. The increase in ET was found to be most sensitive to the increase in g_c but was also supported by increases in available energy and aerodynamic roughness (and thus decrease in aerodynamic

resistance) that accompany this change in vegetation. The managed development of SBH, including the creation of a soil profile and initial planting of barley and then tree vegetation, is very different from the development of the referenced post-burn or post-harvest sites. Regardless, the water use indicators were comparable (*e.g.*, ET) and reasonably within range (*e.g.*, WUE) of other boreal forest ecosystems, particularly aspen stands.

Ongoing study on the development of this site under changing and potentially stressful conditions (*e.g.*, drought) will be invaluable to understanding the resilience of this ecosystem. This future research will also benefit reclamation assessment by facilitating the identification of early trajectories and indicators for reclaimed sites. Of particular interest are regeneration lag times as well as performance trajectories and envelopes for reclaimed sites and how they compare to naturally regenerating sites.

Acknowledgements

Site access and archived data were provided by Syncrude Canada Ltd. while research funds were provided by Canada's Oil Sands Innovation Alliance (COSIA). The Watershed Hydrology Group, field technician Dr. Mike Treberg, and data technician Dr. Gordon Drewitt of McMaster University conducted site setup, maintenance, and data management. Botanical site data, including site index and a supplementary leaf area index, were collected and analyzed by Integral Ecology Group with special thanks going to Justin Straker, Jeff Anderson, Trevor Baker, and Meghan Laidlaw. The acquisition of data sets and the creation of a map were supported by Rebecca Bartlett of Carleton University's Maps, Data and Government Information Centre.

4 FILLING IN A FOREST PATCHWORK: A MULTI-SITE ANALYSIS OF RECLAIMED AND REFERENCE PATCHES OF THE CANADIAN BOREAL FOREST

4.1 Introduction

The boreal biome comprises a suite of integrated landscape types resulting from an interaction of climate, vegetation succession, and disturbance regimes (Margolis and Ryan, 1997; Brandt, 2009; Brümmer *et al.*, 2012). This biome spans the northern circumpolar region where disturbances from industrial activities such as mining and tree harvesting contribute to the patchwork nature of the overall landscape (Brandt, 2009). Surface mining of bitumen in the AOSR is a major industrial activity in Canada with a current estimated footprint of 89,500 ha (0.02% of the Canadian boreal zone) (Government of Canada, 2015). However, the total area of oil sands deposits in Canada is estimated to cover 14 million ha with the type and area of further disturbance dependent upon extraction technologies and market demand (Richardson, 2007).

The recovery of boreal ecosystems after tree harvesting, fires, insect infestations, and windstorms has been examined (Bergeron *et al.*, 1998; Peltzer *et al.*, 2000; Amiro, 2001; Gromtsev, 2002; Shorohova *et al.*, 2009; Amiro *et al.*, 2010). In addition to assessments of forest structural change (Weber and Flannigan, 1997; Soja *et al.*, 2007), assessments of ecosystem functional change such as carbon cycling and water use provide an indication of overall ecosystem productivity and water demands as the ecosystem develops after disturbance (Jones, 2013). Unproductive vegetation due to insufficient water availability suggests that an ecosystem is stressed (Kljun *et al.*, 2006; Petrone *et al.*, 2015), which provides an indication of the post-disturbance ecosystem's

potential to tolerate other disturbances such as insect infestations, heat stress, or nutrient deficiency (Niinemets, 2010). Trajectories of tree growth over time are based on modelled empirical relationships and are used in forestry to assess the current status and future timber production potential of forest stands (Vanclay and Skovsgaard, 1997; Pretzsch, 2009); however, the concept may be expanded to other ecosystem function concepts such as ecosystem carbon dynamics (Kurz *et al.*, 2008). Overall, recovery trajectories have been observed to vary with pre-disturbance land cover type, disturbance type, and microclimate (*e.g.*, moisture and temperature). Trajectories of ecosystem carbon dynamics, for example, may be used to evaluate the current and future functional status of reclaimed ecosystems.

It is unclear how the recovery trajectories of post-disturbance ecosystems in the AOSR vary from those of boreal ecosystems that were disturbed by forest harvesting or fire. To date, research on reclaimed oil sands ecosystems has focused largely on structural components such as soil nutrient composition and availability (Yan *et al.*, 2012; Ojekanmi and Chang, 2014) or tree seedling establishment and growth (Sloan, 2013; Macdonald *et al.*, 2015). Studies examining trajectories of ecosystem functioning after disturbance using EC-derived water, carbon, and energy surface-atmosphere exchanges have not yet included AOSR reclamation sites (Amiro, 2001; Law *et al.*, 2002; Coursolle *et al.*, 2006; Humphreys *et al.*, 2006; Goulden *et al.*, 2011; Brümmer *et al.*, 2012). A recent study focusing on a single reclaimed oil sands ecosystem suggests that water use at that site was within the range of natural variability after approximately a decade (Strilesky *et al.*, 2017).

This study aims to address how carbon cycling and water use of reclaimed oil sands sites will integrate into the continually evolving patchwork of the surrounding boreal forest. A multi-site analysis of eight boreal aspen forest study sites includes four reclaimed oil sands sites constructed with different ecosystem targets and remediation practices, along with four reference sites at various ages of recovery since fire and harvesting. Reclaimed sites refer to ecosystems that were constructed in the AOSR, whereas reference sites were outside of the AOSR but still within the boreal forest region of western Canada. Six of these sites were included in a comparison study for the first time. Analyses were performed on EC-derived fluxes of carbon dioxide and ET to assess how reclaimed and reference ecosystems compare with regard to water use as they recover from disturbances. We anticipate that within 20 years following disturbance the young recovering sites will be within the range of natural variability.

4.2 Methodology

4.2.1 Study Locations

4.2.1.1 Reference and Reclaimed Sites

Eight sites, four reclaimed and four reference, equipped with EC towers were used for these analyses. All sites had complementary meteorological equipment either on-site or nearby, were located within the western Canadian boreal forest, and had trembling aspen present in the tree cover (Figure 4-1; Table 4-1; Table 4-2). The reclaimed sites were constructed boreal forest ecosystems located within an active northern Alberta oil sands mine, whereas the reference sites were boreal forest

Figure 4-1. Map of Alberta and Saskatchewan (left) showing the locations of the reference boreal forest sites with an inset map of the region around Fort McMurray (right) showing the locations of the reclaimed sites. Data from Alberta Environment and Parks (2015), Brandt and Natural Resources Canada (Brandt, 2009), DMTI Spatial Inc. (2014a, 2014b), and Statistics Canada (2016).

ecosystems in various stages of regrowth following other disturbances located within Alberta and Saskatchewan (Figure 4-1).

All four of the reclaimed sites were located ~ 40 km north of Fort McMurray, Alberta within Syncrude Canada Ltd.'s Base Mine (Figure 4-1). They included a range of construction practices (*e.g.*, type and depth of cover materials, type and method of vegetation introduction, and hydrology), targeted outcomes (*e.g.*, isolated upland or integrated upland with lowland), and ages (*i.e.*, available EC data years range from 1 to 20 years since construction) (Figure 4-1, Table 4-1). The *Sandhill Fen 1 (SF1)* and

Table 4-1. Selected historical information and structural characteristics for the reclaimed and reference study sites.

Study Site/ Disturbance Type (Year)	Soil	Tree Vegetation	Development and Site Description
Reclaimed Sites			
Sandhill Fen 1 (SF1), Sandhill Fen 2 (SF2)/ Oil sands mine (2013)	52 ha (35 ha uplands) area: 0.3-0.4 m of clay till or fluvial subsoil topped with harvested forest floor material from jack pine or moist mixed trembling aspen and white spruce sites.	Trembling aspen (<i>Populus tremuloides</i> Michx.), jack pine (<i>Pinus banksiana</i> Lamb.), white spruce (<i>Picea glauca</i> [Moench] Voss), black spruce (<i>Picea mariana</i> Mill.), dogwood (<i>Cornus stolonifera</i> L.), and green alder (<i>Alnus viridis</i> ssp. <i>Crispa</i> (Ait.) Turrill).	Wytrykush <i>et al.</i> (2012) and Nicholls <i>et al.</i> (2016)
South Bison Hill (SBH)/ Oil sands mine (2003)	14 ha area: 1 m of glacial till topped with 20 cm of peat mineral mix cover material.	Trembling aspen, white spruce, balsam poplar (<i>Populus balsamifera</i> L.), and black spruce.	Carey (2008), Huang <i>et al.</i> (2015), and Strilesky <i>et al.</i> (2017)
Southwest Sand Storage (SWSS)/ Oil sands mine (1995)	2500 ha area: 0.45 m of peat mineral mix cover material (mixture of peat and a clay loam textured secondary soil).	Trembling aspen, poplar, Siberian larch (<i>Larix siberica</i> Ledeb.), and willow (<i>Salix</i> sp.).	Naeth <i>et al.</i> (2011)
Reference Sites			
Red Earth Creek #1 (REC1), Red Earth Creek #2 (REC2)/ Tree harvest (REC1 – 2008; REC2 – 2007)	Gray Luvisolic soil developed on glacial moraine till.	Trembling aspen and balsam poplar.	Brown <i>et al.</i> (2014) and Petrone <i>et al.</i> (2015)
Old Aspen (OA)/ Forest fire (1919)	Orthic Luvisolic soil with a thick (~ 10 cm) organic surface layer.	Trembling aspen, balsam poplar, and hazelnut (<i>Corylus cornuta</i> Marsh.).	Black <i>et al.</i> (1996), Chen <i>et al.</i> (1999), Barr <i>et al.</i> (2001), and Griffis <i>et al.</i> (2003)
Western Boreal (WB)/ Forest fire (1989)	Loamy sand textured soil.	Jack pine, trembling aspen, black spruce, balsam poplar, and birch (<i>Betula papyrifera</i> Marsh.).	Amiro <i>et al.</i> (2006a) and Mkhabela <i>et al.</i> (2009)

Sandhill Fen 2 (SF2) EC towers were located within the Sandhill Fen Watershed complex. This complex was established in a pit that was mined from 1977-1999 and subsequently used as a tailings deposit until 2008. Vegetation was planted in 2012 and varied spatially and proportionally based upon the distribution of harvested forest floor materials used as ground cover. The terrain included in the SF2 footprint had a greater proportion of aspen saplings to jack pine (*Pinus banksiana* Lamb.) than SF1, with aspen at SF1 located in hollows of rich organic soil originally intended for perched fens. The SBH study site soil cover was placed in 2001, barley was seeded in 2003, and aspen and white spruce were planted in 2004. By 2013, aspen and white spruce were the dominant tree species with broadleaf tree and coniferous covers accounting for 33.8% and 8.8% per 100 m², respectively. *Southwest Sand Storage (SWSS)* was an active tailings storage facility from 1991 to reclamation in 1995. In 2014, tree cover was 25% and deciduous shrubs (11%) while a mixed understory (ferns, graminoids, and forbs; 42%) and non-vascular ground cover (moss, lichen; 6%) were also present.

Two reference sites were located southwest of the reclaimed sites in northern Alberta while the other two were north of Prince Albert in central Saskatchewan (Figure 4-1). They included a variety of disturbance regimes (*i.e.*, natural and human-caused fires and harvest), tree species composition (*i.e.*, dominance of aspen vs. coniferous), ages (*i.e.*, available EC data years range from 1 to > 80 years since disturbance), and establishment dates (*i.e.*, 1919 to 2008) (Figure 4-1, Table 4-1). *Red Earth Creek 1 (REC1)* and *Red Earth Creek 2 (REC2)* reference sites were located in the same watershed approximately 200 m apart but on different upland catchment areas.

Measurements were available at both sites before and after harvesting. They were harvested 1 year apart with both stands dominated by aspen before and after harvesting. It was important to include these younger reference sites to compare the relatively young reclaimed stands to references of similar age. In addition, these younger reference stands and reclaimed stands have developed under similar climatic conditions. The *Old Aspen (OA)* site was a mature aspen stand with an approximately 21-m-tall aspen overstory located approximately 50 km NW of Prince Albert and on the southern edge of Prince Albert National Park (Black *et al.*, 1996; Barr *et al.*, 2001). Similar to OA, the *Western Boreal (WB)* site was located to the northeast of Prince Albert National Park and had a mixed aspen, jack pine, and black spruce tree canopy (Amiro *et al.*, 2006a).

4.2.1.2 Regional Climate

The climate in the study regions was classified as either Dfb (SF1, SF2, SBH, SWSS, WB) or Dfc (REC1, REC2, OA) according to an updated Köppen-Geiger climate classification system (Kottek *et al.*, 2006). Both climate classifications refer to snow climates (D) with relatively humid summers and winters (f) but differ with one having warm summers with at least four months of the year $> 10^{\circ}\text{C}$ (b) and the other cool summers (c). Environment Canada weather stations at the Fort McMurray and Prince Albert airports reported similar 1981-2010 climate normal values (Environment and Climate Change Canada, 2013, 2013). The average January and July temperatures were -17.4°C and 17.1°C for Fort McMurray, and -17.3°C and 18.0°C for Prince Albert. At Fort McMurray, there was on average 17.7 mm of P in January (23.8 cm of snow and 0.4 mm of rain) and 80.7 mm of rainfall P in July. Prince Albert received 16.2

mm of P in January (19.4 cm of snow and 0.6 mm of rain) and 76.6 mm of rainfall P in July. During July, the climate normal for extreme daily bright sunshine (*i.e.*, the greatest total number of hours with bright sunshine during a day) was 16.9 hours at Fort McMurray and 19.4 hours at Prince Albert. On average, central Saskatchewan's summers (June-July-August) were slightly warmer, drier, and sunnier than northern Alberta.

4.2.2 Flux Measurements and Derived Variables

H, LE, and NEE were measured using the EC technique at each site (Table 4-2). Complementary meteorological variables included R_n , T_{air} , RH, barometric pressure (P_b), K_d or photosynthetically active radiation (PAR), u , and friction velocity (u_*). To generally compare the regions where the study sites were located, daily P records for the study years were taken from Syncrude's Mildred Lake weather station ($57^\circ 02' 28''$ N and $111^\circ 33' 32''$ W), which was located in northern Alberta, and the records for the OA study site, which was located in central Saskatchewan. Datasets covering the period 2001-10 at OA and 2003-05 at WB were retrieved from the Ameriflux network online data sharing portal and have been presented in a number of past studies (Chen *et al.*, 1999; Amiro, 2001; Barr *et al.*, 2001, 2006; Blanken and Black, 2004; Amiro *et al.*, 2006a; Mkhabela *et al.*, 2009). The remaining sites' datasets were collected as part of an inter-institutional research program with energy and/or carbon dioxide fluxes previously reported wholly or in part (Carey, 2008; Brown *et al.*, 2014; Petrone *et al.*, 2015; Nicholls *et al.*, 2016; Strilesky *et al.*, 2017). To facilitate comparison of the eight sites, flux and meteorological traces obtained from respective research teams underwent additional

quality control cleaning, gap-filling, and trace calculation adjustments to ensure the most consistent dataset for comparisons.

Carbon dioxide fluxes (NEE, NEP, GEP, and R), ET, WUE, β , and g_c were calculated using the same procedures outlined by Strilesky *et al.* (2017). NEE was calculated as the sum of the CO₂ flux and the rate of change in CO₂ concentration at the height of EC instrumentation for all sites except OA where an eight-level profile system was used. NEP was estimated as negative NEE. Both NEE and NEP fluxes were removed at night when u^* was below a threshold value: 0.1 m s⁻¹ for SBH, SF1, SF2, SWSS; 0.25 m s⁻¹ for WB (Amiro *et al.*, 2006a); or 0.35 m s⁻¹ for OA (Griffis *et al.*, 2004), REC1, REC2 (Petrone *et al.*, 2015). Respiration was measured directly as nighttime NEP. Summer nighttime R measurements were used to fit an exponential temperature response relationship (Lloyd and Taylor, 1994). The relationship was used to estimate daytime R and fill gaps at night after adjusting estimates for seasonal variability using comparisons with a moving window approach. This entailed using 200 consecutive half hour observations of nighttime R incremented in steps of 40 half-hour measurements. GEP was calculated as the difference between measured daytime NEP and modelled R. Summer GEP data were used to fit a rectangular hyperbolic model (Barr *et al.*, 2004). Estimated GEP were adjusted for seasonality as for R above. These modelled values of GEP were used to fill gaps in daytime GEP while NEP gaps were filled using the difference in modelled GEP and R values.

ET (mm day⁻¹) was calculated as,

$$ET = LE/L_v \quad [4-1]$$

where LE was the latent heat flux and L_v was the latent heat of vaporization calculated using T_{air} .

WUE (g CO₂/kg H₂O) was calculated as,

$$WUE = GEP/ET \quad [4-2]$$

using the molecular weights for CO₂ (44 g mol⁻¹) and water (18 g mol⁻¹) and the density of water. Canopy conductance (g_c , m s⁻¹) was calculated as the inverse of canopy resistance (r_c , s m⁻¹) using a rearranged form of the Penman-Monteith equation (Monteith and Unsworth, 2008),

$$LE = \frac{sR_a + \rho c_p D / r_a}{s + \gamma (1 + r_c / r_a)} \quad [4-3]$$

where s was the change in saturation vapour pressure with temperature (kg m⁻³ °C⁻¹), γ was the psychrometric constant (kg m⁻³ °C⁻¹), R_a was the available energy flux density (R_n minus soil heat flux and the rate of change in energy storage) approximated by the sum of H and LE (W m⁻²), r_a was the aerodynamic resistance (s m⁻¹) calculated as $u/u^*{}^2$, ρ was the density of dry air (kg m⁻³), c_p was the specific heat of air (J kg⁻¹ °C⁻¹), and D was the vapour density deficit of air (kg m⁻³). For analyses involving g_c , non-gap-filled midday (11:00 h to 14:00 h) traces during the growing season were used. For analyses involving daily carbon fluxes, ET, and WUE, gap-filled traces were used.

All data processing and statistical analyses were performed using Matlab (v.8.6, Mathworks, USA). Regression tree analyses were used to explore the influence of environmental factors on EC fluxes in a similar manner to Li *et al.* (2016). Predictor importance estimates for the factors influencing EC fluxes were calculated by taking the

Table 4-2. List of EC tower locations, instrumentation, and sampling rates. All data were processed to half-hour averages.

Site	Location	Years of measurement and year stand established	Data frequency & processing	Sonic anemometer	CO ₂ /H ₂ O gas analyzers	Datalogger
Reclaimed Sites						
Sandhill Fen 1 (SF1)	57.0386°, -111.5850°	2014-15 (2, est. 2012)	10 Hz, EddyPro (LI-COR Inc., Lincoln, NE, USA (LI-COR))	CSAT3 (Campbell Scientific Inc., USA (CSI)) [2014]; R3-50 (Gill Instruments, Hampshire, UK (Gill)) [2015]	LI-7500 (LI-COR)	CR1000 (CSI)
Sandhill Fen 2 (SF2)	57.0379°, -111.5894°	2013-15 (3, est. 2012)	10 Hz, EddyPro (LI-COR)	CSAT3 (CSI)	LI-7500 (LI-COR)	CR1000 (CSI)
South Bison Hill (SBH)	56.9946°, -111.6161°	2003-14 (12, est. 2003)	10 Hz, datalogger [2003-08]; EddyPro [2008-14]	CSAT3 (CSI)	LI-7500 (LI-COR)	CR23X (CSI) [2003-08]; CR3000 (CSI) [2008-14]
Southwest Sand Storage (SWSS)	56.9934°, -111.7326°	2005-06; 2014-15 (4, est. 1995)	10 Hz, datalogger [2005-04]; EddyPro [2014-15]	CSAT3 (CSI) [2005-06]; R3-50 (Gill) [2014-15]	LI-7500 (LI-COR)	CR23X (CSI) [2005-06]; CR3000 (CSI) [2014-15]
Reference Sites						
Red Earth Creek #1 (REC1)	56.0727°, -115.4759°	2007-11 (1 pre-harvest est. 1962, 4 post-harvest est. 2008)	20 Hz, datalogger	CSAT3 (CSI)	LI-7500 (LI-COR)	CR23X (CSI)
Red Earth Creek #2 (REC2)	56.0754°, -115.4765°	2006-15 (1 pre-harvest est. 1962, 9 post-harvest est. 2007)	20 Hz, datalogger	CSAT3 (CSI)	LI-7500 (LI-COR)	CR23X (CSI)
Southern Old Aspen (OA)	53.6288°, -106.1977°	2001-10 (10, est 1919)	20 Hz, user software	R3 (Gill)	LI-6262, LI-7000 (LI-COR)	N/A
Western Boreal Fire Burn - 1989 (WB)	54.2539°, -105.8775°	2003-05 (3, est. 1989)	4 Hz, datalogger	CSAT3 (CSI)	LI-7500 (LI-COR)	CR23X (CSI)

sum of changes in mean squared error related to the regression tree splits for each predictor and then dividing it by the total number of splits.

4.3 Results

4.3.1 Climate

Measurements were made between 2003 and 2015 at the northern Alberta sites and between 2001 and 2010 at the central Saskatchewan sites (Figure 4-2). Relative to their climate normal, the summer seasons (June through August) included wet cool years (2013 in northern Alberta and 2004-05 in central Saskatchewan), dry cool years (2011 in northern Alberta and 2002 in central Saskatchewan), wet warm years (2012 in northern Alberta and 2007 in central Saskatchewan), and dry warm years (2007 in northern Alberta) (Figure 4-2; Figure 4-3). July was typically warmer than June and August (Figure 4-2). In northern Alberta, exceptional conditions occurred in 2006 (SBH, SWSS) when there was a warm June and wet July as well as in 2013 (REC2, SBH, SF2) when there was a lot of P throughout the growing season. In central Saskatchewan, 2001 (OA) was exceptionally dry, 2003 (OA, WB) was also dry but had more P falling in August than previous months, and 2008 (OA) had a wet July. Overall, the summers observed at the northern Alberta sites were warmer and drier than normal and warmer than the Saskatchewan sites, which were cooler and wetter than normal (Figure 4-3). The summers at the northern Alberta sites were warmer (16.8 ± 0.2 °C (± 1 SE) versus 15.5 ± 0.4 °C) and drier (157.0 ± 17.8 mm versus 216.5 ± 24.5 mm total P) than the Saskatchewan sites.

4.3.2 Variations in Water, Carbon, and Energy Fluxes

4.3.2.1 Annual Variation

Daily average summer ET, GEP, and WUE for the reclaimed and reference sites < 20 years of age generally increased after disturbance (Figure 4-4). By 10-20 years, ET was similar to rates at the reference forests > 40 year of age (1.9 ± 0.1 to 3.4 ± 0.1 mm day⁻¹ at OA; 2.5 ± 0.1 and 2.4 ± 0.1 mm day⁻¹ at 46-year-old REC1 and 45-year-old REC2, respectively). The exception to this increasing ET trend was at SWSS with ET ~ 50% of the other similarly aged young stands (1.89 ± 0.1 mm day⁻¹ at 20 years of age). In contrast, the other young stands of similar age had maximum ET of 3.2 ± 0.3 mm day⁻¹ (SBH, 2013, 11 years of age) and 3.3 ± 0.1 mm day⁻¹ (WB, 2005, 16 years of age). Daily average summer GEP ranged from 2.6 ± 0.1 g C m⁻² day⁻¹ (REC2, 2007, 1 year of age) to 11.7 ± 0.3 g C m⁻² day⁻¹ (REC2, 2006, 45 years of age). In comparison, GEP had a year-to-year range of ~ 3 g C m⁻² day⁻¹ for the mature OA stand (Figure 4-4). During the first 20 years of development, the stands appeared to group into two GEP trajectories. SWSS and WB (stands with Siberian larch and jack pine, respectively) had lower GEP than REC2 and SBH (stands with fewer conifers).

Summer daily average WUE ranged from 2.4 ± 0.1 mmol CO₂ mol⁻¹ H₂O (SF2, 2013, 1 year of age) to 9.4 ± 0.1 mmol CO₂ mol⁻¹ H₂O (REC2, 2006, 45 years of age) (Figure 4-4). The WUE range was 2.4 mmol CO₂ mol⁻¹ H₂O for the 10 years of measurements at the mature OA stand (Figure 4-4). Within the 10 to 20 years of age range, WUE at SWSS greatly increased while WUE at WB declined despite similar GEP trajectories. The low WUE at WB corresponded to relatively high ET during cooler

Figure 4-2. Monthly (June-July-August) average daily temperatures ($^{\circ}\text{C}$, right) and total P (mm, left) for the northern Alberta (top) and central Saskatchewan (bottom) regions. For northern Alberta, P is from the Mildred Lake Climate Station (top, left). For central Saskatchewan, P is from the OA study site (bottom, left). Reclaimed site temperature records are black and solid (SF1 – $\blacktriangle$, SF2 – $\blacksquare$, SBH – $\bullet$, SWSS – $\star$) while reference sites are grey and open-faced (REC1 – $\circ$, REC2 – $\square$, OA – $\triangle$, WB – $\star$). Shaded columns delineate years while the dashed horizontal lines represent either the June-August climate normal daily average temperature (right) or monthly average P (left) for the Environment Canada weather stations in Fort McMurray, Alberta (top) or Prince Albert, Saskatchewan (bottom).

Figure 4-3. Average daily temperature vs. total P for the peak period of the growing season (June through August) for the years shown in Figure 4-2. Symbols are described in Figure 4-2.

weather immediately following a period of reduced P (2001-03). The high WUE at SWSS corresponded to relatively low ET during very warm summers immediately following a couple of moist years (2012-13, Figure 4-2). In contrast to ET (Figure 4-4), energy fluxes R_n and H did not generally increase with stand age (Appendix I). The sites were grouped to examine trends in EC flux variables related to reclaimed or reference status (site type), presence of conifers (fewer conifers or more conifers), and time since disturbance (young sites < 20 years old and older sites > 20 years old) (Table 4-3). Grouping variables by tree type did not result in any significant differences for any of the variables using the Mann-Whitney U-Test ($p < 0.05$) (Table 4-3). Also, ET was not significantly different for any of the groupings. Younger forests had significantly lower GEP, WUE, and R_n (Table 4-3). Reclaimed sites had significantly lower WUE, H and β (Table 4-3). When examining the site type and tree type groupings for the forests

Figure 4-4. Chronosequence graphs of average daily June-August evapotranspiration (ET, mm day⁻¹, top), water use efficiency (WUE, CO₂ mol⁻¹ H₂O, middle), and gross ecosystem productivity (GEP, g C m⁻² day⁻¹, bottom). Symbols are described in Figure 4-2.

Figure 4-5. July through August midday Bowen's ratio (β) for sites with data available for 2003-2010. Symbols are described in Figure 4-2.

< 20 years of age, the only significant differences were in H and β between reclaimed and reference site groupings (Table 4-3).

Although β varied among the sites, there were similar temporal patterns. For example, β decreased at OA and WB between 2003 and 2005, while REC1, REC2, and OA had higher β in 2009 relative to 2008 and 2010 (Figure 4-5). There was also a large increase in β at REC2 from 0.84 ± 0.02 to 1.65 ± 0.05 between pre-harvest (2006) and post-harvest (2007) years.

4.3.2.2 Monthly Variation

The variations in total June through August GEP at all sites were best explained by July GEP ($R^2 = 0.91$) although there was a strong relationship with GEP in June ($R^2 = 0.80$) and August GEP ($R^2 = 0.85$) (Figure 4-7). Similar to GEP, variations in WUE and ET were also best explained by respective July values (WUE $R^2 = 0.82$; ET $R^2 = 0.88$) (Figure 4-7). Both July GEP and ET were generally larger than June and August GEP at all sites regardless of grouping (Figure 4-8). In contrast, there was relatively little difference in WUE between months.

Table 4-3. Table of median values for the period June through August along with lower (25%) and upper (75%) quartiles for comparative groupings of daily-averaged EC flux variables. β values were for mid-day. An asterisk (*) indicates the significantly different paired groupings (Mann-Whitney U-Test; $p < 0.05$).

		ET (mm day ⁻¹)	WUE (mmol CO ₂ mol ⁻¹ H ₂ O)	GEP (g C m ⁻² day ⁻¹)	H (W m ⁻²)	β	R _n (W m ⁻²)
Site Type (all sites)	Reclaimed (n = 21)	2.6 (1.9, 3.1)	4.7* (3.8, 5.4)	7.1 (5.5, 8.5)	24* (11, 33)	0.4* (0.3, 0.7)	112 (93, 126)
	Reference (n = 29)	2.3 (2.0, 2.7)	5.6* (4.7, 6.3)	7.6 (6.7, 8.9)	39* (33, 47)	0.8* (0.6, 0.9)	118 (109, 130)
Site Type (< 20)	Reclaimed (n = 21)	2.6 (1.9, 3.1)	4.7 (3.8, 5.4)	7.1 (5.5, 8.5)	24* (11, 33)	0.4* (0.3, 0.7)	112 (93, 126)
	Reference (n = 16)	2.1 (1.9, 2.4)	5.8 (4.2, 6.2)	7.0 (6.1, 7.5)	41* (38, 49)	0.8* (0.7, 0.9)	111 (108, 118)
Tree Type (all sites)	Fewer Conifers (n = 43)	2.4 (2.0, 3.0)	5.4 (4.3, 6.0)	7.3 (5.8, 8.8)	33 (20, 40)	0.7 (0.4, 0.9)	118 (107, 131)
	More Conifers (n = 7)	2.6 (2.1, 2.7)	4.4 (4.2, 5.9)	7.3 (6.9, 7.8)	48 (33, 49)	0.7 (0.4, 0.8)	112 (103, 124)
Tree Type (< 20 years)	Fewer Conifers (n = 30)	2.2 (1.9, 3.0)	5.1 (3.9, 5.9)	6.9 (5.2, 8.0)	34 (17, 40)	0.7 (0.4, 0.9)	111 (103, 121)
	More Conifers (n = 7)	2.6 (2.1, 2.7)	4.4 (4.2, 5.9)	7.3 (6.9, 7.8)	48 (33, 49)	0.7 (0.4, 0.8)	112 (103, 124)
Age (all sites)	< 20 years (n = 37)	2.3 (1.9, 2.8)	4.7* (3.9, 5.9)	7.1* (5.7, 7.9)	34 (22, 44)	0.7 (0.4, 0.8)	112* (103, 124)
	> 20 years (n = 12)	2.7 (2.4, 3.0)	5.6* (5.4, 6.4)	9.2* (8.2, 9.9)	31 (24, 41)	0.6 (0.5, 0.8)	132* (123, 135)

4.3.3 Flux Relationships with Site and Environmental Variables

A regression tree approach was used to examine the relative importance of selected predictors on temporal and spatial variability in annual ET, WUE, GEP, H, and β (Figure 4-9, Appendix III). Predictors that influenced multiple variables included site type (WUE, H, and β), P (H, β), g_c (ET, WUE, GEP, H, β), and D (WUE, H). For all variables but H, the first ‘split’ was on g_c and for H it was tree type. An important predictor for ET, WUE, H, and β is g_c , regardless of site age. D was also significantly correlated with ET ($r = -0.36$) and GEP ($r = -0.46$). The predictors T_{air} , K_d , and tree type influenced only WUE, ET, and H, respectively.

In general, g_c at the reference sites was higher and more variable than at the reclaimed sites (Figure 4-6). Sites with fewer conifers (*e.g.*, SF2, SBH, OA) had higher ET rates with one year at WB a notable exception. Some sites with fewer conifers (REC1, REC2, SBH) had lower or equivalent g_c and ET in the years immediately following disturbance than the older sites with more conifers (SWSS, WB).

Figure 4-6. Daily average ET for June through August versus midday (11:00 h – 14:00 h) g_c . Symbols are described in Figure 4-2.

Figure 4-7. Total evapotranspiration (ET), water use efficiency (WUE), and gross ecosystem productivity (GEP) for July versus June through August. Symbols are described in Figure 4-2. The black lines and equations represent the least squares linear regression models for all of the sites. Note the different y- and x-axis scales for each plot.

Figure 4-8. Median monthly (June – white, July – light grey, and August – dark grey) values of average ET, WUE, GEP, H, β , and R_n for the site type (reclaimed; reference), tree type (fewer conifers; more conifers), and age (< 20 years old; > 20 years old) groupings. Error bars represent lower (25%) and upper (75%) quartiles. Note the different y-axis scale for each plot.

Figure 4-9. Total June through August ET, WUE, GEP, H, β , and R_n regression tree model predictor importance estimates for site type (reference/reclaimed), P, T_{air}, K_↓, tree type (fewer conifers/more conifers), age (< 20 years old/> 20 years old), g_c, and vapour pressure deficit (D) predictors for reclaimed and reference sites. Note the different y-axis scale for each plot.

4.4 Discussion

Reclaimed oil sands study sites are contributing to the patchwork of Canadian boreal forest landscapes (Richardson, 2007; Gosselin *et al.*, 2010; Government of Canada, 2015). In this study, variability in ecosystem functioning was expected due to differences in vegetation and soil characteristics among the constructed and reference forest ecosystems (Table 4-1). However, it was hypothesized that ET, GEP, WUE, and other surface-atmosphere interactions related to the water functioning of these

ecosystems would be similar between reclaimed and reference forests. As shown here, this was largely the case in contrast to other ecosystem studies in the AOSR. A study that examined 29 reclaimed oil sands sites and 18 reference sites representing a range of moisture characteristics noted soil nutrient and vegetation (coverage and species present) differences (Rowland *et al.*, 2009). Another study on soil biogeochemical cycles that compared 15 reference and 26 reclaimed oil sands sites found that the groups were significantly different (Quideau *et al.*, 2013). Of the three aspects of soil biogeochemical cycles examined, there were overlaps between the groups with regard to nutrient availability and microbial communities but not organic matter composition. The study also noted a broad range of boreal forest reference ecosystem characteristics along with the fact that differences among the sites were attributable to vegetation cover rather than soil type. The complex suite of vegetation and soil characteristics that influenced functioning such as biogeochemical cycling at reference sites were in development at the constructed reclaimed sites (Rowland *et al.*, 2009; Quideau *et al.*, 2013).

Appraisal of ecosystem recovery trajectories of water and carbon cycle fluxes helps inform how these reclaimed ecosystems might fully integrate into the boreal landscape, especially in areas that are water limited. The influence of vegetation regrowth on ecosystem fluxes has been illustrated by a number of chronosequence and long-term studies (Mkhabela *et al.*, 2009; Amiro *et al.*, 2010; Goulden *et al.*, 2011; Petrone *et al.*, 2015; Strilesky *et al.*, 2017). Goulden *et al.* (2011) discussed in detail the carbon cycle dynamics within the framework of boreal forest succession. As forests develop following a disturbance, the ecosystems transition from a source of carbon

dioxide to a sink as GEP increases with vegetation regrowth. Carbon sequestration peaks at middle-age followed by a subsequent decrease as forests mature. This was the case here whereby GEP, WUE, and ET increased at a majority of the young sites subsequent to disturbance (ET at SWSS was the exception) and attained functioning similar to older sites by 20 years of age (Figure 4-4). The converging of respective trajectories within a range of natural variability was likely due to common factors limiting water use functioning such as water availability and climatic conditions (Margolis and Ryan, 1997; Law *et al.*, 2002; Brümmer *et al.*, 2012; Zhang *et al.*, 2016).

Although there were few categorical differences in ecosystem functioning in the boreal forests in this study, there was a large degree of variability among stands that could be linked to differences in forest physiological characteristics. As a result, the key variable that was linked to differences among forests was g_c . In particular, there was a strong positive relationship between g_c and ET for all the young stands (Figure 4-6), similar to what has been reported by others for varying vegetation assemblages (Margolis and Ryan, 1997; Jones *et al.*, 2017; Wehr *et al.*, 2017). Jones *et al.* (2017) observed that canopy transpiration accounted for 85% of modelled ET at developing hybrid-poplar plantations after canopy closure while Wehr *et al.* (2017) reported similar seasonal cycles of transpiration and ET for a temperate deciduous forest. For the dominant deciduous aspen and coniferous black spruce tree types in the boreal forest, Margolis and Ryan (1997) noted carbon and water fluxes were higher for deciduous stands than coniferous ones. Again, these are not strictly independent variables but are in agreement with studies where leaf-level g_c is measured independently of whole-plant or ecosystem-scale

ET. The importance of g_c was probably due to its role as an index of driving variables and site characteristics. In order to compute g_c , driving variables such as T_{air} (s , γ , R_a , c_p , ρ), D , and r_a , where the latter depends on surface characteristics of the forest, were incorporated into the Penman-Monteith equation (Monteith and Unsworth, 2008). These variables were also independently identified as being important for differences in WUE (D and T_{air}) and ET (D and K_d) (Figure 4-9).

As expected, ET increased as the vegetation cover increased and matured at most of the study sites (Figure 4-4). In general, leaf and root area increase as vegetation increases in size and quantity with plants able to transpire more water from the surface due to increased water uptake and photosynthetic capability (Kiniry *et al.*, 2008), which results in increases in ET and LE and decrease in β as post-disturbance sites recover (Amiro *et al.*, 2006b; Sharp *et al.*, 2011; Strilesky *et al.*, 2017). However, the increases in ET reported here (Figure 4-4) are small compared to some other vegetation types such as agricultural crops where peak weekly averaged ET increased from 0 to 7.3 mm during a growing season for maize (Wagle *et al.*, 2018). A number of interacting factors likely limited the range of natural variability in ET (Figure 4-4). For example, reduced light penetration to the understory as the canopy closes resulted in thinning of understory vegetation (Berkowitz, 2013). In addition to a reduction in leaf area available to transpire, shading and reduced temperatures also reduced understory ET (Blanken *et al.*, 1997; Baldocchi *et al.*, 2000). The western Canadian boreal forest is characterised by water limitations and cool temperatures, which also limit ET (Baldocchi *et al.*, 2000; Blanken and Black, 2004).

Despite summer ET and GEP following the expected age trajectories, age was not as important a predictor as g_c (Figure 4-9). There were two GEP trajectories for sites immediately following disturbance with less productivity in forests having a higher proportion of conifers (SWSS, WB) compared to forests with fewer conifers (Figure 4-4). With the exception of one year at WB, ET at the two sites with more conifers (WB and SWSS) was also generally lower than the sites with fewer conifers (Figure 4-4). This was anticipated based upon previous studies demonstrating the influence of plant physiology on water use (Barr *et al.*, 2001; Arain *et al.*, 2003). Margolis and Ryan (1997) presented an overview of results from the Boreal Ecosystem-Atmosphere Study (BOREAS), which highlighted the influence of tree species traits and morphology on EC-derived fluxes. In particular, conifers were observed to limit ET even under ideal moisture conditions (Margolis and Ryan, 1997). Similarly, Baldocchi *et al.* (2000) summarized multiple studies to illustrate that physiological factors influence ET with conifer stands having comparatively lower rates (~ 25-75%) than deciduous stands.

In this study, the only significant differences in surface-atmosphere interactions between young reclaimed and reference sites were H and β (Table 4-3; Appendix II), which may potentially be explained by the differences in soil and vegetation cover immediately following disturbance. Reference sites had very different post-disturbance conditions than the constructed reclaimed sites due to the presence of a developed soil profile with distinct surface organic layers and remnant live or dead vegetation after harvest or fire (Rowland *et al.*, 2009; Quideau *et al.*, 2013). Both characteristics would have influenced energy partitioning with the darker organic soil layer and dead vegetation

at the reference sites increasing the emissivity of the surface compared to the relatively higher albedo of the initial grass-cover at the reclaimed sites. In addition, the prior vegetation cover coupled with generally wetter conditions would result in more of the energy absorbed at the surface being converted to H than LE and a higher β at the reference sites. While a relatively large range of β was attributed to grasslands (0.34 – 1.91), a study of 27 sites demonstrated that the lower end of the range for grasslands was similar to the range for the agricultural and deciduous forest land types with the lowest typical overall β range of 0.25 to 0.50 (Wilson *et al.*, 2002). The range of β for grasslands was attributed to varying management practices and sensitivity to soil moisture due, in part, to the differences of root systems at accessing deeper soil water. The initial cover of grasses at the reclaimed sites studied here was not irrigated and likely had shallow rooting systems due to availability of moisture at the surface and the rocky nature of the underlying land cover material. This suggests that the young sites should be at the lower end of the β range as corresponds with the results presented here (Table 4-3).

Previous research noted that temperature, radiation, and water were the main abiotic controls on primary production in forests with all three highlighted as being important limiting factors in the Canadian western boreal region (Boisvenue and Running, 2006). However, these variables were not independently important predictors of the temporal and spatial variability in summer GEP in this study. Varying and unanticipated responses to driving variables have been reported in the literature for other sites. For example, NEE was greater during cloudy conditions rather than during direct sunlight conditions at boreal aspen and Scots pine (*Pinus sylvestris*) forests (Law *et al.*,

2002). The authors of that study reasoned that this was due to increased diffuse light and decreased D, which were both beneficial for photosynthesis, and reduced R due to lower temperatures. It is important to note that the interaction of multiple stressors such as water, light, or nutrient deficiencies may have a greater negative impact on ecosystem functioning than a single stressor (Niinemets, 2010).

The heterogeneous nature of the reference boreal landscape and its surface-atmosphere fluxes of water and carbon is well documented in the literature (Frelich and Reich, 1995; Amiro, 2001; Barr *et al.*, 2001; Amiro *et al.*, 2006a; Brandt, 2009; Goulden *et al.*, 2011; Brümmer *et al.*, 2012). Boreal forest heterogeneity is due to varying vegetation, disturbance types and cycles, and regional climate. While there is a broad range of structural variability among reference sites, reclaimed sites tend to have higher subsoil salinity (Purdy *et al.*, 2005; Trites and Bayley, 2009; Lilles *et al.*, 2012), lower soil organic matter content, more bare ground, and higher numbers of non-native or non-boreal forest plant species (Rowland *et al.*, 2009; Quideau *et al.*, 2013). Despite the increasing contribution of reclaimed oil sands sites in the AOSR to the heterogeneity of the boreal landscape and the significant interest in assessing their potential to integrate into the landscape (Gosselin *et al.*, 2010; Audet *et al.*, 2014, 2014; Macdonald *et al.*, 2015), this, to my knowledge, is the first similar comparative study of constructed ecosystems.

Despite the noted structural differences between reclaimed oil sands and reference landscapes, the results presented here indicate that ecosystem functioning among the reclaimed and reference boreal forest sites is similar with regard to water use, carbon

assimilation, and energy partitioning. The young (< 20 years old) post-disturbance landscapes studied here are within the wide range of natural variability for forest landscape structure and function ~ 10 to 20 years following disturbance (Table 4-4).

Table 4-4. Comparison of ranges and values for selected sites from the literature and the young sites (< 20 years old) presented here. Additional information regarding type and period of measurement as well as vegetation type for the literature values are included in the footnotes for the table.

	NEP	GEP	ET	WUE
Range of total annual values (literature)	~ -600 to 800 g C m ⁻² year ⁻¹ (Amiro <i>et al.</i> , 2010) ^a	700 to 1,800 g C m ⁻² year ⁻¹ (Law <i>et al.</i> , 2002) ^b	221 to 482 mm year ⁻¹ (Brümmer <i>et al.</i> , 2012) ^c	
Range of total July-August values	-313.8 to 364.5 g C m ⁻²	232.2 to 842.8 g C m ⁻²	127.2 to 298.8 mm	
Average daily or monthly values (literature)	-3.8 to 1.6 g C m ⁻² day ⁻¹ (Amiro, 2001) ^d	~ 4 to 13 g C m ⁻² day ⁻¹ (Kljun <i>et al.</i> , 2006) ^e	~ 2-6 mm day ⁻¹ (Black <i>et al.</i> , 1996) ^f	0.02 to 24.2 g CO ₂ kg ⁻¹ H ₂ O (Coursolle <i>et al.</i> , 2006) ^g
Average daily or monthly values	-3.5 to 4.1 g C m ⁻² day ⁻¹ (Jun-Aug)	2.6 to 9.2 g C m ⁻² day ⁻¹ (Jun-Aug)	1.4 to 3.3 mm day ⁻¹ (Jun-Aug)	6.3 to 21.2 g CO ₂ kg ⁻¹ H ₂ O (Aug)

^a Approximate range of annual total values for post-disturbance chronosequences at North American forest sites.

^b Range of annual averages for mixture of grasslands as well as evergreen coniferous, deciduous broadleaf, evergreen broadleaf forests.

^c Range of annual total values reported for mature coniferous, mixed-wood, and deciduous boreal forests.

^d Range of average daily carbon flux values calculated using one week of measurements during two consecutive growing seasons for six of post-disturbance and paired mature broadleaf, coniferous, and mixed-wood reference forest stands.

^e Range of average daily values calculated from five-day averages during the growing season at the OA study site.

^f Range of average daily values during the growing season at the OA study site.

^g Range of total August 2003 values for a chronosequence of post-disturbance to mature forest stands.

4.5 Conclusion

There were few significant differences in ecosystem function between reclaimed oil sands ecosystems and reference boreal ecosystems. The structural differences covered

in the literature are complemented by the functional water use, carbon assimilation, and energy partitioning differences presented here. Despite a lack of categorical difference, there was substantial variability among individual ecosystems and between years at individual sites, which was at least partly attributable to the interaction of multiple influences such as climate and surface cover as represented by the importance of the index driving variable g_c . Regardless of the type of disturbance that an ecosystem was recovering from, water use indicators of ET, WUE, and GEP were within the natural variability of older boreal forest ecosystems by ~ 20 years of age. The similarity in ecosystem functioning with regard to water and carbon cycling suggests that the reclaimed sites examined here have the potential to integrate with reference forest sites within the AOSR boreal mosaic. These results provide baseline values of ecosystem functioning but do not encompass extreme conditions such as drought or cyclical disturbance regimes such as fire. Therefore, further research into the water balance of these locations is required for a more informed assessment of their relations with adjacent landscape types and resilience to changes in weather and climate.

5 THE EDDY COVARIANCE METHOD FOR ASSESSING RECLAIMED ECOSYSTEMS IN THE ATHABASCA OIL SANDS REGION

5.1 Introduction

This chapter explores the potential use of EC-derived variables for monitoring and certification of reclaimed landscapes in the AOSR. To provide background and context for an assessment of the EC technique for this purpose, an overview of the status of certification criteria and indicators for reclaimed AOSR landscapes, including current and alternative assessment practices such as forest inventories (FI), remote sensing (RS), and the EC technique will be given before moving on to the realized and foreseeable contributions of EC data. A large EC data set of ecosystem function and water-use indicators including NEP, GEP, and ET for 79 growing seasons from 15 upland reference and reclaimed sites is used to explore how EC measurements might contribute to AOSR assessment and certification.

Mining operations in the AOSR have been ongoing since the mid-20th century and reclamation activities are important and legally mandated aspects of these operations (Ferguson, 1986; Richardson, 2007; Government of Alberta, 2010). Reclamation involves identifying the targeted outcome of reclamation activities with regard to land use and cover type (CEMA, 2006; Poscente and Charette, 2012), establishing reclamation practices (Hild *et al.*, 2009; Burton and Macdonald, 2011; Audet *et al.*, 2014), and guiding societal perceptions (Nikiforuk, 2010; Levant, 2011; Paskey *et al.*, 2013). Certification is the process of approving a reclaimed landscape based on meeting or exceeding reclamation standards and, when granted to a company, it frees the company from further obligations for that landscape for a period of time (Gosselin *et al.*, 2010).

Over the past nine decades of disturbance and reclamation in the AOSR, the criteria and indicators for reclamation certification have evolved (Powter *et al.*, 2012). Integrating EC-derived assessments of ecosystem function into certification frameworks, which currently focus on structural aspects of an ecosystem at a point in time (Poscente and Charette, 2012), would permit informed evaluations of long-term survival potential, productivity, water use, and other ecosystem services.

5.2 Overview of the Criteria and Indicators for AOSR Landscapes

“Criteria: (plural) A category of conditions or processes by which the achievement of a reclamation objective is assessed. A Criterion (singular) is characterized by one or more related indicators which are used to determine success or to assess change over time.”

- (Poscente and Charette, 2012: iii)

Areas impacted by oil sands mining are legally required to be reclaimed to a land capability equivalent to pre-disturbance landscapes (Gosselin *et al.*, 2010). Equivalent land capability is open to interpretation but the current practice is to rebuild boreal forest landscapes which include upland forests, wetlands, and water bodies (Gosselin *et al.*, 2010). Certifying that reclamation is complete and has been successful requires assessment of the resulting ecosystem using appropriate indicators (Poscente and Charette, 2012). It is important to note that, while not a legal definition, success is also determined by public perception of reclaimed landscapes. The concept of society making a value judgement regarding activities such as oil sands mining, including the companies and other stakeholders involved, and viewing it in a positive manner is referred to as obtaining a social license to operate (Dare, 2014). Nevertheless, the criteria and

indicators for assessment recommended by the Cumulative Environmental Management Association (CEMA) focus on quantitative physical properties of reclaimed landscapes with limited local or Indigenous community engagement (Table 5-1).

Terrestrial and aquatic indicators proposed for assessment and certification of reclaimed mined areas in the AOSR currently focus on structural components of an ecosystem (CEMA, 2006; Poscente and Charette, 2012). Many of the terrestrial indicators are strongly influenced by the Canadian System of Soil Classification with a focus on soil properties such as soil pH, soil salinity, and soil depth as well as geotechnical aspects of the reclamation including geotechnical design, geotechnical stability, and end pit lake percent littoral area (Table 5-1). Soil is important in the development and functioning of an ecosystem via its role supporting the growth of plants including the provision of nutrients and water, controlling the fate of water in the hydrologic system, functioning as a recycling system for nutrients and organic matter, and providing habitats for a diverse group of living organisms (Quideau *et al.*, 2013; Huang *et al.*, 2015).

Other terrestrial indicators include an assessment of weed presence (plant community composition) and status of trees (healthy and vigorous trees) (Table 5-1). To complement these 8 terrestrial indicators deemed suitable and ready to use, 18 more were identified as suitable for inclusion in a certification framework but requiring further development such as defining the measurement method or thresholds before being ready for use (Table 5-1). The majority of these focus on plant species diversity and tree health. Ecosystem health is noted as requiring “methodology and thresholds specific to

the mine reclamation context” (Poscente and Charette, 2012: 22). Similarly, resilience to disturbance is listed but no methodology is outlined. First defining ecosystem health and resilience is important in order to develop methodology and thresholds. One proposed definition of ecosystem health identifies the concept of sustainability, specifically a “system’s ability to maintain structure (organization) and function (vigor) over time in the face of external stress (resilience) [*sic*]”, as encompassing the many facets of this broad concept (Costanza *et al.*, 1992: 240). This corresponds with the definition of resilience noted earlier, namely the ability of an ecosystem to recover following a disturbance (Walker *et al.*, 2004). It is also compatible with the study of ecosystem water and biogeochemical functions via the EC technique presented here. None of the indicators explicitly addresses ecosystem water use but indicators such as soil moisture and connectivity within the landscape and the aquatic indicator hydroperiod include components of the water cycle. With respect to biogeochemical cycling and the carbon cycle in particular, the NEP of an ecosystem is listed as an indicator but it is equated to site index (SI), an index used in the forest industry related to harvestable timber (Table 5-1).

Thresholds for these indicators are founded in different evaluation schemes. For example, geotechnical design and geotechnical stability require approval from the Energy Resources Conservation Board (ERCB; now the Alberta Energy Regulator) while plant community composition – weeds requires the absence of noxious weeds. Overall, many of the indicators as well as their measure, method, and thresholds are not yet clearly defined.

Table 5-1. List of terrestrial and aquatic indicators recommended for reclamation certification in the Athabasca Oil Sands Region (AOSR) by the Cumulative Environmental Association's (CEMA) Reclamation Working Group (RWG). The Energy Resources Conservation Board (ERCB) referred to in the comments was subsequently incorporated into the Alberta Energy Regulator. Adapted from Table 3 in Poscente and Charette (2012: 22–24).

Suitable (S) and Ready (R)	Indicator	RWG Comments on Status or Application
<i>Terrestrial Indicators</i>		
SR	Soil pH	Can be easily assessed and adaptive management responses are reasonable.
SR	Soil salinity	Indicates the ability to reclaim lands to specific ecosystems.
SR	Soil depth	Reflects the Environmental Protection and Enhancement Act (EPEA) mine approval conditions.
S	Ecosystem net primary productivity (site index)	Include as an indicator, but not just specific to commercial forestry.
S	Plant community composition – characteristic species	Gaps in juvenile stand data in the revegetation manual characteristic species table need to be addressed.
SR	Plant community composition – weeds	Deal with tolerances for non-prohibited weeds in the following indicator (<i>i.e.</i> , Plant community composition – diversity...)
S	Plant community composition – diversity, richness, evenness, and abundance	Account for acceptable limits of non-prohibited weeds. Need to understand reference conditions.
S	Regeneration of trees in commercial forest stands	Develop the threshold for the mine reclamation context.
SR	Trees are healthy and vigorous	Applicable to reclaimed land designated as commercial forest end land use, part of existing establishment survey.
S	Tree height of commercial forest stands at performance age	Develop the threshold for the mine reclamation context.
S	Commercial forest targets – ecosite area summary table	The threshold needs to be developed relevant to the mine reclamation context.
S	Ecosystem health	Need to define the methodology and thresholds specific to the mine reclamation context.
S	Wildlife species with important ecological role	Need to better define the scale of measurement and measure capability, not actual use.
S	Wildlife habitat targets	Need clarification from the Wildlife Task Group.
S	Wildlife habitat targets that support consumptive and non-consumptive uses	Consumptive uses suggest recreation activities.

Suitable (S) and Ready (R)	Indicator	RWG Comments on Status or Application
S	Wildlife habitat targets that support cultural, spiritual, medicinal, and ceremonial purposes as defined through stakeholder consultation	Need to develop this indicator in consultation with indigenous stakeholders.
S	Viable and healthy populations of wildlife	Need to determine or define the “viability” part of the indicator. Certification will not be evaluated on presence of wildlife, but on habitat capability.
S	Connectivity within the landscape	Reclamation requirements need to be addressed before criteria may be developed.
S	Landscape mosaic	Reclamation requirements need to be addressed before criteria may be developed.
S	Species and community diversity	Require research to develop indices to measure and evaluate diversity. Need to determine the baseline from which to compare measures against.
S	Achieve biodiversity targets that support cultural, spiritual, medicinal, and ceremonial purposes	Need to develop this indicator in consultation with indigenous stakeholders.
SR	Geotechnical design	Landform design requires signoff by a geotechnical engineer and the ERCB.
SR	Geotechnical stability	Landform stability performance requires signoff by a geotechnical engineer and the ERCB prior to reclamation certification.
S	Foliar nutrients	Need to define threshold. Research is underway.
S	Resilience	Resilient to natural disturbances and climatic variation.
SR	End pit lake percent littoral area	Timing of measure is at the construction stage and the measure is up to 3 metres depth of the mean design surface water elevation.
<i>Aquatic Indicators</i>		
SR	End pit lake littoral slope	Measure from shore to 3 metres depth.
S	End pit lake littoral zone reclamation materials	Needs work to define the measure (<i>i.e.</i> , physical or chemical properties).
SR	End pit lake total dissolved solids	May require monitoring for a minimum 10-year period prior to mine closure. Perhaps consider defining a threshold rather than a trend.
SR	End pit lake water column mixing	Measure trend from the end of construction through to the time of certification.
SR	End pit lake water level variability	Could have a drop in elevation each year and remain within the threshold, resulting in an over-all decrease of surface elevation.

Suitable (S) and Ready (R)	Indicator	RWG Comments on Status or Application
SR	End pit lake water balance	Focus the indicator on water quality benefits to having connectivity, not fish habitat (fish habitat will be accounted for in other indicators).
S	End pit lake bed stability	More applicable to shallow systems where wind and wave action will have a greater influence on re-suspension of fine tailings.
S	Fen organic matter accumulation	Specific to peatlands.
SR	Fen water quality	Upfront measurement of water quality is critical to determine if a fen design is viable.
S	Wetland traditional ecological plants	Further work is required on traditional ecological knowledge indicators.
S	Typical fen plants	Certification may require indicators associated with health/vigour (performance), abundance and percent cover.
SR	Wetland hydroperiod	Applies to all wetlands on the reclaimed landscape, both opportunistic and planned.
SR	Marsh wet meadow plant index of biotic integrity	Would need to measure all wet meadow polygons on a landform in preparation for certification.
SR	Marsh open water plant index of biotic integrity	Would need to measure all open water polygons on a landform in preparation for certification.

5.3 Forest Inventories

Many of the proposed terrestrial indicators are measured as part of traditional FIs (Kangas and Maltamo, 2006). Forest inventories require extensive work in the field to make measurements and collect samples. Forest inventory measurements quantify the qualities and quantities of vegetation using physical tree characteristics (*e.g.*, tree diameter at breast height of 1.3 m (DBH), tree height, and age) and determine stand characteristics (*e.g.*, density of tree stems per unit area, species composition, mortality, and the value of timber) (Kangas and Maltamo, 2006; United States Department of Agriculture Forest Service, 2018). Another related metric used primarily for research purposes is leaf area index (LAI), which denotes the leaf area (one- or two-sided or

projected) per unit ground area (Chen *et al.*, 1997). Soil characteristic indicators are common to other land assessments in Canada and elsewhere such as the Canada Land Inventory, which describes the land capability for agriculture, forestry, *etc.* (Stunden Bower, 2018). In the AOSR, soil structural characteristics are assessed using the guidelines in the *Land Capability Classification System for Forest Ecosystems in the Oil Sands, 3rd Edition* (LCCS), which is a 148 page manual outlining how to determine the final land rating and affiliated land capability class for forested sites (CEMA, 2006). At replicated site locations, a soil pit 1 m deep must be dug to collect soil samples from each soil horizon to permit qualified personnel to make qualitative assessments of the soil characteristics. Samples may then be processed in a lab to determine factors such as pH and nutrient content.

A common FI value not currently outlined in the LCCS is SI (CEMA, 2006), which refers to the expected stand height at a given reference age (Chen *et al.*, 1998; Skovsgaard and Vanclay, 2008). For example, a SI of 24 for the dominant aspen tree species in a reclaimed upland forest means that at 50 years of age the average height of the aspen trees in the stand will be 24 m. A SI of 30 indicates a more productive stand because the trees are growing faster. Site indices are used to make growth and yield projections for forest stands (Chen *et al.*, 1998; Huang *et al.*, 2009a). Growth curves demonstrate the relationship between stand age and a specific characteristic, such as height or bole diameter, and may be used to estimate that characteristic at a future date/stand age (Carmean *et al.*, 1989). Site class is a subjective categorization of site productivity based on SI values (Skovsgaard and Vanclay, 2008). Skovsgaard and

Vanclay (2008) provided a Sitka spruce (*Picea sitchensis* [Bong.] Carr.) example whereby site classes of one and four referred to SIs of 28 and 16, respectively, meaning that a stand designated with a site class of one was more productive. Both SI and site class are used as measures of tree productivity and reflect a combination of physical and biological factors of a site location that impact the growth of trees (Skovsgaard and Vanclay, 2008).

The SI metric originated during the introduction of an ecological approach to tree cultivation (silviculture) and management in Europe circa the early 1700s (Daubenmire, 1976). Prior to this time period, wood supplies were dwindling. SI served the need for a method to assess the productivity and quality of trees associated with a particular habitat or environment in order to properly locate tree plantations and mitigate the loss of wood resources (Daubenmire, 1976). However, since forest productivity is the result of complex interactions that affect the growing conditions for plants, changes in climate mean that a SI calculated under a certain set of conditions will not necessarily be applicable during the entire period of growth to the SI reference age (Boisvenue and Running, 2006). In the case of reclaimed landscapes comprised of several connected ecosystem types which are not always intended to directly support timber production, SI and other FI are not always relevant.

Costs associated with FI vary with technology and site accessibility (Hopkinson *et al.*, 2004). For example, equipment such as tape measures and tangent light gauges may be inexpensive but nevertheless require a large number of person hours or expensive helicopter time for site access. A key advantage to FI is the large amount of data, based

upon established protocols, that is available through the commercial forest industry and various government agencies in Canada and elsewhere (Halliwell *et al.*, 1995; Kangas and Maltamo, 2006; Skovsgaard and Vanclay, 2008; Kimmins, 2011; United States Department of Agriculture Forest Service, 2018). All of these measures focus on ecosystem components and provide a snapshot in time of a dynamic ecosystem (Kimmins, 2011). One of the key disadvantages is that the complexity and nuances of ecosystem health and ecosystem resilience to stressors such as drought are only partially or indirectly assessed with FI and, again, focus primarily on trees. Biogeochemical cycling and water use by the ecosystem as a whole cannot be readily determined using FI.

5.4 Remote Sensing

Satellite and aircraft-based RS have been used extensively for vegetation assessment and land classification (Huete *et al.*, 1997a; Lillesand *et al.*, 2004; Czerwinski *et al.*, 2014; Dacre *et al.*, 2017). There is a plethora of indicators available for assessing ecosystem vegetation that may be directly or indirectly related to recommended terrestrial indicators (Table 5-1). Some examples of RS indices include chlorophyll vegetation index (CVI), evaporative stress index (ESI), enhanced vegetation index (EVI), normalized difference vegetation index (NDVI), soil adjusted vegetation index (SAVI), and simple ratio vegetation index (SR) (Czerwinski *et al.*, 2014; Karan *et al.*, 2016; Padmanaban *et al.*, 2017; Chasmer *et al.*, 2018). NDVI has been used in reclamation studies (Karan *et al.*, 2016; Dacre *et al.*, 2017; Padmanaban *et al.*, 2017; Chasmer *et al.*, 2018). Basically, NDVI represents the greenness of vegetation and is calculated as $NDVI = (W_{NIR} - W_R) / (W_{NIR} + W_R)$ using the near infrared (W_{NIR}) and red (W_R)

spectral bands (Huete *et al.*, 1997a; Lillesand *et al.*, 2004). The theory underlying the NDVI calculation is that abundant and healthy vegetation absorbs more visible light for photosynthesis and reflects more infrared light than sparse or unhealthy vegetation, which results in higher NDVI values (Lillesand *et al.*, 2004). Research into establishing relationships among RS and FI measurements such as LAI and plant biomass often reveals empirical relationships that are site specific (Kennedy, 2018). In the context of the boreal forest, NDVI and SAVI were noted as being more comparable to the foliage indicators of LAI and canopy cover than SR in a remote sensing study of 15 reclaimed and reference sites in the AOSR (Chasmer *et al.*, 2018). However, NDVI saturates around an LAI of 4.0 which reduces its applicability to forested landscapes that may have much larger LAI values (Huete *et al.*, 1997a; Czerwinski *et al.*, 2014). LIDAR has been used both from aircraft and ground-based systems to collect FI such as tree height and DBH at forest sites in southern Ontario (Hopkinson *et al.*, 2004). LIDAR data have also been used to create a canopy-height model used by researchers to characterize study sites and study changes in the canopy over time (Petrone *et al.*, 2015).

Land classification involves sorting pixels into land cover categories based upon set parameters (Lillesand *et al.*, 2004). This approach was used by Gillanders *et al.* (2008) to track spatial changes in land classification in the AOSR through time to document the increase in mining affected areas and decrease in different vegetation classes. Similar to some FI metrics, RS is less useful for assessment of integrated landscapes. For example, a recent study that examined reclaimed drill well pads noted the difficulty in separating vegetation into upland forests and wetland classes (Dacre *et*

al., 2017). Shrub- and tree-dominated wetland categories in particular were difficult to distinguish (Dacre *et al.*, 2017). However, others have successfully used RS to identify and monitor wetland characteristics in other environments (Padmanaban *et al.*, 2017; Millard *et al.*, 2018). There are some circumstances where vegetation assessments using RS products may be a better indicator of LCCS land capability ratings since FI characterizes structural components of an ecosystem, particularly soil characteristics, and has not yet resulted in a clear correlation between predicted and measured forest productivity in reclaimed areas (CEMA, 2006).

Some of the advantages of RS include relatively long records and high spatial coverage and availability. For example, LANDSAT images dating back to 1972 with near-global coverage are available to the public for free (United States Geological Survey (USGS), 2017). While some imagery may be low in cost and easy to obtain, a disadvantage is that specialized software (*e.g.*, ArcGIS) and qualified personnel (*e.g.*, with a certificate or degree in the field accompanied by practical experience) may be required to properly process and interpret RS data (Ma *et al.*, 2015). In addition, another disadvantage with RS is that some data can be negatively influenced by certain weather conditions (*e.g.*, cloud cover), by equipment malfunction (*e.g.*, spatial or spectral loss due to damaged sensors), and by sensor limitations such as limited spatial (*e.g.*, MODIS with resolution in the hundreds of metres) or spectral resolution (*e.g.*, AVHRR/3 has six channels with the broadest band covering 1 μm of wavelength). Some RS imagery also requires tasking which increases cost as custom data are acquired based upon set spatial and temporal specifications intended to address image availability issues.

Remote sensing is a potentially valuable method that can be used within assessment and certification protocols in the AOSR by complementing or replacing more manual FI data. Alberta Environment invested in compiling a geospatial database of existing oil sands industrial and reclamation features dating back to 1985 (Bampfylde *et al.*, 2010). The objectives were to develop a database with baseline imagery for future assessments of change in order to understand the impacts of development on the environment and support annual reporting processes. As of 2013, the area of permanently reclaimed land was ~ 8,000 ha with the active mining area estimated to be ~ 89,500 ha (Council of Canadian Academies, 2015).

It has been argued that RS is the only viable technology for assessing vegetation structural and functional changes of AOSR landscapes (Gillanders *et al.*, 2008). Despite this conclusion, there are only a few studies using RS to examine reclaimed AOSR landscapes (Gillanders *et al.*, 2008; Dacre *et al.*, 2017; Chasmer *et al.*, 2018). In addition, as with FI, there are limitations to using RS indices to assess a number of the proposed indicators (Table 5-1) such as ecosystem health and resilience since RS indices are only indirect assessments of productivity and water use and require empirical and often site-specific relationships that may change as stressors change.

5.5 Overview of the EC technique

CEMA (2006) proposed that criteria and indicators should accommodate current best reclamation practices and evolve as research and practice are evaluated. There is room for development of indicators that assess the functioning of reclaimed ecosystems with techniques such as EC that could complement or replace FI and RS-based indicators.

The EC technique uses micrometeorological theory to directly sample the turbulent exchange of energy and trace gases between a surface and the atmosphere. A review of the use of the EC technique for assessing ecosystem functioning was presented by Baldocchi *et al.* (2001) nearly two decades ago. Since then, field manuals have been developed to facilitate appropriate equipment setup and use (Burba, 2013; Audet *et al.*, 2014). In addition, researchers and companies have developed software to assist with processing (*Eddy Pro*, 2016; *EasyFlux DL*, 2018; Skaggs *et al.*, 2018), organizing and monitoring data (*FluxSuite*, 2015; *EasyFlux Web*, 2018), and applying quality assurance protocols (*TOVI*, 2018). For example, the method has been applied to study a variety of terrestrial ecosystem topics such as carbon cycling in northern peatlands (Roulet *et al.*, 2007), role of tree plantations on local water dynamics (Jones *et al.*, 2017), and irrigation practices of commercial crops (Cammalleri *et al.*, 2013). Networks of long-term EC sites exist in North America (AmeriFlux), Europe (EuroFlux), and Asia (AsiaFlux), as well as other locations (United States Department of Energy (USDE), 2018). Recently, Baldocchi (2014) proposed that future EC research should involve the use of complementary RS and ecosystem-climate model data to develop integrated ecosystem assessments.

The foundational theory of the EC technique was developed starting in the 1950s but the transition into an established method for evaluating ecosystem functioning did not occur until the 1990s when the required sensor technologies were developed (Aubinet *et al.*, 2012). The EC technique for the measurement of fluxes of heat, water vapour (H₂O), and carbon dioxide (CO₂), for example, involves measuring the concentration of selected

entities at high frequency (carried by drafts of air past a sensor) (Figure 2-3) and the concurrent fluctuations in vertical wind speed. The covariance of vertical wind speed and trace gas or temperature fluctuations can be used to compute the flux after addressing instrumentation effects (Baldocchi *et al.*, 2001; Aubinet *et al.*, 2012; Burba, 2013). An IRGA measures the concentration of CO₂ and H₂O and a sonic anemometer thermometer measures the wind speed in three directions and temperature while a data logger records the observations (Figure 2-3). Additional equipment is often used to collect complementary meteorological data such as RH, T_{air}, and radiation components. Installing an EC tower is relatively expensive due to the need for specialized equipment (*e.g.*, IRGA and anemometer), construction costs (*e.g.*, large towers), provision of power (*e.g.*, solar panels or permanent power line), and qualified personnel (*e.g.*, field and data technicians) (Aubinet *et al.*, 2012; Burba, 2013). While manuals and software programs for processing, applying quality assurance protocols, and gap-filling data collected using the EC technique are now available, skilled personnel are still required to make informed setup and data processing decisions based on the EC technique's theoretical considerations. For example, selecting an appropriate tower location and sensor height involves evaluating the surface roughness and wind dynamics of the location to ensure that the flux footprint (*i.e.*, flux source area) is representative of the ecosystem being evaluated. Also, processing requires trained hands when accounting for coordinate rotation and spectral corrections to determine high and low frequency losses to the flux signal. Once fluxes at appropriate time steps are calculated (typically 30 minutes), the

flux time series and associated statistics are evaluated for quality. Finally, gaps in the time series are filled using a variety of man-hour intensive techniques.

Ecosystem function variables derived using the EC fluxes include NEP, GEP, ET, and WUE. NEP is taken as the negative of CO₂ flux combined with the rate of change in CO₂ storage below the EC instrumentation. To derive GEP, NEP is partitioned between GEP and ecosystem respiration (ER) using a variety of methods (Griffis *et al.*, 2004; Skaggs *et al.*, 2018). NEP is the difference between the net CO₂ uptake by all photosynthesizing vegetation, and ER reflects both autotrophic (plant, R_{aut}) and heterotrophic (animal, R_{het}) respiration. WUE is the ratio of GEP to ET and provides a direct indication of how efficient the vegetation in an ecosystem is at accumulating biomass with regard to water use and is a factor in the long-term viability of an ecosystem (Kramer and Boyer, 1995; Ewers *et al.*, 2011; Sharp *et al.*, 2011). ET includes both transpiration and surface evaporation, is an essential variable in the ecosystem water balance, and can be used to assess if an ecosystem is operating within its available water supply.

5.6 The use of the EC technique for assessment of reclaimed AOSR landscapes

Eddy covariance measurements of surface-atmosphere exchanges may contribute to AOSR reclamation research and assessment in a number of ways. They can be used to 1) provide integrative measures of ecosystem functioning on a quasi-continuous basis to evaluate a number of the proposed indicators (Table 5-1) as well as some potential new indicators, 2) enable comparison with other ecosystems within the AOSR and elsewhere via publicly available datasets, which may be useful to establish indicator thresholds, 3)

be applied to a wide variety of ecosystem types (*e.g.*, forests and wetlands), and 4) integrate with other assessment practices and frameworks such as FI and carbon taxation, respectively.

In addition to assessment for certification, assessment of reclamation decisions and techniques require methods to assess the most cost-effective solutions. For example, Carrera-Hernández *et al.* (2012) used a process model to show that 0.5 to 1.0 m depth of reclamation material coupled with a water table deeper than 2 m are ideal for construction of aspen-dominated wetlands. Another modelling study concluded that there is no additional benefit to reclamation covers greater than 100 cm with respect to soil water availability (Huang *et al.*, 2015). Research techniques to assess reclamation trials include instrumentation to monitor soil moisture characteristics and target seedling growth and survival. However, ecosystem-scale ET, GPP, and WUE during and beyond the growing season may provide an integrated assessment of ecosystem health.

5.6.1.1 Integrative Measures of Ecosystem Functioning

Instead of characterizing isolated ecosystem structural components such as soil moisture or species composition at a moment in time (Table 5-1), the variables derived using the EC technique take into account the entirety of the ecosystem within the upwind source area (*e.g.*, the footprint) of the tower-mounted sensors. Measurements are typically made at 30-minute time steps but may be integrated over the period EC instrumentation was operating. This is particularly useful for understanding temporally and spatially variable ecosystem characteristics and functions such as ecosystem health, biogeochemical cycling, and water use and budgets. In this study, I make use of prior

Table 5-2. Measurement periods and descriptions for the EC sites provided in the data set with appropriate eddy covariance (EC) data: Evapotranspiration (ET); net ecosystem productivity (NEP); and gross ecosystem productivity (GEP).

Site	Location (Latitude, Longitude)	Years site data available and year stand established	Dominant Tree Species	Available Growing Season Measurements
Reclaimed AOSR Sites				
CB 11	57.0550°, -111.6585°	2017 (1, est. 2006)	White spruce (<i>Picea glauca</i> (Moench) Voss), Trembling aspen (<i>Populus tremuloides</i> Michx.)	LAI; ET; NEP; GEP
Cell 11A	56.8940°, -111.3808°	2007-11; 2013-14; 2016-17 (9, est. 2005)	Jack pine (<i>Pinus banksiana</i> Lamb.)	LAI (2013-14; 2016-17); ET (2007-11; 2017); NEP (2007-11; 2017); GEP (2007-11; 2017)
Jack Pine	57.0652°, -111.6636°	2007-14 (8, est., 1993)	Jack pine	LAI (2013-14); ET (2007-12); NEP (2007-12); GEP (2007-12)
Sandhill Fen 1 (upland)	57.0386°, -111.5850°	2013-17 (5, est. 2012)	Trembling aspen, Balsam poplar (<i>Populus balsamifera</i> L.)	LAI; ET (2014-15); NEP (2014-15); GEP (2014-15)
Sandhill Fen 2 (upland)	57.0379°, -111.5894°	2012-17 (3, est. 2012)	Trembling aspen, Black spruce (<i>Picea mariana</i> Mill.)	LAI (2013-17); ET (2012-15; 2017); NEP (2012-15; 2017); GEP (2012-15; 2017)
Sandhill Fen 3	57.0404°, -111.5894°	2013-15 (3, est. 2012)	N/A (pond – no trees)	LAI (2013); ET; NEP; GEP
South Bison Hill	56.9946°, -111.6161°	2003-17 (15, est. 2003)	Trembling aspen	LAI (2013-17); ET; NEP; GEP
Southwest Sand Storage	56.9934°, -111.7326°	2005-06; 2014-15 (4, est. 1995)	Trembling aspen, Siberian larch (<i>Larix siberica</i> Ledeb.)	LAI (2014); ET; NEP; GEP
Suncor Fen	56.9310°, -111.4169°	2013-17 (5, est. 2013)	Black spruce, Jack pine	LAI; ET; NEP; GEP
Reference Boreal Sites				
JACOS	56.3210°, -111.6495°	2010-2014 (5, est. 1996)	Black spruce	LAI (2017); ET; NEP; GEP
PFLORA	56.3747°, -111.2339°	2013-16 (4, est. 1886)	Black spruce	LAI (2013-14); ET; NEP; GEP
Poplar	56.9386°, -111.5486°	2013-16 (4, est. 1941)	Tamarack (<i>Larix laricina</i> [Du Roi] K. Koch), Black spruce	LAI (2013-14); ET; NEP; GEP

Site	Location (Latitude, Longitude)	Years site data available and year stand established	Dominant Tree Species	Available Growing Season Measurements
Red Earth Creek 1	56.0727°, -115.4759°	2007-11 (1 pre- harvest est. 1962, 4 post-harvest est. 2008)	Trembling aspen	ET; NEP; GEP
Red Earth Creek 2	56.0754°, -115.4765°	2005-17 (2 pre- harvest est. 1962, 13 post-harvest est. 2007)	Trembling aspen	LAI (2013-17); ET (2006-2015); NEP (2006-2015); GEP (2006- 2015)
Red Earth Creek 3	56.0728°, -115.4757°	2008-09; 2013-17 (10, est. 2007)	Trembling aspen	LAI (2013-17); ET (2008-09); NEP (2008-09); GEP (2008-09)

study results and I use a large EC dataset of treed boreal reclaimed and reference sites (Table 5-2) to further demonstrate potential applications for AOSR reclamation assessment and certification.

Two of the indicators currently proposed to assess vegetation growth and health include net primary productivity (NPP) and an assessment of whether “trees are healthy and vigorous” (Poscente and Charette, 2012: 22). Although SI has been proposed as one methodology to assess NPP, that metric’s focus is aboveground timber productivity. Alternatively, these indicators may be directly quantified using EC-derived NEP, the net exchange of carbon with the atmosphere, and GEP, the total uptake of carbon by all vegetation in the footprint, not just trees, and integrated over a full growing season, a year, or multiple years. They may be compared to NEP and GEP measured at other reclaimed and natural sites to evaluate expected growth trajectories. For example, Strilesky *et al.* (2017) studied a single reclaimed forest site from inception to 12 years of age and indicated that growth rates resulted in functioning similar to other boreal forest sites by ~ 10 years of age. This was demonstrated by determining annual GEP rates (*i.e.*, the early growth trajectory) and comparing them with values for other sites in the boreal

forest at maturity and at various stages post-disturbance reported in the literature.

Elsewhere, a study of multiple sites focused on the responses of four reclaimed and four reference sites to environmental forcings (Chapter 4). This study reported that grouping annual growing season (June to August) GEP by age resulted in significant differences in GEP, whereas groupings based on reference or reclaimed site type and tree type did not result in significant differences. Thus, for growth trajectory comparison purposes, it is more appropriate to use sites greater than 10 years of age and compare with reference sites of a similar age.

Ecosystem characteristic thresholds are integral to the concept of certification because indicators for selected criteria must fall within a set range marked by lower and upper limits in order to be deemed acceptable (Cullinane Thomas *et al.*, 2012; Poscente and Charette, 2012; Berkowitz, 2013). Reference boreal sites provide a range of natural variability in ecosystem functioning and can be used to determine these thresholds (Figure 5-1, Figure 5-2). An examination of GEP values for the data set used here shows that there is a wide range of natural variability for boreal sites ($\sim 1000 \text{ g C m}^{-2}$ per growing season), that there is value in grouping together sites by secondary factors such as dominant tree type (broadleaf trees have generally higher GEP, Figure 5-1), and that newly constructed wetlands have GEP lower than the range of variability for reference boreal peatlands and upland reference sites (Figure 5-2). These are pertinent observations when considering establishment of baseline criteria and assessment timelines for certification. These data also show that while there is a greater variability in summer

Figure 5-1. June-August gross ecosystem productivity (GEP, top), net ecosystem productivity (NEP, middle), and evapotranspiration (ET, 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, and the $\circ$ are the outliers. 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 5-2. June-August GEP for young reference and reclaimed sites. The grey shaded area represents the range of variability for the reference sites. The Sandhill Fen 3 lowland site, which did not have a dominant tree cover identified in the data set, is categorized as “Reclaimed – Not Applicable”.

GEP and NEP for reclaimed sites, the median values for reclaimed sites relative to reference sites are not significantly different (Figure 5-1).

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 (Amiro *et al.*, 2010; Goulden *et al.*, 2011). Using the EC-derived GEP values from 7 sites covering 42 site years in the AOSR and elsewhere in the Canadian boreal region, a logarithmic relationship ($R^2 = 0.56$) of GEP at age since disturbance for young broadleaf tree sites provides a means of estimating whether a reclaimed ecosystem with this dominant tree cover is within the range of expected productivity during this early growth trajectory (Figure 5-3). This is also useful to assess whole-ecosystem productivity before trees are large enough to employ FI methods to

Figure 5-3. 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 Fen 3 lowland site, which did not have a dominant tree cover identified in the data set, is categorized as “Reclaimed – Not Applicable”.

monitor their growth. Accounting for CO₂ losses through decomposition and autotrophic respiration (Figure 5-3), NEP varies in a similar way during the development of a forest ecosystem with a trend from a source of CO₂ immediately post-disturbance to a strong sink at an intermediate age and inter-annual variability associated with changes in weather, moisture, and vegetation conditions (Law *et al.*, 2002; Amiro *et al.*, 2010; Goulden *et al.*, 2011).

Understanding the hydrological functioning of an ecosystem is critical for ascertaining its potential long-term sustainability because if water demands exceed supply, the reclaimed ecosystem will likely fail (Kramer and Boyer, 1995; Jones, 2013). The AOSR is characterized by a water deficit. When long term water losses via overland runoff, groundwater flow, surface evaporation, and transpiration by vegetation are in excess of water inputs, it may result in drought or saline toxicity (Gosselin *et al.*, 2010). This information influences planning and practice for landscape closure and design in the AOSR. Design factors taken into consideration include topography and slope gradients (Kelln *et al.*, 2008; Ketcheson and Price, 2016), type and depth of cover material (Carrera-Hernández *et al.*, 2012; Ojekanmi and Chang, 2014; Huang *et al.*, 2015), and vegetation cover (Naeth *et al.*, 2011; Chen *et al.*, 2018).

EC-derived ET could be a useful indicator for assessment. It has been analyzed for a number of reclaimed AOSR sites including the SBH aspen-dominated site and the Sandhill Fen and Nikanotee Fen wetland watersheds (Nicholls *et al.*, 2016; Ketcheson *et al.*, 2017; Strilesky *et al.*, 2017). Nicholls *et al.* (2016) and Ketcheson *et al.* (2017) used ET analyses to suggest that it is possible to construct wetlands that support hydrological

functioning of typical boreal landscapes. Nicholls *et al.* (2016) noted that ET rates at the Sandhill Fen were controlled by climate and that rates lower than surrounding reference wetlands indicate that water use will change as the wetland develops. Based upon the argument that hydrological processes are prominent in regulating wetland function, Ketcheson *et al.* (2017) highlighted the ability of the Nikanotee Fen to sustain wet conditions. At SBH, it has been shown that the site was functioning within the range of natural ET variability for reference boreal forests at ~ 10 years of age and did not show evidence of water stress using thresholds established in the literature (Strilesky *et al.*, 2017). Although there is a great deal of variability in ET during the early post-disturbance years, the majority of reclaimed sites in another study were found to have rates within the range of natural variability 10-20 years following disturbance (Chapter 4). GEP and ET for the data set used here, which included sites at various ages post-disturbance, were not significantly different between reclaimed and reference site groupings (Figure 5-1).

At this time, there are no published studies examining how reclaimed oil sands landscapes recover from subsequent disturbances such as fire or harvesting. However, with continued monitoring of EC fluxes at reclaimed sites, there is an opportunity to directly observe resilience after such a disturbance. In addition, when these ecosystems' EC-derived variables deviate from and then return (or do not return) within established thresholds, the factors that resulted in the deviation may be identified (*e.g.*, drought) and the mechanisms that lead to this resilience (or lack thereof) may be identified. For example, similar studies on non-reclaimed (*i.e.*, reference) sites in the boreal region

reported a lag time of ~ 1 growing season from the start of the drought before ecosystem functioning as measured using EC-derived variables was noticeably affected (Kljun *et al.*, 2006; Petrone *et al.*, 2015). A mature aspen stand in Saskatchewan was particularly sensitive to drought compared to coniferous black spruce and jack pine stands with reduced NEP in the second (6%) and third (34%) years of drought (Kljun *et al.*, 2006). Similarly, aspen stands within 5 years post-disturbance in Alberta had lagged reductions in productivity following the initiation of drought conditions, and ultimately transitioned from being a carbon sink immediately prior to the drought to a carbon source following establishment of drought conditions (Petrone *et al.*, 2015).

5.6.1.2 *Using Available Data Sets To Compare With Other Ecosystems*

As noted above, publicly available long-term EC flux datasets provide comparative data with which to evaluate growing and evolving reclaimed AOSR ecosystems. Online data storage portals with fair-use policies include hundreds of sites in North America and globally (Fluxnet Canada Team, 2016; AmeriFlux, 2017; USDE, 2018). These sites include North American boreal forest sites with a wide range of forest types, ages, and disturbance histories whose datasets and synthesis studies are available for use (Law *et al.*, 2002; Coursolle *et al.*, 2006; Amiro *et al.*, 2010; Goulden *et al.*, 2011; Brümmer *et al.*, 2012). They are particularly valuable to better understand the range of boreal ecosystem function for context when evaluating AOSR ecosystem functioning. From a long-term research perspective, contributing EC data from reclaimed sites to these databases would in turn provide baseline values for continued evaluation of reclamation strategies and techniques.

5.6.1.3 *Applicability To A Variety of Ecosystem Types*

Another benefit of the EC technique touched upon earlier is that it has been used to assess the functioning of different landscape types (Roulet *et al.*, 2007; Cammalleri *et al.*, 2013; Nicholls *et al.*, 2016; Ketcheson *et al.*, 2017; Strilesky *et al.*, 2017). To date, criteria and indicators have focused on the soil and vegetation of upland forests but the pre-disturbance landscape in the AOSR included wetlands and water bodies in addition to upland forests (Gosselin *et al.*, 2010; Poscente and Charette, 2012). The EC technique has been applied to forested and wetland terrain types in the AOSR reclamation studies highlighted in this paper and a broader range of potential reference sites (Law *et al.*, 2002; Coursolle *et al.*, 2006; Humphreys *et al.*, 2006; Brümmer *et al.*, 2012; Petrone *et al.*, 2015).

5.6.1.4 *Integration With Other Assessment Practices And Regulatory Frameworks*

The spatial and temporal coverage of EC-derived data may be complementary to other ecosystem structural and functional assessments. The development of suitable relations among metrics will assist with addressing gaps in assessment coverage (Figure 5-4). Stakeholders in the AOSR have invested considerable time, effort, and money into collecting baseline and ongoing FI data and RS surveys for reclaimed ecosystems (Richardson, 2007; Gillanders *et al.*, 2008; Kessler *et al.*, 2010; Naeth *et al.*, 2011; COSIA, 2016; Ketcheson *et al.*, 2016). However, recent research in the AOSR and in other regions suggests the potential to selectively integrate these research methods to capitalize upon the functional assessment of EC, spatial coverage of RS, and established historical data and continued collection of FI data (Bampfylde *et al.*, 2010; Czerwinski *et*

al., 2014; Karan *et al.*, 2016; Nicholls *et al.*, 2016; Padmanaban *et al.*, 2017; Strilesky *et al.*, 2017; Chasmer *et al.*, 2018). While most of these studies demonstrate the use of a technique to track temporal changes (Czerwinski *et al.*, 2014; Karan *et al.*, 2016; Padmanaban *et al.*, 2017; Strilesky *et al.*, 2017) or development of baseline data sets (Bampfylde *et al.*, 2010; Nicholls *et al.*, 2016; Strilesky *et al.*, 2017), linking of RS, EC-derived indicators, and field measurements to study changes in ecosystem functioning at reclaimed sites in the AOSR did highlight the usefulness of such studies for tracking changes following disturbance (Chasmer *et al.*, 2018). A body of literature on comparison or integration of RS and FI to study forests also exists with methods of determining productivity a primary focus (Badreldin and Sanchez-Azofeifa, 2015; Schweiger *et al.*, 2017). Overall, integration of these disparate techniques is being investigated in many fields and the applications to date suggest that integration is a recommended path for future assessment and certification of AOSR sites. Several examples of EC-FI integration, as well as pertinent observations, developed using the unique data set available for this paper are provided below.

There is a strong linear relationship ($R^2 = 0.77$) between total June-August GEP and peak of growing season leaf area index (LAI) for reclaimed AOSR sites (Figure 5-5). For these same sites, NEP is a logarithmic function of LAI (Figure 5-6, $R^2 = 0.61$). The coefficients of determination increase when sites are categorized by site type (e.g. reference versus reclaimed (Figure 5-6). This suggests that an assessment of LAI during the month of July at young reclaimed sites may be used to estimate the productivity of these ecosystems. There is a well-known relationship between remotely-sensed NDVI

Figure 5-4. Conceptual diagram of spatial and temporal coverage associated with three methods to measure ecosystem productivity in an aspen-dominated boreal forest: Micrometeorological techniques (*e.g.*, EC), satellite remote sensing (RS), and forest inventory (FI). Spatial coverage: EC data represent the tower ‘footprint’ (see main text), which varies due to surface cover and atmospheric conditions and ranges from a few metres to hundreds of metres (Aubinet *et al.*, 2012); RS pixels represent an area of ground whose size depends on sensor and platform (*e.g.*, satellite-based sensors: 0.3 m for SPOT, 10 m for LANDSAT, 250 to 1000 m for MODIS) (Lillesand *et al.*, 2004); and FI which may provide single tree to plot-scale assessments of specific ecosystem structure components (*e.g.*, trees that have reached a minimum height) but do not necessarily integrate all ecosystem components nor their functions with many measurements only suitable for forest ecosystems. Temporal coverage: EC towers may be placed at suitable sites regardless of the age of the vegetation cover and data sets > 10 years are available (Aubinet *et al.*, 2012); RS depends on sensor and platform with limitations in image frequency (*e.g.*, revisit period: 5 for SPOT, 16 days for LANDSAT, 1 to 2 days for MODIS) an important factor (National Aeronautics and Space Administration, 2018; USGS, 2018) while long-term monitoring using some indices may be ineffective once reflectance data is no longer sensitive to increasing forest LAI at a certain growth stage (Huete *et al.*, 1997b; Chasmer *et al.*, 2018); and FI requires person time to revisit measurement plots with a number of metrics unsuited for young sites (Vasiliauskas and Chen, 2002).

Figure 5-5. Peak of growing season leaf area index (LAI) against total growing season gross ecosystem productivity (GEP) for reference and reclaimed sites. The lines and models represent respective least squares linear regressions for reference sites (brown), reclaimed sites (green), and the total data set (grey). The Sandhill Fen 3 lowland site, which did not have a dominant tree cover identified in the data set, is categorized as “Reclaimed – Not Applicable”.

and LAI, although this relationship has limitations with remotely-sensed NDVI ‘greening out’ (*i.e.*, saturating) at a leaf area index (LAI) of 3-4 m² m⁻² (Huete *et al.*, 1997b; Czerwinski *et al.*, 2014; Chasmer *et al.*, 2018). Relationships were of poor quality beyond an LAI of 3.0 for reclaimed and reference AOSR forest stands (Chasmer *et al.*, 2018), which is below the average LAI values identified for 11 Fluxnet Canada Research Network study sites for the 2003-2005 period (Chen *et al.*, 2006). Two of the three sites below this threshold had jack pine as the dominant tree cover while the third site with mature aspen trees (OA) was recovering from a drought (Chen *et al.*, 2006; Kljun *et al.*, 2006). This saturation limits monitoring of vegetation growth and associated ecosystem functioning of some ecosystems such as forests, particularly after initial development.

Figure 5-6. Peak of growing season leaf area index (LAI) against total growing season net ecosystem productivity (NEP) for reference and reclaimed sites. The logarithmic curve (dark grey line), 95% confidence interval range for the curve (light grey shaded area), and affiliated equation (grey text) are fit to the entire data set. The Sandhill Fen 3 lowland site, which did not have a dominant tree cover identified in the data set, is categorized as “Reclaimed – Not Applicable”.

The importance of tree diameter at 1.3 m (i.e., breast height) for many yield and growth models of forest stands based on FI measurements, which may not be attained until aspen are ~ 6-7 years of age and black spruce are ~ 18 years of age, is a factor limiting the applicability of FI at young sites (Vasiliauskas and Chen, 2002). Nevertheless, development of relationships among metrics could permit the practice of using a preferred technique based upon cost or logistical requirements in order to assess ecosystems for certification.

A complementary aspect of integration with other assessment practices is the potential to contribute to regulatory frameworks not directly related to reclamation certification. In Alberta, the Carbon Competitiveness Incentive regulation mandates that

facilities such as oil sands mines that have emitted 100,000 tonnes or more of greenhouse gases in any given year since 2003 must account for their carbon emissions with annual emissions exceeding an approved benchmark charged \$30 per tonne (Government of Alberta, 2017, 2018). A NEP of $100 \text{ g C m}^{-2} \text{ year}^{-1}$ for a developing reclaimed forest site would equate to an uptake of one tonne of C per hectare. For comparison, the 2017 June-August NEP value for the SBH site is 336 g C m^{-2} , which does not account for carbon losses via ER in winter or potential gains outside of the peak growing season annual period. Year-round measurements are available at Sandhill Fen 3 (Table 5-2), which is situated over a constructed wetland. June-August NEP increased from -117 to 202 g C m^{-2} over three years and corresponded to the increase in annual values from -242 to $77 \text{ g C m}^{-2} \text{ year}^{-1}$ (Clark, 2018). The relationship between growing season GPP and annual NEP has been noted via the significance of growing season length on annual NEP at North American boreal (mixed-wood and Jack pine) and European (Scots pine) forests (Zha *et al.*, 2009; Danielewska *et al.*, 2015; Froelich *et al.*, 2015). Although there is no direct mechanism to offset emissions using reclaimed ecosystem CO_2 uptake, the carbon budget of these reclaimed ecosystems and how they develop post-construction is of relevance for efforts to anticipate how Canadian forests will react to climate change (Kurz *et al.*, 2008). The use of EC data to establish carbon budgets would benefit from year-round infrastructure, preferably with an ample and constant power supply and closed-path IRGA for optimal performance in winter and wet conditions, in order to capture annual measurements.

5.6.1.5 Considerations

There are additional aspects of the EC technique that should be taken into consideration when examining its appropriateness for ongoing monitoring and certification of reclaimed sites. The logistical and monetary costs of setting up an EC monitoring site along with long-term maintenance and management are significant. Partly as a result of equipment and power considerations, the majority of EC sites examined here only have growing season data available. Non-growing season/winter ER is a significant source of carbon loss on an annual time scale. Winter NEP ranges from emission rates of $0.27 \text{ g C m}^{-2} \text{ day}^{-1}$ for boreal wetlands to $0.70 \text{ g C m}^{-2} \text{ day}^{-1}$ for deciduous forests, and annual measurements are required to account for these losses (Wang *et al.*, 2011). Year-round operations of EC sites requires access for regular maintenance and capacity to store and process large volumes of data, while metadata regarding changes in equipment and site characteristics are part of the critical information that needs to be stored and maintained to facilitate processing and interpretation of EC data. As noted by Baldocchi (2014), EC research has entered the realm of “big data”.

Equipment failure and cleaning of data may result in the loss of large amounts of critical data and this is especially of concern at remote and less frequently visited sites. Falge *et al.* (2001) noted in their study on gap-filling techniques for EC data that on average only 65% of an annual EC dataset is available for analysis. Both gap-filling and processing of the raw data has a significant impact on the final values (Massman and Lee, 2002). Variations of $\pm 25 \text{ g C m}^{-2} \text{ year}^{-1}$ and -45 to $200 \text{ g C m}^{-2} \text{ year}^{-1}$ have been reported in comparative studies on gap-filling techniques (Falge *et al.*, 2001; Moffat *et*

al., 2007). It is important to understand how processing may influence final results when comparing processed data – even the same data set – from different sources. Although these issues may limit the operation and interpretation of multiple EC sites, as noted above, the relationships between June-August and annual EC-derived variables are strong. Thus a few key sites operated year-round with common processing and gap-filling methodologies may be used to extend and interpret the growing season data obtained at other reclaimed and reference sites.

Other key reclamation issues in the AOSR include establishing adequate nutrient supplies for plants (Quideau *et al.*, 2013; Jung *et al.*, 2014) and avoiding an accumulation of sodium salts and residual hydrocarbons in plants and soil (Noah *et al.*, 2015; Kessel *et al.*, 2018). These issues are linked to a number of proposed indicators including soil salinity, ecosystem NPP, ecosystem health, and resilience, among others (Table 5-1). EC-derived variables of ET and GEP may be useful in identifying reclaimed ecosystems that are struggling based upon comparative assessments of carbon assimilation and water usage (Baldocchi *et al.*, 2001). However, evaluating reclaimed ecosystems for issues such as sodium toxicity and limited bioavailable nutrients requires different methods or complementary data.

5.7 Conclusion

This study illustrates the potential to use EC measurements of growing season ET, GEP, NEP, and WUE as indicators to assess ecosystems and develop thresholds using publicly available datasets and ongoing monitoring in the AOSR. Specifically, the EC-derived metrics of GEP and NEP may contribute to the already proposed net primary

productivity indicator, and ET and WUE may act as indicators for a new water use criteria category. The EC method can complement FI and RS data in both spatial and temporal scales, expand the number of CEMA indicators focused on ecosystem function, and provide information that will contribute meaningfully to the iterative cycle of research, practice, and assessment of reclaimed AOSR landscapes. While a suite of thresholds for the EC-derived indicators have not been developed, preliminary analyses presented here demonstrate that baseline data is available and that the natural range of variability may perform as upper and lower limit guidelines. However, further work is required to define criteria, indicators, and thresholds. Overall, this chapter argues the need to evaluate ecosystem functioning as well as structural components and presents a proof-of-concept for the use of the EC technique in assessment and certification of reclaimed AOSR landscapes.

6 CONCLUSION

This thesis establishes the methodology and justification for evaluating ecosystem function in reclaimed upland landscapes in the AOSR within the context of monitoring and certification practices. The research arc presented in this thesis began with a proof-of-concept for the EC technique to measure forest water use over time (Chapter 3). Chapter 4 established that climate and surface cover are dominant influences on ecosystem functioning. Finally, the thesis demonstrated the meaningful use of ecosystem function metrics as measured using the EC technique within reclamation certification frameworks (Chapter 5). This research design reflected a transition from a focus on basic science (*i.e.*, curiosity about the functioning of reclaimed landscapes) to applied science (*i.e.*, using the results to improve reclamation assessment and certification practices). Execution of the research project produced both intended and complementary outcomes.

The main outcome of this research project addressed the stated primary goal to evaluate the suitability of water use indicators of ET, GEP, and WUE for assessing the functioning of reclaimed forested landscapes in the AOSR. This goal was addressed in part by collecting these EC-derived variables for reclaimed and reference sites and presenting them in a format useful for developers of certification frameworks, that is, as time-aggregated values within time series analyses and in comparison to literature and reference site results. A major finding was that reclaimed sites were functioning within the range of natural variability with regard to water use after an initial period of variation following disturbance of ~ 10-20 years. Overall, the influence of the ecosystem structure (*e.g.*, vegetation assemblages) was greater than reclaimed or reference status. For

example, changes in vegetation cover type and weather conditions were driving factors in variations of ecosystem functioning and influences were similar for the different site types. This was the initial use of the EC technique to evaluate new boreal landscapes in the AOSR and to compare them to existing reference ones. As such, a notable gap in the understanding of the carbon and water use functioning of these ecosystems was partially addressed. However, further work expanding upon the number and type of study locations is required to increase understanding of the broad range of reclaimed ecosystems and provide a foundation for inclusion of EC-derived metrics in certification frameworks. Baseline values of potential productivity and water use indicators of GEP, NEP, ET, and WUE for reclaimed and reference sites were established via analysis of unique and existing data sets that will be available for developing certification thresholds for these indicators. They will also be available for future researchers studying issues such as the change in these sites over time and the influence of factors such as climate change. Collectively, the research presented here demonstrates that water use indicators of ecosystem functioning should be considered for assessment and certification practices in the AOSR.

While the focus of the research project was on identifying water use indicators for reclaimed ecosystems in the AOSR and using them to assess intra-site temporal changes and inter-site spatial differences for these landscapes, a number of complementary outcomes were achieved. These included producing an archive of EC data for the benefit of multiple stakeholders and an analysis of the nature of certification frameworks.

The execution of this research project required the identification and exchange of research data among multiple stakeholders. In particular, EC and ancillary (meteorological and site characteristic) data sets from disparate sources (researcher, industry, and government managed databases) were obtained, analysed, and subsequently shared in original or value-added formats. Participation in this process highlighted the value in archiving of and access to scientific data. Due to the difficulties in dealing with large data sets along with the temporal and spatial fragmentation of research teams, direct measurements and metadata were often misplaced when funding for projects ended and workers, technicians, graduate students, or post-doctoral fellows moved on. Facilitating ongoing and long-term access to these data sets would directly benefit the broader scientific community. Access to extensive and properly referenced data sets increases the production of high-quality research investigations regardless of field of study (Tenopir *et al.*, 2011; Wicherts *et al.*, 2011; Baldocchi, 2014; Bond- Lamberty, 2018). It would also indirectly benefit industry and society. The social license to operate that industry strives for would benefit from the transparency of making data on reclaimed landscapes publicly accessible. A greater understanding of the functioning of reclaimed landscapes and the resulting informed regulatory decisions regarding certification metrics would be of benefit to society in general. A framework for archiving and distributing EC data is an ongoing legacy of the international Fluxnet programs (AmeriFlux, 2017), and some of these publicly available data sources were utilized within this research project. Providing information on reclaimed sites to established data portals would be an efficient and effective way to meaningfully contribute to the preservation of data critical for future

reclamation research in the AOSR. Notably, these data sets would be useful for comparison and temporal change studies as well as for identifying thresholds for EC-derived certification indicators.

The research process also reiterated the need to visualize certification frameworks as living documents. This view accommodates changes (regulatory, technological, and societal) required over the timespan of the industrial activities while acknowledging that previous successes were the result of then-current best practices (Poscente and Charette, 2012). Such an approach encompasses previous reclamation activities such as Gateway Hill and acknowledges that reconstruction of existing reclaimed landscapes, which may not necessarily comply with current guidelines, is not practical. It also permits the flexibility to include social-based criteria and indicators which are unlikely to be fully addressed until reclaimed landscapes are available for traditional or public uses (*e.g.*, hunting and recreational activities). This research contributes to the scientific assessment of reclaimed landscapes but this scope does not minimize the importance of assessment criteria that do not fall within the physical environment perspective. It is likely that the subsequent substantial hurdle to confirmation of certification guidelines following selection of physical criteria, which is strongly linked to scientific research, will be integrating social uses and perspectives.

Another idea that a living document-based certification framework provides an avenue for addressing is “failure”. Namely, the idea may be incorporated into a certification framework if and when it is adequately addressed. The wide range of natural variability noted in the research results perhaps suggests that any constructed ecosystem

will eventually achieve ecosystem function metrics within the range of natural variability. It was assumed that managed recovery was required for the reclaimed ecosystems in this study, despite the lack of a definition for reclamation “failure”. There is corroboration in the literature that ecosystems find a way to thrive despite adverse growing conditions such as those created by severe disturbance and management practices. For example, a study assessing the impact of salinity found that aspen trees could and did grow on boreal sites previously considered unsuitable for forest vegetation (Lilles *et al.*, 2012). While their DBH measurements were approximately 50% lower than trees with more favourable conditions, they were still considered to be commercially viable. The feasibility of disturbed AOSR landscapes establishing ecosystem structures that support functioning similar to reference ecosystems when left to un-managed recovery (*e.g.*, atop tailings piles without extensive ecosystem engineering) has not been investigated. Implementing reclamation strategies involving islands of unmanaged landscapes within a reclaimed area would explore this question. In addition, studies of post-construction disturbance (*e.g.*, fire, insect outbreak, severe drought, or harvesting) would provide a needed and valuable assessment of the resilience of these reclaimed ecosystems. In particular, resilience to fire is important to assess as it is a traditional mechanism of boreal forest disturbance and recovery that is generally eliminated by management of reclaimed sites in the AOSR. Studies on these topics would provide relevant information regarding ecosystem resilience and the nature of ecosystem failure for reclamation managers and regulators.

There is an understanding that the extraction of bitumen will continue into the foreseeable future and that there is value in conducting research that contributes to the

efficient reclamation of disturbed landscapes (Richardson, 2007; Gosselin *et al.*, 2010; Audet *et al.*, 2014). An uncomfortable concept that merits reference is that without proper handling of research data and tracking of living certification documents, the money and effort invested in reclamation practices may be wasted if technological advances or need deem mining of the residual oil in reclamation substrates feasible for collection. Simply put, if reclaimed landscapes are disturbed to permit future open pit mining, it would be beneficial to have legacy documents to draw upon for future reclamation activities.

The scope of this project was crafted to explore the specific topic of using the EC technique to identify water use indicators and certification of reclaimed upland landscapes in the AOSR. However, many of the complementary concepts derived while executing the research project and situating the research within the context of the societal, industrial, and governmental milieu provide foundations for further thought and future research. Combined, the results of the research and complementary outcomes form a value-added contribution to literature in the field of AOSR reclamation research.

7 REFERENCES

- Aber J, Neilson RP, McNulty S, Lenihan JM, Bachelet D, Drapek RJ. 2001. Forest Processes and Global Environmental Change: Predicting the Effects of Individual and Multiple Stressors. *BioScience* **51** (9): 735–751. DOI: 10.1641/0006-3568(2001)051[0735:FPAGEC]2.0.CO;2
- Alberta Environment. 2010. Guidelines for Reclamation to Forest Vegetation in the Athabasca Oil Sands Region, 2nd Edition. Prepared by the Terrestrial Subgroup of the Reclamation Working Group of the Cumulative Environmental Management Association, Fort McMurray, AB.
- Alberta Environment and Parks. 2015. Shapefiles for Oil Sands Project Boundaries and Points: 1985 to 2013. Alberta Environment and Parks: Alberta. Available at: <http://osip.alberta.ca/library/Dataset/Details/671> [Accessed 25 November 2016]
- Allen RG, Pereira LS, Raes D, Smith M, others. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. *FAO, Rome* **300** (9): D05109
- AmeriFlux: Measuring carbon, water and energy flux across the Americas. 2017. *AmeriFlux*. Available at: <http://ameriflux.lbl.gov/> [Accessed 26 September 2017]
- Amiro BD. 2001. Paired-tower measurements of carbon and energy fluxes following disturbance in the boreal forest. *Global Change Biology* **7** (3): 253–268. DOI: 10.1046/j.1365-2486.2001.00398.x
- Amiro BD, Barr AG, Barr JG, Black TA, Bracho R, Brown M, Chen J, Clark KL, Davis KJ, Desai AR, *et al.* 2010. Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *Journal of Geophysical Research: Biogeosciences (2005–2012)* **115** (G4).
- Amiro BD, Barr AG, Black TA, Iwashita H, Kljun N, McCaughey JH, Morgenstern K, Murayama S, Nesic Z, Orchansky AL, *et al.* 2006a. Carbon, energy and water fluxes at mature and disturbed forest sites, Saskatchewan, Canada. *Agricultural and Forest Meteorology* **136** (3–4): 237–251. DOI: 10.1016/j.agrformet.2004.11.012
- Amiro BD, Chen JM, Liu J. 2000. Net primary productivity following forest fire for Canadian ecoregions. *Canadian Journal of Forest Research* **30** (6): 939–947. DOI: 10.1139/x00-025
- Amiro BD, Orchansky AL, Barr AG, Black TA, Chambers SD, Chapin III FS, Goulden ML, Litvak M, Liu HP, McCaughey JH, *et al.* 2006b. The effect of post-fire stand age on the boreal forest energy balance. *Agricultural and Forest Meteorology* **140** (1–4): 41–50. DOI: 10.1016/j.agrformet.2006.02.014

- Arain MA, Black TA, Barr AG, Griffiths TJ, Morgenstern K, Nesic Z. 2003. Year-round observations of the energy and water vapour fluxes above a boreal black spruce forest. *Hydrological Processes* **17** (18): 3581–3600. DOI: 10.1002/hyp.1348
- Atkins FJ, MacFadyen AJ. 2008. A Resource Whose Time Has Come? The Alberta Oil Sands as an Economic Resource. *Energy Journal*: 77–98.
- Aubinet M, Vesala T, Papale D. 2012. *Eddy Covariance: A Practical Guide to Measurement and Data Analysis*. Springer: New York, NY, USA.
- Audet P, Pinno BD, Thiffault E. 2014. Reclamation of boreal forest after oil sands mining: anticipating novel challenges in novel environments. *Canadian Journal of Forest Research* **45** (3): 364–371. DOI: 10.1139/cjfr-2014-0330
- Badreldin N, Sanchez-Azofeifa A. 2015. Estimating Forest Biomass Dynamics by Integrating Multi-Temporal Landsat Satellite Images with Ground and Airborne LiDAR Data in the Coal Valley Mine, Alberta, Canada. *Remote Sensing* **7** (3): 2832–2849. DOI: 10.3390/rs70302832
- Baker JM, Westman CN. 2018. Extracting knowledge: Social science, environmental impact assessment, and Indigenous consultation in the oil sands of Alberta, Canada. *The Extractive Industries and Society* **5** (1): 144–153. DOI: 10.1016/j.exis.2017.12.008
- Baldocchi DD. 2014. Measuring fluxes of trace gases and energy between ecosystems and the atmosphere – the state and future of the eddy covariance method. *Global Change Biology* **20** (12): 3600–3609. DOI: 10.1111/gcb.12649
- Baldocchi DD, Falge E, Gu L, Olson R, Hollinger D, Running S, Anthoni P, Bernhofer C, Davis K, Evans R, *et al.* 2001. FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem–Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities. *Bulletin of the American Meteorological Society* **82** (11): 2415–2434. DOI: 10.1175/1520-0477(2001)082<2415:FANTTS>2.3.CO;2
- Baldocchi DD, Kelliher FM, Black TA, Jarvis P. 2000. Climate and vegetation controls on boreal zone energy exchange. *Global Change Biology* **6** (S1): 69–83. DOI: 10.1046/j.1365-2486.2000.06014.x
- Bampfylde CJ, Hughes S, Pagec D, Purdy BG, Stanley S, Syed A. 2010. Compiling a geospatial database of existing oil sands industrial features for Alberta Environment. In *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*.
- Barr AG, Betts AK, Black TA, McCaughey JH, Smith CD. 2001. Intercomparison of BOREAS northern and southern study area surface fluxes in 1994. *Journal of Geophysical Research: Atmospheres* **106** (D24): 33543–33550. DOI: 10.1029/2001JD900070

- Barr AG, Black TA, Hogg EH, Kljun N, Morgenstern K, Nesic Z. 2004. Inter-annual variability in the leaf area index of a boreal aspen-hazelnut forest in relation to net ecosystem production. *Agricultural and Forest Meteorology* **126** (3–4): 237–255. DOI: 10.1016/j.agrformet.2004.06.011
- Barr AG, Morgenstern K, Black TA, McCaughey JH, Nesic Z. 2006. Surface energy balance closure by the eddy-covariance method above three boreal forest stands and implications for the measurement of the CO₂ flux. *Agricultural and Forest Meteorology* **140** (1–4): 322–337. DOI: 10.1016/j.agrformet.2006.08.007
- Bergeron O, Margolis HA, Coursolle C, Giasson M-A. 2008. How does forest harvest influence carbon dioxide fluxes of black spruce ecosystems in eastern North America? *Agricultural and Forest Meteorology* **148** (4): 537–548. DOI: 10.1016/j.agrformet.2007.10.012
- Bergeron Y, Engelmark O, Harvey B, Morin H, Sirois L. 1998. Key issues in disturbance dynamics in boreal forests: Introduction. *Journal of Vegetation Science* **9** (4): 464–468.
- Berkowitz JF. 2013. Development of restoration trajectory metrics in reforested bottomland hardwood forests applying a rapid assessment approach. *Ecological Indicators* **34**: 600–606. DOI: 10.1016/j.ecolind.2013.06.025
- Black TA, Den Hartog G, Neumann HH, Blanken PD, Yang PC, Russell C, Nesic Z, Lee X, Chen SG, Staebler R, *et al.* 1996. Annual cycles of water vapour and carbon dioxide fluxes in and above a boreal aspen forest. *Global Change Biology* **2** (3): 219–229.
- Blanken PD, Black TA. 2004. The canopy conductance of a boreal aspen forest, Prince Albert National Park, Canada. *Hydrological Processes* **18** (9): 1561–1578. DOI: 10.1002/hyp.1406
- Blanken PD, Black TA, Yang PC, Neumann HH, Nesic Z, Staebler R, den Hartog G, Novak MD, Lee X. 1997. Energy balance and canopy conductance of a boreal aspen forest: Partitioning overstory and understory components. *Journal of Geophysical Research: Atmospheres* **102** (D24): 28915–28927. DOI: 10.1029/97JD00193
- Boisvenue C, Running SW. 2006. Impacts of climate change on natural forest productivity – evidence since the middle of the 20th century. *Global Change Biology* **12** (5): 862–882. DOI: 10.1111/j.1365-2486.2006.01134.x
- Bonan GB. 2008. Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science* **320** (5882): 1444–1449. DOI: 10.1126/science.1155121
- Bond- Lamberty B. 2018. Data Sharing and Scientific Impact in Eddy Covariance Research. *Journal of Geophysical Research: Biogeosciences* **123** (4): 1440–1443. DOI: 10.1002/2018JG004502

- Borkenhagen A, Cooper DJ. 2016. Creating fen initiation conditions: a new approach for peatland reclamation in the oil sands region of Alberta. *Journal of Applied Ecology* **53** (2): 550–558. DOI: 10.1111/1365-2664.12555
- Bostock HS. 1970. Physiographic subdivisions of Canada. In *Geology and Economic Minerals of Canada, Economic Geology Report 1*, Douglas RWJ (ed.). Geological Survey of Canada: Ottawa, ON, Canada; 9–30.
- Bostock HS. 2014. Physiographic regions of Canada. DOI: 10.4095/293408
- Brandt JP. 2009. The extent of the North American boreal zone. *Environmental Reviews* **17**: 101–161. DOI: 10.1139/A09-004
- Brown SM, Petrone RM, Chasmer L, Mendoza C, Lazerjan MS, Landhäusser SM, Silins U, Leach J, Devito KJ. 2014. Atmospheric and soil moisture controls on evapotranspiration from above and within a Western Boreal Plain aspen forest. *Hydrological Processes* **28** (15): 4449–4462. DOI: 10.1002/hyp.9879
- Brümmer C, Black TA, Jassal RS, Grant NJ, Spittlehouse DL, Chen B, Nesic Z, Amiro BD, Arain MA, Barr AG, *et al.* 2012. How climate and vegetation type influence evapotranspiration and water use efficiency in Canadian forest, peatland and grassland ecosystems. *Agricultural and Forest Meteorology* **153**: 14–30. DOI: 10.1016/j.agrformet.2011.04.008
- Burba G. 2013. *Eddy Covariance Method for Scientific, Industrial, Agricultural, and Regulatory Applications: A Field Book on Measuring Ecosystem Gas Exchange and Areal Emission Rates*. LI-COR Biosciences: Lincoln, NE, USA.
- Burton PJ, Macdonald SE. 2011. The Restorative Imperative: Challenges, Objectives and Approaches to Restoring Naturalness in Forests. *Silva Fennica* **45** (5): 843–863.
- Cammalleri C, Rallo G, Agnese C, Ciralo G, Minacapilli M, Provenzano G. 2013. Combined use of eddy covariance and sap flow techniques for partition of ET fluxes and water stress assessment in an irrigated olive orchard. *Agricultural Water Management* **120**: 89–97. DOI: 10.1016/j.agwat.2012.10.003
- Campbell GS. 1977. *An Introduction to Environmental Biophysics*. Springer-Verlag New York Inc.: New York, USA.
- Canada's Oil Sands Innovation Alliance. 2016. About COSIA. Available at: <http://www.cosia.ca/about-cosia> [Accessed 8 March 2016]
- Carey SK. 2008. Growing season energy and water exchange from an oil sands overburden reclamation soil cover, Fort McMurray, Alberta, Canada. *Hydrological Processes* **22** (15): 2847–2857. DOI: 10.1002/hyp.7026

- Carmean WH, Hahn JT, Jacobs RD; 1989. *Site index curves for forest tree species in the eastern United States*. Available at: <http://www.treesearch.fs.fed.us/pubs/10192> [Accessed 9 February 2016]
- Carrera-Hernández JJ, Mendoza CA, Devito KJ, Petrone RM, Smerdon BD. 2012. Reclamation for aspen revegetation in the Athabasca oil sands: Understanding soil water dynamics through unsaturated flow modelling. *Canadian Journal of Soil Science* **92** (1): 103–116. DOI: 10.4141/cjss2010-035
- Chapin FS, Mcguire AD, Randerson J, Pielke R. 2000. Arctic and boreal ecosystems of western North America as components of the climate system. *Global Change Biology* **6** (S1): 211–223. DOI: 10.1046/j.1365-2486.2000.06022.x
- Chasmer L, Baker T, Carey SK, Straker J, Strilesky SL, Petrone R. 2018. Monitoring ecosystem reclamation recovery using optical remote sensing: Comparison with field measurements and eddy covariance. *Science of The Total Environment* **642**: 436–446. DOI: <https://doi.org/10.1016/j.scitotenv.2018.06.039>
- Chen HY, Biswas SR, Sobey TM, Brassard BW, Bartels SF. 2018. Reclamation strategies for mined forest soils and overstorey drive understorey vegetation. *The Journal of Applied Ecology* **55** (2): 926. DOI: 10.1111/1365-2664.13018
- Chen HY, Klinka K, Kabzems RD. 1998. Site index, site quality, and foliar nutrients of trembling aspen: relationships and predictions. *Canadian Journal of Forest Research* **28** (12): 1743–1755
- Chen JM, Govind A, Sonnentag O, Zhang Y, Barr AG, Amiro BD. 2006. Leaf area index measurements at Fluxnet-Canada forest sites. *Agricultural and Forest Meteorology* **140** (1): 257–268
- Chen JM, Rich PM, Gower ST, Norman JM, Plummer S. 1997. Leaf area index of boreal forests: Theory, techniques, and measurements. *Journal of Geophysical Research: Atmospheres* **102** (D24): 29429–29443. DOI: 10.1029/97JD01107
- Chen WJ, Black TA, Yang PC, Barr AG, Neumann HH, Nesic Z, Blanken PD, Novak MD, Eley J, Ketler RJ, *et al.* 1999. Effects of climatic variability on the annual carbon sequestration by a boreal aspen forest. *Global Change Biology* **5** (1): 41–53. DOI: 10.1046/j.1365-2486.1998.00201.x
- Christopherson RW. 2003. *Geosystems: An introduction to physical geography*. Pearson Education, Inc.: Upper Saddle River, NJ, USA.
- Clark MG. 2018. The initial biometerology of the constructed Sandhill Fen Watershed in Alberta, Canada. Carleton University, Ottawa, ON, Canada.

- Closure and Reclamation Team, Syncrude Canada Ltd. 2003. Syncrude Gateway Hill Site (S4 Area): Reclamation Certification Application.
- Costanza R, Norton B, Haskell B. 1992. *Ecosystem Health: New Goals for Environmental Management*. Island Press: Washington, DC, USA. Available at: <http://journals.sagepub.com/doi/10.1177/027046769401400438> [Accessed 30 September 2018]
- Council of Canadian Academies. 2015. *Technological Prospects for Reducing the Environmental Footprint of Canadian Oil Sands*. Council of Canadian Academies: Ottawa, ON, Canada.
- Coursolle C, Margolis HA, Barr AG, Black TA, Amiro BD, McCaughey JH, Flanagan LB, Lafleur PM, Roulet NT, Bourque CP-A, *et al.* 2006. Late-summer carbon fluxes from Canadian forests and peatlands along an east west continental transect. *Canadian Journal of Forest Research* **36** (3): 783–800. DOI: 10.1139/x05-270
- Cullinane Thomas CM, Skrabis KE, Gascoigne W. 2012. Ecosystem restoration [Chapter 4] - In: The Department of Interior's Economic Contributions, FY2011. U.S. Department of the Interior, Office of Policy Analysis, Reston, VA, USA.
- Cumulative Environmental Management Association. 2006. Land Capability Classification System for Forest Ecosystems in the Oil Sands, 3rd Edition. Government of Alberta, Alberta Environment, Edmonton, AB, Canada.
- Czarnecki J, Radoev B, Schramm LL, Slavchev R. 2005. On the nature of Athabasca Oil Sands. *Advances in Colloid and Interface Science* **114–115**: 53–60. DOI: 10.1016/j.cis.2004.09.009
- Czerwinski CJ, King DJ, Mitchell SW. 2014. Mapping forest growth and decline in a temperate mixed forest using temporal trend analysis of Landsat imagery, 1987–2010. *Remote Sensing of Environment* **141**: 188–200. DOI: 10.1016/j.rse.2013.11.006
- Dacre CK, Palandro DA, Oldak A, Ireland AW, Mercer SM. 2017. High-resolution satellite imagery applied to monitoring revegetation of oil-sands-exploration well pads. *Environmental Geosciences* **24** (4): 167–182.
- Danielewska A, Urbaniak M, Olejnik J. 2015. Growing Season Length as a Key Factor of Cumulative Net Ecosystem Exchange Over the Pine Forest Ecosystems in Europe. *International Agrophysics* **29** (2): 129–135. DOI: 10.1515/intag-2015-0026
- Dare M (Lain). 2014. Community engagement and social licence to operate. **32** (3): 188–197.
- Daubenmire R. 1976. The use of vegetation in assessing the productivity of forest lands. *The Botanical Review* **42** (2): 115–143. DOI: 10.1007/BF02860720

- Davidson DJ, Gismondi M. 2011. Visualizing the Tar Sands Through Time. In *Challenging Legitimacy at the Precipice of Energy Calamity*. Springer: New York, NY, USA; 39–68.
- Devito K, Mendoza C, Qualizza C. 2012. Conceptualizing Water Movement in the Boreal Plains. Implications for Watershed Reconstruction. Report. Available at: <https://era.library.ualberta.ca/public/view/item/uuid:571917f4-a0a8-4906-8c54-4c4e4656958d/> [Accessed 20 April 2015]
- DMTI Spatial Inc. 2014a. Major Water Regions (MJWTR). DMTI Spatial Inc.: Markham, ON, Canada. Available at: http://geo.scholarsportal.info/#r/details/_uri@=311685684 [Accessed 28 November 2016]
- DMTI Spatial Inc. 2014b. Populated Placenames (PPN). DMTI Spatial Inc.: Markham, ON, Canada. Available at: http://geo.scholarsportal.info/#r/details/_uri@=1690133422 [Accessed 28 November 2016]
- Dompierre KA, Barbour SL, North RL, Carey SK, Lindsay MBJ. 2017. Chemical mass transport between fluid fine tailings and the overlying water cover of an oil sands end pit lake. *Water Resources Research* **53** (6): 4725–4740. DOI: 10.1002/2016WR020112
- EasyFlux DL. 2018. Campbell Scientific Inc.: Logan, UT, USA.
- EasyFlux Web*. 2018. Campbell Scientific Inc.: Logan, UT, USA.
- Eddy Pro. 2016. LI-COR Biosciences: Lincoln, NE, USA.
- Environment and Climate Change Canada. 2013. Canadian Climate Normals 1981-2010 Fort McMurray (A) Station Data. Available at: http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnName&txtStationName=Fort+McMurray&searchMethod=contains&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=2519&dispBack=1 [Accessed 20 September 2017]
- Environment Canada. 2013. Canadian Climate Normals 1981-2010 Station Data - Climate - Environment Canada. Available at: http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnName&txtStationName=Fort+McMurray&searchMethod=contains&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=2519&dispBack=1 [Accessed 5 July 2016]

- Ewers BE, Bond-Lamberty B, Mackay DS. 2011. Consequences of Stand Age and Species' Functional Trait Changes on Ecosystem Water Use of Forests. In *Size- and Age-Related Changes in Tree Structure and Function*, Meinzer FC, Lachenbruch B, Dawson TE (eds). Springer: Dordrecht, Netherlands; 481–505. DOI: 10.1007/978-94-007-1242-3_18
- Falge E, Baldocchi DD, Olson R, Anthoni P, Aubinet M, Bernhofer C, Burba G, Ceulemans R, Clement R, Dolman H, *et al.* 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology* **107** (1): 43–69. DOI: 10.1016/S0168-1923(00)00225-2
- Farley KA, Jobbagy EG, Jackson RB. 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. *Global Change Biology* **11** (10): 1565–1576. DOI: 10.1111/j.1365-2486.2005.01011.x
- Ferguson BG. 1986. *Athabasca Oil Sands: Northern Resource Exploration, 1875-1951*. University of Regina Press: Regina, Saskatchewan.
- Fluxnet Canada Team. 2016. FLUXNET Canada Research Network - Canadian Carbon Program Data Collection, 1993-2014. DOI: 10.3334/ORNLDAAAC/1335
- FluxSuite*. 2015. LI-COR Biosciences: Lincoln, NE, USA.
- Frelich LE, Reich PB. 1995. Spatial Patterns and Succession in a Minnesota Southern-Boreal Forest. *Ecological Monographs* **65** (3): 325–346. DOI: 10.2307/2937063
- Froelich N, Croft H, Chen JM, Gonsamo A, Staebler RM. 2015. Trends of carbon fluxes and climate over a mixed temperate–boreal transition forest in southern Ontario, Canada. *Agricultural and Forest Meteorology* **211–212**: 72–84. DOI: 10.1016/j.agrformet.2015.05.009
- Gillanders SN, Coops NC, Wulder MA, Goodwin NR. 2008. Application of Landsat satellite imagery to monitor land-cover changes at the Athabasca Oil Sands, Alberta, Canada. *The Canadian Geographer / Le Géographe canadien* **52** (4): 466–485. DOI: 10.1111/j.1541-0064.2008.00225.x
- Goldstein PZ. 1999. Functional Ecosystems and Biodiversity Buzzwords. *Conservation Biology* **13** (2): 247–255. DOI: 10.1046/j.1523-1739.1999.013002247.x
- Golley FB. 1993. *A history of the ecosystem concept in ecology: More than the sum of the parts*. Yale University Press: New Haven.
- Gosselin P, Hrudey SE, Naeth A, Plourde A, Therrien R, Van Der Krak G, Xu Z. 2010. The Royal Society of Canada Expert Panel: Environmental and Health Impacts of Canada's Oil Sands Industry: Report. Royal Society of Canada, Ottawa, ON, Canada.

- Goulden ML, McMillan AMS, Winston GC, Rocha AV, Manies KL, Harden JW, Bond-Lamberty BP. 2011. Patterns of NPP, GPP, respiration, and NEP during boreal forest succession. *Global Change Biology* **17** (2): 855–871. DOI: 10.1111/j.1365-2486.2010.02274.x
- Government of Alberta. 2010. Reclamation. *Alberta's Oil Sands*. Available at: <http://www.oilsands.alberta.ca/reclamation.html> [Accessed 4 March 2016]
- Government of Alberta. 2014. Climate and Geography. Available at: <http://alberta.ca/climateandgeography.cfm> [Accessed 11 November 2014]
- Government of Alberta. 2017. Capping oil sands emissions. Available at: <https://www.alberta.ca/climate-oilsands-emissions.aspx> [Accessed 31 March 2018]
- Government of Alberta. 2018. Carbon levy and rebates. Available at: <https://www.alberta.ca/climate-carbon-pricing.aspx> [Accessed 31 March 2018]
- Government of Canada PW and GSC. 2015. Oil sands - a strategic resource for Canada, North America and the global market. Land use and reclamation: M164-4/7-1-2011E-PDF - Government of Canada Publications. Available at: <http://publications.gc.ca/site/eng/395813/publication.html> [Accessed 16 December 2017]
- Griffis TJ, Black TA, Gaumont-Guay D, Drewitt GB, Nesic Z, Barr AG, Morgenstern K, Kljun N. 2004. Seasonal variation and partitioning of ecosystem respiration in a southern boreal aspen forest. *Agricultural and Forest Meteorology* **125** (3): 207–223. DOI: 10.1016/j.agrformet.2004.04.006
- Griffis TJ, Black TA, Morgenstern K, Barr AG, Nesic Z, Drewitt GB, Gaumont-Guay D, McCaughey JH. 2003. Ecophysiological controls on the carbon balances of three southern boreal forests. *Agricultural and Forest Meteorology* **117** (1): 53–71. DOI: 10.1016/S0168-1923(03)00023-6
- Gromtsev A. 2002. Natural disturbance dynamics in the boreal forests of European Russia: A review. *Silva Fennica* **36** (1): 41–55.
- Halliwel D, Apps M, Price D. 1995. A survey of the forest site characteristics in a transect through the central Canadian boreal forest. *Water, Air, and Soil Pollution* **82** (1–2): 257–270. DOI: 10.1007/BF01182839
- Hein FJ. 2016. Oil Sands Pioneers: How Scientists and Entrepreneurs Made the Unconventional More “Conventional”. In *AAPG Annual Convention and Exhibition*. Calgary, Alberta, Canada. Available at: http://www.searchanddiscovery.com/pdfz/documents/2016/80545hein/ndx_hein.pdf.html [Accessed 20 November 2017]

- Hein FJ, Cotterill DK. 2006. The Athabasca Oil Sands - A Regional Geological Perspective, Fort McMurray Area, Alberta, Canada. *Natural Resources Research* **15** (2): 85–102. DOI: 10.1007/s11053-006-9015-4
- Heyes A, Leach A, Mason CF. 2018. The Economics of Canadian Oil Sands. *Review of Environmental Economics and Policy* **12** (2): 242–263. DOI: 10.1093/reep/rey006
- Hild AL, Shaw NL, Paige GB, Williams ML, others. 2009. Integrated reclamation: approaching ecological function. In *National Meeting of the American Society of Mining and Reclamation, Billings, MT*. Available at: <http://www.asmr.us/Publications/Conference%20Proceedings/2009/0578-Hild-WY.pdf> [Accessed 24 November 2014]
- Hooper DU, Chapin FS, Ewel JJ, Hector A, Inchausti P, Lavorel S, Lawton JH, Lodge DM, Loreau M, Naeem S, *et al.* 2005. Effects of Biodiversity on Ecosystem Functioning: A Consensus of Current Knowledge. *Ecological Monographs* **75** (1): 3–35. DOI: 10.1890/04-0922
- Hopkinson C, Chasmer L, Young-Pow C, Treitz P. 2004. Assessing forest metrics with a ground-based scanning lidar. *Canadian Journal of Forest Research* **34** (3): 573–583. DOI: 10.1139/x03-225
- Huang M, Barbour SL, Carey SK. 2015. The impact of reclamation cover depth on the performance of reclaimed shale overburden at an oil sands mine in Northern Alberta, Canada. *Hydrological Processes* **29** (12): 2840–2854. DOI: 10.1002/hyp.10229
- Huang S, Meng SX, Yang Y. 2009a. A growth and yield projection system (GYPSY) for natural and post-harvest stands in Alberta. Technical Report T/216. Forestry Division, Alberta Sustainable Resource Development, Edmonton, AB, Canada.
- Huang S, Morgan DJ, Klappstein G, Heidt J, Yang Y, Greidanus G. 2009b. A growth and yield projection system (GYPSY) for natural and regenerated lodgepole pine stands in Alberta. Technical Report T/216. Forestry Division, Alberta Sustainable Resource Development.
- Huete AR, Liu HQ, Batchily K, van Leeuwen W. 1997a. A Comparison of Vegetation Indices over a Global Set of TM Images for EOS-MODIS. *Remote Sensing of Environment* **59** (3): 440–451. DOI: 10.1016/S0034-4257(96)00112-5
- Huete AR, Liu HQ, van Leeuwen W. 1997b. The use of vegetation indices in forested regions: issues of linearity and saturation. In *Geoscience and Remote Sensing, 1997. IGARSS '97. Remote Sensing-A Scientific Vision for Sustainable Development., 1997 IEEE International*; IEEE: 1966–1968.

- Humphreys ER, Lafleur PM, Flanagan LB, Hedstrom N, Syed KH, Glenn AJ, Granger R. 2006. Summer carbon dioxide and water vapor fluxes across a range of northern peatlands. *Journal of Geophysical Research: Biogeosciences* **111** (G4): G04011. DOI: 10.1029/2005JG000111
- Jax K, Setälä H. 2005. Function and ‘Functioning’ in Ecology: What Does It Mean? *Oikos* **111** (3): 641–648.
- Jones H, Black TA, Jassal RS, Nesic Z, Grant N, Bhatti JS, Sidders D. 2017. Water balance, surface conductance and water use efficiency of two young hybrid-poplar plantations in Canada’s aspen parkland. *Agricultural and Forest Meteorology* **246**: 256–271. DOI: 10.1016/j.agrformet.2017.04.007
- Jones HG. 2013. *Plants and Microclimate: A Quantitative Approach to Environmental Plant Physiology*. Cambridge University Press: New York, NY, USA.
- Jung K, Duan M, House J, Chang SX. 2014. Textural interfaces affected the distribution of roots, water, and nutrients in some reconstructed forest soils in the Athabasca oil sands region. *Ecological Engineering* **64**: 240–249. DOI: 10.1016/j.ecoleng.2013.12.037
- Kangas A, Maltamo M. 2006. *Forest Inventory: Methodology and Applications*. Springer Science & Business Media.
- Karan SK, Samadder SR, Maiti SK. 2016. Assessment of the capability of remote sensing and GIS techniques for monitoring reclamation success in coal mine degraded lands. *Journal of Environmental Management* **182**: 272–283. DOI: 10.1016/j.jenvman.2016.07.070
- Kelln C, Barbour SL, Qualizza C. 2008. Controls on the spatial distribution of soil moisture and solute transport in a sloping reclamation cover. *Canadian Geotechnical Journal* **45** (3): 351–366. DOI: 10.1139/T07-099
- Kennedy BE. 2018. Multi-Angle Spectroscopic Remote Sensing of Arctic Vegetation Biochemical and Biophysical Properties. Thesis, Carleton University. Available at: <https://curve.carleton.ca/99cad44c-8c88-49c2-99ba-d0ffd3927fc2> [Accessed 20 May 2018]
- Kessel ED, Ketcheson SJ, Price JS. 2018. The distribution and migration of sodium from a reclaimed upland to a constructed fen peatland in a post-mined oil sands landscape. *Science of The Total Environment* **630**: 1553–1564. DOI: 10.1016/j.scitotenv.2018.02.253
- Kessler S, Barbour SL, van Rees KCJ, Dobchuk BS. 2010. Salinization of soil over saline-sodic overburden from the oil sands in Alberta. *Canadian Journal of Soil Science* **90** (4): 637–647. DOI: 10.4141/cjss10019

- Ketcheson SJ, Price JS. 2016. Comparison of the hydrological role of two reclaimed slopes of different ages in the Athabasca oil sands region, Alberta, Canada. *Canadian Geotechnical Journal* **53** (9): 1533–1546. DOI: 10.1139/cgj-2015-0391
- Ketcheson SJ, Price JS, Carey SK, Petrone RM, Mendoza CA, Devito KJ. 2016. Constructing fen peatlands in post-mining oil sands landscapes: Challenges and opportunities from a hydrological perspective. *Earth-Science Reviews* **161**: 130–139. DOI: 10.1016/j.earscirev.2016.08.007
- Ketcheson SJ, Price JS, Sutton O, Sutherland G, Kessel E, Petrone RM. 2017. The hydrological functioning of a constructed fen wetland watershed. *Science of the Total Environment* **603**: 593–605.
- Kimmins JPH. 2011. *Balancing Act: Environmental Issues in Forestry*. UBC Press: Vancouver, B.C., Canada.
- Kiniry JR, Macdonald JD, Kemanian AR, Watson B, Putz G, Prepas EE. 2008. Plant growth simulation for landscape-scale hydrological modelling. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques* **53** (5): 1030–1042. DOI: 10.1623/hysj.53.5.1030
- Kljun N, Black TA, Griffis TJ, Barr AG, Gaumont-Guay D, Morgenstern K, McCaughey JH, Nesic Z. 2006. Response of Net Ecosystem Productivity of Three Boreal Forest Stands to Drought. *Ecosystems* **9** (7): 1128–1144. DOI: 10.1007/s10021-005-0082-x
- Kljun N, Calanca P, Rotach MW, Schmid HP. 2004. A Simple Parameterisation for Flux Footprint Predictions. *Boundary-Layer Meteorology* **112** (3): 503–523. DOI: 10.1023/B:BOUN.0000030653.71031.96
- Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. 2006. World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift* **15** (3): 259–263.
- Kramer PJ, Boyer JS. 1995. *Water relations of plants and soils*. Academic Press: San Diego, CA, USA.
- Kurz WA, Stinson G, Rampley G. 2008. Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbances? *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **363** (1501): 2259–2268. DOI: 10.1098/rstb.2007.2198
- Kwak J-H, Chang SX, Naeth MA, Schaaf W. 2015. Coarse woody debris extract decreases nitrogen availability in two reclaimed oil sands soils in Canada. *Ecological Engineering* **84**: 13–21. DOI: 10.1016/j.ecoleng.2015.07.012

- Law BE, Falge E, Gu L, Baldocchi DD, Bakwin P, Berbigier P, Davis K, Dolman AJ, Falk M, Fuentes JD, *et al.* 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. *Agricultural and Forest Meteorology* **113** (1–4): 97–120. DOI: 10.1016/S0168-1923(02)00104-1
- Lehosmaa K, Jyvasjarvi J, Virtanen R, Ilmonen J, Saastamoinen J, Muotka T. 2017. Anthropogenic habitat disturbance induces a major biodiversity change in habitat specialist bryophytes of boreal springs. *Biological Conservation* **215**: 169–178. DOI: 10.1016/j.biocon.2017.09.010
- Levant E. 2011. *Ethical Oil: The Case for Canada's Oil Sands*. McClelland & Stewart: Plattsburgh, NY, USA.
- Li H, Zhang F, Li Y, Wang J, Zhang L, Zhao L, Cao G, Zhao X, Du M. 2016. Seasonal and inter-annual variations in CO₂ fluxes over 10 years in an alpine shrubland on the Qinghai-Tibetan Plateau, China. *Agricultural and Forest Meteorology* **228–229**: 95–103. DOI: 10.1016/j.agrformet.2016.06.020
- Lilles EB, Purdy BG, Macdonald SE, Chang SX. 2012. Growth of aspen and white spruce on naturally saline sites in northern Alberta: Implications for development of boreal forest vegetation on reclaimed saline soils. *Canadian Journal of Soil Science* **92** (1): 213–227. DOI: 10.4141/cjss2010-032
- Lillesand TM, Kiefer RW, Chipman JW. 2004. *Remote sensing and image interpretation*. John Wiley & Sons, Inc: New York, NY, USA.
- Litvak M, Miller S, Wofsy SC, Goulden M. 2003. Effect of stand age on whole ecosystem CO₂ exchange in the Canadian boreal forest. *Journal of Geophysical Research: Atmospheres* **108** (D3): 8225. DOI: 10.1029/2001JD000854
- Lloyd J, Taylor JA. 1994. On the Temperature Dependence of Soil Respiration. *Functional Ecology* **8** (3): 315–323. DOI: 10.2307/2389824
- Loreau M, Naeem S, Inchausti P, Bengtsson J, Grime JP, Hector A, Hooper DU, Huston MA, Raffaelli D, Schmid B, *et al.* 2001. Biodiversity and Ecosystem Functioning: Current Knowledge and Future Challenges. *Science* **294** (5543): 804–808.
- Ma Y, Wu H, Wang L, Huang B, Ranjan R, Zomaya A, Jie W. 2015. Remote sensing big data computing: Challenges and opportunities. *Future Generation Computer Systems* **51**: 47–60. DOI: 10.1016/j.future.2014.10.029
- Macdonald SE, Snively AEK, Fair JM, Landhäusser SM. 2015. Early trajectories of forest understory development on reclamation sites: Influence of forest floor placement and a cover crop. *Restoration Ecology* **23** (5): 698–706. DOI: 10.1111/rec.12217

- Malhi Y, Baldocchi DD, Jarvis PG. 1999. The carbon balance of tropical, temperate and boreal forests. *Plant, Cell & Environment* **22** (6): 715–740. DOI: 10.1046/j.1365-3040.1999.00453.x
- Margolis HA, Ryan MG. 1997. A physiological basis for biosphere–atmosphere interactions in the boreal forest: An overview. *Tree physiology* **17** (8–9): 491–499.
- Masliyah J, Zhou ZJ, Xu Z, Czarnecki J, Hamza H. 2004. Understanding Water-Based Bitumen Extraction from Athabasca Oil Sands. *The Canadian Journal of Chemical Engineering* **82** (4): 628–654. DOI: 10.1002/cjce.5450820403
- Massman WJ, Lee X. 2002. Eddy covariance flux corrections and uncertainties in long-term studies of carbon and energy exchanges. *Agricultural and Forest Meteorology* **113** (1): 121–144. DOI: 10.1016/S0168-1923(02)00105-3
- McDermott V. 2013. Syncrude marks bison ranch anniversary. *Fort McMurray Today*. Available at: <http://www.fortmcmurraytoday.com/2013/07/08/syncrude-celebrates-bison-ranch-anniversary> [Accessed 22 March 2015]
- McDonald T, Gann GD, Jonson J, Dixon KW. 2016. International standards for the practice of ecological restoration - including principles and key concepts. Washington, D.C, USA. Available at: www.ser.org
- Millard K, Thompson DK, Parisien M-A, Richardson M. 2018. Soil Moisture Monitoring in a Temperate Peatland Using Multi-Sensor Remote Sensing and Linear Mixed Effects. *Remote Sensing* **10** (6).
- Mkhabela MS, Amiro BD, Barr AG, Black TA, Hawthorne I, Kidston J, McCaughey JH, Orchansky AL, Nesic Z, Sass A, *et al.* 2009. Comparison of carbon dynamics and water use efficiency following fire and harvesting in Canadian boreal forests. *Agricultural and Forest Meteorology* **149** (5): 783–794. DOI: 10.1016/j.agrformet.2008.10.025
- Moffat AM, Papale D, Reichstein M, Hollinger DY, Richardson AD, Barr AG, Beckstein C, Braswell BH, Churkina G, Desai AR, *et al.* 2007. Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. *Agricultural and Forest Meteorology* **147** (3): 209–232. DOI: 10.1016/j.agrformet.2007.08.011
- Mollard FPO, Roy M-C, Foote AL. 2015. Performance of wetland forbs transplanted into marshes amended with oil sands processed water. *Environmental Monitoring and Assessment* **187** (3): 125. DOI: 10.1007/s10661-015-4365-1
- Monteith J, Unsworth M. 2008. *Principles of Environmental Physics*. Elsevier: Boston, MA, USA.

- Mossop GD. 1980. Geology of the Athabasca Oil Sands. *Science* **207** (4427): 145–152. DOI: 10.1126/science.207.4427.145
- Müller F. 1997. State-of-the-art in ecosystem theory. *Ecological Modelling* **100** (1–3): 135–161. DOI: 10.1016/S0304-3800(97)00156-7
- Naeth MA, Chanasyk DS, Burgers TD. 2011. Vegetation and soil water interactions on a tailings sand storage facility in the Athabasca oil sands region of Alberta Canada. *Physics and Chemistry of the Earth, Parts A/B/C* **36** (1–4): 19–30. DOI: 10.1016/j.pce.2010.10.003
- National Aeronautics and Space Administration. 2018. MODIS Web: Moderate Resolution IMaging Spectroradiometer. Available at: <https://modis.gsfc.nasa.gov/about/> [Accessed 1 October 2018]
- Nelson JA, Carvalhais N, Migliavacca M, Reichstein M, Jung M. 2018. Water-stress-induced breakdown of carbon-water relations: indicators from diurnal FLUXNET patterns. *Biogeosciences* **15** (7): 2433–2447. DOI: 10.5194/bg-15-2433-2018
- Nicholls EM, Carey SK, Humphreys ER, Clark MG, Drewitt GB. 2016. Multi-year water balance assessment of a newly constructed wetland, Fort McMurray, Alberta. *Hydrological Processes* **30** (16): 2739–2753. DOI: 10.1002/hyp.10881
- Niinemets Ü. 2010. Responses of forest trees to single and multiple environmental stresses from seedlings to mature plants: Past stress history, stress interactions, tolerance and acclimation. *Forest Ecology and Management* **260** (10): 1623–1639. DOI: 10.1016/j.foreco.2010.07.054
- Nikiforuk A. 2010. *Tar Sands: Dirty Oil and the Future of a Continent*. Greystone Books/David Suzuki Foundation: Vancouver, B.C., Canada.
- Noah M, Poetz S, Vieth-Hillbrand A, Wilkes H. 2015. Detection of residual oil sand derived organic material in developing soils of reclamation sites by ultra high resolution mass spectrometry. *Environmental science & technology* **49** (11): 6466–6473. DOI: 10.1021/es506013m
- Nwaishi F, Petrone RM, Price JS, Andersen R. 2015. Towards Developing a Functional-Based Approach for Constructed Peatlands Evaluation in the Alberta Oil Sands Region, Canada. *Wetlands*: 1–15.
- Ojekanmi AA, Chang SX. 2014. Soil Quality Assessment for Peat–Mineral Mix Cover Soil Used in Oil Sands Reclamation. *Journal of Environment Quality* **43** (5): 1566. DOI: 10.2134/jeq2014.02.0061
- Oke TR. 1987. *Boundary Layer Climates*. Routledge (Taylor & Francis Group): New York, NY, USA.

- Padmanaban R, Bhowmik A, Cabral P. 2017. A Remote Sensing Approach to Environmental Monitoring in a Reclaimed Mine Area. *ISPRS International Journal of Geo-information* **6** (12): 401. DOI: 10.3390/ijgi6120401
- Paskey J, Steward G, Williams A. 2013. *The Alberta Oil Sands Then and Now: An Investigation of the Economic, Environmental and Social Discourses Across Four Decades*.
- Peltzer DA, Bast ML, Wilson SD, Gerry AK. 2000. Plant diversity and tree responses following contrasting disturbances in boreal forest. *Forest Ecology and Management* **127** (1–3): 191–203. DOI: 10.1016/S0378-1127(99)00130-9
- Petrone RM, Chasmer L, Hopkinson C, Silins U, Landhäusser SM, Kljun N, Devito KJ. 2015. Effects of harvesting and drought on CO₂ and H₂O fluxes in an aspen-dominated western boreal plain forest: early chronosequence recovery. *Canadian Journal of Forest Research* **45** (1): 87–100. DOI: 10.1139/cjfr-2014-0253
- Pickett ST. 1987. Space-for-Time Substitution as an Alternative to Long-Term Studies. In *Long-Term Studies in Ecology: Approaches and Alternatives*. Springer-Verlag: New York, NY, USA.
- Pinno BD, Hawkes VC. 2015. Temporal Trends of Ecosystem Development on Different Site Types in Reclaimed Boreal. *Forests* **6** (6): 2109–2124. DOI: 10.3390/f6062109
- Pitman AJ. 2005. On the Role of Geography in Earth System Science. *Geoforum* **36** (2): 137–148. DOI: 10.1016/j.geoforum.2004.11.008
- Pojar J. 1996. Environment and biogeography of the western boreal forest. *The Forestry Chronicle* **72** (1): 51–58. DOI: 10.5558/tfc72051-1
- Poscente M, Charette T. 2012. Criteria and Indicators Framework for Oil Sands Mine Reclamation Certification. Charette Pell Poscente Environmental Corp., Sherwood Park, AB, Canada.
- Powter C, Chymko N, Dinwoodie G, Howat D, Janz A, Puhlmann R, Richens T, Watson D, Sinton H, Ball K, *et al.* 2012. Regulatory history of Alberta's industrial land conservation and reclamation program. *Canadian Journal of Soil Science* **92** (1): 39–51. DOI: 10.4141/cjss2010-033
- Pretzsch H. 2009. Forest dynamics, growth, and yield. In *Forest Dynamics, Growth and Yield*. Springer: London, England; 1–39.
- Purdy BG, Macdonald SE, Lieffers VJ. 2005. Naturally Saline Boreal Communities as Models for Reclamation of Saline Oil Sand Tailings. *Restoration Ecology* **13** (4): 667–677. DOI: 10.1111/j.1526-100X.2005.00085.x

- Quideau SA, Swallow MJB, Prescott CE, Grayston SJ, Oh S-W. 2013. Comparing soil biogeochemical processes in novel and natural boreal forest ecosystems. *Biogeosciences* **10** (8): 5651–5661. DOI: 10.5194/bg-10-5651-2013
- Renault S, Lait C, Zwiazek JJ, MacKinnon M. 1998. Effect of high salinity tailings waters produced from gypsum treatment of oil sands tailings on plants of the boreal forest. *Environmental Pollution* **102** (2–3): 177–184. DOI: 10.1016/S0269-7491(98)00099-2
- Richardson L. 2007. *The oil sands: Toward sustainable development: Report of the Standing Committee on Natural Resources*. Standing Committee on Natural Resources: Ottawa.
- Roulet NT, Lafleur PM, Richard PJH, Moore TR, Humphreys ER, Bubier J. 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology* **13** (2): 397–411. DOI: 10.1111/j.1365-2486.2006.01292.x
- Rowland SM, Prescott CE, Grayston SJ, Quideau SA, Bradfield GE. 2009. Recreating a Functioning Forest Soil in Reclaimed Oil Sands in Northern Alberta: An Approach for Measuring Success in Ecological Restoration. *Journal of Environment Quality* **38** (4): 1580. DOI: 10.2134/jeq2008.0317
- Schlesinger WH, Bernhardt ES. 2013. *Biogeochemistry: An Analysis of Global Change*. Academic Press: Amsterdam; Boston.
- Schweiger AK, Schütz M, Risch AC, Kneubühler M, Haller R, Schaepman ME. 2017. How to predict plant functional types using imaging spectroscopy: Linking vegetation community traits, plant functional types and spectral response. *Methods in Ecology and Evolution* **8** (1): 86–95. DOI: 10.1111/2041-210X.12642
- Sharp M, Ananicheva M, Arendt A, Hagen J-O, Hock R, Josberger E, Moore RD, Pfeffer WT, Wolken GJ. 2011. Chapter 7: The Effects of Forest Disturbance on Hydrologic Processes and Watershed Response. In *Snow, Water, Ice and Permafrost in the Arctic (SWIPA): Climate Change and the Cryosphere*. Arctic Monitoring and Assessment Programme (AMAP): Oslo; 7–1 to 7–61. Available at: <https://oaarchive.arctic-council.org/handle/11374/699> [Accessed 15 November 2015]
- Shorohova E, Kuuluvainen T, Kangur A, Jõgiste K. 2009. Natural stand structures, disturbance regimes and successional dynamics in the Eurasian boreal forests: a review with special reference to Russian studies. *Annals of Forest Science* **66** (2): 201–201. DOI: 10.1051/forest/2008083
- Skaggs TH, Anderson RG, Alfieri JG, Scanlon TM, Kustas WP. 2018. Fluxpart: Open source software for partitioning carbon dioxide and water vapor fluxes. *Agricultural and Forest Meteorology* **253–254**: 218–224. DOI: 10.1016/j.agrformet.2018.02.019

- Skovsgaard JP, Vanclay JK. 2008. Forest site productivity: A review of the evolution of dendrometric concepts for even-aged stands. *Forestry* **81** (1): 13–31. DOI: 10.1093/forestry/cpm041
- Sloan J. 2013. Fertilization at planting influences seedling growth and vegetative competition on a post-mining boreal reclamation site. *New Forests* **44** (5): 687–701.
- Soja AJ, Tchebakova NM, French NHF, Flannigan MD, Shugart HH, Stocks BJ, Sukhinin AI, Parfenova EI, Chapin FS, Stackhouse PW. 2007. Climate-induced boreal forest change: Predictions versus current observations. *Global and Planetary Change* **56** (3–4): 274–296. DOI: 10.1016/j.gloplacha.2006.07.028
- Statistics Canada. 2016. 2016 Census – Boundary Files: Provinces/territories. Statistics Canada: Ottawa, ON. Available at: <http://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/bound-limit-2016-eng.cfm> [Accessed 28 November 2016]
- Stenberg P. 1996. Correcting LAI-2000 estimates for the clumping of needles in shoots of conifers. *Agricultural and Forest Meteorology* **79** (1): 1–8. DOI: 10.1016/0168-1923(95)02274-0
- Straker J, Donald G. 2011. Assessing re-establishment of functional forest ecosystems on reclaimed oil sands mine lands. Available at: <http://circle.ubc.ca/handle/2429/42303> [Accessed 24 September 2014]
- Strilesky SL, Humphreys ER, Carey SK. 2017. Forest water use in the initial stages of reclamation in the Athabasca Oil Sands Region. *Hydrological Processes* **31** (15): 2781–2792. DOI: 10.1002/hyp.11220
- Stunden Bower S. 2018. Tools for Rational Development: The Canada Land Inventory and the Canada Geographic Information System in Mid-twentieth century Canada. *Scientia Canadensis: Canadian Journal of the History of Science, Technology and Medicine / Scientia Canadensis : Revue canadienne d’histoire des sciences, des techniques et de la médecine* **40** (1): 44–75. DOI: 10.7202/1048925ar
- Tansley AG. 1935. The Use and Abuse of Vegetational Concepts and Terms. *Ecology* **16** (3): 284–307. DOI: 10.2307/1930070
- Tenopir C, Allard S, Douglass K, Aydinoglu AU, Wu L, Read E, Manoff M, Frame M. 2011. Data sharing by scientists: practices and perceptions. *PloS one* **6** (6): e21101. DOI: 10.1371/journal.pone.0021101
- Tetreault GR, McMaster ME, Dixon DG, Parrott JL. 2003. Using reproductive endpoints in small forage fish species to evaluate the effects of Athabasca oil sands activities. *Environmental Toxicology and Chemistry* **22** (11): 2775–2782. DOI: 10.1897/03-7

- Tissot BP, Welte DH. 1984. *Petroleum formation and occurrence*. Springer-Verlag: Berlin, Germany.
- TOVI. 2018. LI-COR Biosciences: Lincoln, NE, USA.
- Trites M, Bayley SE. 2009. Vegetation communities in continental boreal wetlands along a salinity gradient: Implications for oil sands mining reclamation. *Aquatic Botany* **91** (1): 27–39. DOI: 10.1016/j.aquabot.2009.01.003
- United States Department of Agriculture Forest Service. 2018. Forest Inventory and Analysis National Program - Tools and Data. Available at: <https://www.fia.fs.fed.us/tools-data/index.php> [Accessed 26 August 2018]
- United States Department of Energy O of S. 2018. Fluxdata - Regional Networks. *Fluxdata*. Available at: <http://fluxnet.fluxdata.org/about/regional-networks/> [Accessed 2 April 2018]
- United States Geological Survey USD of the I. 2017. Landsat Missions Timeline | Landsat Missions. Available at: <https://landsat.usgs.gov/landsat-missions-timeline> [Accessed 7 February 2018]
- United States Geological Survey USD of the I. 2018. Landsat 8 | Landsat Missions. Available at: <https://landsat.usgs.gov/landsat-8> [Accessed 1 October 2018]
- Unknown. 2008. Syncrude earns reclamation certificate. *Canadian Mining Journal* **129** (3): 11–11.
- Vancley JK, Skovsgaard JP. 1997. Evaluating forest growth models. *Ecological Modelling* **98** (1): 1–12. DOI: 10.1016/S0304-3800(96)01932-1
- Vasiliauskas S, Chen HY. 2002. How long do trees take to reach breast height after fire in northeastern Ontario? *Canadian Journal of Forest Research* **32** (10): 1889–1892. DOI: 10.1139/x02-104
- Wagle P, Gowda PH, Moorhead JE, Marek GW, Brauer DK. 2018. Net ecosystem exchange of CO₂ and H₂O fluxes from irrigated grain sorghum and maize in the Texas High Plains. *Science of The Total Environment* **637–638**: 163–173. DOI: 10.1016/j.scitotenv.2018.05.018
- Walker B, Holling CS, Carpenter SR, Kinzig A. 2004. Resilience, Adaptability and Transformability in Social-Ecological Systems. *Ecology and Society* **9** (2): 5.
- Wang T, Ciais P, Piao SL, Otle C, Brender P, Maignan F, Arain A, Cescatti A, Gianelle D, Gough C, *et al.* 2011. Controls on winter ecosystem respiration in temperate and boreal ecosystems. DOI: 10.5194/bg-8-2009-2011

- Weber B. 2012. Rebuilding land destroyed by oil-sands may not restore it, researchers say. *The Globe and Mail*. Available at: <http://www.theglobeandmail.com/news/national/rebuilding-land-destroyed-by-oil-sands-may-not-restore-it-researchers-say/article552879/> [Accessed 11 March 2015]
- Weber MG, Flannigan MD. 1997. Canadian boreal forest ecosystem structure and function in a changing climate. *Environmental Reviews* **5** (3–4). Available at: <http://cfs.nrcan.gc.ca/publications?id=18860> [Accessed 7 November 2015]
- Weber MG, Stocks BJ. 1998. Forest fires and sustainability in the boreal forests of Canada. *Ambio* **27** (7): 545–550.
- Wehr R, Commane R, Munger JW, McManus JB, Nelson DD, Zahniser MS, Saleska SR, Wofsy SC. 2017. Dynamics of canopy stomatal conductance, transpiration, and evaporation in a temperate deciduous forest, validated by carbonyl sulfide uptake. *Biogeosciences* **14** (2): 389–401. DOI: 10.5194/bg-14-389-2017
- Wever LA, Flanagan LB, Carlson PJ. 2002. Seasonal and interannual variation in evapotranspiration, energy balance and surface conductance in a northern temperate grassland. *Agricultural and Forest Meteorology* **112** (1): 31–49. DOI: 10.1016/S0168-1923(02)00041-2
- Wicherts JM, Bakker M, Molenaar D. 2011. Willingness to Share Research Data Is Related to the Strength of the Evidence and the Quality of Reporting of Statistical Results. *PLOS ONE* **6** (11): e26828. DOI: 10.1371/journal.pone.0026828
- Wilson KB, Baldocchi DD, Aubinet M, Berbigier P. 2002. Energy partitioning between latent and sensible heat flux during the warm season at FLUXNET sites. *Water Resources Research* **38** (11): 1294–1305.
- Winter JM, Eltahir EA. 2010. The sensitivity of latent heat flux to changes in the radiative forcing: A framework for comparing models and observations. *Journal of Climate* **23** (9): 2345–2356.
- Wytrykush C, Vitt DH, McKenna G, Vassov R. 2012. Chapter 8: Designing landscapes to support peatland development on soft tailings deposits: Syncrude Canada Ltd.'s Sandhill Fen Research Watershed initiative. In *Restoration and Reclamation of Boreal Ecosystems*. Cambridge University Press: Boca Raton, FL, USA.
- Yan E-R, Hu Y-L, Salifu F, Tan X, Chen ZC, Chang SX. 2012. Effectiveness of soil N availability indices in predicting site productivity in the oil sands region of Alberta. *Plant and Soil* **359** (1–2): 215–231. DOI: 10.1007/s11104-012-1202-y

- Zha T, Barr AG, Black TA, McCaughey JH, Bhatti J, Hawthorne I, Krishnan P, Kidston J, Saigusa N, Shashkov A, *et al.* 2009. Carbon sequestration in boreal jack pine stands following harvesting. *Global Change Biology* **15** (6): 1475–1487. DOI: 10.1111/j.1365-2486.2008.01817.x
- Zhang J, Nielsen SE, Mao L, Chen S, Svenning J-C. 2016. Regional and historical factors supplement current climate in shaping global forest canopy height. *Journal of Ecology* **104** (2): 469–478. DOI: 10.1111/1365-2745.12510
- Zhang W, Miller PA, Jansson C, Samuelsson P, Mao J, Smith B. 2018. Self-Amplifying Feedbacks Accelerate Greening and Warming of the Arctic. *Geophysical Research Letters* **45**. DOI: 10.1029/2018GL077830
- Zhu K, Zhang J, Niu S, Chu C, Luo Y. 2018. Limits to growth of forest biomass carbon sink under climate change. *Nature Communications* **9** (1): 2709. DOI: 10.1038/s41467-018-05132-5

8 APPENDICES

8.1 Appendix I

Chronosequence graphs of average half-hourly June-August net radiation (R_n , W m^{-2} , top), sensible heat flux (H , W m^{-2} , middle), and latent heat flux (LE , W m^{-2} , bottom). Symbols are described in Figure 4-2.

8.2 Appendix II

Bi-monthly net radiation (R_n , $W\ m^{-2}$, ●), sensible heat flux (H , $W\ m^{-2}$, △), and latent heat flux (LE , $W\ m^{-2}$, ■) for the summer months of June, July, and August at the greatest age of maturity that measurements were available at each site.

8.3 Appendix III

Regression trees were used to examine the relative importance of selected predictors on temporal and spatial variability in annual ET, WUE, GEP, H, β , and R_n at the study sites. Annual average values were used for water, carbon, and energy flux variables. The predictor variables are site type (reclaimed = 1; reference = 0), precipitation (P), air temperature (T_{air}), incoming shortwave radiation ($K_{\downarrow}$), tree type (more conifers = 1; fewer conifers = 0), age (< 20 years old = 1, > 20 years old = 0), canopy conductance (g_c), and vapour pressure deficit (D).