

**THE GROWING SEASON WATER BALANCE AND CONTROLS ON  
EVAPOTRANSPIRATION IN WETLAND RECLAMATION TEST CELLS FORT  
MCMURRAY, ALBERTA**

**By**

**Jean-Pascal R. Faubert, B.Sc.**

**A thesis submitted to the Faculty of Graduate Studies  
in partial fulfillment of the requirements of the degree of**

**Master of Science**

**Carleton University  
Ottawa, Ontario**

**© 2012 Jean-Pascal R. Faubert**



Library and Archives  
Canada

Published Heritage  
Branch

395 Wellington Street  
Ottawa ON K1A 0N4  
Canada

Bibliothèque et  
Archives Canada

Direction du  
Patrimoine de l'édition

395, rue Wellington  
Ottawa ON K1A 0N4  
Canada

*Your file Votre référence*

*ISBN: 978-0-494-87837-8*

*Our file Notre référence*

*ISBN: 978-0-494-87837-8*

#### NOTICE:

The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

#### AVIS:

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque et Archives Canada de reproduire, publier, archiver, sauvegarder, conserver, transmettre au public par télécommunication ou par l'Internet, prêter, distribuer et vendre des thèses partout dans le monde, à des fins commerciales ou autres, sur support microforme, papier, électronique et/ou autres formats.

L'auteur conserve la propriété du droit d'auteur et des droits moraux qui protègent cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

---

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.

Conformément à la loi canadienne sur la protection de la vie privée, quelques formulaires secondaires ont été enlevés de cette thèse.

Bien que ces formulaires aient inclus dans la pagination, il n'y aura aucun contenu manquant.

Canada

### **Abstract**

In the oil sands mining region near Fort McMurray, Alberta, efforts to establish specific wetland reclamation techniques are underway. During the 2010 growing season, the water balance of 12 plots (cells) of different soil and vegetation treatments were studied with emphasis on understanding the controls on evapotranspiration (ET) and the effects of construction techniques. Cell hydrologic behaviour was distinct from natural wetlands due to frequent artificial irrigation. ET ranged from  $\sim 0.6 \text{ mm day}^{-1}$  to  $\sim 8.2 \text{ mm day}^{-1}$  with a mean of  $\sim 3.2 \text{ mm day}^{-1}$  and variation among the cells was attributed to the construction techniques used, specifically placement period and soil depth. ET was weakly correlated to individual environmental variables; however, multivariate statistical models revealed complex interactions among environmental variables that acted to control ET. Cumulative water balances indicated certain construction techniques produced ET rates comparable to natural wetlands, which may be an important factor in improving the long-term sustainability of reclaimed wetlands.

## **Acknowledgments**

Financial support for this thesis was provided by Syncrude Canada Ltd. Their dedication to restoring lands disturbed by oil sands mining operations, and for encouraging student-led research should be applauded.

I would like to thank my supervisor, Sean Carey. His enthusiasm and kind demeanor along with his willingness to help out in the field and in the office helped make this a truly enjoyable experience.

I would also like to thank Murray Richardson for his valuable comments on the manuscript and for numerous hours of help with everything R related.

Mike Treberg provided invaluable help with instrument calibration and setup, along with technical and field support. Exceptional field assistance was provided by Mark “Pugs” Puglsey and Mahsa Dyanat-Najed of the 2010 Carleton University research team and Syncrude’s environmental research staff of Jessica Clark, Lori Cyprien, Chris Beirling along with Laura Gaulton of Terracon Consulting. Sophie Kesler of O’Kane Consultants provided soil temperature and precipitation data along with help troubleshooting various instruments.

I would like to thank the many new friends I have made in the Department of Geography and Environmental Studies at Carleton University for their helpful advice and good conversation as this work was carried out.

Finally, I am deeply appreciative of the love and encouragement provided by my family, in particular my father, as well as by my girlfriend, Victoria. I surely could not have done this without them.

## Table of Contents

<b>Abstract.....</b>	<b>ii</b>
<b>Acknowledgements.....</b>	<b>iii</b>
<b>Table of Contents.....</b>	<b>iv</b>
<b>List of Tables.....</b>	<b>vi</b>
<b>List of Figures.....</b>	<b>vii</b>
<b>1.0 Introduction.....</b>	<b>1</b>
<b>2.0 Background .....</b>	<b>7</b>
2.1 Boreal Wetlands .....	7
2.2 Water Balance Approach.....	10
2.3 Evapotranspiration.....	12
2.4 Previous Research.....	17
2.4.1 <i>Vegetation and ET</i> .....	18
2.4.2 <i>ET in Natural Systems</i> .....	21
2.4.3 <i>ET in Disturbed and Constructed Wetlands</i> .....	23
<b>3.0 Study Site and Methodology .....</b>	<b>28</b>
3.1 Study Site.....	28
3.2 Field Methods .....	38
3.3 Analytical Methods.....	41
3.3.1 <i>Irrigation</i> .....	41
3.3.2 <i>Data Processing</i> .....	44
3.3.3 <i>Soil Properties</i> .....	45
3.3.4 <i>Statistical Analysis and Modeling</i> .....	48
<b>4.0 Results .....</b>	<b>53</b>
4.1 Study Site Conditions .....	53
4.1.1 <i>General Climate (Precipitation and Temperature)</i> .....	53
4.1.2 <i>Microclimate Conditions</i> .....	54
4.1.3 <i>Water Table Depth</i> .....	56
4.1.4 <i>LAI</i> .....	57
4.2 Growing season ET .....	59
4.2.1 <i>Daily ET rates</i> .....	59
4.2.2 <i>Statistical Testing</i> .....	67
4.2.3 <i>ET and Environmental Factors – Linear Regression and Correlation</i> .....	69
4.3 Multiple Linear Regression Models .....	77
4.3.1 <i>Initial models</i> .....	77
4.3.2 <i>Models with Interactions</i> .....	77
4.4 Recursive Partitioning – Tree Models .....	83
4.5 Cell Water Balances .....	87
4.5.1 <i>Inputs and Outputs</i> .....	87
4.5.2 <i>Cumulative Water Balances – 2010 Growing Season</i> .....	89
<b>5.0 Discussion .....</b>	<b>93</b>
5.1 The Problem .....	93
5.2 The Cells.....	93
5.3 Controlling Factors on ET .....	94
5.3.1 <i>Multiple Linear Regression Models</i> .....	95

5.3.2	<i>Recursive Partitioning Models</i> .....	97
5.4	Effects of Treatments .....	99
5.5	Context – Comparison with Other Natural and Constructed Sites .....	101
5.6	Implications for Future Research .....	104
<b>6.0</b>	<b>Conclusions</b> .....	<b>107</b>
<b>7.0</b>	<b>References</b> .....	<b>111</b>

## List of Tables

<b>Table 2.1</b> <i>Primary characteristics of bogs and fens, the two most common types of wetlands in the Boreal region (adapted from NWWG, 1997)</i> .....	8
<b>Table 3.1</b> <i>Treatment combinations for each of the 12 study cells</i> .....	33
<b>Table 3.2</b> <i>Vegetation composition in the two different soil/vegetation treatments – live peat reansplant and stockpiled peat mixture. ✓✓ indicates that the species had become dominant (adapted from Piquard, 2010)</i> .....	36
<b>Table 4.1</b> <i>2010 growing season weather as compared to the 1971-2000 climate normal for the Fort McMurray airport (Environment Canada)</i> .....	53
<b>Table 4.2</b> <i>Statistical significance test results for the effects of construction techniques on ET. Both parametric and non-parametric tests at the 95% confidence level were used. Only placement period resulted in significant differences in ET. Significant differences are indicated in bold</i> .....	68
<b>Table 4.3</b> <i>Pairwise difference of means and the associated Wilcoxon Rank Sum Test significance test results at the 95% level. Upper diagonal portion shows the actual difference in daily mean ET between the two depths while the lower diagonal section reports the corresponding p-value at the 95% significance level. Significant differences are indicated in bold</i> .....	69
<b>Table 4.4</b> <i>A cell pooled data correlation matrix between ET and five controlling environmental factors with the top/right side of the matrix displaying the associated Spearman's rank correlation coefficient (<math>r_s</math>) and the bottom/left displaying the corresponding p-value. Significant relationships are highlighted in bold. Also of note are the correlations between controlling factors themselves</i> .....	71
<b>Table 4.5</b> <i>All cell pooled multiple linear regression model terms, estimates of their coefficients, and associated p-values. The models overall adjusted <math>r^2</math> value is 0.4235 with a p-value of <math>2.2e^{-16}</math>. In this table, Wdspd is wind speed, Kdown is incoming shortwave radiation, Temp is air temperature, Wtd is the water table depth and VPD is the vapour pressure deficit</i> .....	81
<b>Table 4.6</b> <i>Summary of predicted and actual change in water for storage for each of the cells at the end of the study period. The relative difference between these two terms is a good indication of water balance accuracy and/or the presence of leaking cells</i> .....	91
<b>Table 5.1</b> <i>Summary of ET rates according to construction techniques that caused statistically significant differences. Data reported are mean and maximum values for the 2010 growing season</i> .....	102
<b>Table 5.2</b> <i>Summary of ET rates from previous wetland studies. Data are reported mean and maximum values for the growing season period. Wetland type is as reported by the authors. (adapted from Lafleur et al. 2005)</i> .....	103

## List of Figures

<b>Figure 2.1</b> Comparison of tabulated daily ET rates from a collection of Canadian studies. Boxes show the mean daily rate while whiskers denote the min and max observed values. The number above and to the right of the boxes indicates the number of studies used in compiling the results. Bog and poor fen types, common to the boreal region have relatively lower ET rates than other wetland types (from Lafleur, 2008).	22
<b>Figure 3.1</b> Location of Fort McMurray in northern Alberta, Canada and the study site situated 40 km northwest of the city within Syncrude Canada Ltd. Mildred Lake Mine (inset).	28
<b>Figure 3.2</b> As built plan showing location of the study site within the mine (inset) site setup including irrigation networks and surrounding land cover (from BGC, 2010).	29
<b>Figure 3.3</b> Aerial view of study (a) and oblique view of an individual cell (b).	30
<b>Figure 3.4</b> Lining of the cells involved digging a trench at the edge of the cell (A) manually stretching geosynthetic liner over base of cell (B) covering with 20 cm of clay (C) and compacting (D) (from BGC, 2009).	32
<b>Figure 3.5</b> Vegetation found in stockpiled cells (a) and live peat transplant cells (b) on July 7th 2010 (DOY 188).	37
<b>Figure 3.6</b> Lysimeter boxes in situ (a) and about to be weighed to record change in mass (b).	40
<b>Figure 3.7</b> The irrigation network setup used for finding iterative solutions to pipe and valve flow rates using the Hardy Cross method. Valve outflow varied according to the number and position of open valves and the distance between them.	43
<b>Figure 4.1</b> Mean daily (12 pm to 12 pm) fluxes of microclimate variables: incoming solar radiation (a), VPD (b), wind speed (c), and air temperature (d) over the course of the study period.	55
<b>Figure 4.2</b> Mean daily (12 pm to 12 pm) hydroperiods for each cell for the duration of the study period. Dashed lines represent the ground surface at the measurement point.	57
<b>Figure 4.3</b> LAI progression in each cell over the study.	58
<b>Figure 4.4</b> Boxplots showing the daily pooled ET data from all the cells over the course of the study period. Missing boxes indicate days with no data for any cell. Upper and lower limits of the boxes indicate the first and third quartiles respectively while the whiskers indicate the range of observations. Mean values are represented by a solid line and circles (o) represent outliers.	60
<b>Figure 4.5</b> The 100 cm stockpiled soil mixture summer placement cell at the beginning of the study (a) and the same cell at the end of the study period (b). Notice the dramatic increase in the vegetation especially the cattails and grasses.	62
<b>Figure 4.6</b> Daily ET measurements in each cell for the duration of the study period.	63
<b>Figure 4.7</b> Boxplot displaying statistical information on daily ET for each cell over the course of the study period. Upper and lower limits of the boxes indicate the first and third quartiles respectively while the whiskers indicate the range of observations. Mean values are represented by a solid line and circles (o) represent outliers. Notches indicate the 95% confidence intervals.	65

- Figure 4.8** *Boxplot displaying daily ET for the duration of the study period pooled according to placement period. Upper and lower limits of the boxes indicate the first and third quartiles respectively while the whiskers indicate the range of observations. Mean values are represented by a solid line and circles (o) represent outliers. Notches indicate the 95% confidence intervals.* \_\_\_\_\_ 66
- Figure 4.9** *Boxplot displaying daily ET for the duration of the study period pooled according to soil type. Upper and lower limits of the boxes indicate the first and third quartiles respectively while the whiskers indicate the range of observations. Mean values are represented by a solid line and circles (o) represent outliers. Notches indicate the 95% confidence intervals.* \_\_\_\_\_ 66
- Figure 4.10** *Boxplot displaying daily ET for the duration of the study period pooled according to soil depth, Upper and lower limits of the boxes indicate the first and third quartiles respectively while the whiskers indicate the range of observations. Mean values are represented by a solid line and circles (o) represent outliers. Notches indicate the 95% confidence intervals.* \_\_\_\_\_ 67
- Figure 4.11** *Scatter plots of ET and mean daily incoming shortwave radiation for each cell in the study. Correlations significant at the 95% level are shown.* \_\_\_\_\_ 72
- Figure 4.12** *Scatter plots of ET and mean daily VPD for each cell in the study. Correlations significant at the 95% level are shown.* \_\_\_\_\_ 73
- Figure 4.13** *Scatter plots by cell of water table depth to mean daily ET. Very little correlation was observed in any cell, likely due to consistent irrigation resulting in water rarely being a limiting component. Also, this situation may be heteroscedastic due to the influence of the irrigation regime and thus making the significance of any relationships questionable.* \_\_\_\_\_ 74
- Figure 4.14** *Scatter plots of ET and mean daily wind speed for each cell in the study. No correlations significant at the 95% level existed.* \_\_\_\_\_ 75
- Figure 4.15** *Scatter plots of ET and mean daily air temperature for each cell in the study. No correlations significant at the 95% level existed.* \_\_\_\_\_ 76
- Figure 4.16** *Observed ET plotted against predicted ET using a multiple linear regression model without interaction for each cell in the study. After models were trimmed for 95%, the majority ended up being very close to single linear regression models between shortwave radiation and ET.* \_\_\_\_\_ 78
- Figure 4.17** *Observed ET plotted against predicted ET using a multiple linear regression model with interaction terms, for each cell in the study. Models were often over-fit, and produced outliers so unreasonable they cannot be shown in figures.* \_\_\_\_\_ 80
- Figure 4.18** *All cell pooled data plot of Observed ET against predicted ET using a multiple linear regression model with interaction terms. Model contained 12 variables, easily satisfying the n/3 general rule and AIC test, resulting in a model able to predict ET based on the five controlling factors without over-fitting.* \_\_\_\_\_ 82
- Figure 4.19** *Recursive partitioning tree model for all cell pooled data. At each node (branch) indicates the variable and the threshold in which the most amount of deviance in the data is obtained. For given conditions of environmental variables, below the indicated threshold follow the branch to the left and above the threshold follow the branch to the right. Once the bottom of the tree has been reached, the predicted values of ET are provided.* \_\_\_\_\_ 84
- Figure 4.20** *Observed ET plotted against ET predicted by recursive partitioning tree model for all cell pooled data. Compared with the plot using the multiple linear regression model with interaction terms (Figure 4.17), the tree model produced a more robust model with a lower RMSE.* \_\_\_\_\_ 85

- Figure 4.21** *Observed ET plotted against ET predicted by a cell specific recursive partitioning “tree” model. Tree models were found to consistently produce reasonable predictions of ET with relatively low RMSE, and without over-fitting the data.* \_\_\_\_\_ 86
- Figure 4.22** *Water balance inputs organized by month for each cell for the duration of the study period.* \_\_\_\_\_ 87
- Figure 4.23** *Water balance outputs (ET) arranged by month using recursive partitioning model gap filled data for each cell for the duration of the study period.* \_\_\_\_\_ 89
- Figure 4.24** *Cumulative water balance plots for each cell in the study. Outputs are composed of directly measured ET and gap filled ET determined using a cell specific recursive partition (tree) model. Blue lines indicate inputs, red lines indicate outputs, green lines represent the predicted change in storage, while black lines represent the actual change in storage.* \_\_\_\_\_ 90

## 1.0 Introduction

Canada has approximately 150 million hectares of wetlands – transitional areas between terrestrial and aquatic systems where either the water table is at or near the surface or the land is covered by shallow water (Cowardin et al. 1979). The majority of these wetlands are located in northern or boreal regions (NWWG, 1997, Roulet et al. 1997). The Boreal ecosystem is located between 50 and 70 degrees north latitude covering about one third of the Canadian land surface and has wetlands scattered throughout (NRC, 2009; Baldocchi et al. 2000). Because of their size, wetlands in the Boreal biome have a major influence on the regional climate, water cycling and storage as well as the biodiversity of plant and animal species (Vitt and Chee, 1990; Blanken et al. 2001).

As mining and other human activities expand northward, disturbance and destruction of sensitive northern ecosystems are becoming more common. Economic demand has increased activities such as logging and mining, which can be very destructive and are disturbing large areas. Alberta Environment estimated that directly disturbed lands in Alberta covered 950 km<sup>2</sup> in 2004, up from 430 km<sup>2</sup> in 2003 (Wykonilloicz et al. 2005; Alberta Environment, 2003). Most recent estimates project that currently planned oil sands development in northern Alberta will lead to a cumulative disturbance of 2000 km<sup>2</sup> (Wykonilloicz et al. 2005). Reclamation and regeneration of logged or burned sites can often occur naturally and/or with proper management practices. However, at mining sites, such as those of the oil sands in northern Alberta, regeneration on a meaningful timescale is not possible without a reclamation regime.

Traditional oil sands mining is a strip mining process that involves the removal of surface material (overburden) to access the underlying ore body. Before mining, vegetation and soil are removed and, in the case of wetland soils, salvaged and stored for reclamation material. The Alberta Enhancement and Protection Act (EPEA) dictates that lands must be returned to a capability similar to those which had existed before mining occurred (Alberta Environment, 1994). The goal of the EPEA is to minimize the detrimental effects of oil sands mining by ensuring regeneration of important northern ecosystems. The Alberta Provincial Government requires oil sands extractors to submit detailed plans for mine closure and landscape reclamation in order to be licensed (Alberta Environment, 1994).

After extraction has occurred, the landscape differs from the generally flat Boreal landscape that was there before. Common practice is to “cap” the newly exposed surface with varying thicknesses and mixtures of soil designed to promote the growth of target ecosystems. This can create reclamation sites where the soil-vegetation-atmosphere continuum and surface hydrology are highly modified (Elshorbagy et al. 2005; Carey, 2008; Keshta et al. 2009). There is considerable uncertainty as to whether reclaimed sites operate hydrologically in a manner similar to natural Boreal ecosystems. This uncertainty results from the nature of the disturbed soil, which often have high salt contents and altered properties that can limit water availability and jeopardize the long-term feasibility and sustainability of target ecosystems. This is especially true of northern wetlands that serve important roles in local hydrology but also in biogeochemical cycling and act as ecologic reserves to countless species of wildlife (Vitt and Chee, 1990). To date, reclamation has focused

primarily on upland (forested) ecosystems, as wetland reclamation has just entered its first phases.

Effective reclamation of disturbed wetlands is often very challenging. Due to profound changes to the landscape and the underlying soil, reclaimed sites may not provide the same ecosystem services as natural sites do. Disturbed and/or exposed peat has very different hydrophysical characteristics and often presents a problem in maintaining constant water levels (Lucchese et al. 2009; Price and Whitehead, 2001). Water table fluctuations may remain problematic until a suitably thick layer of organic matter develops, which can hold water and dampen the effects of drought (McNeil and Waddington, 2003). Changes in water availability can limit and/or slow the re-establishment of surface vegetation, especially mosses (Van Seters and Price, 2001). The newly exposed peat typically has much different soil properties, such as lower porosity, and thus a lower water storage potential which can increase runoff and limit water availability to the overlying peat and vegetation (Cagampan and Waddington, 2008). Vegetative components play an integral role in the hydrologic functioning of a wetland and so their absence may slow wetlands return to a pre-disturbance state (Shantz and Price, 2006). Greater fluctuations in the water table can also lead to larger variations in soil temperatures as energy is partitioned into the evapotranspiration (ET) of water during dry/wet periods. Increased ET can reduce the moisture content of the peat and subsequently cause soil temperatures to rise. Raised soil temperatures can speed decomposition of peat and increase runoff rates, thus exacerbating the water table issues (Petroni et al. 2004). Additionally, ET is a very significant process in the cycling of water and nutrients through a wetland system, and so is directly linked to its

ecological productivity (Lafleur, 2008). Because of the importance of ET to ecosystems, understanding the environmental and biophysical processes that control ET, and the way in which it responds to changes in microclimatic conditions, is a key requirement when assessing the effectiveness of specific reclamation strategies (Qualizza et al. 2004; Elshorbagy et al. 2005). Effective ecosystem restoration may be best accomplished by implementing a comprehensive strategy that uses information about the original ecosystems along with data collected on potential techniques for construction or rehabilitating ecosystems. Development of such a strategy may be achieved through quantification of the key components of wetland functioning via instrumentation, and the development of our understanding of important processes through observation, monitoring and modeling. The establishment of an effective ecosystem restoration strategy is of great interest to the many oil sands operators, as it will work to lower costs, and perhaps more importantly, reduce liability (*cf.* Moore, 2008)

Canada's largest oil sands extractor, Syncrude Canada Ltd., has built a site at its Mildred Lake mine, where potential techniques of constructing Boreal wetlands (reclamation regime) can be tested. The construction of 28 mini-wetlands or "cells" in which variations to soil, water, vegetation and application season (treatments) can be tested and assessed, will help guide reclamation practices with regards to constructing and recreating wetlands.

Each of these cells measures roughly 25 m by 15 m and was lined first with an impermeable synthetic material and then overlain with a 15-20 cm layer of clay. The liner prevents the cells from losing or gaining water from sources other than

precipitation, as is typical of northern bogs. After construction, the cells were filled with a specific soil mixture and then covered with different treatments designed to replicate major wetland construction strategies. The four treatments include: full vegetation cover transplanted from a nearby natural wetland in (i) summer or (ii) winter 2008, and vegetation established from seed and planted in a stockpiled peat mulch mixture that was placed in (iii) summer or (iv) winter 2008. Furthermore, each of these four treatment combinations was attempted in soil depths of 15, 50 and 100 cm. There is also a compaction version of each treatment combination in which the underlying soil mixtures were flattened before transplanting/planting occurred, perhaps in an attempt to see the effects of having heavy machinery drive over top during construction. There are 28 total cells containing potential strategies for constructing wetlands at the Mildred Lake Mine site which includes two cells that are watered using processed water from the mine and two control cells with no soil or vegetation at all.

This thesis examines the 2010 growing season water balance of 12 of the 28 cells whose reclamation strategies are thought to have the greatest chance of success. The 12 cells were not compacted and composed of different combinations of vegetation, soil depth, and placement season. The central research objective was to examine and quantify the magnitude and variation of the water balance and its components among the 12 cells being studied. Three secondary objectives established in order to help achieve this main goal include:

1. Identify the controlling factors on ET, presumed to be the largest component of the water balance.

2. Create models capable of accurately predicting ET in each of the cells for use in gap-filling time series with missing data.
3. Establish the effect of treatments (if any) on ET and the water balance.
4. Place individual cell water balance components in the context of natural systems and discuss the implications for future reclamation strategies.

This study will contribute to an enhanced understanding of the causal relationships between the treatment variables, the environmental controls and ET in wetland reclamation test cells. It will improve our understanding of constructed wetland hydrological fluxes and provide baseline information for best practices in wetland reclamation projects.

## **2.0 Background**

This chapter provides a review of (1) boreal wetlands; (2) the water balance approach to assess the storage and movement of water through environmental systems; (3) the process of evapotranspiration (ET) and its controls; and (4) relevant findings from past studies and/or literature.

### **2.1 Boreal Wetlands**

Wetlands are characterized as transitional lands between terrestrial and aquatic systems, where the water table is at or near the surface or the land is covered by shallow water (Cowardin et al. 1979). The Canadian National Wetlands Working Group (NWWG) (1997) defines a wetland as land that is saturated with water long enough to promote wetland or aquatic processes as characterized by poorly drained soils, hydrophytic vegetation and various kinds of biological activity which are adapted to a wet environment. Wetlands tend to exist in areas where the water table is at or near the surface for most of the year. This means that wetlands are generally restricted to areas where precipitation exceeds ET/runoff or where inputs from surface and/or subsurface sources significantly offset water losses (Price et al. 2005).

The vast expanse of forest that spans across Canada's sub-arctic latitudes, known as the Boreal Forest, has many wetlands areas. Wetlands in the Boreal region are typically of two common types: bogs and poor fens. In general, both are considered relatively low nutrient systems. Bogs are peat-forming wetlands that primarily receive water and nutrients from precipitation only (NWWG, 1997). This single water source and the slow movement of water within the wetland result in low levels of available

nutrients. Low nutrient wetlands are referred to as ombrotrophic systems.

Fens in the Boreal region are similar to bogs except for two important differences (Table 2.1). First, fens have accumulations of decomposed organic matter (peat) greater than 40 cm. Second, unlike bogs, fens receive water from at least one source other than precipitation. This secondary source is usually in the form of surface or groundwater flow, and typically contains some amount of available nutrients. The additional inputs of water can greatly improve the nutrient level of these types of wetlands. Increased nutrient wetland systems are known as minerotrophic. These differences allow fens to support more complex vegetation systems than bogs, which can often include a greater variety of herbaceous vascular plants and shrubs (NWWG, 1997). However, fens in the boreal region often have little input of water that they behave more like ombrotrophic systems (bogs) rather than minerotrophic ones; these fens are known as “poor fens”.

Table 2.1 Primary characteristics of bogs and fens, the two most common types of wetlands in the Boreal region (adapted from NWWG, 1997)

Class/Status	Bogs	Fens
<b>Peat</b>	• Accumulation of peat >40cm	• Accumulation of peat
<b>Surface</b>	• Surface raised or level with surrounding terrain	• Surface is level with the water table, with water flow on the surface and through the subsurface
<b>Water Table</b>	• Water table at or slightly below the surface and raised above the surrounding terrain	• Fluctuating water table which may be at, or a few centimeters above or below, the surface
<b>Nutrient</b>	• Low (Ombrotrophic)	• Low – High (Ombrotrophic – Minerotrophic)
<b>Moss</b>	• Moderately decomposed <i>Sphagnum</i> peat with woody remains of shrubs	• Decomposed sedge or brown moss peat
<b>Vegetation</b>	• Frequently dominated by <i>Sphagnum</i> mosses with tree, shrub or treeless vegetation cover.	• Vascular plants and shrubs characterize the vegetation cover

Nutrient level is the single most important determining factor of the type and range of vegetation that a wetland can support. Because of their relatively low nutrient levels, bogs and fens typically have significant moss cover with little vascular plant/tree cover (NWWG, 1997; Bridgham, 1999). Vascular plants and trees that are commonly associated with northern bogs and fens are typically small and slow growing and often very sparse within the system (Bridgham, 1999; Rouse, 2000). Because of wet conditions that limit contact with oxygen, organic material in these systems does not break down quickly and so boreal bogs and fens tend to have deep accumulations of partially decomposed organic matter or “peat” (NWWG, 1997; Holden, 2005).

Low nutrient wetlands are often layered throughout the soil (peat) profile with two major strata called the acrotelm and the catotelm (Ingram, 1978). The upper most layer, the acrotelm, is a zone of aeration where peat is in intermittent contact with the atmosphere. This layer is composed mainly of organic matter that is poorly decomposed and usually undergoes variations in moisture content due to fluctuations in the water table (Ingram, 1983). The acrotelm typically has a high porosity and specific yield, resulting in a high water storage capacity, which dampens the effects of a fluctuating water table near the surface and allows for relatively moist conditions to be maintained throughout most of the year (Price, 1996). The lower layer, the catotelm, is permanently saturated and highly decomposed. This results in smaller pore space and lower specific yield. This two-layer structure of northern bogs and fens is important for water transport and storage, and disturbance of its properties can have dramatic consequences on hydrologic function (Cagampan and Waddington, 2008).

Wetlands comprise nearly 50% of the Western Boreal Plain (Vitt et al.2000). These wetlands are usually dominated by black spruce (*Picea mariana*), although often in low density which permits a large portion of light to reach the surface (Heijmans et al. 2004). This allows for understory species such as *Sphagum spp*, feathermoss and lichen spp to thrive and subsequently play an important role in the exchange of energy and mass (water) with the surrounding environment (Vitt et al. 2000). These understory/surface species of vegetation are extremely important for water exchange (Williams and Flanagan, 1996), and can account for as much as 65% of the total water loss from wetland ecosystems (Lafleur and Schreader, 1994).

## 2.2 Water Balance Approach

The constructed test cells in this study were designed and built to mimic the bog type wetlands described in Table 2.1. In order to assess the transfer of water in and out of these cells, each cell can be viewed as a single open system. Non-steady state conservation of mass (water) in these systems can be represented by Equation 2.1, where inputs ( $I$ ) minus outputs ( $O$ ) are equal to the change in storage ( $\Delta S$ ).

$$I - O = \Delta S \quad (2.1)$$

The establishment of boundaries allows for a formula or “balance” that represents the movement of water into or out of the system (individual cells) to be applied. This water balance is similar to Equation 2.1, in which additions are offset by losses, resulting in a change in the water storage of the system. The water balance of any bounded environmental system can be described in the general form:

$$P + Q_{in} + G_{in} - Q_{out} - G_{out} - ET + \epsilon = \Delta S \quad (2.2)$$

where,  $P$  is precipitation in the form of rain or snow,  $Q$  is the surface runoff into or out of the system,  $G$  is the groundwater seepage in or out of the system,  $ET$  is evapotranspiration and  $\Delta S$  denotes the change in water storage of the system itself. In this general form, the components on the left side represent inputs (additions) and outputs (losses) of the system while the right hand side represents the cumulative change in storage. Also, an error term,  $\epsilon$ , is added in order to account for some degree of measurement error. All terms are typically expressed as a depth of water (e.g. mm).

This general form of the water balance does not apply directly to the study cells given their design and construction. Therefore, by modifying the general form in Equation 2.2, a water balance related specifically to the movement of water in each cell was created (Equation 2.3). The resultant equation quantifies the change in water storage over time as a function of water related inputs and outputs occurring in each cell over the study period. There are some important differences between this cell specific water balance and the general form.

$$P + Irr - ET - L + \epsilon = \Delta S \quad (2.3)$$

Here, the inputs are composed of precipitation,  $P$ , in the form of rain only, and the water that is artificially added to each cell through the irrigation network,  $Irr$ . This change is important, as the inputs now comprise a much larger component than in a natural system during the summer growing season where typically intermittent convective storms provide the vast majority of water inputs to the system. The major output is evapotranspiration,  $ET$ , occurring within each cell. In natural bogs where lateral movement of water is insignificant,  $ET$  is an important component of the water balance, as it represents the only major loss of water from the system (Baldocchi et al.

1997; Wever et al. 2002). Thus, ET should also be a substantial part of the water balance of each cell as they were designed to function like natural bogs with negligible transfer of water in or out. A leakage term,  $L$ , has been added to represent the potential for water seepage through the sides or bottom of the cells. The impermeable liner was designed to keep leakage to a minimum, but they are susceptible to cracks and punctures. Again, an error term,  $\epsilon$ , is added in order to account for some degree of measurement error. Finally,  $\Delta S$  denotes the change in water storage of the peat/soil mixture over the course of the study period and could be positive or negative, although natural wetlands typically experience a loss in storage during the growing season (Price, 2003).

### 2.3 Evapotranspiration

Evapotranspiration (ET) is the movement of free surface water, soil pore water, and water transpired from vegetation to the atmosphere, and is the process that links the water and energy cycles (Oke, 1987). ET requires energy; consequently the amount of energy available at the wetland surface has direct control on ET and other processes. Net incoming energy ( $R_n$ ) is the net gain in short wave and long wave radiation (energy) at the Earth's surface.  $R_n$  is then dispersed into the environment through turbulent and conductive forms of transfer, as shown in the surface energy balance (Equation 2.4).

$$R_n = LE + H + G + S \quad (2.4)$$

This equation relates  $R_n$  to four processes of energy (heat) distribution: heating of the soil ( $G$ ), potential storage within the vegetation and the air column below the canopy

( $S$ ), direct transfer of heat energy from surface to atmosphere ( $H$ ), and energy used for the latent heat (water vapour) transfer ( $LE$ ). All fluxes are typically represented in  $W m^{-2}$  or MJ, and  $LE$  is the energy that is consumed in evaporating water from the surface to the atmosphere and is directly connected to the water balance of any system. Since ET is the primary loss of water in the study cells,  $LE$  becomes a very important process as it represents the link between their respective energy and water balances.

Latent heat flux, or the amount of energy used for evaporative processes, can be estimated as a function of the meteorological factors that drive the evaporation process and surface factors that act to inhibit or enhance it. Although there are different equations utilized to estimate  $LE$ , and subsequently ET, the most widely used is the Penman-Monteith equation (Equation 2.5) (Monteith, 1981, 1965). The strength of this equation is that it incorporates a mass transfer (water) component with an energy balance component in a way that does not require surface temperature measurements like many other approaches to estimate ET (Dingman, 2002). Furthermore, it considers both the energy (heat) that drives the ET process (the diabatic term on the left side of the numerator) with the turbulent transfer of water away from the surface (the adiabatic term on the right of the numerator). In combining these approaches, the Penman-Monteith equation is often termed a combination model and is commonly expressed as:

$$LE = \frac{\Delta(R_n - G - S) + \rho_w C_w VPD r_a}{\Delta + \gamma(1 + r_a r_s)} \quad (2.5)$$

where  $\Delta$  ( $g m^{-3} \text{ } ^\circ C^{-1}$ ) is the relation between saturation vapour pressure and temperature,  $(R_n - G - S)$  ( $W m^{-2}$ ) is a term representing the available energy,  $\rho_w$  ( $g m^{-3}$ ) and  $C_w$  ( $J Kg^{-1} K^{-1}$ ) are the density and specific heat capacity of water

respectively,  $VPD$  (kPa) is the atmospheric vapour pressure deficit,  $r_a$  ( $m\ s^{-1}$ ) and  $r_s$  ( $m\ s^{-1}$ ) are the aerodynamic and stomatal resistances respectively, and  $\gamma$  ( $g\ m^{-3}\ ^\circ C^{-1}$ ) is the psychrometric constant (Oke, 1987). The derivation of this equation assumes that there is no advected energy, which is generally not valid for free water bodies but are usually reasonable when considering a predominantly vegetated surface (Dingman, 2002).

The Penman-Monteith equation may provide information into which environmental factors influence the rate at which ET occurs. The equation (Equation 2.5) attempts to quantify ET by using five main environmental components that affect it in some capacity. They are: available energy ( $R_n - G - S$ ), vapour pressure deficit ( $VPD$ ), the saturation vapour pressure curve which is a function of temperature ( $\Delta$ ), turbulent mixing of air ( $r_a$ ), and the resistance of the canopy, ( $r_s$ ), controlled by vegetation through stomata (Lafleur, 2008, Lott and Hunt, 2001). These five variables are connected to more tangible and measurable micrometeorological factors through known relations and empirical estimates (Dingman, 2002). Therefore, quantifying and understanding these five micrometeorological components directly in the field may achieve a better estimate of ET and an understanding of its controls.

Available energy is the driving force behind ET. Evaporating water requires relatively large amounts of energy, and this energy ultimately comes from the sun. As discussed above, the surface energy balance (Equation 2.4) shows how energy is partitioned among different fluxes, one of which is the latent heat transfer or ET. In general, during long, mainly sunny days that are common in northern Alberta during the peak growing season, a large amount of energy is partitioned into the latent heat

flux, and subsequently ET is able to proceed at high rates (Humphreys et al. 2006).

Vapour pressure deficit (*VPD*) is a measure of the ability of the air to receive water vapour based on an existing gradient. This gradient is the saturation vapour pressure ( $e^*$ ) for that given temperature minus the actual vapour pressure ( $e$ ).

$$VPD = e^* - e \quad (2.6)$$

*VPD* and air temperature are closely linked since saturated and actual vapour pressures are highly dependent on temperature (Oke, 1987). Air temperature regulates the maximum saturated vapour pressure; higher air temperatures can achieve greater *VPD*'s, thus enhancing the potential for ET.

*VPD* can act as a control on ET as it expresses an effective demand on surface moisture, be it open water, soil or vegetation, into the atmosphere. During the day, vapour pressure is typically greatest near the surface and decreases with height in the atmosphere; consequently the flux of water vapour is upward, away from the surface (Lafleur, 2008). The amount of water vapour that is evaporated into the atmosphere is dependent on the magnitude of the vapour pressure gradient and the degree to which the atmosphere is able to maintain this gradient by removing moisture from the lower atmosphere. This is a function of the turbulence in the boundary layer.

Turbulence refers to air mixing occurring in the atmosphere. Mixing generally occurs as a result of vertical, circular swirling air currents or eddies. Wind velocities and thermal layering in the atmosphere control near surface eddies (Oke, 1987). In general, higher wind speeds produce more mixing and greater turnover of air, and thus a greater potential for water vapour to be moved away from the surface. Ground features also play a role in affecting turbulence, as obstacles tend to create disturbance,

which in turn leads to increased wind speeds and larger eddies (Oke, 1987).

Turbulence is often represented by the aerodynamic resistance term  $r_a$ , which is a ratio of the horizontal wind speed ( $u$ ) to the square of friction velocity of the surface ( $u^*$ ), both measured in  $\text{m s}^{-1}$  (Equation 2.7).

$$r_a = u / (u^*)^2 \quad (2.7)$$

Friction velocity is a function of the mean wind speed at a given height and the surface roughness length. Roughness length is a measure of the aerodynamic roughness of a surface and is related to the height of the roughness elements. Other factors such as shape, density and distribution of the elements also affect this variable. Surface roughness length is commonly estimated as 10% of the height of the surface elements, which in this study were various types of vegetation (Oke, 1987).

The type of vegetation, near surface moisture status, and the depth to the water table in the soil can influence how much water is transferred to the surrounding environment. The ability of vegetation to restrict the release of water into the air is referred to as surface (or sometimes stomatal) resistance ( $r_s$ ). Vegetative controls on ET, via surface resistance, are an integral part of the seasonal energy and water balance of Boreal bogs and fens (Brown et al. 2010). Surface resistance is dependent on many vegetative and environmental factors and often varies greatly through time and space. Perhaps the most important environmental factor that affects surface resistance is the availability of water. Vegetation tends to close its stomata during prolonged periods of stress, which can be caused by, among other genetic and environmental factors, little or no access to water (Dingman, 2002). The depth of the water table below the surface can have a control on the availability of water for ET through free surface or soil

evaporation or via plant uptake and subsequent transpiration. Although water availability is not explicitly considered in the Penman-Monteith equation (Equation 2.5), it can still be an important factor affecting ET (Ingram, 1983; Lafleur et al. 2005). This may be especially true in northern regions (such as the study site) that often have relatively dry growing seasons (Humphreys et al. 2006).

Overall, the Penman-Monteith equation is widely applied because it provides a framework that incorporates both biotic and abiotic elements that control ET in a vegetated zone (Baldocchi et al. 2000). However, the application of evaporation models based on homogenous land cover, like the Penman-Monteith equation, to wetlands creates potential problems relating to the spatial scale of measurements (Lafleur and Rouse, 1988). Wetlands are generally composed of heterogeneous land cover, with patches of wet and dry areas, which may have very different values for many of the factors used in the Penman-Monteith equation and thus may lead to point estimates of ET being unrepresentative of the wetland as a whole (Gavin and Agnew, 2003).

## **2.4 Previous Research**

Wetland ET research began when urban expansion prompted the need to determine the best way to drain and/or clear wetlands (Drexler et al. 2004). More recently, interest in wetland ET has come from the need to understand the processes and function of these ecosystems, particularly from a management perspective. There has been considerable effort studying natural, disturbed and constructed wetlands to quantify the water balance (of which ET is a major component) in an attempt to

determine their water requirements and hydrological regimes (Carter, 1986; Rosenberry and Winter, 1997). This information can be used to measure fluxes of contaminants or nutrients, transpiration habits of wetland vegetation, phytoremediation, groundwater modeling and even global climate modeling (Drexler et al. 2004). Still, wetland ET remains poorly characterized due to the high variability in both space and time (Souch et al. 1996). Drexler (2004) suggests that this may be caused by the relative differences in the multitude of techniques used to measure ET and/or the fact that it is challenging to obtain reliable results given the lack of uniformity in shape, surface cover, hydrology and topography of wetlands. In this section some of the past research in wetland ET that is relevant to this particular study will be presented.

#### ***2.4.1 Vegetation and ET***

Along with free water and soil water sources, the contribution to ET from vegetation is considered an integral component of wetland ET, where processes at the vegetation community scale affect the total ecosystem exchanges of water (Brown et al. 2010). The exact vegetation composition within Boreal wetlands is dependent on the spatial variability of the surface moisture characteristics. The interaction between vegetation and moisture conditions may be even more important to Boreal bogs and fens because of limited lateral flow gradients (Devito et al. 2005). This lack of water movement has been shown to enhance components of vertical moisture exchange, perhaps amplifying the importance of surface moisture-vegetation interactions (Smerdon et al. 2005). Williams and Flanagan (1996) suggest that concentrated moisture patterns only act to encourage vertical water movement and are often

prompted by gradients between moisture rich peat and the drier air above.

During dry periods, vegetation and soil are more resistant to water movement into the atmosphere (Lafleur, 2008). Since different plant species have differing abilities to conserve or release water, plant type is a very important consideration for ET. Water loss from mosses and other non-vascular plants differs from that of vascular plants. During photosynthesis in vascular plants, water coming mainly from their roots is released as vapour through stomata on their leaves and stems. Because vascular plants have extensive systems of roots allowing fairly consistent access to water, ET in wetlands rich in vascular plants often relies on the transpiration capacity of the plant canopy itself (Heijmans et al. 2004). In contrast, mosses evaporate water from their surface rather transpiring like vascular plants. Tightly packed single leaves and water holding structures (known as hyaline cells) that are supported by the small branches of the capitulum. These tightly packed cells force water through the capitulum where water is evaporated (Lafleur, 2008; Ingram, 1983). Mosses do not have a water transport system like vascular plants, and their stems do not conduct any water. The dead leaves and branches create a network of small pores and water moves up through this network and from the sides of the stems due to capillary gradients. If the water table is at or near the surface, the network will work efficiently because water can diffuse across small distances. However, if the water table is lower, the stems will not be in contact with water, and the transpiration rates will decrease (Lafleur et al. 2005). As mosses dry out they are unable to draw water to the surface efficiently, and so significant decreases in ET are possible. Several studies have noted a sharp decline in ET rates as mosses dry out and are unable to move water through capillary action

(Price, 1991; Kim and Verma, 1996).

To better understand the movement of water within northern bogs and fens, Price et al. (2009) performed a laboratory experiment to study the mechanisms of water transport within *Sphagnum* moss and from the moss into the atmosphere. The authors transplanted small pieces of moss and, using controlled environmental conditions (air temperature, relative humidity, amount and duration of incoming solar radiation, and air mixing), measured the subsequent ET. Their results confirmed that water flux in *Sphagnum* while undergoing ET is predominantly in the form of liquid capillary diffusion. The results also confirmed, surprisingly, that despite large pore spaces present in peat, water vapour movement below the surface was a negligible portion of net water flow. ET ranged from 3.9 mm d<sup>-1</sup> to 4.8 mm d<sup>-1</sup>, with an average of 4.5 mm d<sup>-1</sup> under constant environmental conditions (average T=20.7 °C, RH=31.3%, 12 hours of artificial UV light per day, constant air circulation). The authors also found that a portion of the latent heat flux occurred below ground, creating the potential for errors when trying to estimate the available energy to perform ET. They suggest that models such as the Penman-Monteith equation (Equation 2.5) may have limited validity in moss dominated systems given that such models assume that radiative and convective fluxes occur at a common reference surface.

The manner in which water becomes available to plants and mosses has been studied in both natural and disturbed wetlands. Lafleur et al. (2005) studied ET over 5 growing seasons at a natural bog in eastern Ontario and found that ET was weakly related to the depth of the water table. ET appeared to be affected by the depth to the water table only when it dropped below a specific threshold, which was thought to be

associated with the rooting depth of the vascular plants at the site. The concept of a critical water table threshold was also suggested in previous studies, such as Ingram (1983), Nicholas and Brown (1980), and Lafleur et al. (2005). Price (1996) studied a disturbed and an undisturbed section of a bog complex in northern Quebec and found that changes in the composition of the underlying soil can greatly reduce the specific yield (water holding ability) of peat and cause exaggerated water table changes in disturbed wetlands. The study concluded that poor moss growth on disturbed surfaces can often be attributed to the inability of mosses to obtain water from the underlying peat, which holds water at greater suction than non-vascular plants like mosses can generate.

#### **2.4.2 *ET in Natural Systems***

ET in natural bogs and fens is quite low compared to that in other wetland systems such as marshes and swamps (Lafleur, 2008). However, ET in bogs and fens may still approach the maximum potential rate possible for the given environmental conditions. Near maximum potential ET in bogs and fens may occur under at least one of the following conditions: (i) a large amount of the surface area is open water (Price, 1994), (ii) the area is dominated by vascular vegetation (Lafleur, 1990), or (iii) the moss cover is moist because of dew, fog or rain (Price, 1991). Vegetative controls and hydrologic restrictions can limit ET in bogs and fens. A compilation of many studies conducted across Canada that have measured actual ET rates of wetlands is shown in Figure 2.1. Many of these studies observed that *Sphagnum* dominated bogs and poor fens had the smallest mean ET rates. Meanwhile, rich fens, which are dominated by vascular plants, and other wetland types common to lower latitudes such as swamps,

were observed to have similar ET rates, higher than those of bogs and poor fens (Lafleur, 2008). Marshes, which are dominated by aquatic vegetation such as tall reeds, had the highest ET rates.

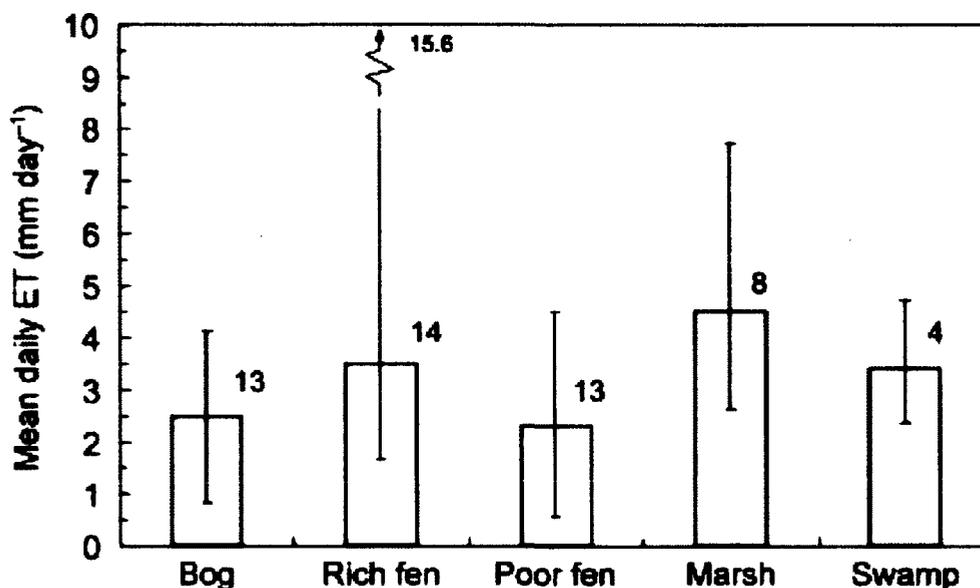


Figure 2.1 Comparison of tabulated daily ET rates from a collection of Canadian studies. Boxes show the mean daily rate while whiskers denote the min and max observed values. The number above and to the right of the boxes indicates the number of studies used in compiling the results. Bog and poor fen types, common to the boreal region have relatively lower ET rates than other wetland types (from Lafleur, 2008).

Roulet et al. (1997) compiled data from studies on wetlands from across Canada and had similar findings regarding wetland ET. Bogs had the lowest measured maximum ET rate ( $0.4 \text{ mm hr}^{-1}$ ). Meanwhile, maximum ET rates for fens were observed to be slightly higher than those for bogs ( $0.52 \text{ mm hr}^{-1}$ ). Brown et al. (2010) reported comparable rates from a typical wetland system of the western boreal plains, dominated by mosses and sparse vascular vegetation. Peak ET ranged from  $0.2 - 0.6 \text{ mm hr}^{-1}$  depending on location, vegetation composition and time period. Of note was that *Sphagnum* ET rates were greatest early in the growing season ( $0.6 \text{ mm hr}^{-1}$ ) but began to decrease as the season progressed, while lichens were observed to have

higher ET rates late in the growing season ( $0.4 \text{ mm hr}^{-1}$ ). The authors commented that different varieties of non-vascular vegetation control ET differently throughout the growing season, and so should be considered a key component of wetland water balances at the sub-landscape scale.

Humphreys et al. (2006) reported on ET measurements of several northern wetland systems ranging from bog to extreme-rich fen. Midday ET ranged only from  $0.21 - 0.34 \text{ mm hr}^{-1}$  despite a wide range of vegetation types and combinations in each wetland. One key finding was that ET was primarily driven by radiation at all sites, particularly when water availability was not a restriction and when VPD was high. As sites dried up, ET rates dropped, particularly at sites with many vascular plants and trees but less so at sites with significant *Sphagnum spp* cover. Kellner (2001) also noted vegetative controls decreasing ET rates in conditions thought to yield high ET rates (e.g. high  $R_n$  and  $VPD$ ). In this study of a Swedish wetland, ET was again most strongly linked to radiation than to any other controlling factor. Furthermore, there was a strong trend between rising stomatal resistance ( $r_s$ ) and increasing VPD. In contrast, vegetative conductance showed a weakly negative correlation with available energy, decreasing slightly under sunnier conditions (increased radiation). These findings suggest that although ET is driven by four controlling factors, vegetative responses to these controlling factors may also be an integral mechanism in the process of ET. (Kellner, 2001)

#### **2.4.3 ET in Disturbed and Constructed Wetlands**

Disturbance of a wetland causes changes to its physical properties, the depth to the water table and the vegetation, and consequently may have implications for ET at

reclaimed sites. Peat that is exposed during disturbance can actually have a higher water retention capacity (specific retention;  $S_r$ ) than living or non-decomposed dead mosses (Schlotzhaur and Price, 1999), due to its finer pore structure and higher bulk density (Okruszko, 1995). The changes in disturbed peat may allow capillary movement of moisture to more readily sustain surface moisture compared to hummocks in natural wetlands (Price and Waddington, 2000). Thus, changes in peat properties can help supply the evaporating surface with sustained moisture. Based on this process, and other vegetative and drainage factors, Van Seters (1999) suggested that total ET (losses) may increase with time elapsed since disturbance and/or abandonment. The notion of ET increasing after disturbance has been suggested in other studies. Petrone et al. (2003) found that restoration techniques that resulted in a higher water table, higher soil moisture and the re-emergence of vascular plants created higher ET losses than in an adjacent unrestored site. It was suggested that not only did the increased density of vascular plants increase transpiration but that it also increased surface roughness, which further enhanced ET through greater turbulent transfer.

ET at disturbed sites may be more spatially variable, due to changes in soil properties and vegetative conditions. In a two-year study, Van Seters and Price (2001) found that average ET rates at a disturbed (harvested) bog were similar to that at a nearby undisturbed bog, but showed much more variability of ET rates depending on location. ET rates were lower in raised areas ( $1.9 \text{ mm d}^{-1}$ ) and much higher in lower areas and/or ones of high moisture where *Sphagnum* was present ( $3.6 \text{ mm d}^{-1}$ ), resulting in an average similar to that at the natural site ( $2.9 \text{ mm d}^{-1}$ ). The authors also

found that ET represented the greatest loss of water from the disturbed site over the two growing seasons being studied. ET was responsible for 92% and 84% of water loss during 1997 and 1998 respectively, with runoff from slopes and ditches making up the remaining portion. The water balances of the disturbed site showed that ET was much larger than precipitation, 1.4 and 1.3 times greater in 1997 and 1998 respectively. This difference resulted in substantial decreases in water storage, -75 mm and -100 mm in 1997 and 1998 respectively, compared to a -58 mm (1998 only) decrease in water storage at the natural site. The decreases in water storage was thought to have been responsible for greater depth to, and fluctuations of, the water table at the disturbed site, and may be a major factor in limiting regeneration and reestablishment of natural wetland functioning. It was suggested that these spatial variations in ET and runoff resulted in a much different water balance than that of a relatively uniform distribution of losses common in natural bog systems.

It is not yet fully understood how ET occurs in constructed wetlands, as compared with natural wetlands. Lott and Hunt (2001) studied a constructed wetland complex built directly adjacent to an existing natural fen in the northern United States. As measured by a weighing lysimeter, the constructed fen had a significantly lower daily ET rate ( $3.5 \text{ mm d}^{-1}$ ) throughout the growing season than the natural site ( $5.6 \text{ mm d}^{-1}$ ). Given the relative consistency of other environmental and climatic factors, it was suggested that this difference was attributable to differences in the availability of water in the rooting zone and the timing of plant senescence.

Campagam and Waddington (2008) studied the effects of upper layer (acrotelm) peat transplanting on hydrologic properties and function. They compared a

natural portion of wetland to a section that had recently been harvested using the trench extraction restoration technique. This method involves the removal of the vegetative acrotelm (1-2 m), harvesting a portion of the thicker, denser lower layer (catotelm) beneath and then replacing the acrotelm back on top of the now much deeper and older catotelm. They found that the transplanted site maintained a higher water table compared to the natural site but that this did not result in higher volumetric water content (VWC) at the surface as would be expected. The authors suggested that the removal and replacement of the acrotelm might have damaged it structurally, resulting in great variation in VWC at the surface. This in turn may alter its ability to move water up through the profile for exchange with the atmosphere through ET in the same fashion as undisturbed peat. ET at the transplanted site was estimated to be over two times ( $10 \text{ mm d}^{-1}$ ) that at the natural site ( $4\text{-}5 \text{ mm d}^{-1}$ ) by using a mass balance approach and quantifying daily fluxes in VWC. It is hypothesized that this extreme diurnal change in VWC is partially related to the aforementioned changes in the peat structure and not just to ET alone, even though soil moisture characteristics were similar at both sites. The acrotelm was extracted in large blocks, retained and then placed onto exposed peat leaving large spaces or gaps between them, which can cause significant changes in the peat structure. The authors suggested that the lateral movement (expansion/contraction) within the peat matrix might be exaggerating the apparent fluctuations of VWC, and consequently of ET.

Drexler et al. (2004) outlined two important phenomena that may affect ET at the study site, namely its shape/size and its geographic location. First, wetlands surrounded by areas with low ET such as bare soil, tend to have higher ET than

wetlands surrounded by forest. This is known as the “oasis effect”. Second, long narrow wetlands and those on the fringes of lakes and rivers tend to have higher ET than large expanses of wetland that have higher ratios of area to perimeter – known as the “clothesline effect”. The oasis effect is a result of advection over areas of differing moisture creating sharp gradients in VPD and other factors while the clothesline effect occurs because of increased ventilation through a smaller, more isolated canopy (Linacre, 1976). The site in which the current study was performed may be subject to both the oasis and the clothesline effects. It is completely surrounded by mining operations composed of predominantly dry and bare soils. The cells (test plots) are very small for wetlands and so have a very small area to perimeter ratio. The processes discussed above are normally not of great concern when studying natural wetlands but could be extremely important in the construction of wetlands adjacent to major mining and development operations as is the case here.

### 3.0 Study Site and Methodology

#### 3.1 Study Site

The study site is located approximately 40 km NNW of Fort McMurray, Alberta ( $57^{\circ} 03.8' N$ ,  $111^{\circ} 39.8' W$ , elev.~370 m) (Figure 3.1). The region has a continental Boreal climate, with mean monthly temperature ranges from  $-18.8^{\circ}C$  to  $16.8^{\circ}C$  (Jan. - Jul.) and an average annual precipitation of 456 mm, of which approximately 220 mm typically falls during the study period (DOY 152 to DOY 230 –June 1<sup>st</sup> to August 18<sup>th</sup>, 2010) (Environment Canada, 2011). The growing season for the Fort McMurray region is relatively short, with an average of 157 frost-free days (Environment Canada, 2011).

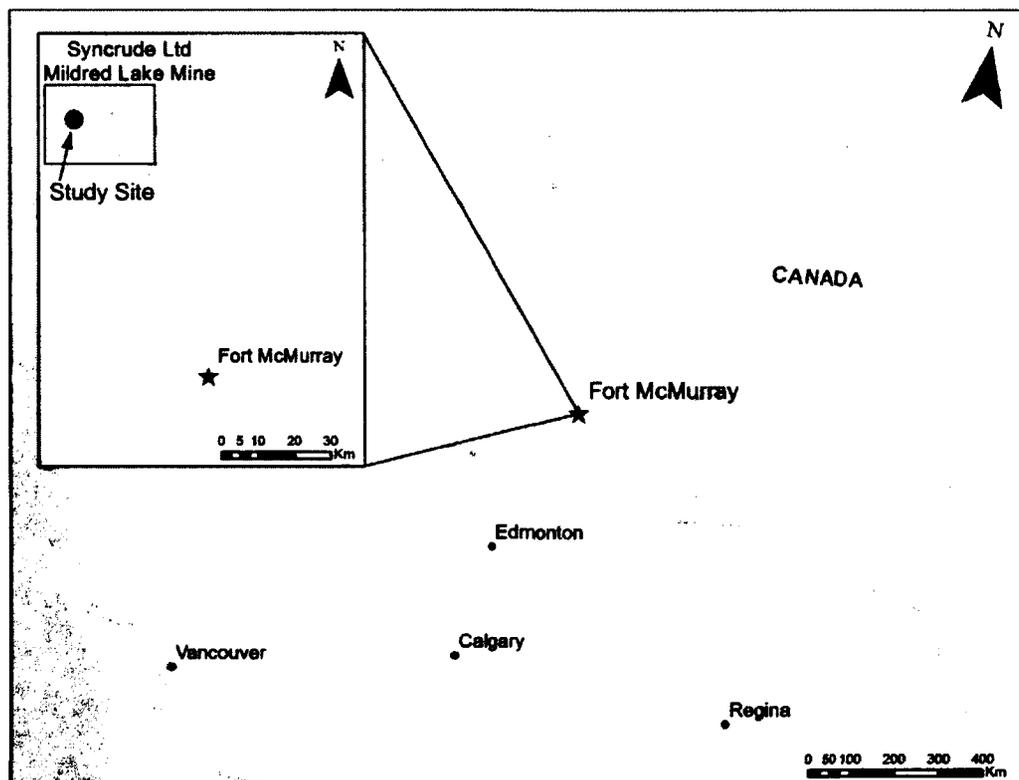


Figure 3.1 Location of Fort McMurray in northern Alberta, Canada and the study site situated 40 km northwest of the city within Syncrude Canada Ltd. Mildred Lake Mine (inset).

The study site is located in the northern section of Syncrude's Mildred Lake Mine on an elevated hilltop that is just west of the current active mine (Figure 3.2). The site is surrounded by land disturbed by construction and mining activities. North of the site is a large expanse of dry processed sand while to the east is an open storage area where industrial equipment is stored. To the west of the site is a shallow reservoir of fresh water and to the south there are a series of dirt roads with intermittent vegetation cover. The study site and its adjacent land cover can be seen in Figure 3.3.

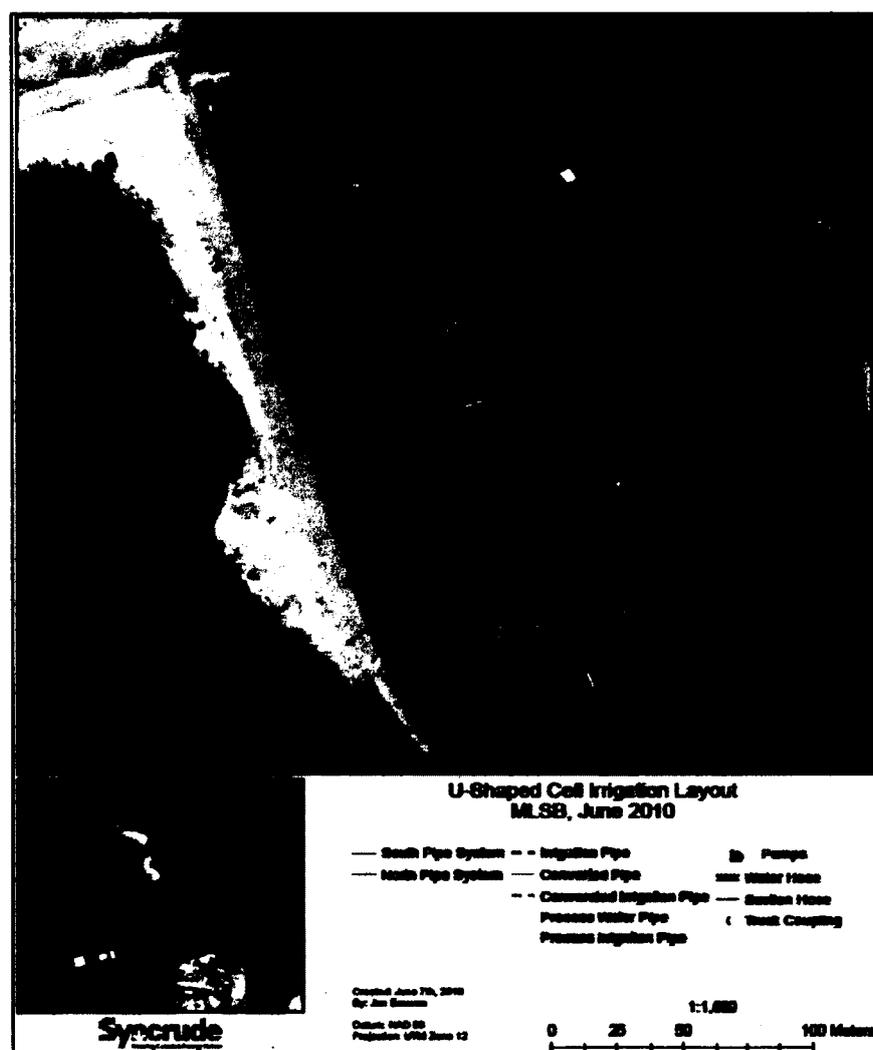


Figure 3.2 As built plan showing location of the study site within the mine (inset) site setup including irrigation networks and surrounding land cover (from BGC, 2010).

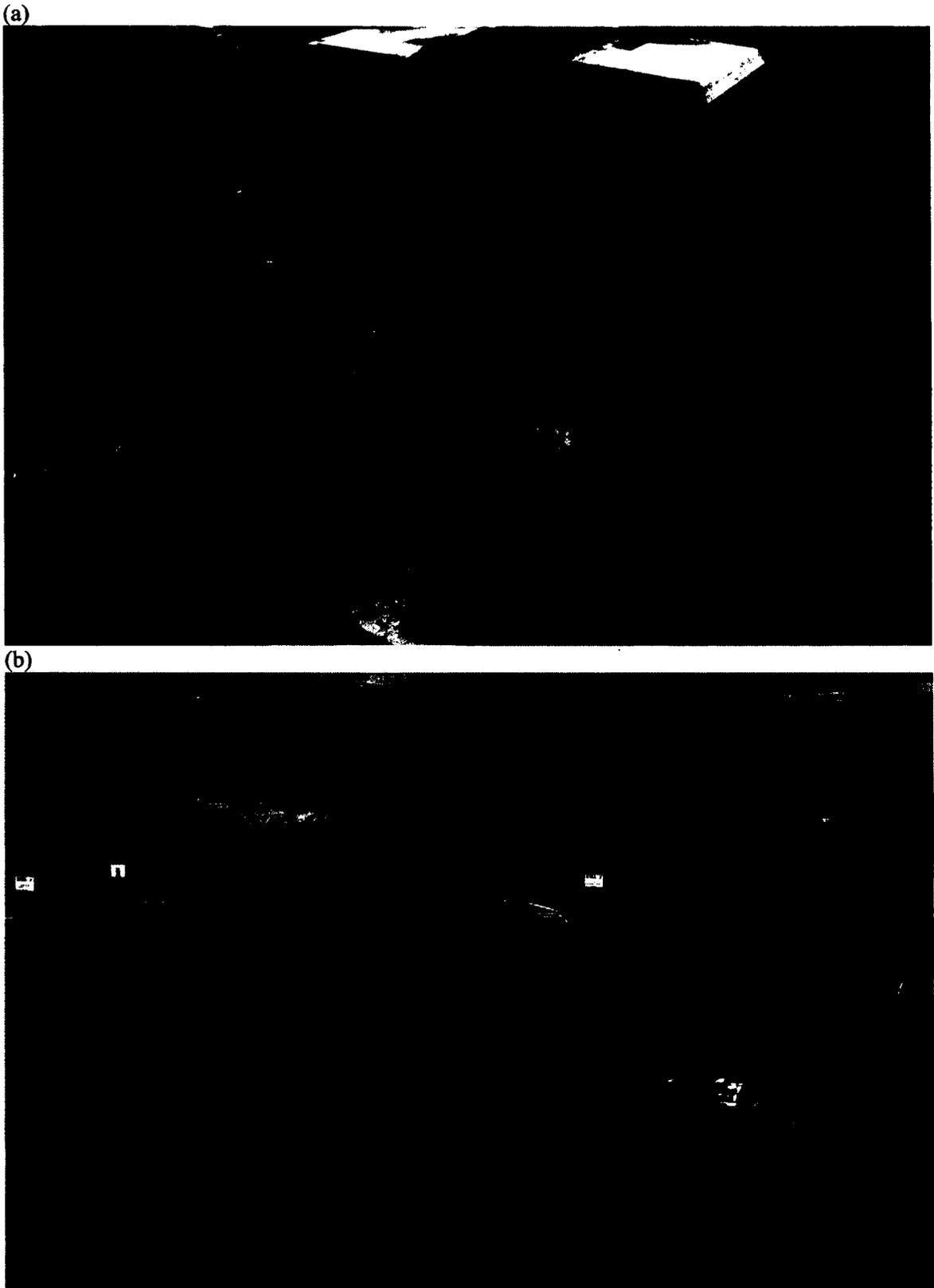


Figure 3.3 Aerial view of study (a) and oblique view of an individual cell (b).

The site, called the U-Shaped cell, was previously a composite tailings site in the southwest portion of the Mildred Lake Settling Basin. From August to November 2008 the site was covered with clean clay reclamation material and then transformed into series of small, disconnected rectangular pits about one metre deep. Each rectangular pit, or “cell”, measured approximately 20 m by 13 m. The pits were separated by narrow ridges of clay that created small pathways between the cells. Each cell was then lined with an impermeable synthetic liner (20 mm Enviroflex Geomembrane) and then overlain with 20 cm of compacted clay. The construction process is detailed in Figure 3.4. Great attention was placed on the design and installation of the cell liners in order to prevent water from entering or leaving, either laterally or vertically, through the sides or base of the cells. The effectiveness of the liner to isolate cells from the surrounding environment is uncertain, and will be discussed more in the Results and Discussion sections.

The test cells received different treatments that represent potential wetland construction and regeneration techniques. Syncrude has defined and implemented several combinations of construction techniques that are thought to be suitable and feasible, specifically for this environment. The present study monitored six treatment combinations that were applied in both summer and winter 2008, involving a total of 12 cells. Treatment variables included: i) the origin of the vegetation, ii) the depth of the soil/peat mixture and iii) the season in which the treatment combinations were applied (Table 3.1). Vegetation in the cells was from either a live transplant from a nearby natural fen slated for mining or from seedlings grown in a greenhouse and planted in the spring of the first year. The transplanted vegetation was removed

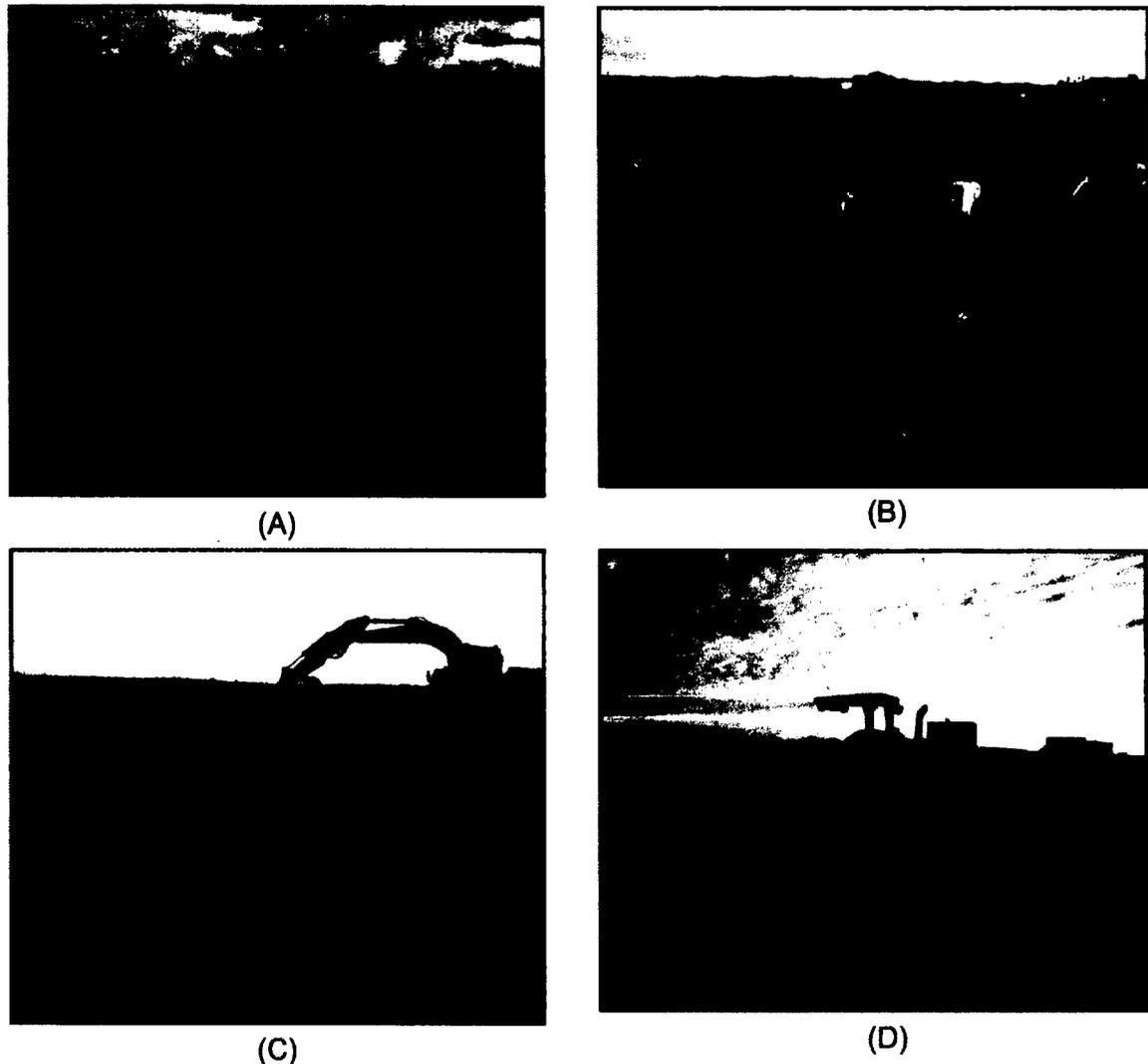


Figure 3.4 Lining of the cells involved digging a trench at the edge of the cell (A) manually stretching geosynthetic liner over base of cell (B) covering with 20 cm of clay (C) and compacting (D) (from BGC, 2009).

using specialized equipment from a nearby fen that was slated for mining. A large scoop with a flat bottom was used to obtain large square blocks of peat including surface vegetation, which were then secured and transported to the site. The blocks had thicknesses of roughly 15, 50 or 100 cm. The cells that did not receive a live transplant were filled with a stockpiled mixture of organic debris and peat. This stockpiled mixture is collected as nearby areas are cleared for mining and the top organic layer is processed and stored in piles on site for future use as a soil cover. The stockpiled

mixture was also laid down in depths of 15, 50 or 100 cm after which greenhouse vegetation was planted by hand. Each treatment combination was applied either in summer (September 2008) or winter (January 2009) to assess the affect of seasonality on soil/peat harvest and placement, and vegetation started in greenhouses were planted the following spring.

Table 3.1 Treatment combinations for each of the 12 study cells.

<b>Cell Name</b>	<b>Soil/Vegetation Origin</b>	<b>Peat/Soil Mixture Depth</b>	<b>Application Season</b>
<b>S-P-100 cm</b>	Live transplant from nearby natural wetland	100 cm	Summer
<b>S-P-50 cm</b>	Live transplant from nearby natural wetland	50 cm	Summer
<b>S-P-15 cm</b>	Live transplant from nearby natural wetland	15 cm	Summer
<b>W-P-100 cm</b>	Live transplant from nearby natural wetland	100 cm	Winter
<b>W-P-50 cm</b>	Live transplant from nearby natural wetland	50 cm	Winter
<b>W-P-15 cm</b>	Live transplant from nearby natural wetland	15 cm	Winter
<b>S-S-100 cm</b>	Planted seedlings in Stockpiled mixture	100 cm	Summer
<b>S-S-50 cm</b>	Planted seedlings in Stockpiled mixture	50 cm	Summer
<b>S-S-15 cm</b>	Planted seedlings in Stockpiled mixture	15 cm	Summer
<b>W-S-100 cm</b>	Planted seedlings in Stockpiled mixture	100 cm	Winter
<b>W-S-50 cm</b>	Planted seedlings in Stockpiled mixture	50 cm	Winter
<b>W-S-15 cm</b>	Planted seedlings in Stockpiled mixture	15 cm	Winter

In an attempt to replicate natural wetland conditions, the water table was artificially kept at, or very near, the surface by adding fresh water to each cell from a reservoir through a pipe system. The system consists of two irrigation loops, with each loop having an intake at the reservoir and release valves at each of the cells that it serves. During the late summer when the reservoir was low, water was brought in by truck and directly connected to the irrigation system.

Vegetation in the cells differed considerably between the transplanted cells and those made of a stockpiled peat mixture. The transplanted cells have a mixture of typical boreal fen vegetation and emergent vegetation that have established since construction. Native species include: Labrador tea (*Ledum groenlandicum*), bog blueberry (*Vaccinium uliginosum*), bog cranberry (*Vaccinium oxycoccos*), cotton grass (*Eriophorum virginicum*), horsetail (*Equisetum spp*), black spruce (*Picea mariana*), dwarf birch (*Betula pumila*), and *Sphagnum spp*. Emergent vegetation in the transplanted cells include large groups of cattails (*Typha latifolia*), foxtail barley (*Hordeum jubilatatum*), field horsetail (*Equisetum arvense*), fireweed (*Epilobium augustifolium*), celery leaved buttercup (*Ranunculus sceleratus*), water sedge (*Carex aquatilis*), ribbon grass (*Phalaris arundinacus*) and grasses *Salix spp* and *Poa spp*.

The stockpiled cells contain a less diverse mix of vegetation as only a few species that were thought to have a high chance of success were planted. These species include water sedge *Carex aquatilis*, ribbon grass *Phalaris arundinacus*, tickle grass (*Agrostis scabra*), along with small trees such as dwarf birch (*Betula pumila*) and tamarack (*Larix laricina*). Similar to the transplanted cells, emergent species such as cattails (*Typha latifolia*), barley foxtail (*Hordeum jubilatatum*), and western dock

(*Rumex longifolius*), as well as grasses *Salix spp.* and *Poa spp.* have established over large areas of the stockpiled cells and in some cases are now the dominant species.

Other minor emergent species in the stockpiled mixture cells include: perennial sow thistle (*Sonchus arvensis*), ball mustard (*Nesia paniculata*), narrow leaved hawksbeard (*Crepis tectorum*), small bedstraw (*Galium trifidum*), celery leaved buttercup (*Ranunculus sceleratus*), and cinquefoil (*Potentilla norvegica*). A more detailed summary of the vegetation found in each type of cell is listed in Table 3.2 with photo examples shown in Figure 3.5.

Table 3.2 Vegetation composition in the two different soil/vegetation treatments – live peat reansplant and stockpiled peat mixture. ✓✓ indicates that the species had become dominant (adapted from Piquard, 2010).

Type of Vegetation	Live Transplant Cells	Stockpiled Mixture Cells
/	✓	
Bog blueberry ( <i>Vaccinium uliginosum</i> )	✓	
Bog cranberry ( <i>Vaccinium oxycoccos</i> )	✓	
Cotton grass ( <i>Eriophorum virginicum</i> )	✓	
Black spruce ( <i>Picea mariana</i> )	✓	
Dwarf birch ( <i>Betula pumila</i> )	✓	
<i>Sphagnum spp</i>	✓	
Common Cat tail ( <i>Typha latifolia</i> )	✓	✓✓
Foxtail Barley ( <i>Hordeum jublatum</i> )	✓	✓
Grasses ( <i>Salix spp</i> )	✓	✓
Water Sedge ( <i>Carex aquatilis</i> )	✓	✓
Ribbon Grass ( <i>Phalaris arundinacus</i> )	✓	✓
<i>Poa spp</i>	✓	✓
Tamarack ( <i>Larix larcina</i> )		✓
Western dock ( <i>Rumex longifolius</i> )		✓
Fireweed ( <i>Epilobium augustifolium</i> )	✓	✓
Water Hemlock ( <i>Cicuta maculata</i> )		✓
Tickle Grass ( <i>Agrostis scabra</i> )		✓✓
Field Horsetail ( <i>Equisetum arvense</i> )	✓	✓
Narrow Leaved Hawks Beard ( <i>Crepis tectorum</i> )		✓
Ball Mustard ( <i>Nesia paniculata</i> )		✓
Perennial Sow Thistle ( <i>Sonchus arvensis</i> )		✓
Small Bedstraw ( <i>Galium trifidum</i> )		✓
Celery Leaved Buttercup ( <i>Ranunculus sceleratus</i> )	✓	✓
Cinquefoil ( <i>Potentilla norvegica</i> )		✓

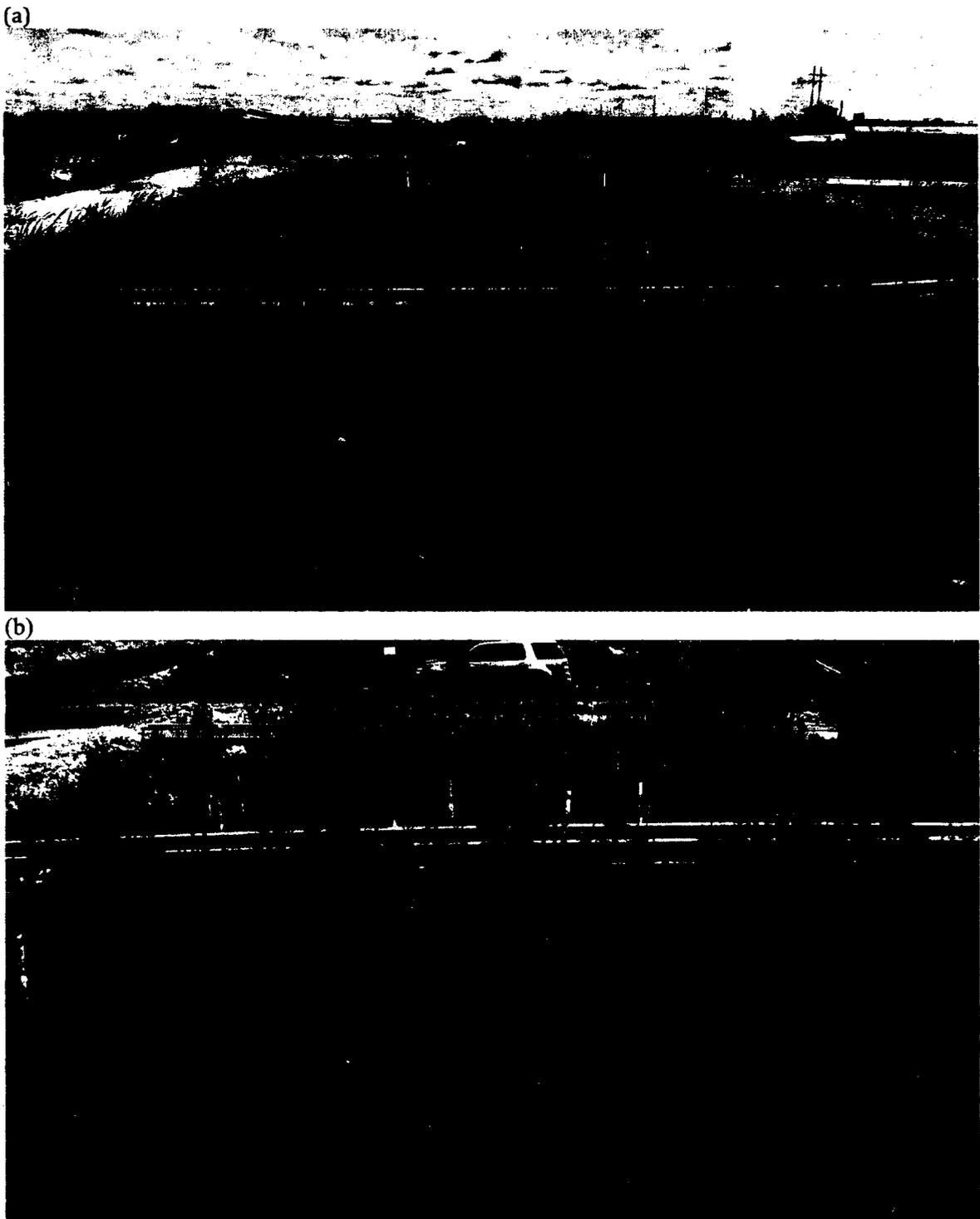


Figure 3.5 Vegetation found in stockpiled cells (a) and live peat transplant cells (b) on July 7th 2010 (DOY 188).

### 3.2 Field Methods

The study ran for most of the 2010 growing season. Meteorological measurements began on DOY 152 (1<sup>st</sup> June, 2010) and ended on DOY 230 (18<sup>th</sup> August, 2010).

Instruments were installed at a height of 2.8 m at a central location at the site. Air temperature and relative humidity were measured using a hydrometer (HMP35, Vaisala). Wind speed was measured with a cup anemometer (Met One 014A, Campbell Scientific). All instruments were connected directly to a data logger (CR23x, Campbell Scientific); measurements were taken every five seconds and averaged over 30 min intervals.

Incoming short-wave radiation was measured with a pyranometer (SP Lite, Kipp and Zonen) located at a meteorological tower approximately 1 km away, which was sufficiently close to have had similar sky conditions over the course of a day. Incoming solar radiation ( $K_{\downarrow}$ ) comprises the largest component of the available energy and thus can provide a reasonable indication of available energy on a daily basis (Oke, 1987). Because of logistical constraints, and given the strong relationship between solar radiation and net radiation ( $R_n$ ), incoming solar radiation ( $K_{\downarrow}$ ) was measured in place of net available energy.

Precipitation was measured using a tipping bucket rain gauge (TE 525M, Texas Electronics). Daily precipitation totals were also cross-referenced against measurements made at the Fort McMurray airport by Environment Canada. Although there is some agreement between the two sets of measurements, there are also considerable differences in both the magnitude and timing of precipitation as summer

rainfall is largely convective in nature and is dominated by high intensity short duration storms with high spatial variability.

ET was measured using manual weighing lysimeters (Figure 3.6). One clear, rectangular, plastic box of 6.5 L volume was installed in a representative location in each cell. Vegetation and soil were carefully removed with a cutting device and placed in the lysimeters, which were then re-installed flush with the surrounding terrain. Each lysimeter was weighed daily (logistics and weather permitting) on a 20 kg capacity scale with 0.5 g precision (EB15, Ohaus), and change in mass was recorded. Moisture in the lysimeters was maintained at levels similar to the surrounding terrain by checking with a TDR moisture probe every few days and adding or removing water, and recording the new mass.

The near-surface temperature of each cell was measured using a soil thermistor (109B, Campbell Scientific). Wind speed approximately 2.8 m above the evaporating surface was measured with a cup anemometer (014A, Met One), averaged over 30 minute periods, and sent to a data logger (CR10x, Campbell Scientific).

The water table depth of each cell was recorded using a logging pressure transducer (Levellogger JR model 3001 and Barrologger, Solinst) located in a standpipe piezometer. The pressure transducer made readings every 10 minutes, and the readings were corrected for atmospheric pressure variations. Daily manual measurements of well stick-up height, depth to water in the well and peat reference height were also made.

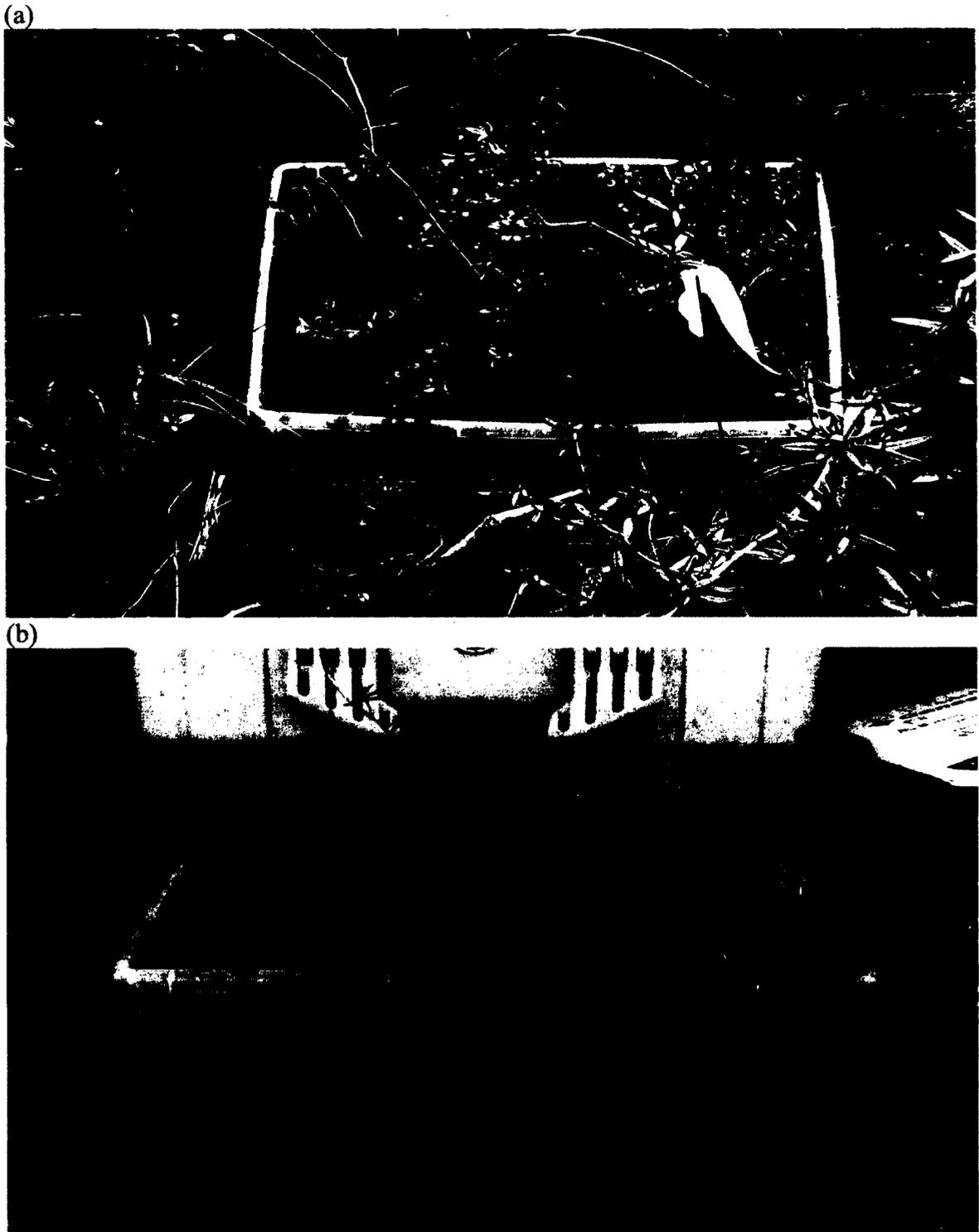


Figure 3.6 Lysimeter boxes in situ (a) and about to be weighed to record change in mass (b).

The Leaf Area Index (LAI) was assessed at five locations directly adjacent to the boardwalks in each cell, every 2-3 weeks from DOY 175 (23 June, 2010) to DOY 228 (16 August, 2010), using a LAI-2000 plant canopy analyzer (LI-COR) with a 180° view restriction. This restriction was used to remove any potential interference created by the boardwalks. Measurements were made under both cloudy and clear sky conditions, typically during early or mid afternoon. In situations where the LAI-2000 could view foliage lit by direct sunlight, the possibility of LAI being underestimated increased. An attempt was made to reduce direct beam radiation by casting a shadow on the sensor (if it was not a completely cloudy day), as suggested in the LAI-2000 instruction manual.

### 3.3 Analytical Methods

#### 3.3.1 Irrigation

Because multiple cells were watered at the same time, irrigation volumes had to be calculated using the Hardy Cross method (Cross, 1936). This technique uses an iterative method to determine the flow inside a circuit of multiple branches in which given static conditions are known, but the flow within each branch and out of open valves is not (Lopes, 2003). The output volume will vary depending on which valves are open, and the length of pipe between valves. The conservation of mass and energy dictates that flow arriving at a node must equal the sum of the flows leaving the node.

$$Q_1 + Q_2 + \dots + Q_n - Q_{n-1} = 0 \quad (3.1)$$

Pressure, or head loss between valves, which affects flow rate, can be described by the generalized Bernoulli equation:

$$h_1 - h_2 = \frac{p_1 - p_2}{\rho g} + \frac{v_1^2 - v_2^2}{2g} + z_1 - z_2 \quad (3.2)$$

Here  $p$  is pressure,  $\rho$  is the fluid density,  $v$  is the velocity of the fluid,  $g$  is the acceleration due to gravity and  $z$  is the height of each valve. Head loss is directly related to flow rate under constant conditions and so the flow rate at each valve can be estimated and corrected iteratively based on the relation of head loss to flow rate:

$$h_1 - h_2 = \frac{8Q^2}{\pi^2 g} \left[ \frac{1}{d^4} \left( f \frac{\Delta L}{d} \right) \right] \quad (3.3)$$

where  $Q$  is the volumetric flow rate,  $g$  is the acceleration due to gravity,  $d$  is the pipe diameter,  $L$  is the branch length and  $f$  is the Darcy-Weisbach friction factor.

Daily irrigation volumes were found using the Hardy Cross method software application produced by Thermal Analysis Systems (1998). This software requires that open valves, the lengths and direction of flow between them, given conditions such as pipe diameter and pressure, along with an estimated flow rate at each valve. A simple example circuit is shown in Figure 3.7. A network diagram was created for each combination of open valves that was used in the irrigation process of the study cells. Input parameters included the number of open valves and the equivalent length of pipe between each valve, the diameter of the pipe (2 inch) and its friction factor, the temperature, viscosity and density of the fluid (water), and the assumed initial pressure and flow rate of the loop.

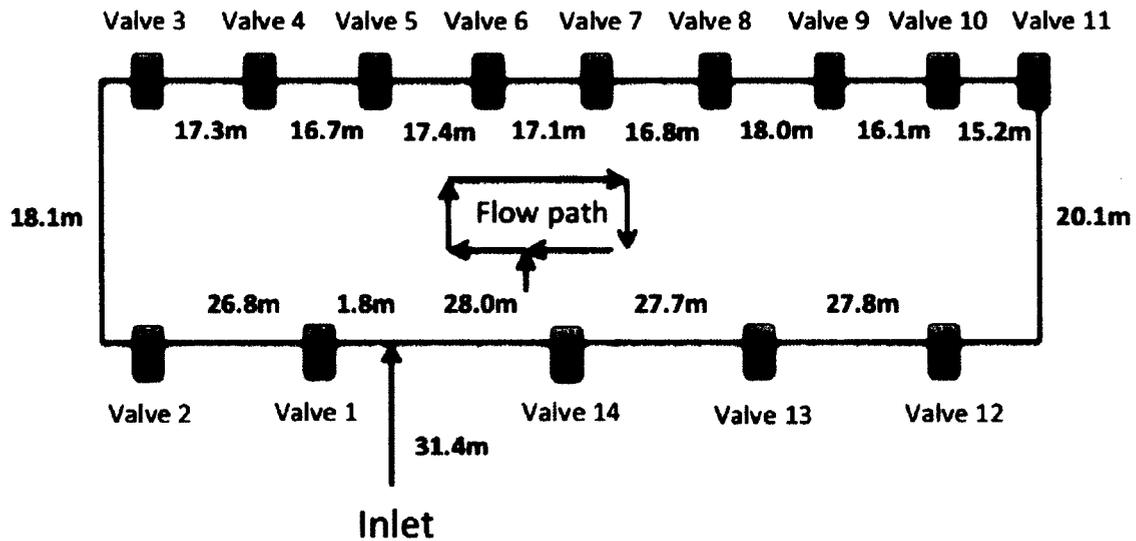


Figure 3.7 The irrigation network setup used for finding iterative solutions to pipe and valve flow rates using the Hardy Cross method. Valve outflow varied according to the number and position of open valves and the distance between them.

Each circuit was given an arbitrary flow direction and assumed flow rates at each valve for a variety of situations in which multiple valves around the circuit were opened. The software iteratively found the actual flow rates in each section of pipe between each valve under the given conditions. The flow rate out of each valve is then the difference between the flow rates of the pipe sections on either side of the valve. This flow rate was then multiplied by the number of minutes each combination was in operation on any given day. Irrigation volumes were then converted to a depth in mm by converting litres to  $\text{m}^3$  and then dividing by the surface area of each cell. However, it is very difficult to verify the accuracy of applying this method to this situation. Because irrigation volumes had to be back calculated, this method can provide only estimates of irrigation volumes. These calculations require several assumptions and thus increase the potential for error.

### ***3.3.2 Data Processing***

Daily lysimeter mass changes were converted into a depth of water equivalent, using the volume and surface area of the container. Mass changes were not recorded on days in which heavy rain occurred but were recorded on days in which small accumulations, generally  $< 0.5\text{mm}$ , were recorded by the tipping bucket rain gauge on site. These depths were added to the ET depths according to the time in which they occurred thus correcting for small additions of water into the lysimeters during days with minor rain events. Days with heavier rain events often resulted in mass increases in the lysimeters and so were given an ET value of zero. Daily cell ET was summed over the study period in order to estimate losses of water from the system.

Environmental variables were averaged and logged in half-hour increments throughout the entire study period. In order for environmental variables to match the timing of ET measurements, daily averages were computed from noon to noon as opposed to actual date change (midnight to midnight).

Water level data was scanned for anomalous data points caused by the disturbance of the logger during other measurements in the well or water sampling. These disturbances generally only lasted for a few minutes but often affected the pressure transducer for hours while the pressure in the logger stabilized. A small number of anomalous data points were removed. After this, a water table offset was created in order to calculate the actual position of the water table above or below the ground surface, as opposed to just a measure of the amount of water above the transducer.

### ***3.3.3 Soil Properties***

In order to determine soil properties, cores were taken from each cell using a peat profile sampler (Wardenaar, Eijkelkamp). The sampler was pushed vertically down into the peat in a back and forth motion to the point where the base of the corer hit denser material, (clay), which marked the base of the cell. Once the core was removed and brought to the surface a small portion of clay liner that was picked up in the sampler was removed. Cores measured 10 cm by 12 cm and varied in depth according to each particular cell. Each core was then wrapped tightly in plastic wrap and placed into pre-made wooden cases designed minimize disturbance to the cores. Figure 3.8 shows the steps of the sampling process. Samples were shipped back to Carleton University. Cores were frozen and then, using a band saw, cut into 5 cm sections of known volume in order to assess soil properties.

Specific yield is the volume of stored water released per unit surface area, per unit decline of water table (Dingman, 2002). Specific yield of each section was calculated by obtaining their 24-hour drainage curves. Sections were thawed for 24 hours, placed in containers, and completely saturated (24 hour soak). Samples were then allowed to drain through a filter (#1, Whatman), with their change in mass being recorded every few minutes at first, then every hour with a final measurement after 24 hours. Conversely, the relative volume of water retained in the aquifer during a water table drop is referred to as specific retention (Dingman, 2002). Specific retention can be estimated as the difference between one and the specific yield.

The sections were then placed in an 80°C oven for 24 hours to evaporate all remaining water. Once dry, bulk density of the sections was calculated. Bulk density was calculated according to equation 3.4:

$$\rho_b = \frac{m_{dry}}{V_s} \quad (3.4)$$

where  $\rho_b$  ( $\text{g cm}^{-3}$ ) is the bulk density of the sample ( $\text{g cm}^{-3}$ ),  $m_{dry}$  is the mass of the oven-dried sample, and  $V_s$  is the volume of the section. From the estimation of bulk density, porosity of the samples can be estimated using equation 3.5

$$\emptyset = 1 - \frac{\rho_b}{\rho_s} \quad (3.5)$$

$\emptyset$  represents porosity (no units),  $\rho_b$  is the bulk density of the subsection and  $\rho_s$  is the organic particle density. Organic particle density has been noted to range from 1.0 to 1.5  $\text{g cm}^{-3}$  depending on the degree of decomposition (Young and Spycher, 1979; Golchin et al. 1994; Hassink, 1995; Ladd et al. 1995; Skopp, 2000; Ellies et al. 2003). Decomposition was moderate so a value of 1.3  $\text{g cm}^{-3}$  was selected for the organic particle density.

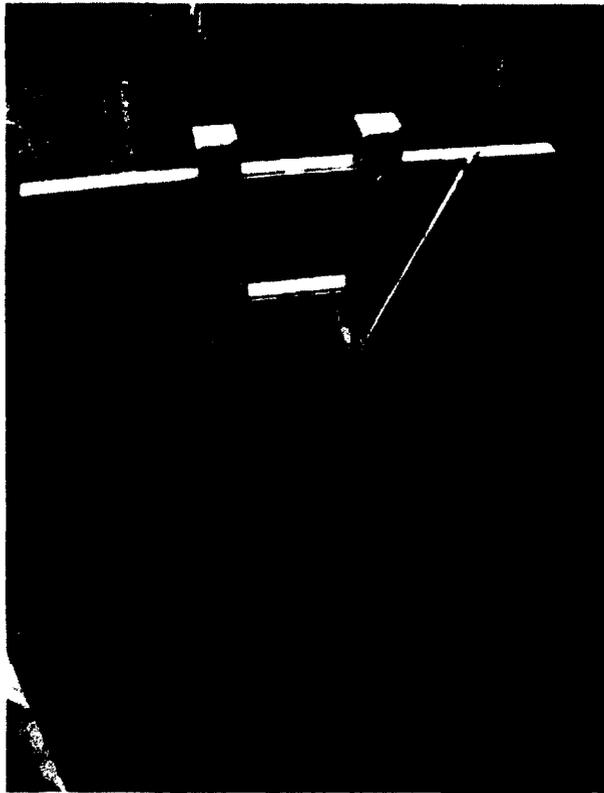


Figure 3.8 Soil Sampling using the Wardenaar peat profile sampler.

### ***3.3.4 Statistical Analysis and Modeling***

Data was prepared in Microsoft Excel (2011) and then imported into R statistical software (R Development Core Team, 2009) for further analysis. ET by cell and micrometeorological factors were organized as a daily time series. Certain environmental variables related to ET were calculated from existing measurements. For example, as VPD was not measured directly, it was determined using the air temperature and relative humidity (RH). Also, depth of the water table from the surface had to be determined using the levellogger data and the manual well stick-up height.

Descriptive statistics, histograms and quantile-quantile plots were used to assess data normality in order to determine appropriate statistical tests. The majority of the variables were reasonably normally distributed. However, some groups of data, specifically cell ET time series that lacked a sufficient number of measurements, showed some skewness and/or kurtosis. Where necessary, non-parametric tests were conducted.

The ET data sets for each cell were grouped according to treatment variable to test the effects of different treatment methods on evaporative losses over the study period. As some ET groupings were significantly skewed, a Wilcoxon rank-sum test was used to test differences among the treatments variables of placement period and soil/vegetation type (2 levels). Differences attributable to soil depth (3 levels), were tested using one-way ANOVA based rank-sum tests. Each test was performed at the 95% significance level. These tests provided information into which treatment variables may have had an effect on ET.

In order to gain insight into which environmental factors may have been controlling ET under specific conditions, a series of linear regressions and correlation analyses were performed. Simple linear regression was first conducted on controlling environmental factors such as incoming solar radiation, air temperature, VPD, wind speed and depth of the water table. However, bivariate linear regression was not able to explain the complex process of ET in these cells and how it is controlled and regulated by many environmental factors simultaneously; this was indicated by the few significant correlations between individual variables and ET. Therefore, multiple linear regressions were performed in R to better understand and represent the process of ET at this site. Multiple linear regression models that incorporated all 5 of the environmental variables at a time were created in R for each cell, each treatment group and for the entire site as a whole. Initially these models displayed only marginally better correlations than the individual ones. However, the addition of interaction terms to the multiple linear regression models produced very strong correlations with ET. These multiple linear regression models with interactions incorporate the individual effects of each of the five environmental explanatory variables on ET, but also create new variables that represent the effects of two or more of the variables on ET. In this concept of explanatory variable interactions, the simultaneous effects of two or more variables on a resultant process are not simply additive, but a change in one variable can result in a change in the relationships between the response variable and a second independent variable. Because a new variable is created for every potential interaction between two or more of the five environmental variables, each model could, in theory, have up to 31 possible variables to explain the change in ET. However, not all

variables were relevant in explaining the resulting ET and so variables that were not significant at the 95% level were manually removed using a reverse step-wise process (AIC). This formula (equation 3.7) is essentially a measure of deviance that can be used to determine if an extra explanatory variable is warranted.

$$AIC = -2\log - likelihood + 2p \quad (3.6)$$

Here,  $p$  represents the number of parameters in the model and is the “penalty” added to the criterion for every explanatory variable added to the model. A lower AIC score is preferred to a higher and unless an additional variable causes a reduction in deviance of at least 2, AIC will not decrease, and the additional explanatory variable was not warranted (Crawley, 2005).

Creating multiple linear regression models with interaction terms can lead to over-fitting of the data. Over-fitting may be a common occurrence when the number of explanatory variables is large compared to the number of real observations. There is often a trade-off between model simplicity and fit and so the ideal model is generally a compromise of the two (Crawley, 2005). As a rule of thumb, Crawley (2005) suggests that the number of explanatory variables ( $v$ ) should never exceed one-third of the number of observations ( $n$ ). Failure to adhere to this rule may result in a better fit of the data but only with a very complicated model that may well have a single parameter to explain each observation.

In order to obtain more insight into the complex process of ET at the site and potential predictive uses while minimizing the risk of over-fitting the data, the statistical method of recursive partitioning or “tree” modeling was used in R (Breiman et al. 1984). Recursive partitioning can be very useful for interpreting which

explanatory variables most strongly influence the response variable, and for identifying potential statistical interactions between explanatory variables. Recursive partitioning systematically selects threshold values for each explanatory variable and divides the data according to that threshold. It then computes the number of explained variances associated with that partition and proceeds to split the dataset into two new groups according to the variable and threshold value with the most explanatory power. This process is then repeated recursively for each new group until no further variance can be explained (a saturated model) or an *a priori* stopping point is reached. The result is a decision tree with each node showing the variable and threshold that explained the most amount of variance for that particular subset of the data. The tree can then be “pruned” to contain the number of branches that best reflects the best trade-off between nodes and total deviance.

Recursive partitioning trees may also help to highlight the presence of statistical interactions among the explanatory variables on the resultant process. Modeling via recursive partitioning, as with multiple linear regression, may help to highlight potential interactions, which becomes useful when attempting to understand correlations and model data for uses in gap filling practices.

Tree models were created for each cell and for pooled groups according to construction techniques using ET observations. Models were then “pruned” manually to lowest number of branches (decisions) after which any further added branches failed to improve the predictive ability by a significant margin. The optimum point in which to prune was determined by plotting deviance against the size of the model and finding the inflection point of this plot. The inflection point, or the last point in which the

increase in size (complexity) of the model is not balanced out by a reduction in deviance and is thus deemed not to be beneficial to the model, was chosen as the optimum number of branches for the model. Tree models were then tested by comparing predicted ET to actual observations and assessing the models' residuals.

Both multiple linear regression and recursive partitioning models provided interesting and valuable insight into ET and the idea of variable interaction. However, recursive partitioning tree models were used for gap filling practices in order to complete individual cell water balances. These models were deemed to produce reliable predictions of ET using the five controlling environmental variables without producing extreme outliers due to model over-fitting.

## 4.0 Results

### 4.1 Study Site Conditions

#### 4.1.1 General Climate (Precipitation and Temperature)

The weather during the study period (2010 growing season) was warmer and much drier than the 30-year climate normal (Table 4.1). Both June and July experienced warmer than normal mean temperatures, 16.7°C compared to 14.7°C in June and 18.5°C compared to 16.8°C in July, while August was slightly cooler than normal at 15.1°C compared to 15.3°C. June and July also experienced much less precipitation than normal. Only 14.7 mm of precipitation fell compared to the 74.8 mm normal in June, while July saw 51 mm compared to the 81.3 mm normal.

The study site was located about 50 km north of the Fort McMurray airport and weather conditions were noticeably different. This was particularly true of precipitation, as it often fell as isolated showers or convective storms during the early portion of the summer. June in particular was warmer and drier at the study site with only 14.7 mm of precipitation at the study site compared to 49.5 mm at Fort McMurray airport.

Table 4.1 2010 growing season weather as compared to the 1971-2000 climate normal for the Fort McMurray airport (Environment Canada).

<b>Air Temperature (°C)</b>			
	<b>June</b>	<b>July</b>	<b>August</b>
<b>1971-2000 Normal</b>	14.7	16.8	16.1*
<b>Fort McMurray Airport</b>	15.5	17.4	17.0*
<b>Study Site</b>	16.7	18.5	17.8*

\* August 1<sup>st</sup> to 18<sup>th</sup>, 2010.

<b>Precipitation (mm)</b>			
	<b>June</b>	<b>July</b>	<b>August</b>
<b>1971-2000 Normal</b>	74.8	81.3	40.8**
<b>Fort McMurray Airport</b>	49.5	58.0	31.5**
<b>Study Site</b>	14.7	51.0	40.0 **

\*\* August 1<sup>st</sup> to 18<sup>th</sup>, 2010.

#### **4.1.2 Microclimate Conditions**

Daily mean fluxes of incoming short wave radiation, VPD, wind speed and air temperature are presented in Figure 4.1. As mentioned, daily fluxes were measured from 12 pm to 12 pm and values represent the preceding 24 hr period.

Shortwave radiation was highest near the beginning of the study period in mid-June (DOY 167-176), and began to diminish thereafter (Figure 4.1a). Incoming radiation can be expected to peak around the summer solstice. However, this was not the case in this study as radiation peaked shortly before the solstice. The early peak may have also been produced by a long period of high atmospheric pressure in June that resulted in many clear sky days, followed by a period cloudy days later in the month. Other periods of high pressure in July resulted in short periods of high shortwave radiation (DOY182-184, DOY 201-205 and DOY 207-209), yet those periods were still part of a gradual declining trend from June peak.

VPD followed a similar trend to solar radiation, having relatively high deficits in mid-June and then transitioning to smaller deficits later in the study period (Figure 4.1b). There is one exception to this: VPD had its largest value in late July (DOY 201-204), during a 3-4 day spike that saw mean daily values reach 1.6 kPa. This was likely caused by particularly warm, dry weather at the site, as there were corresponding increases in solar radiation and air temperature.

Wind speed at the cells (measured at a height of 2.8 m) fluctuated considerably (Figure 4.1c). Daily average wind speed exceeded  $4 \text{ ms}^{-1}$  on eight days during the study (DOY 159, 182-185, 194, 206 and 226) and peaked at  $5.2 \text{ ms}^{-1}$  (DOY 183). While daily average wind speed peaked at just over  $5 \text{ ms}^{-1}$ , half hour average speeds

were often much higher reaching speeds of nearly  $9 \text{ ms}^{-1}$ . Typically, wind speeds were higher in the afternoon, often producing small dust storms and blowing loose vegetation/debris.

Mean daily air temperature was relatively stable during the study period (Figure 4.1d). Daily average temperatures rarely fell below  $14^\circ\text{C}$  (DOY 159-161, 229) or exceeded  $20^\circ\text{C}$  (DOY 164,193,195-6, 204-5, 210-11, 218). Of note is that the mean daily air temperature appeared to increase towards the end of the study reaching a peak of  $24^\circ\text{C}$  in late July (DOY 205). Warm temperatures continued through the beginning of August, even though there was a noticeable decline in the incoming solar radiation.

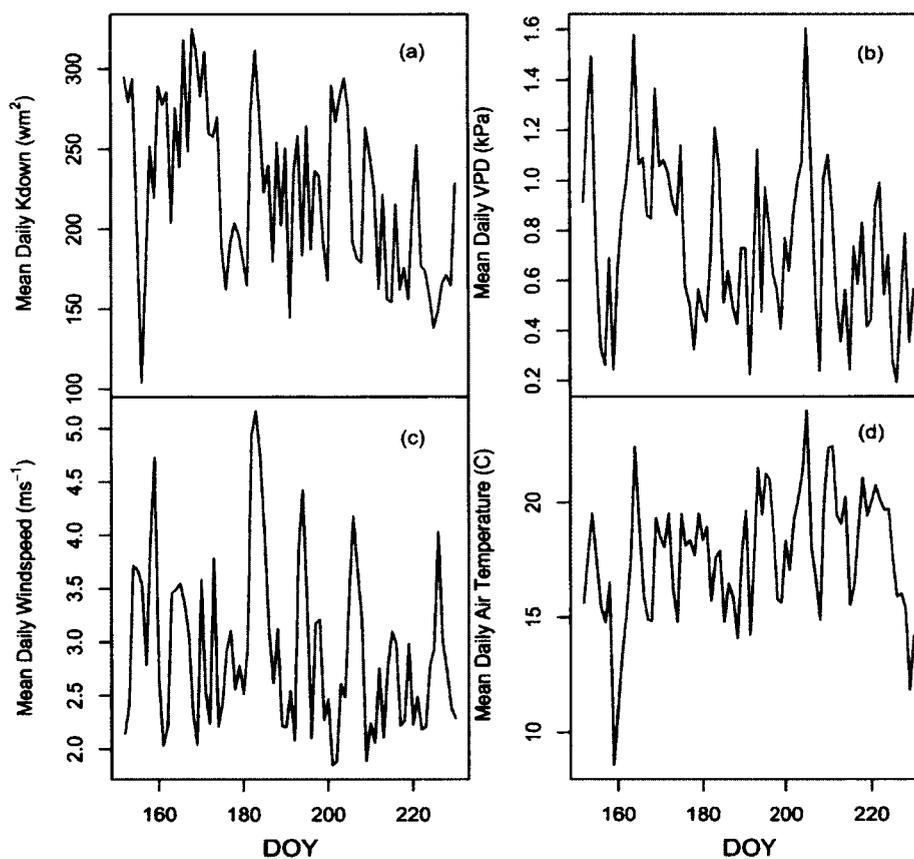


Figure 4.1 Mean daily (12 pm to 12 pm) fluxes of microclimate variables: incoming solar radiation (a), VPD (b), wind speed (c), and air temperature (d) over the course of the study period.

### **4.1.3 Water Table Depth**

The water table was kept artificially high by means of irrigation and many of the cells underwent frequent wetting and drying cycles. Mean daily water table depth for each of the 12 cells is shown in Figure 4.2. Water table depth was measured at a central location in each cell using a pipe piezometer. It should be noted that many of the cells had variable microtopography, so the recorded values are representative of the water table to ground surface relationship at that point in the cell.

Each cell had a unique hydroperiod. Six cells were submerged at the measurement point for the entire study period (S-P-15cm, S-S-15cm, W-P-15cm, W-P-50cm, S-P-100cm, W-P-100cm), while four cells never experienced ponded water (W-S-15cm, W-S-50cm, S-S-100cm, W-S-100cm). The remaining two cells (S-P-50cm and S-S-50cm) had a water table that fluctuated above and below the surface. Transplanted peat cells, particularly those constructed in the winter, had higher water tables compared to those constructed in summer. These cells tended to have greater variation of micro-topography, with open water a common occurrence in fractures among the peat blocks. Deeper cells (100 cm) also typically experienced greater fluctuations in water table depth, likely because they received long, but infrequent, irrigation.

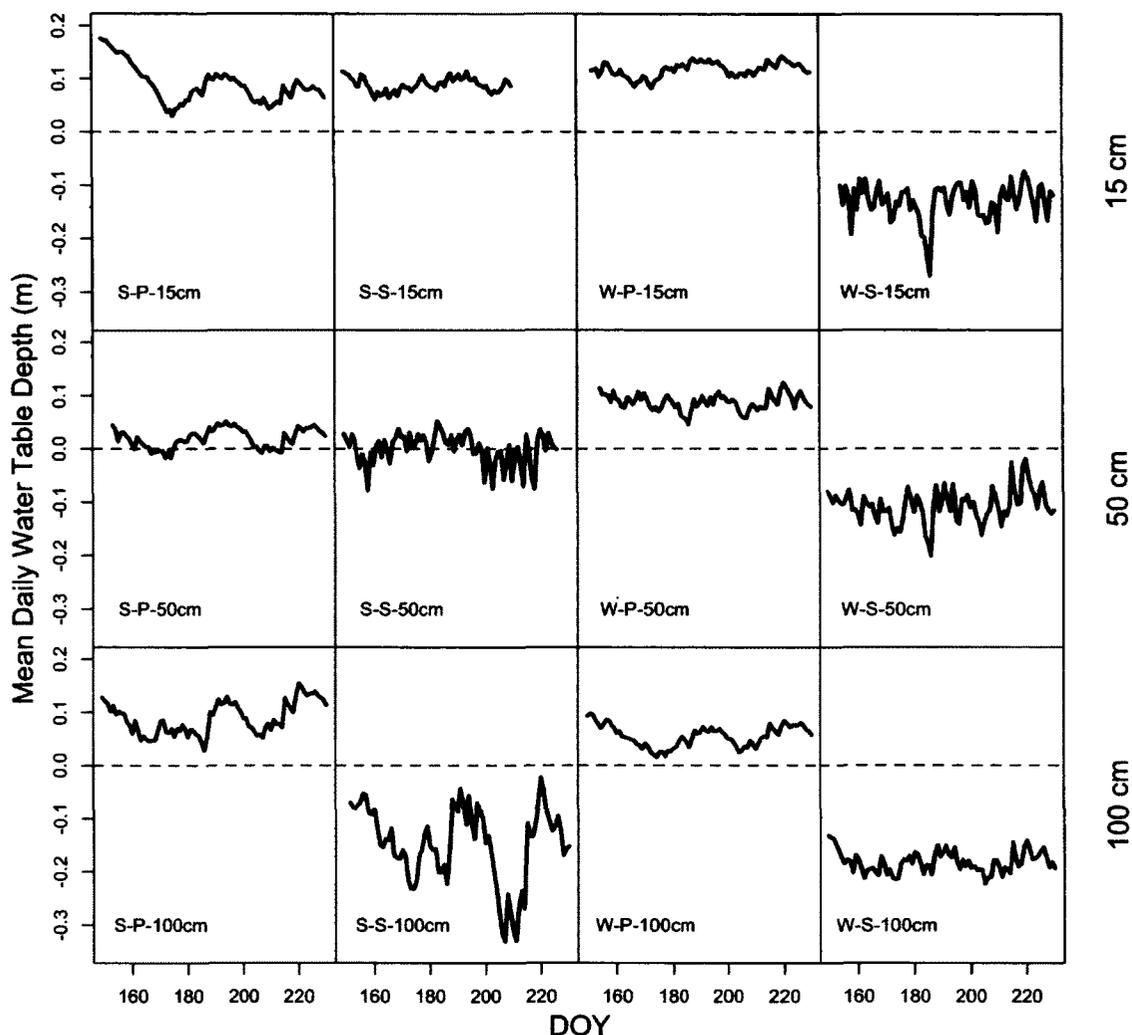


Figure 4.2 Mean daily (12 pm to 12 pm) hydroperiods for each cell for the duration of the study period. Dashed lines represent the ground surface at the measurement point.

#### 4.1.4 LAI

Because of instrument malfunction, LAI measurements began at the end of June and were performed approximately every 15 days from that point on (Figure 4.3). LAI exhibited an increase during the study period due to vegetation growth throughout the growing season.

In the 15 cm cells (top row, Figure 4.3), LAI increased slightly over the growing season. However, with less vegetation already established, the increases in

LAI were not as great as increases at the deeper cells. The increase in LAI in the 50 cm cells (middle row, Figure 4.3) was notable during the latter stages of the growing season. The deepest, 100 cm cells (bottom row, Figure 4.3) had variable trends, the two stockpiled peat mixture cells had very prominent increases and the two transplanted peat cells had very little change in LAI.

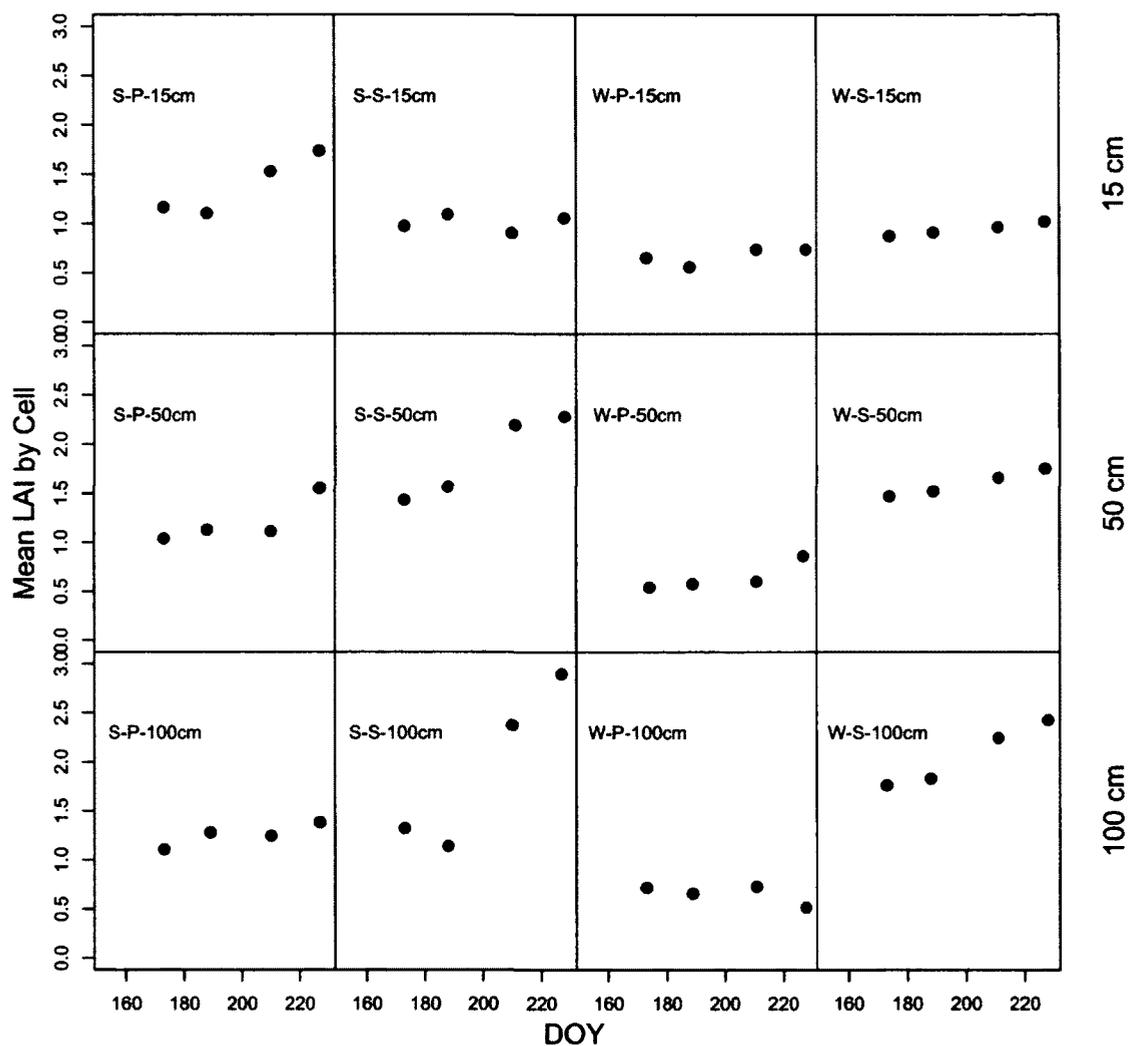


Figure 4.3 LAI progression in each cell over the study.

The differences in LAI progression between the soil type, peat transplant and stockpiled mixture, were evident across all depths. At first, LAI was generally similar across all cells regardless of construction techniques. As the season progressed, deep

cells and/or those with stockpiled soil mixture began to undergo increases in LAI. The 100 cm stockpiled soil mixture cells experienced the greatest increase of any cells and also displayed the largest LAI of the study.

The apparent connection between LAI increase and soil type and soil depth is associated with the large number of invasive cattails (*Typha latifolia*) growing in these cells. The cattails appeared in the cells during the 2009 growing season and have since begun to take over many moist sections of the cells, particularly stockpiled cells. These species were not intended to be in the cells and so must have established from seed after blowing in. Figure 4.4 shows a photo of the same cell in early June and again in mid-August, showing the large growth of the cattails. This species of plant is extremely fast growing and may have grown upwards of 1 m in some cells over the course of the study.

## 4.2 Growing season ET

### 4.2.1 Daily ET rates

Across all cells, measured daily ET rates ranged from  $\sim 0.6 \text{ mm day}^{-1}$  to over  $8.2 \text{ mm day}^{-1}$ , with mean daily ET ranging from  $\sim 1.2 \text{ mm day}^{-1}$  to  $5.8 \text{ mm day}^{-1}$  (Figure 4.6). Early June experienced a day of very high mean ET (DOY 153) then stabilized and maintained a relative high ET rate for nearly two weeks (DOY 158-169). Late June (DOY 170-180) saw a steady period of light rain, which resulted in lower ET rates (for the days in which measurement was possible). Near the beginning of July there were several days of relatively high ET (DOY 181-182) that was followed by a long period in which convective storms were common, limiting the number of measurements to

four between DOY 183 and 199. Late July experienced a small period of increased ET rates (DOY 200-204) after which they began to decline notably. Throughout August, daily ET rates were relatively low ( $\sim 2 \text{ mm day}^{-1}$ ), with the lowest recorded values coming shortly before the end of the study (DOY 227, 229).

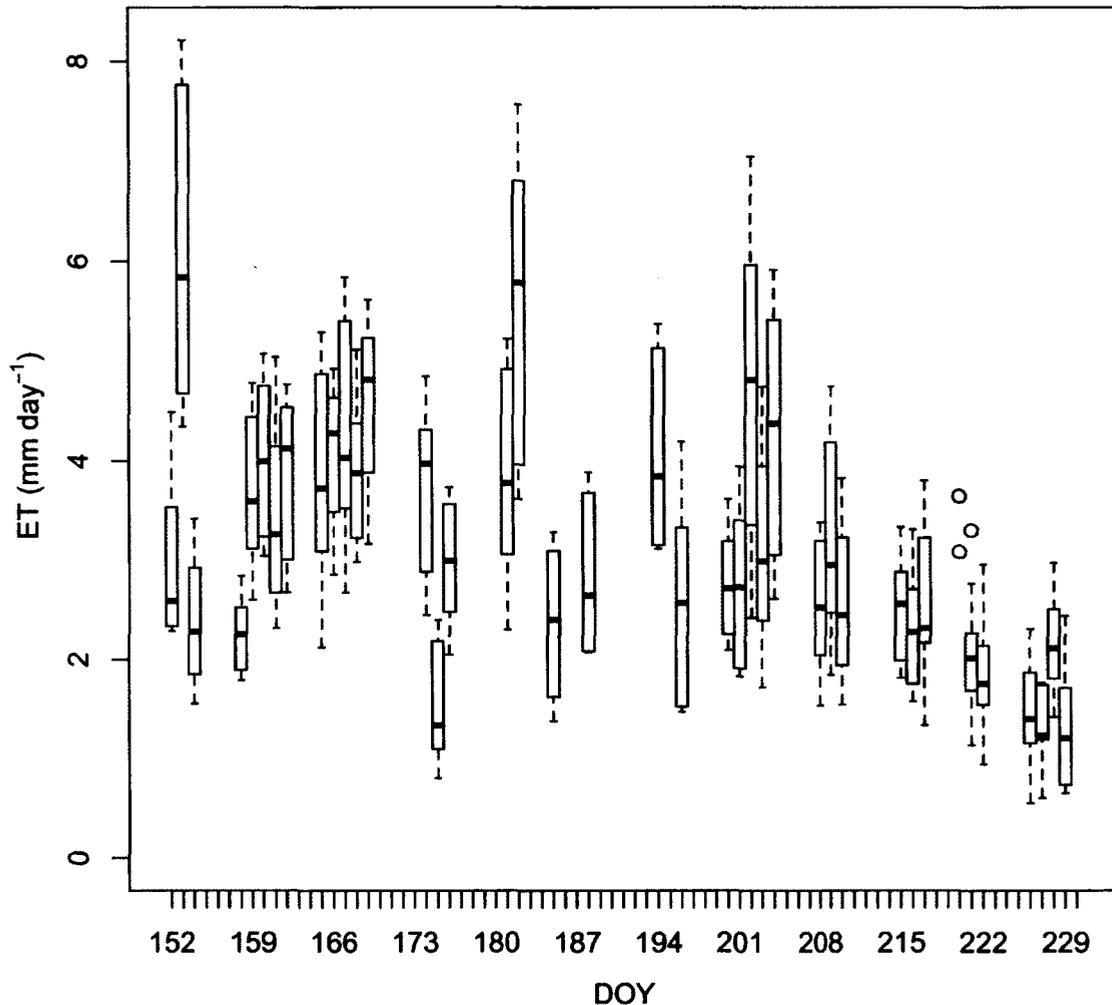
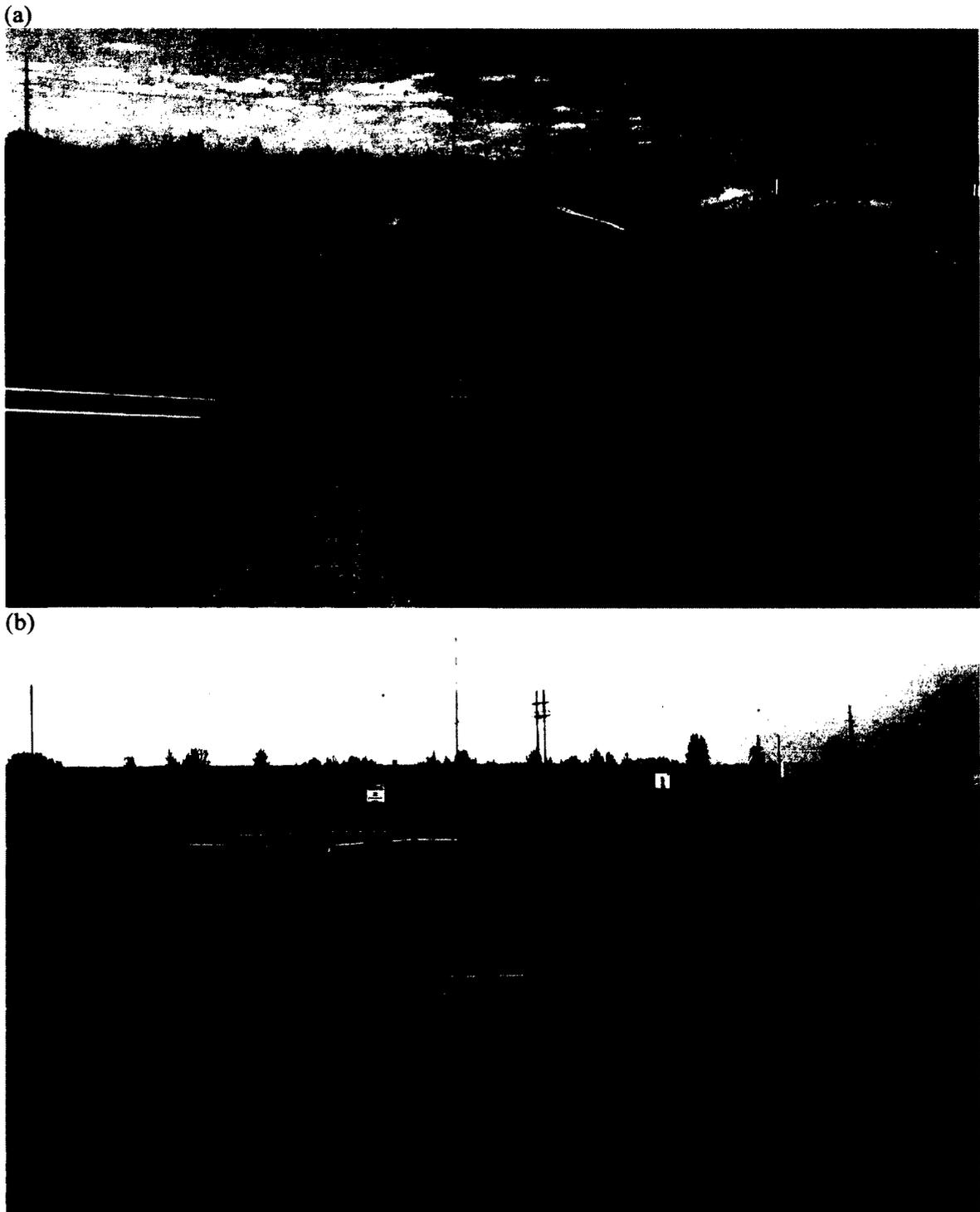


Figure 4.4 Boxplots showing the daily pooled ET data from all the cells over the course of the study period. Missing boxes indicate days with no data for any cell. Upper and lower limits of the boxes indicate the first and third quartiles respectively while the whiskers indicate the range of observations. Mean values are represented by a solid line and circles (○) represent outliers.

ET varied noticeably by cell (construction technique combination) and by DOY (Figure 4.6). Daily ET at the study site reached its peak early June (DOY 153) for the majority of the cells with other high rates also occurring later in the month (DOY 167-169). ET rose again for short periods in July (DOY 182, 202, 204) and then began to diminish, with much lower rates in August for most of the cells. Overall, daily ET exceeded  $7 \text{ mm day}^{-1}$  on seven occasions, with a maximum of  $8.2 \text{ mm day}^{-1}$  (DOY 153, W-S-50cm). All seven of these occasions occurred for winter placement cells of varying soil mixtures (four peat, three stockpiled mixture) and depths (four 15 cm, two 50 cm, one 100 cm).



**Figure 4.5** The 100 cm stockpiled soil mixture summer placement cell at the beginning of the study (a) and the same cell at the end of the study period (b). Notice the dramatic increase in the vegetation especially the cattails and grasses.

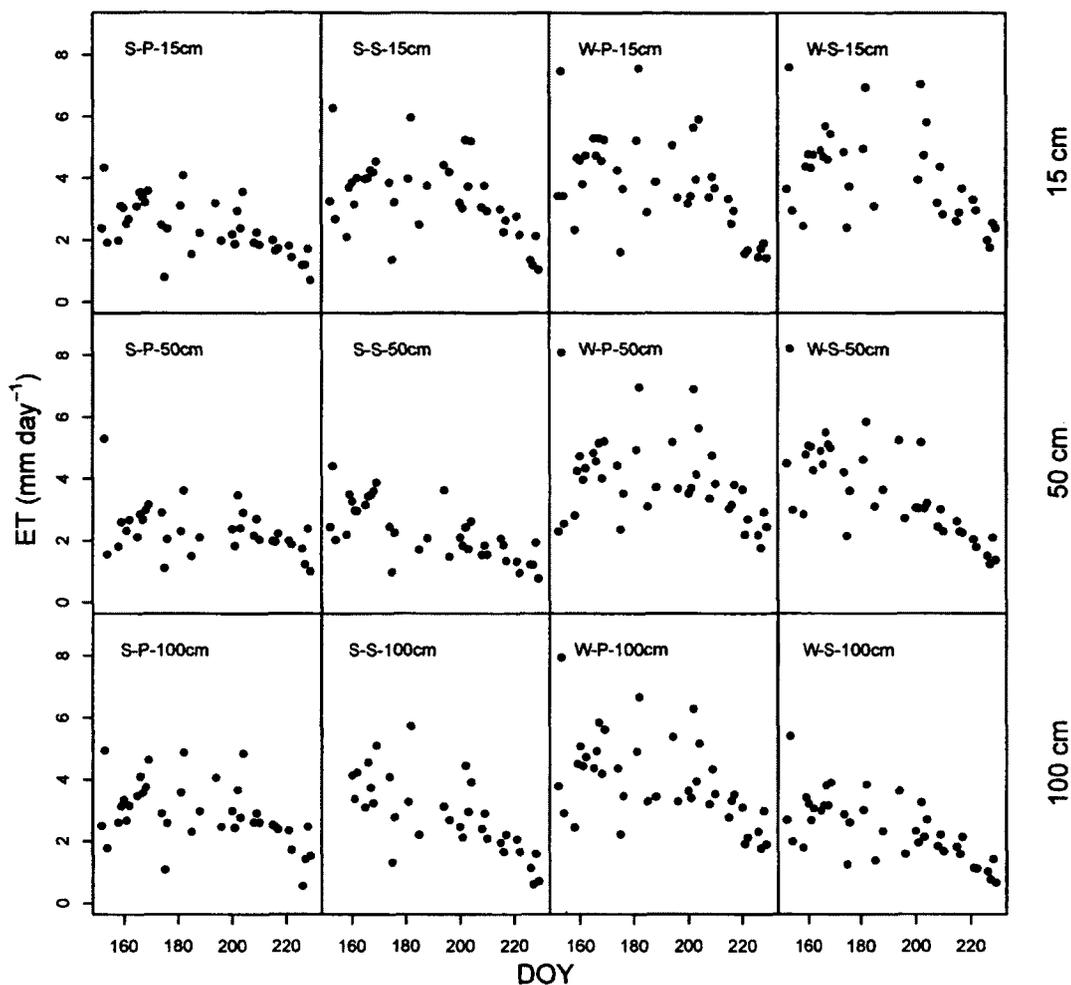


Figure 4.6 Daily ET measurements in each cell for the duration of the study period.

In order to compare ET within the cells as well as between them, boxplots of ET for each cell were generated (Figure 4.7). In general, ET was lower for cells constructed in summer than for those constructed in winter. Also, the deeper cells (50 cm, 100 cm) typically had lower ET rates than the shallower cells (15 cm) of similar construction techniques. To view the effect of construction techniques on ET, data was grouped according to the three major treatments: placement period, soil type, and soil depth. Boxplots of growing season ET grouped according to placement period (Figure

4.8), soil type (Figure 4.9) and soil depth (Figure 4.10) help reveal the differences that may be attributable to that particular construction technique. Placement period (Figure 4.8) appears to have had an effect on ET. Cells constructed in winter had a higher maximum, minimum and total range of daily ET and mean ET was nearly 1 mm greater in winter constructed cells than in summer ones.

In contrast, soil type and soil depth appeared to have limited effect on daily ET differences. Cells filled with the stockpiled mixture had ET rates similar to those filled with live transplanted peat. Stockpiled cells had a slightly smaller range of ET rates, but the mean daily ET values were similar –  $2.27 \text{ mm day}^{-1}$  compared to  $2.16 \text{ mm day}^{-1}$  for stockpiled and transplanted respectively. Soil depth had a small, yet noticeable, effect on ET suggesting decreasing ET with increasing depth of soil but the differences were quite small. The shallower 15 cm cells had slightly higher maximum, minimum and mean daily ET rates than the deeper cells of comparable construction. Deeper 100 cm cells typically had lower maximum and minimum daily ET rates. Mean daily ET rates for the 50 cm were the lowest observed, albeit only slightly lower than in the 100 cm cells.

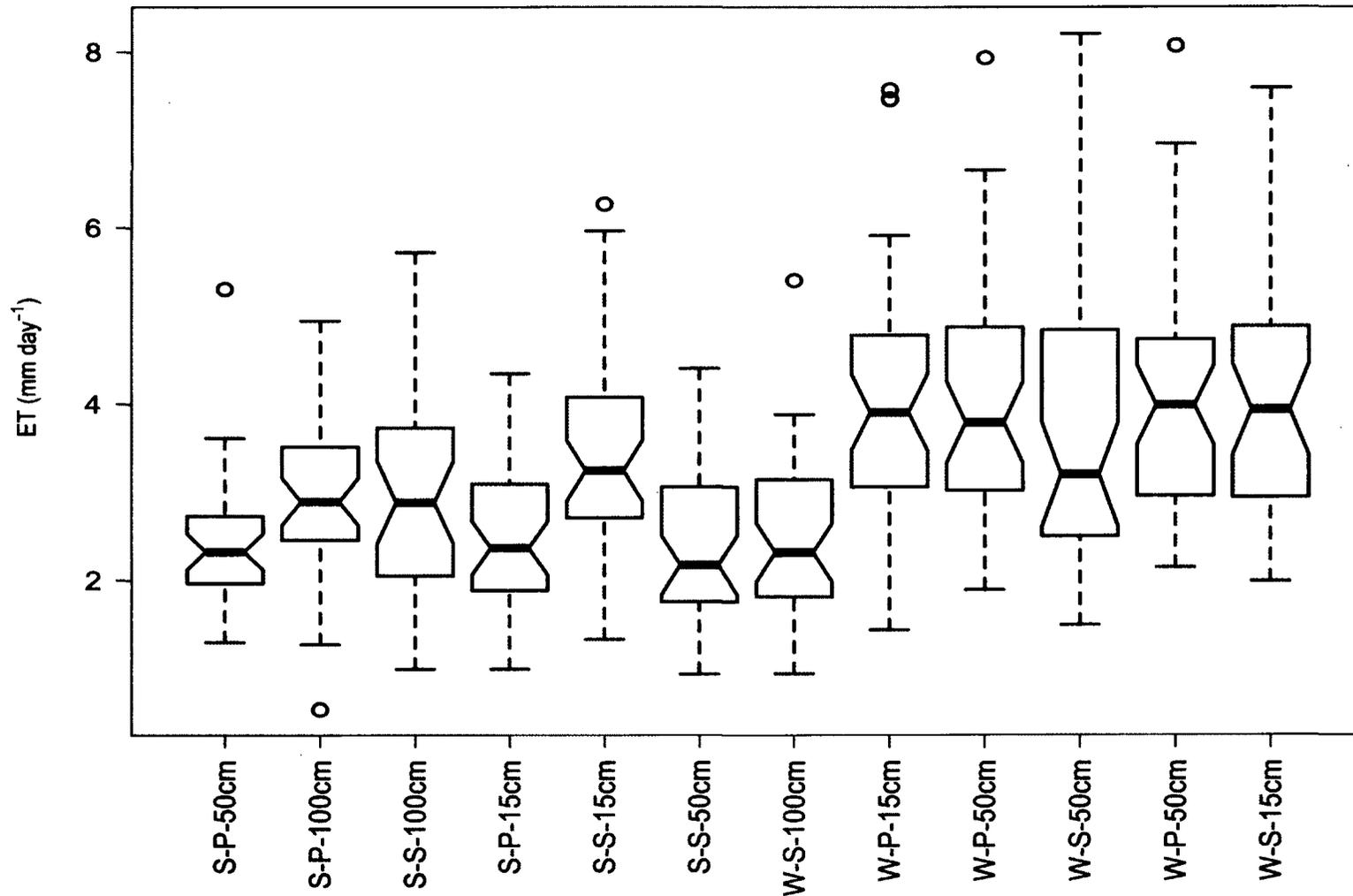


Figure 4.7 Boxplot displaying statistical information on daily ET for each cell over the course of the study period. Upper and lower limits of the boxes indicate the first and third quartiles respectively while the whiskers indicate the range of observations. Mean values are represented by a solid line and circles (o) represent outliers. Notches indicate the 95% confidence intervals.

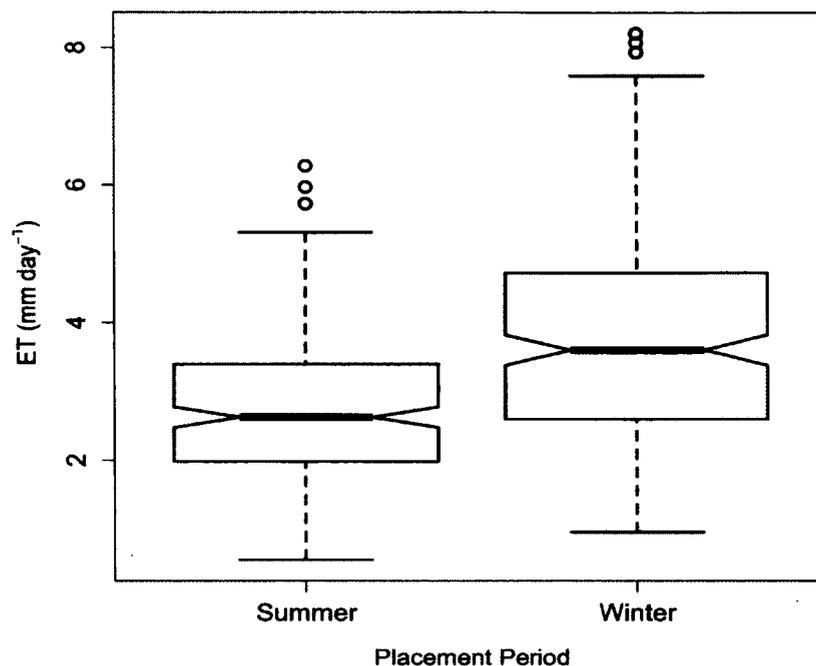


Figure 4.8 Boxplot displaying daily ET for the duration of the study period pooled according to placement period. Upper and lower limits of the boxes indicate the first and third quartiles respectively while the whiskers indicate the range of observations. Mean values are represented by a solid line and circles (o) represent outliers. Notches indicate the 95% confidence intervals.

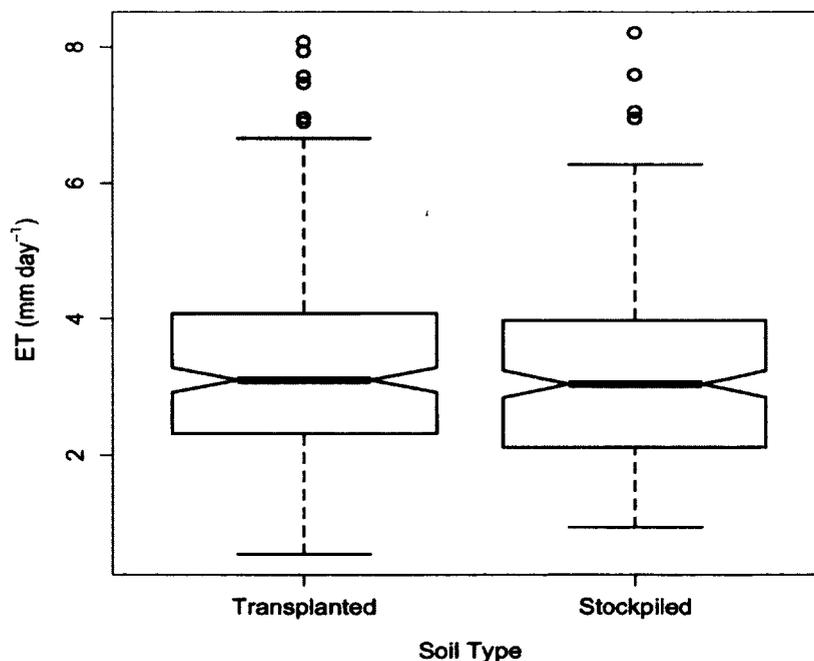


Figure 4.9 Boxplot displaying daily ET for the duration of the study period pooled according to soil type. Upper and lower limits of the boxes indicate the first and third quartiles respectively while the whiskers indicate the range of observations. Mean values are represented by a solid line and circles (o) represent outliers. Notches indicate the 95% confidence intervals.

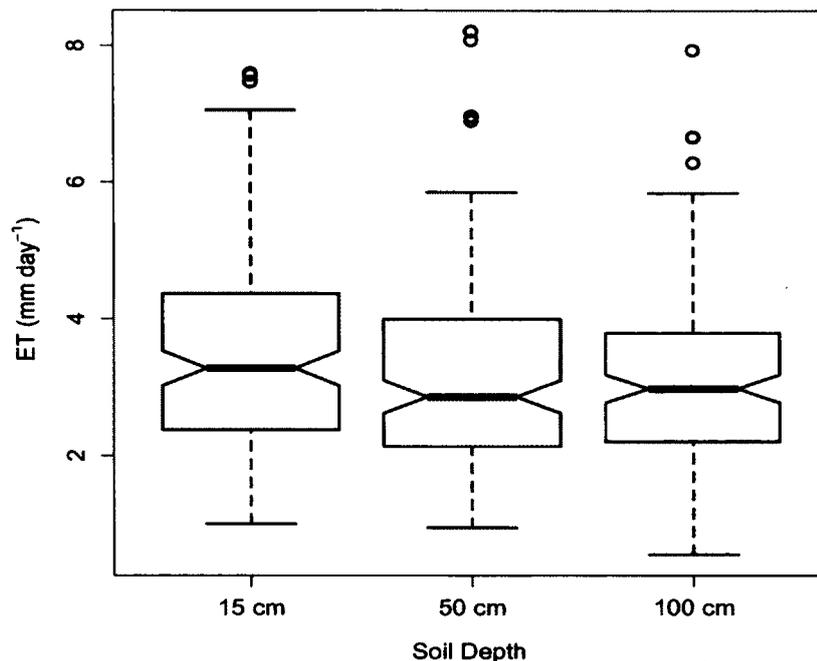


Figure 4.10 Boxplot displaying daily ET for the duration of the study period pooled according to soil depth, Upper and lower limits of the boxes indicate the first and third quartiles respectively while the whiskers indicate the range of observations. Mean values are represented by a solid line and circles (o) represent outliers. Notches indicate the 95% confidence intervals.

#### 4.2.2 Statistical Testing

The statistical significance of the differences in ET caused by construction techniques was assessed using a variety of statistical tests. The data was analyzed for normality and most groups of cells showed near normal tendencies. However, some groups did indicate some degree of skewness, and groups were also checked for statistical differences using non-parametric tests (e.g. Wilcoxon rank sum test or Kruskal-Wallis rank sum test), which do not require the assumption that the data is normally distributed. These tests use ranks of the data within a group and produce generally more conservative results than parametric tests. Using non-parametric tests generally lowers the chance of committing Type 1 and Type 2 errors (accepting a false

hypothesis or rejecting a true hypothesis). A summary of the findings is highlighted in Table 4.2.

Table 4.2 Statistical significance test results for the effects of construction techniques on ET. Both parametric and non-parametric tests at the 95% confidence level were used. Only placement period resulted in significant differences in ET. Significant differences are indicated in bold.

Factor	Wilcoxon Rank-Sum Test	Kruskal-Wallis Rank-Sum Test
Placement Period	<b>W = 15896</b> <b>p-value &lt;0.001</b>	n/a
Soil Type	W = 27369 p-value = 0.25	n/a
Soil Depth	n/a	<b>Chi-squared = 6.88</b> <b>p-value &lt;0.05</b>

Placement period proved to be a statistically significant factor for ET at the 95% level. The Wilcoxon rank sum test confirms that cells constructed in winter have consistently higher daily ET rates than those constructed in summer over the duration of the study period. A possible explanation for this is that winter cells were visibly more degraded, with less vegetation and more areas of open water.

In contrast, there were no significant differences between the cells of different soil type. Cells filled with transplanted peat or stockpiled mixture had similar ET rates (3.24 mm day<sup>-1</sup> to 3.09 mm day<sup>-1</sup> for peat and stockpiled respectively), even though vegetation and irrigation regimes varied between the two construction techniques. The high *p* value confirms that ET rates in cells of each of the two different soil types were not significantly different.

To compare the three soil depth groups, an ANOVA based test in which the difference of means can be tested for three or more groups was used. Again, because the data showed some degree of non-normality, the non-parametric Kruskal-Wallis

rank sum test was used to assess statistical significance. The results indicated that there was at least one significantly different daily ET in cells of different depths. However, the  $p$ -value was relatively high ( $p = 0.032$ ) suggesting the significance may be low. Because the Kruskal-Wallis rank sum test only indicated the presence of a significant difference, and not which group is causing this difference, a pair wise matrix analysis, in which each depth is compared to each other depth in one to one paired tests was also performed. The results of this analysis are presented in Table 4.3.

Table 4.3 Pairwise difference of means and the associated Wilcoxon Rank Sum Test significance test results at the 95% level. Upper diagonal portion shows the actual difference in daily mean ET between the two depths while the lower diagonal section reports the corresponding  $p$ -value at the 95% significance level. Significant differences are indicated in bold.

	15 cm	50 cm	100 cm
15 cm	–	<b>-0.32 mm day<sup>-1</sup></b>	<b>-0.38 mm day<sup>-1</sup></b>
50 cm		–	+0.055 mm day <sup>-1</sup>
100 cm			–

Soil depth had a significant effect on ET but only for the shallowest cells (15 cm). The 15 cm deep cells had significantly higher daily ET rates compared to the deeper 50 cm and 100 cm cells, while no significant difference was detected between the two deepest soil depth groups (50 cm and 100 cm). Although the differences in ET between the 15 cm cells and the two deeper ones were significant, the magnitude of the difference is relatively small (0.32 - 0.38 mm day<sup>-1</sup>).

#### **4.2.3 ET and Environmental Factors – Linear Regression and Correlation**

To assess the relative influence of environmental factors in controlling variations in ET, exploratory correlations were conducted for individual cell ET with incoming solar radiation, VPD, wind speed, air temperature and water table depth. Figures 4.11 to 4.15 present scatter plots of mean daily ET against daily mean values of each

environmental variable. Linear regression lines and equations with associated coefficients of determination ( $r^2$ ) are presented on the scatter plots for cells that had significant relationships (95%,  $p < 0.05$ ).

Of all the environmental variables, incoming shortwave radiation showed the strongest relationship with ET. All twelve cells had significant positive linear regressions between ET and incoming solar radiation at the 95% level and had  $r^2$  values that ranged from 0.18 to 0.50 (Figure 4.11).

VPD and water table depth showed significant relationship with ET in only a few cells (Figures 4.12 and 4.13 respectively). Three cells had a significant linear regression between ET and VPD at the 95% level (W-S-15 cm,  $r^2 = 0.12$ ; S-P-50 cm,  $r^2 = 0.11$ ; S-S-100 cm,  $r^2 = 0.18$ ). Two cells had a significant linear regression between ET and water table depth, however the relationship was not in the direction that might be expected; one cell had a negative relationship (S-P-100 cm,  $r^2 = 0.21$ ) while one had a positive relationship (S-S-50 cm,  $r^2 = 0.16$ ). Presumably, increased VPD and a water table depth near the surface should result in higher ET, however the linear relationships between these individual variables and ET do not appear to be very strong at this site. This lack of strong relationships of ET with water table depth and, to a lesser extent, VPD is likely influenced by the irrigation regime. Having an excess of water at the surface regardless of the environmental conditions may have created heteroscedastic situation in which the connection between water availability at the surface-atmosphere boundary and ET, was hidden by variability among other factors.

Wind speed and air temperature did not have any significant linear relationships (95%) at the individual cell level (Figures 4.14 and 4.15 respectively).

Looking at the entire site pooled data (all cells) and using the more conservative Spearman rank correlation test, ET was correlated with incoming shortwave radiation ( $r_s = 0.47$ ) and to a lesser extent with the vapour pressure deficit ( $r_s = 0.23$ ). Complete pooled data Spearman correlations are shown in Table 4.4. Water table depth had little effect on ET (Not shown, all cell average  $r_s = 0.12$ ), again likely because the cells were routinely watered and the water table was rarely much below the surface of the cells. Wind speed and air temperature showed very weak correlations with ET.

Table 4.4 A cell pooled data correlation matrix between ET and five controlling environmental factors with the top/right side of the matrix displaying the associated Spearman's rank correlation coefficient ( $r_s$ ) and the bottom/left displaying the corresponding p-value. Significant relationships are highlighted in bold. Also of note are the correlations between controlling factors themselves.

	ET	Shortwave Radiation	VPD	Wind Speed	Air Temperature
ET	-	<b>0.47</b>	<b>0.23</b>	-0.04	-0.05
Shortwave Radiation		-	<b>0.62</b>	<b>-0.28</b>	.02
VPD			-	<b>-0.41</b>	<b>0.53</b>
Wind Speed				-	<b>-0.25</b>
Air Temperature					-

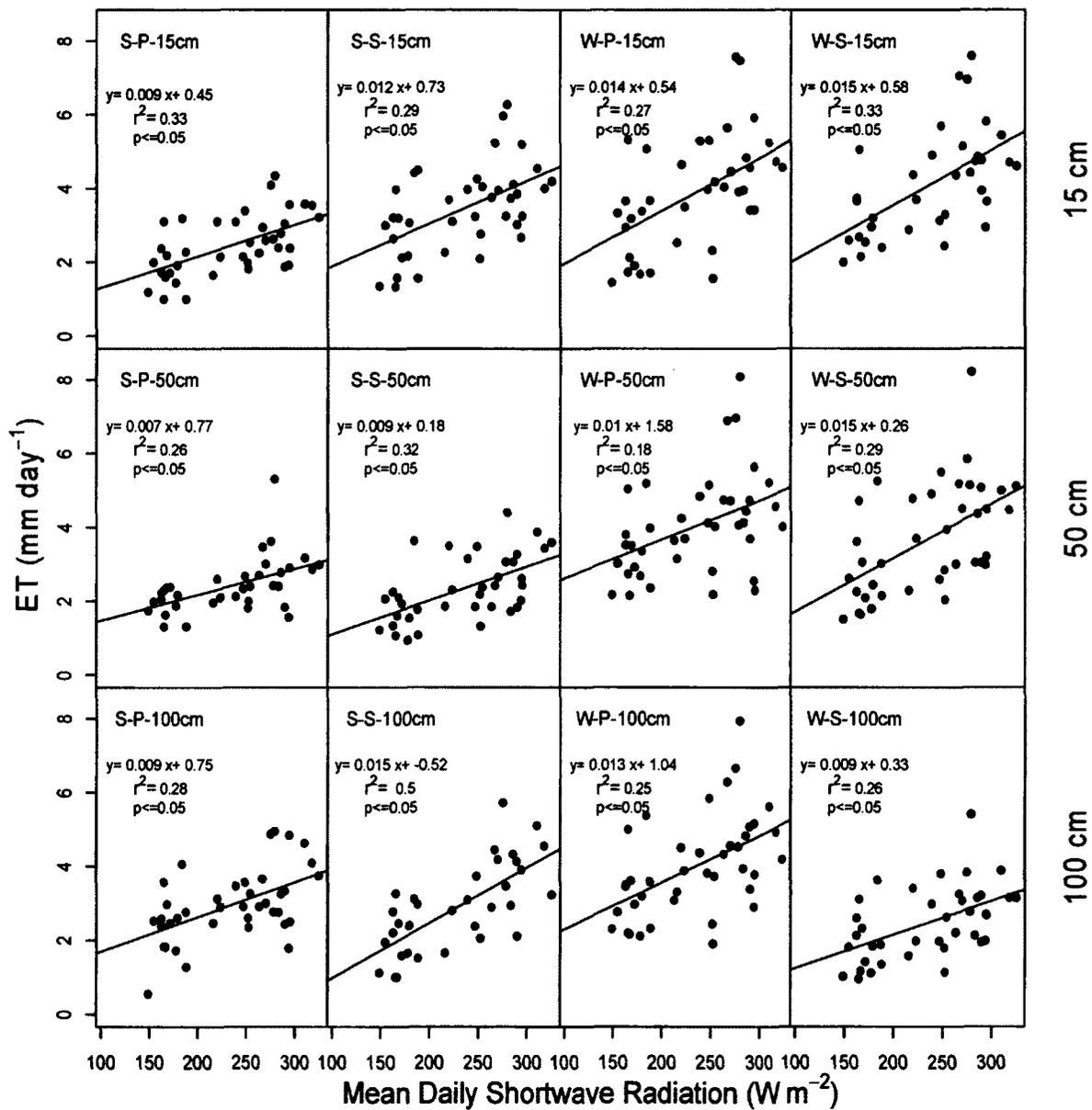


Figure 4.11 Scatter plots of ET and mean daily incoming shortwave radiation for each cell in the study. Correlations significant at the 95% level are shown.

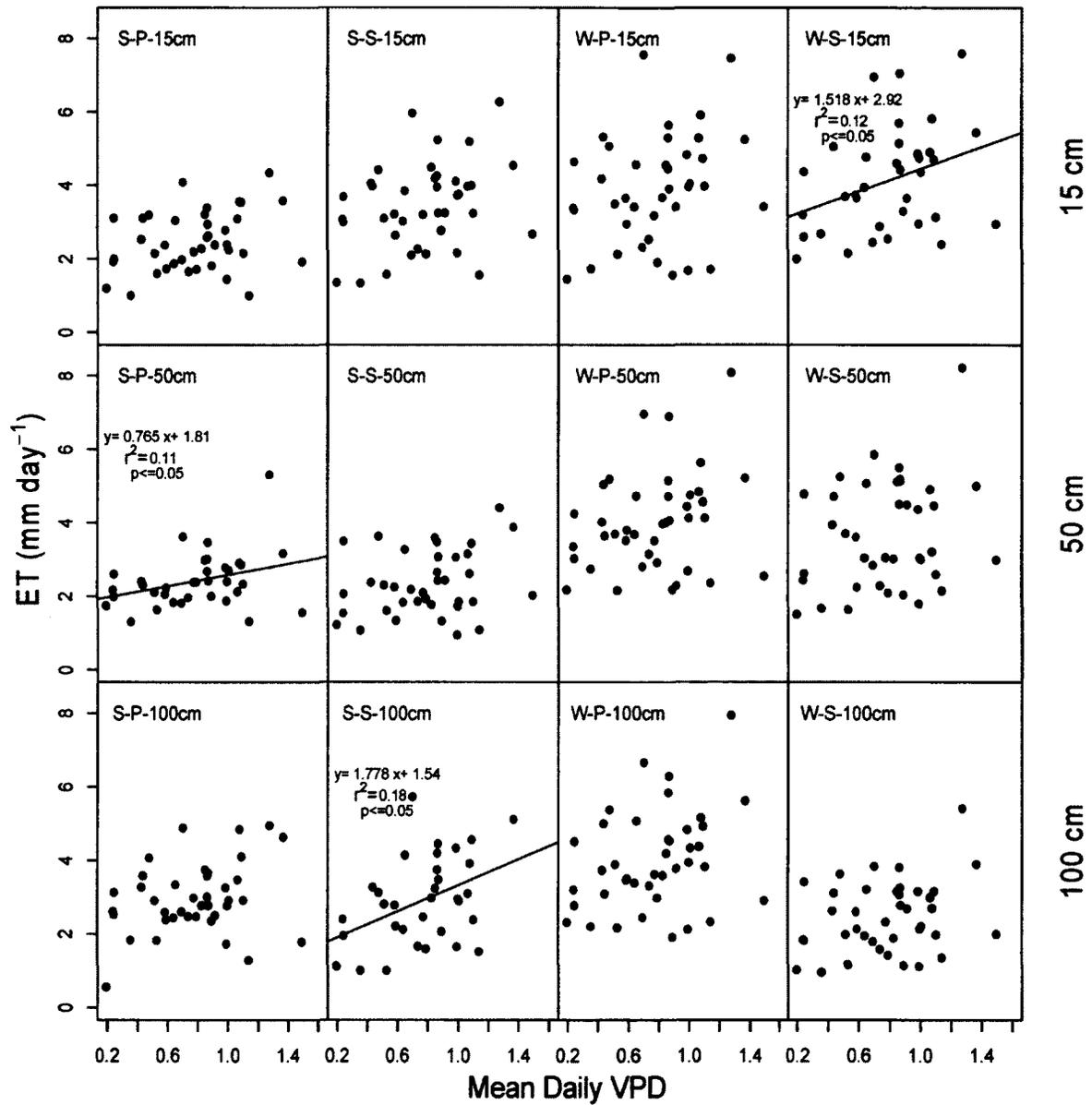


Figure 4.12 Scatter plots of ET and mean daily VPD for each cell in the study. Correlations significant at the 95% level are shown.

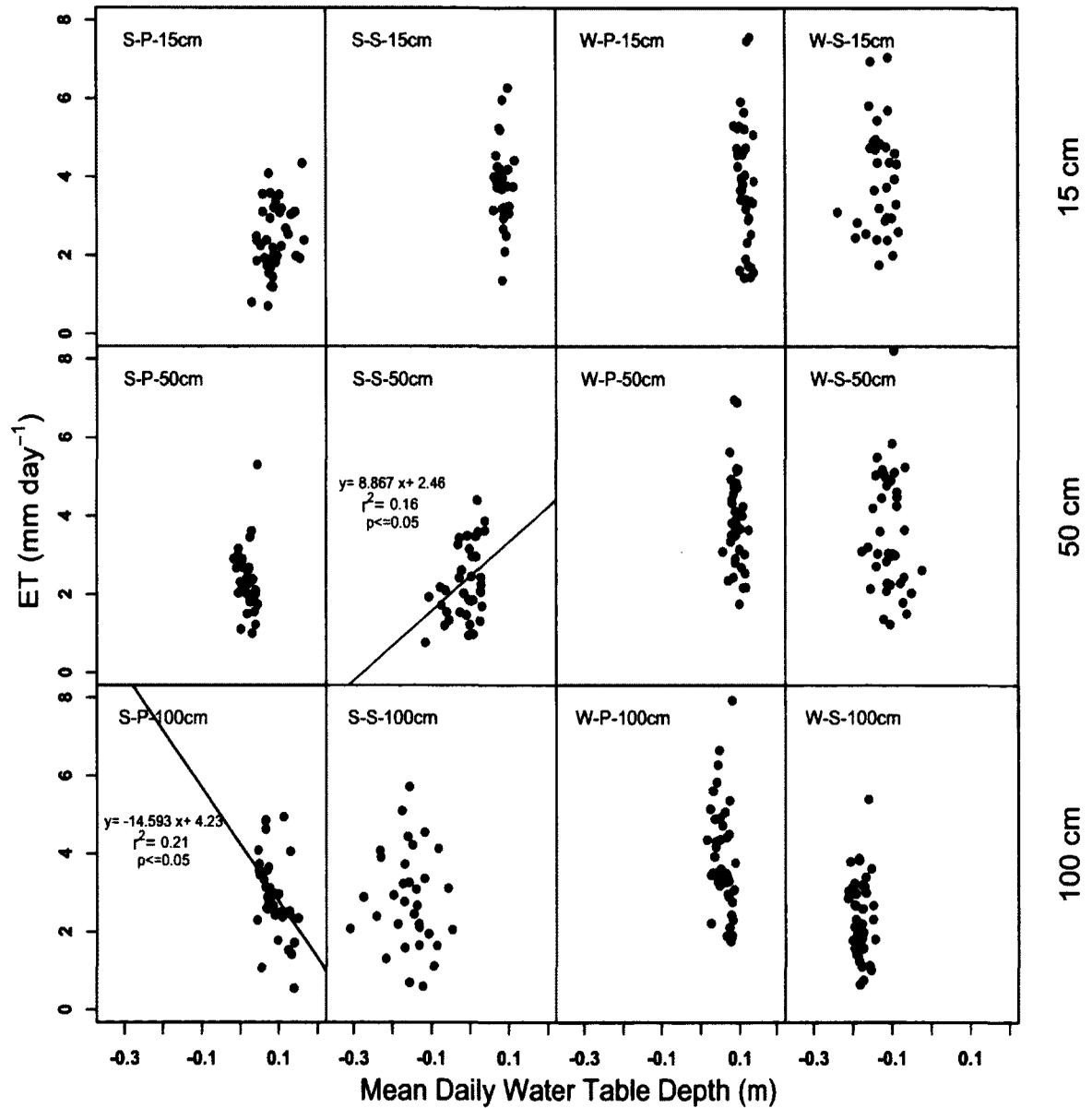


Figure 4.13 Scatter plots by cell of water table depth to mean daily ET. Very little correlation was observed in any cell, likely due to consistent irrigation resulting in water rarely being a limiting component. Also, this situation may be heteroscedastic due to the influence of the irrigation regime and thus making the significance of any relationships questionable.

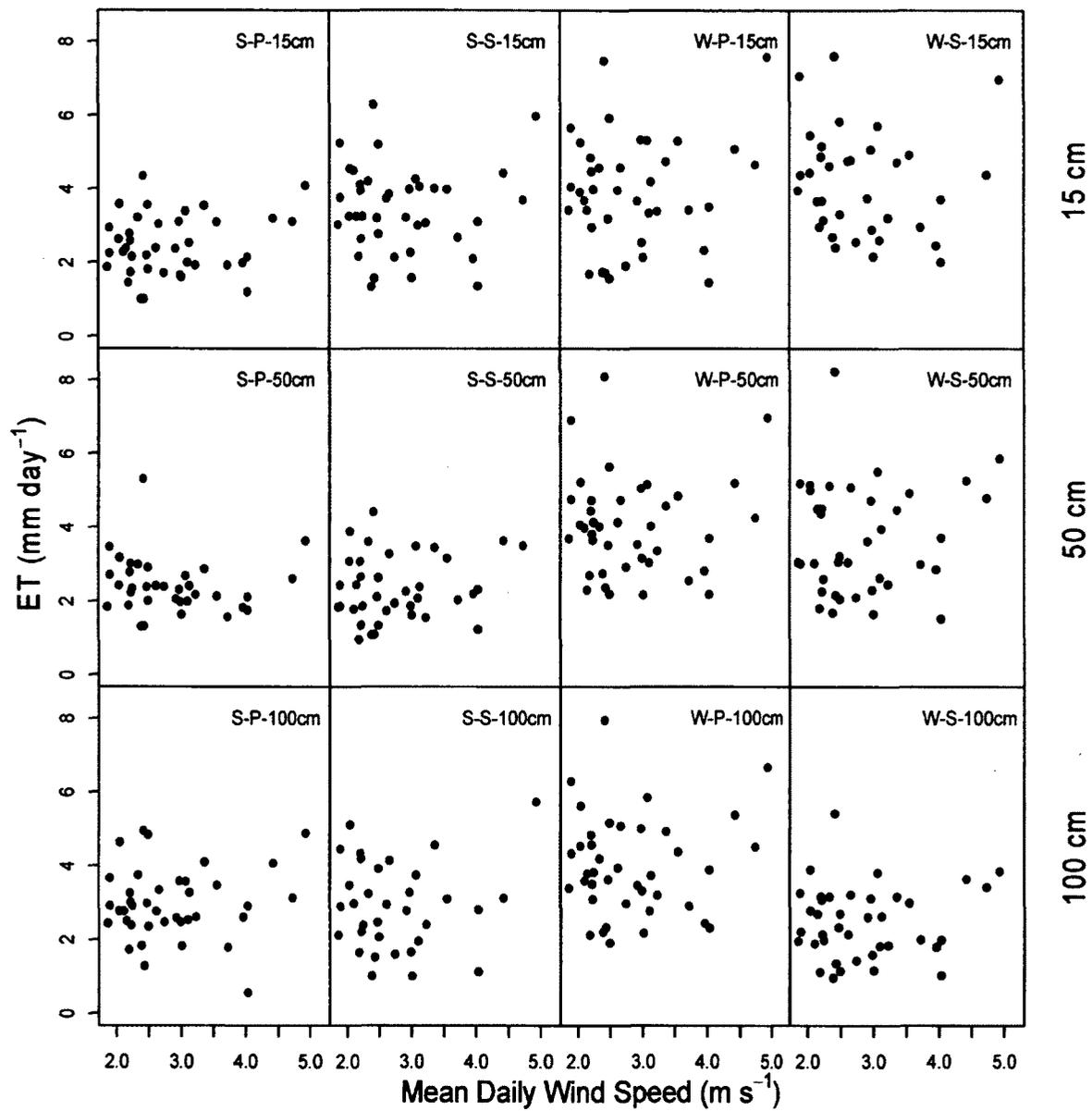


Figure 4.14 Scatter plots of ET and mean daily wind speed for each cell in the study. No correlations significant at the 95% level existed.

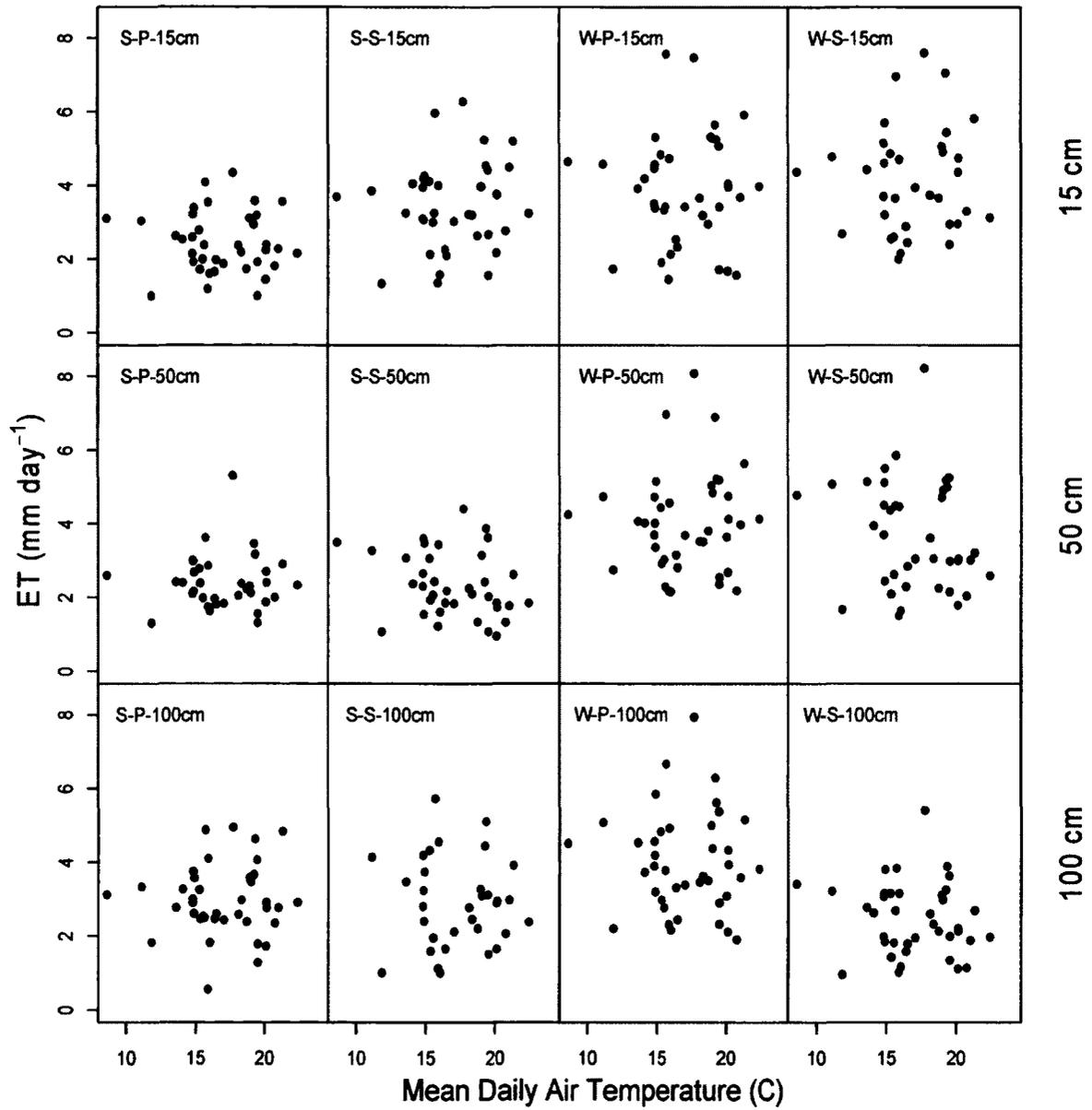


Figure 4.15 Scatter plots of ET and mean daily air temperature for each cell in the study. No correlations significant at the 95% level existed.

### **4.3 Multiple Linear Regression Models**

#### ***4.3.1 Initial models***

The lack of strong correlations between ET and environmental factors presumed to be controlling ET led to the creation of multiple linear regression models in order to 1) help provide further insight into the controls on ET at the study site, and 2) gap fill missing ET data for use in the water balance.

An individual multiple linear regression model was developed for each of the 12 cells in the study (Figure 4.16). Each model was initially constructed using cell specific ET measurements and data for the five environmental variables. The models were then trimmed according to AIC (Akaike's Information Criterion, section 3.3), by removing the next insignificant variable that caused no additional reduction in deviance. Also, the models attempted to adhere to the general  $n/3$  rule for the total number of variables. A final model for each cell was composed of different total numbers and combinations of variables, indicating the relative importance of different environmental variables in cells of differing construction techniques.

#### ***4.3.2 Models with Interactions***

Due to the lack of strong direct correlations among environmental variables, there is a possibility that ET in the cells is controlled by a combination of the environmental factors acting together. The nature of the interactions between groups of environmental factors and ET is poorly understood (Souch et al. 1996; Drexler et al. 2004). It is possible that models that consider these interactions amongst environmental variables may be a more robust and accurate technique for gap filling and future prediction of

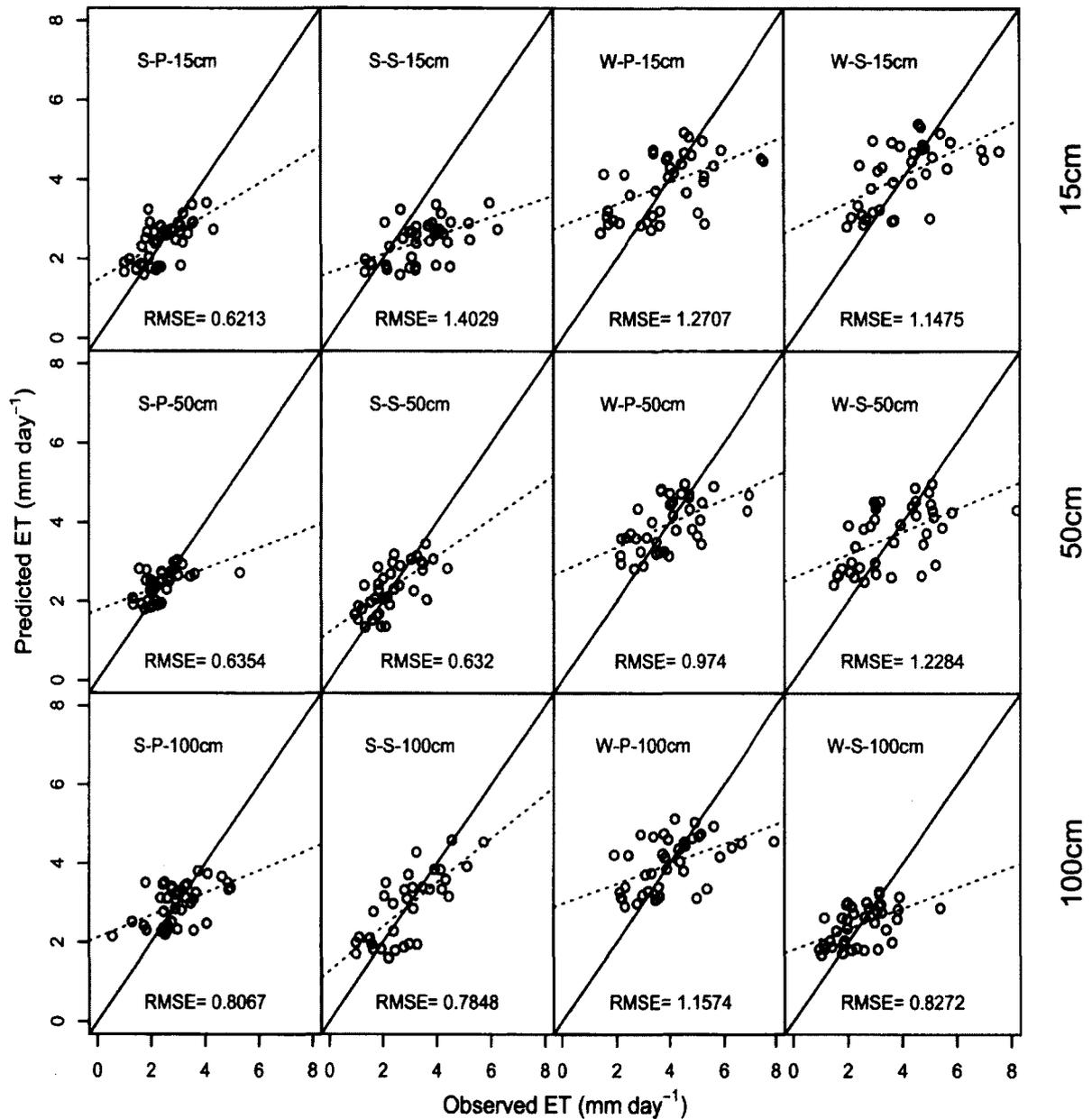


Figure 4.16 Observed ET plotted against predicted ET using a multiple linear regression model without interaction for each cell in the study. After models were trimmed for 95%, the majority ended up being very close to single linear regression models between shortwave radiation and ET.

ET. Therefore, the multiple regression models were re-designed to incorporate the interactions by adding a term to the model representing the interaction between two or more variables (Figure 4.17). The effect of including interactions in the models is evident when comparing observed ET plotted against predicted ET for each cell with and without interaction terms respectively (Figures 4.16 and 4.17).

The models without interaction terms became, in most cases, a linear relationship between incoming solar radiation and ET after non-significant variables were removed. This resulted in high RMSE values as models were biased, consistently under-predicting ET. The performance of the simple linear regression models again suggests the need to incorporate terms that represent two or more environmental factors working together. The addition of interaction terms to the models greatly improved the significance of the models and also reduced the RMSE. However, the models tended to over-fit the data due to the number of significant terms, often not satisfying AIC. The models with interactions often produced highly accurate predictions of ET for the majority of the data, but also occasionally produced highly unreasonable predictions of ET. These unreasonable outliers were typically significantly under or over the range or potential ET values and often occurred in situations of extreme values (high and low) of environmental factors. The inability to keep predictions of ET near the range observed values at all times suggests that the models were over-fit to the data.

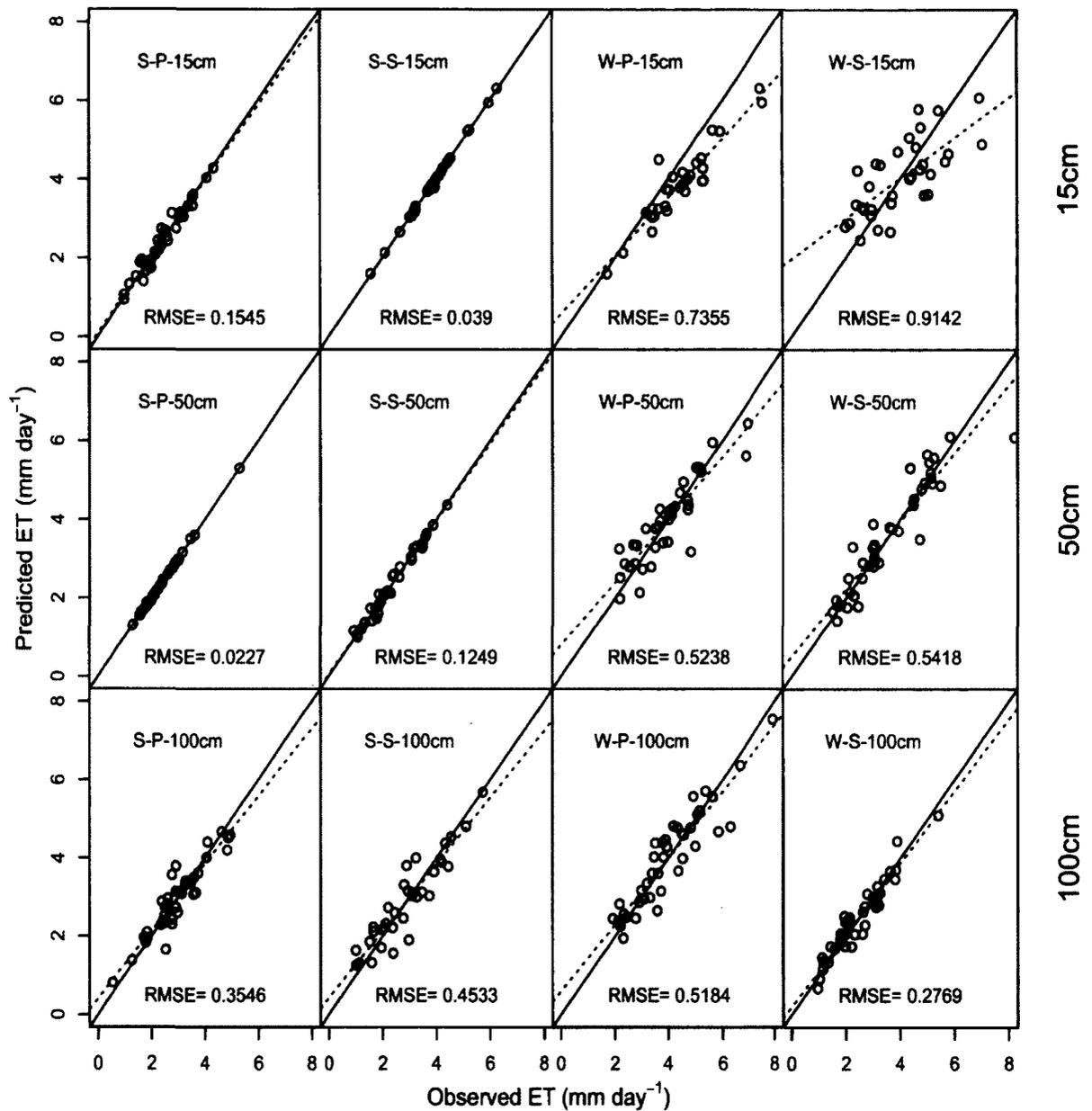


Figure 4.17 Observed ET plotted against predicted ET using a multiple linear regression model with interaction terms, for each cell in the study. Models were often over-fit, and produced outliers so unreasonable they cannot be shown in figures.

The over-fitting of the models is primarily due to the low number of observations of ET for certain cells ( $n \sim 40$ ). However, when data was pooled to increase the number of observations (i.e. by construction technique or all cells together), the tendency of the models with interactions to over-fit the data decreased. Often this came at the expense of lower correlation coefficients and higher RMSE values, but overall the models performed reasonably well. An example of one such model is shown in Table 4.5 with its associated plot of predicted ET against observed ET in Figure 4.18.

Table 4.5 All cell pooled multiple linear regression model terms, estimates of their coefficients, and associated p-values. The models overall adjusted  $r^2$  value is 0.4235 with a p-value of  $2.2e^{-16}$ . In this table, Wdspd is wind speed, Kdown is incoming shortwave radiation, Temp is air temperature, Wtd is the water table depth and VPD is the vapour pressure deficit.

Model Term	p-value
Kdown	$3.1e^{-14}$
Wdspd	$3.3e^{-13}$
Temp	$1.3e^{-05}$
Wtd	0.019
Wdspd+Kdown	$3.0e^{-16}$
Kdown+VPD	$4.3e^{-11}$
Temp+VPD	$2.6e^{-10}$
Wdspd+Temp	$4.6e^{-09}$
Kdown+Temp	$3.5e^{-09}$
Wdspd+Kdown+Temp	$5.3e^{-11}$
Wdspd+Kdown+VPD	$1.2e^{-07}$
Wdspd+Temp+VPD	$1.2e^{-07}$

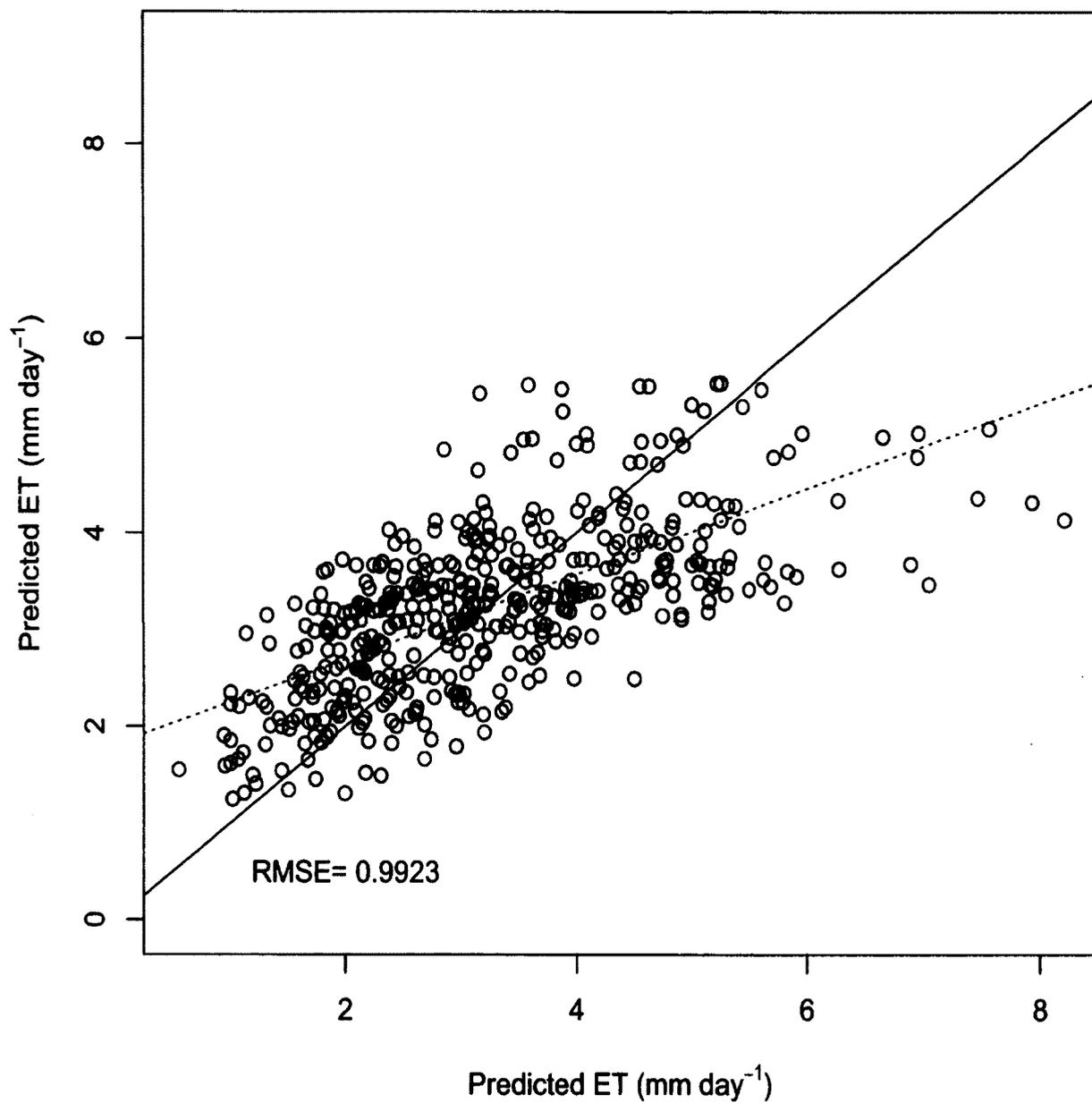


Figure 4.18 All cell pooled data plot of Observed ET against predicted ET using a multiple linear regression model with interaction terms. Model contained 12 variables, easily satisfying the  $n/3$  general rule and AIC test, resulting in a model able to predict ET based on the five controlling factors without over-fitting.

#### **4.4 Recursive Partitioning – Tree Models**

As mentioned previously (Section 3.4), recursive partition models or “trees” differ from multiple regression models in that data is broken up according to specific thresholds of explanatory variables that result in the least amount of deviance (Crawley, 2005). This technique offers the potential to include interactions between variables, but also the thresholds at which those variables may become important. In contrast to the multiple linear regression models, recursive partitioning models may be capable of predicting ET without a strong tendency to over-fit data (Crawley, 2005).

The tree method provided a highly effective, visual way to determine which environmental variables were most responsible in controlling ET and the important thresholds related to their connection with ET. The pooled all cell tree model is shown in Figure 4.19 with its predicted ET plotted against observed ET shown in Figure 4.20.

Because the tree models were less influenced by low numbers of observations, they generally did not over-fit the data. The tree models typically had a slightly higher RMSE for large pooled data groups than the multiple linear regression models. However, the tree models provided reasonable estimates of ET far more often, with only very few predictions deemed to be outliers. Figure 4.21 displays the individual cell tree model predicted ET plotted against observed ET for the 12 study cells. Comparing the effectiveness of the tree models with the multiple linear regression models with interaction terms (Figure 4.17), it is evident that although the tree models have more dispersion in the data, the lack of extreme outliers results in a very similar RMSE. The ability of the tree models to consistently produce accurate and reasonable predictions of ET is a major advantage over multiple linear regression models.

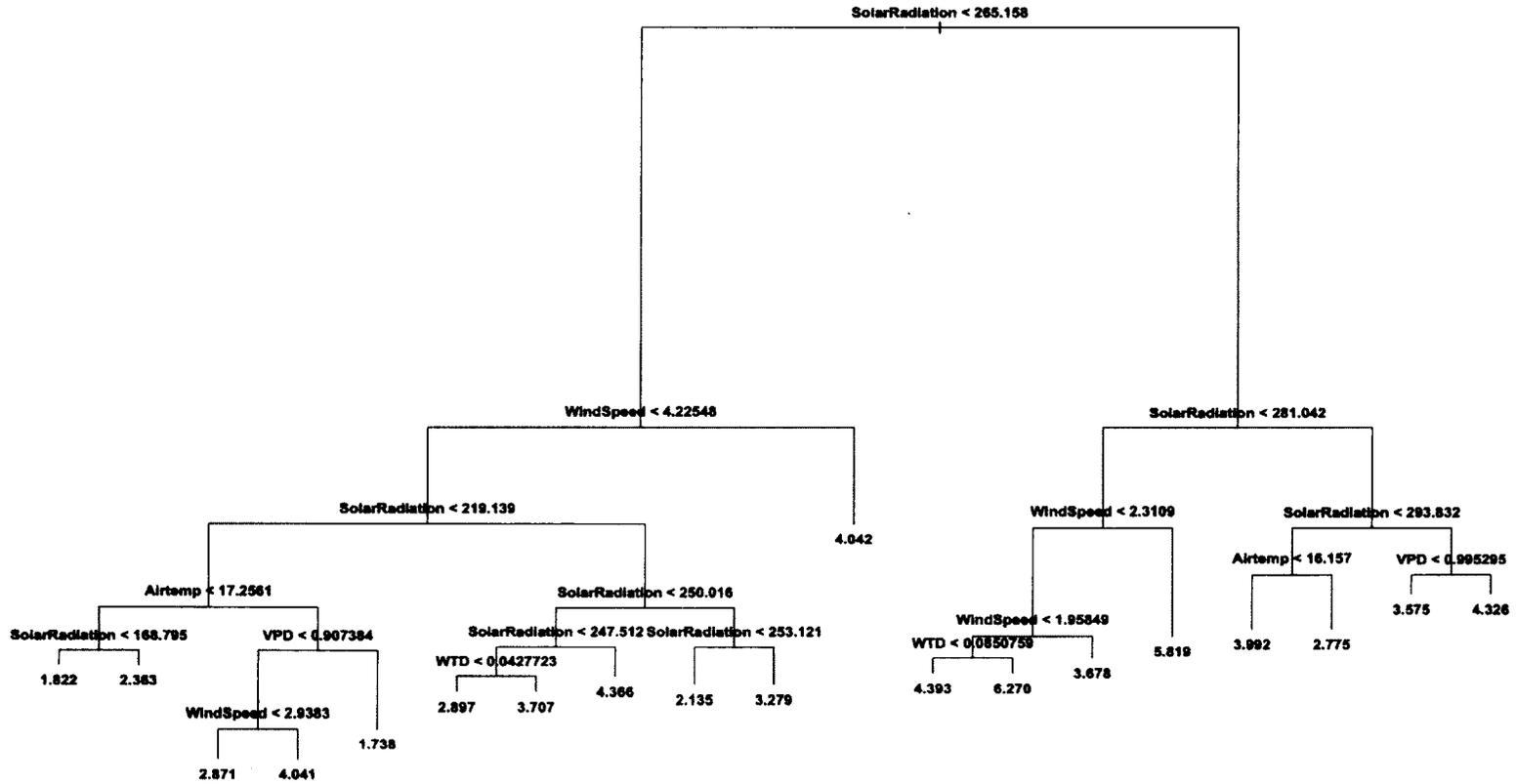


Figure 4.19 Recursive partitioning tree model for all cell pooled data. At each node (branch) indicates the variable and the threshold in which the most amount of deviance in the data is obtained. For given conditions of environmental variables, below the indicated threshold follow the branch to the left and above the threshold follow the branch to the right. Once the bottom of the tree has been reached, the predicted values of ET are provided.

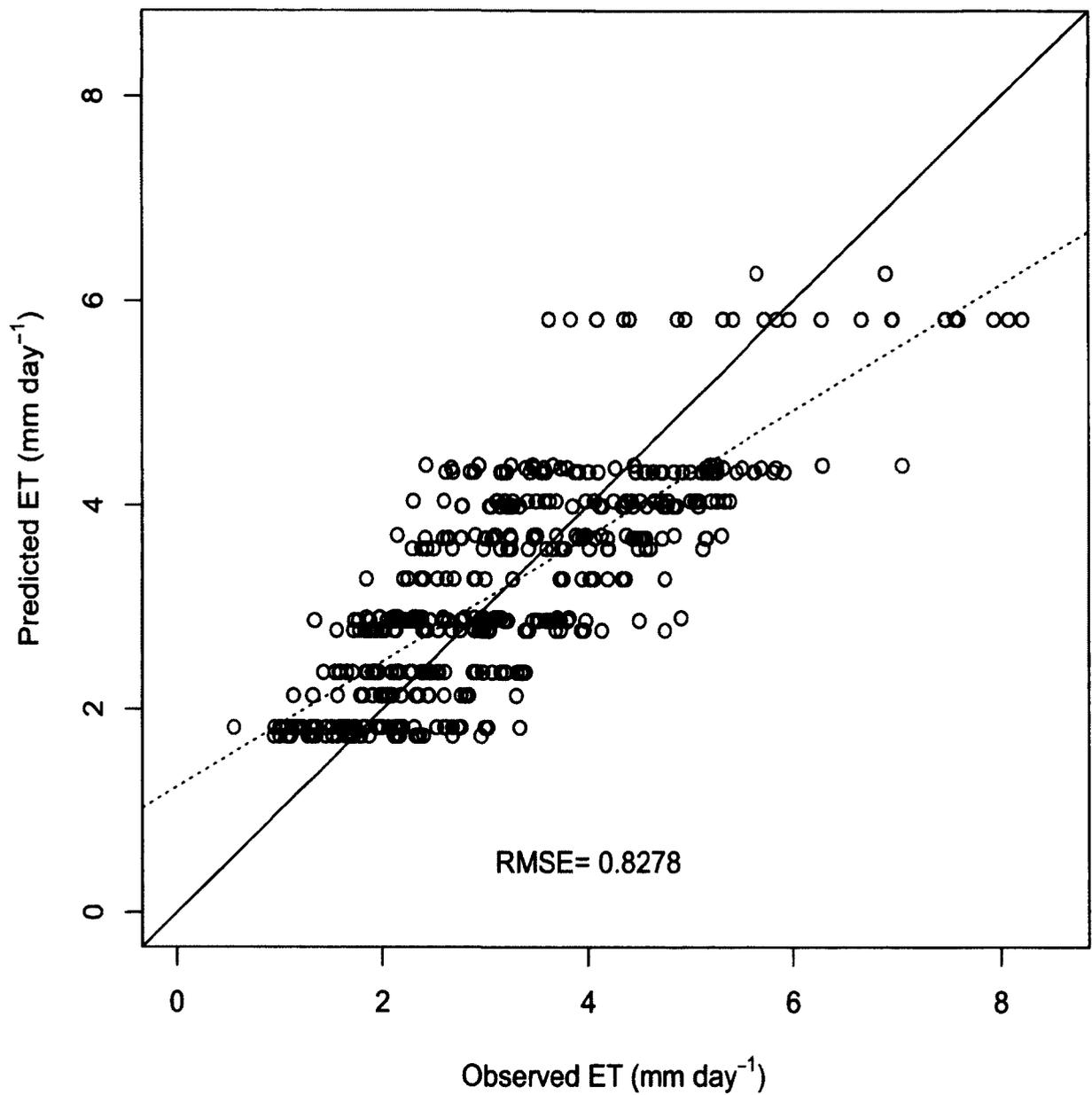


Figure 4.20 Observed ET plotted against ET predicted by recursive partitioning tree model for all cell pooled data. Compared with the plot using the multiple linear regression model with interaction terms (Figure 4.17), the tree model produced a more robust model with a lower RMSE.

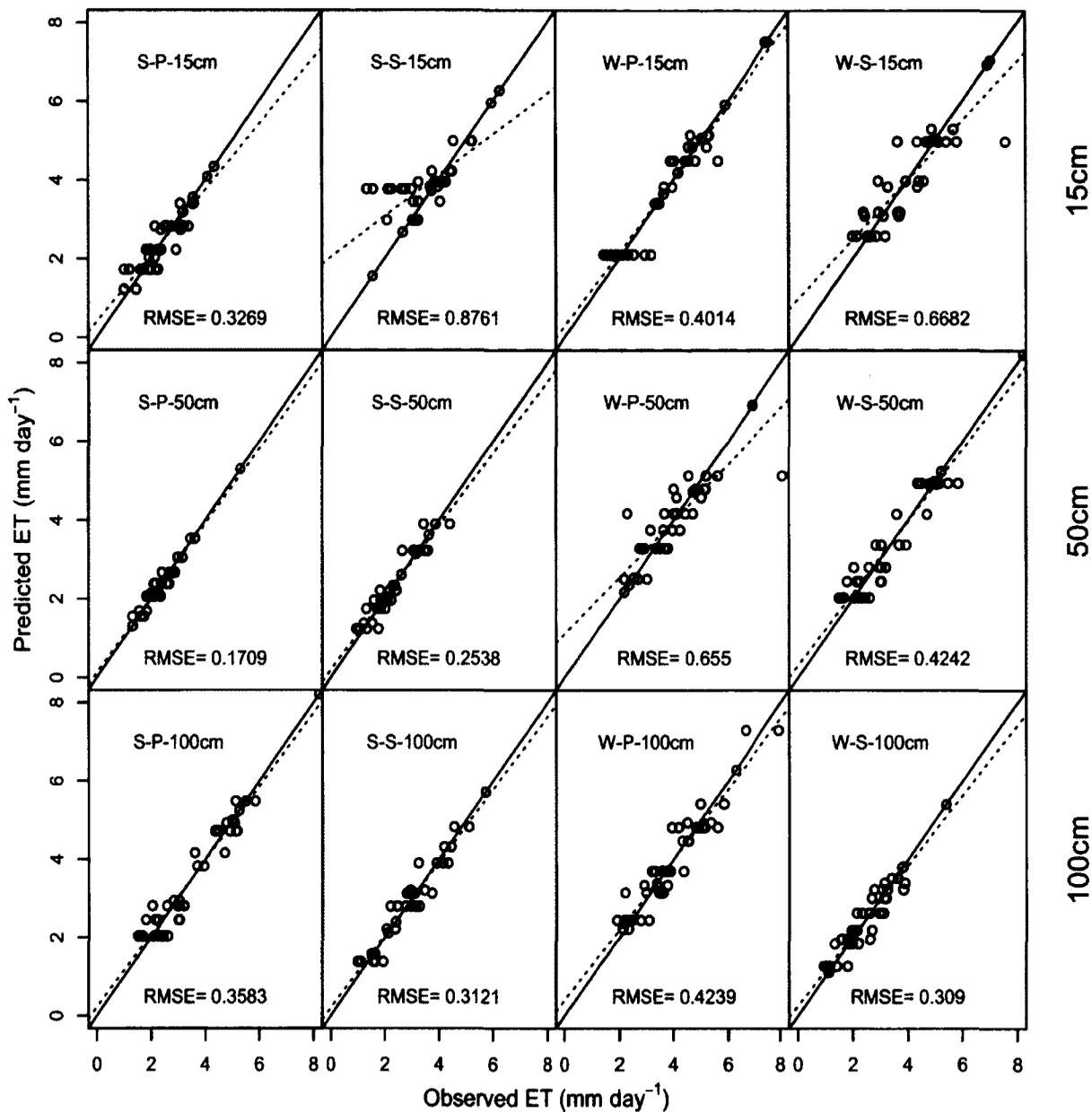


Figure 4.21 Observed ET plotted against ET predicted by a cell specific recursive partitioning “tree” model. Tree models were found to consistently produce reasonable predictions of ET with relatively low RMSE, and without over-fitting the data.

## 4.5 Cell Water Balances

### 4.5.1 Inputs and Outputs

Water balances were calculated for each of the 12 cells in the study, according to equation 2.3. Inputs comprised the irrigation totals for each cell along with the precipitation at the site (Figure 4.22). These totals ranged from ~ 200 mm to ~475 mm, with June accounting for the bulk of the inputs for most cells. The hot, dry weather led to very high irrigation volumes and subsequently high inputs, even with very little precipitation. The apparent great variation in input depth suggests that some cell liners may have leaked.

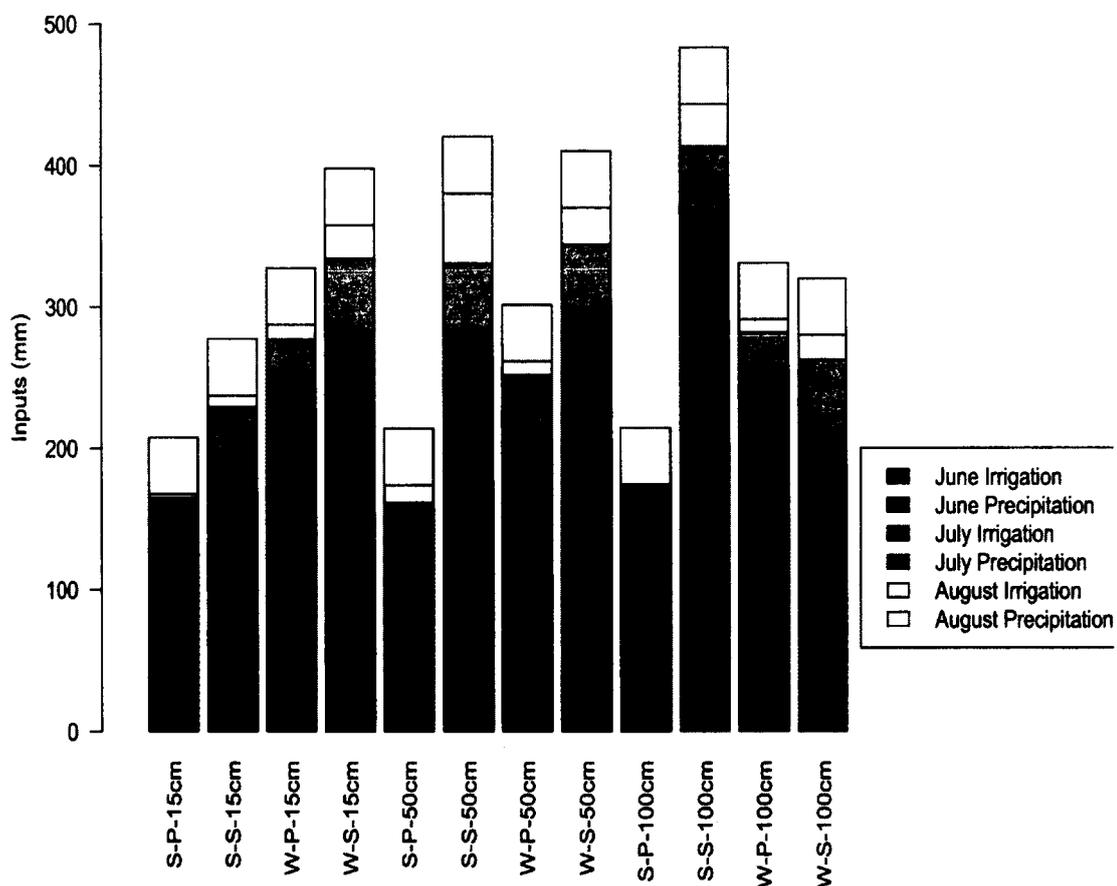


Figure 4.22 Water balance inputs organized by month for each cell for the duration of the study period.

Outputs for the cells were assumed to be entirely of losses through ET. However, due to logistical and environmental constraints, ET could not be measured every day. Therefore, in order to obtain a more accurate estimation of cell outputs, missing data was gap filled with ET predicted by the recursive partitioning tree model (Section 4.4) specific to each cell. Tree models were chosen because they did not over fit the data and produce extreme outliers. Figure 4.24 displays the outputs comprised of measured ET and gap filled model predicted ET.

Overall, output (ET) totals in the cells displayed a similar amount of variability as the inputs did. Outputs ranged from ~175 mm to ~325 mm. As mentioned, June had many relatively high ET days and so comprised the bulk of the outputs for the majority of cells. July totals were slightly less than June, perhaps due to more days with precipitation events. ET slowed down notably towards the end of the growing season, reflected in the much lower output totals for August. These large differences in output totals amongst cells can likely be attributed to differences in construction techniques (treatments).

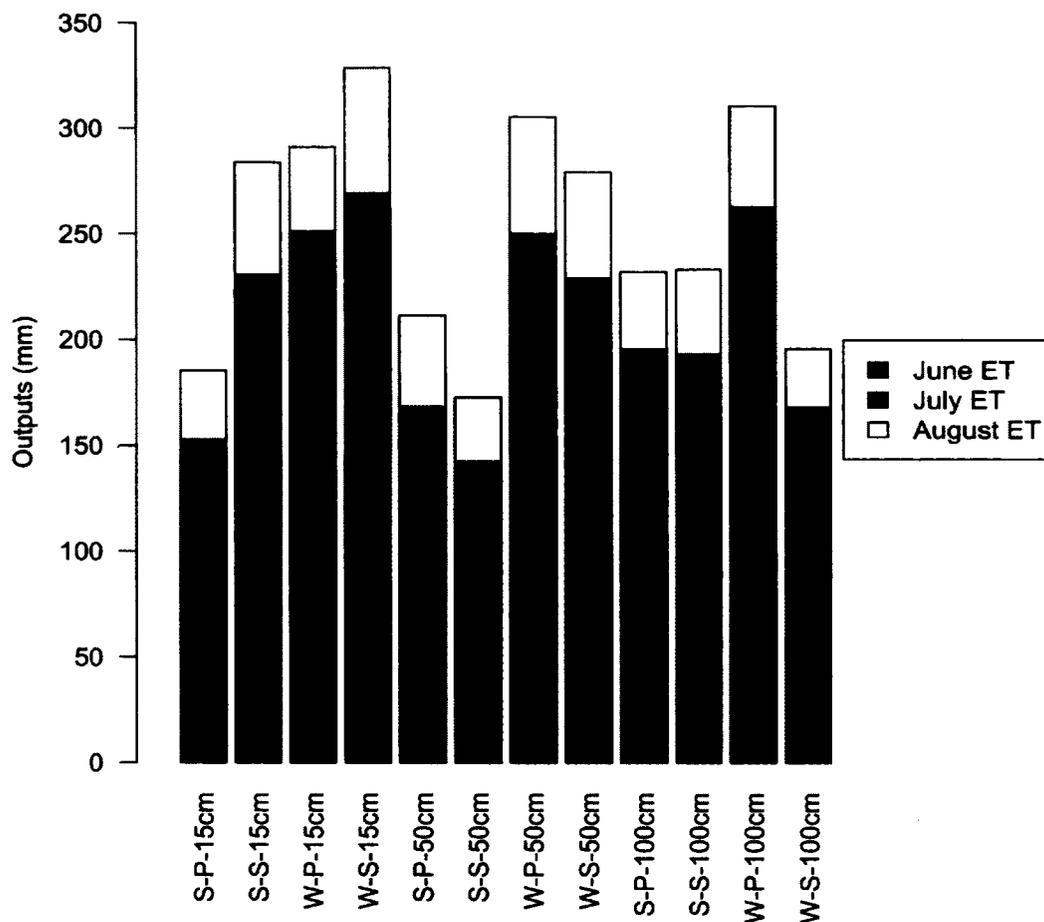


Figure 4.23 Water balance outputs (ET) arranged by month using recursive partitioning model gap filled data for each cell for the duration of the study period.

#### 4.5.2 Cumulative Water Balances – 2010 Growing Season

Cumulative water balances were calculated to track the progression of inputs and outputs and the change in water storage of the cells (Figure 4.25). Comparison of inputs and outputs with the actual change in storage (water table change multiplied by the specific yield) acts as a check to the predicted change in water storage. By comparing inputs and outputs, an estimate of the magnitude of the water balance and its components can be made and differences and similarities between cells can be analyzed and perhaps attributed to specific construction techniques.

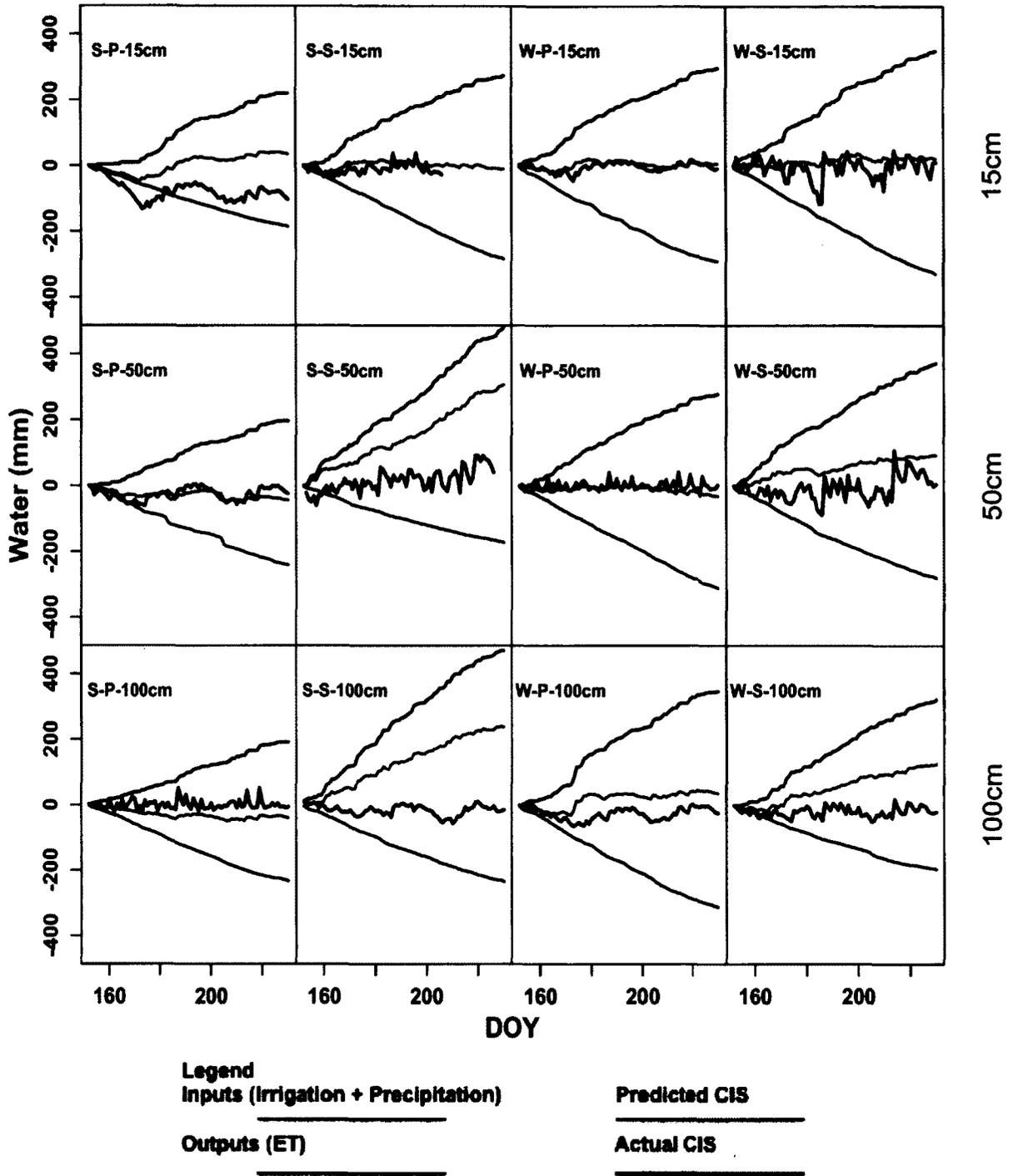


Figure 4.24 Cumulative water balance plots for each cell in the study. Outputs are composed of directly measured ET and gap filled ET determined using a cell specific recursive partition (tree) model. Blue lines indicate inputs, red lines indicate outputs, green lines represent the predicted change in storage, while black lines represent the actual change in storage.

Half of the cells were estimated to have experienced a very small change in water storage as inputs and outputs were very similar; this was supported quite closely by the change in the water table depth. Six cells (S-S-15 cm, W-P-15 cm, W-S-15 cm, S-P-50 cm, W-P-50 cm, S-P-100 cm) exhibited a predicted change in storage very near to that of the actual change in storage (Table 4.6). Differences between these cells were relatively small, ranging from 35 mm (W-P-50 cm) to as low as 11 mm (W-S-15 cm), and so should be considered as reasonable estimates of the overall water balance in these cells.

Table 4.6 Summary of predicted and actual change in water for storage for each of the cells at the end of the study period. The relative difference between these two terms is a good indication of water balance accuracy and/or the presence of leaking cells.

Cell	Predicted Change In Storage (mm)	Actual Change in Storage (mm)	Difference (mm)
S-P-15 cm	35	-103	138
S-S-15 cm	-10	-28	18
W-P-15cm	6	-9	15
W-S-15cm	21	9	11
S-P-50 cm	-44	-24	19
S-S-50 cm	307	40	267
W-P-50 cm	-32	3	35
W-S-50 cm	93	5	88
S-P-100 cm	-40	-6	34
S-S-100 cm	238	-15	253
W-P-100 cm	36	-25	60
W-S-100 cm	126	-21	147

Three cells produced cumulative water balances with large differences in predicted change compared to actual change in water storage. These three cells (S-P-15 cm, W-S-50 cm, W-P-100 cm) had discrepancies greater than those of the first group, 138 mm, 88 mm and 60 mm respectively (Table 4.6). These differences in the

cumulative water balance are large enough to suggest a potential measurement issue but not so large to indicate a major technical or logistical problem with the cells.

Based on the water balance estimates, three cells (S-S-50 cm, S-S-100 cm, W-S-100 cm) would have had a large gain in storage yet, based on actual changes in the water table, true storage change was much less. The summer placement, stockpiled mixture cells of 50 cm and 100 cm were estimated to have had nearly twice as much inputs as output, a surplus of close to 200 mm (Figure 4.24). This difference between inputs and outputs was not supported by the actual change in storage, which in both cases remained very close to 0, or by visual confirmation of any significant water level change. The presence of such a large discrepancy may be a strong indication that the liners in these cells were leaking significant amounts of water. Approximate water depth leakage estimates for these three cells are substantial at  $-3.4 \text{ mm day}^{-1}$  (102 L),  $-1.9 \text{ mm day}^{-1}$  (57 L), and  $-2.9 \text{ mm day}^{-1}$  (87 L) for S-S-50 cm, S-S-100 cm, and W-S-100 cm cells, respectively.

## **5.0 Discussion**

### **5.1 The Problem**

Most of the oil sands mining areas are located near the southern fringe of the Boreal biome. This ecosystem is typically composed of vast areas of forests, forested wetlands, bogs, fens and swamps. With regards to ecosystem reclamation related to oil sands mining, upland forest systems have been established in the region with some degree of success. However, little work has been undertaken on designing and establishing important lowland ecosystems that maintain saturated conditions and wetland vegetation.

Reclaiming and constructing wetlands after mining presents many challenges. Topography must be created in some way as to reflect the natural landscapes while controlling for erosion and stability. Soil material must be salvaged during mining and later placed atop reclamation surfaces, resulting in a profile that is considerably altered compared to the pre-mining landscape. The climate of the region is cold, with a short growing season that limits vegetation growth. Furthermore, the region around Fort McMurray is relatively dry, placing limits on vegetation and presenting a challenge in maintaining moist conditions required for wetland systems.

### **5.2 The Cells**

In an attempt to evaluate techniques to construct large-scale wetland systems, Syncrude Canada Ltd created a series of test plots (the U-shaped cells), 12 of which were studied for this thesis. The cells were designed to behave similarly to natural boreal wetlands (bogs), by adding liners to limit deep percolation and lateral flow, and

thus confining the majority of exchanges to those between the surface and the atmosphere. However, unlike natural wetlands, water was added via irrigation to maintain conditions suitable vegetation establishment. Because of the irrigation, the cells had a distinct hydrological difference compared with natural wetlands, which must be acknowledged when considering the implications of study results.

Each cell investigated was unique due to the combination of three construction strategies (soil/vegetation type, soil depth, and soil placement period). There were large visible differences among the cells; some were lush with green vegetation while others contained very little live vegetation with areas of exposed degrading organic material. Invasive vegetation (grasses and cattails) was predominant in some cells, whereas others largely consisted of native species. Hydrologically, some cells had ponded water for the bulk of the growing season, whereas others were comparably dry. The combinations of construction techniques are directly responsible for these differences, which strongly impacted cell water balances.

### **5.3 Controlling Factors on ET**

Due to the presence of liners in all cells, ET was the dominant loss of water and became the central focus of this study as water management of future wetlands will be largely controlled by surface-atmosphere coupling. It is unclear whether test-scale wetland plots respond to the same environmental drivers as natural wetlands and whether results from this study can be scaled up to larger wetlands. Regardless, understanding the relative influence of placement strategy on ET will provide a first-

order estimate of how management techniques can affect water losses to the atmosphere.

ET varied spatially and temporally at the study site. Highest ET rates were observed at the beginning of the study period in early June, were generally steady in July and began to decrease in August (Figures 4.5 and 4.6). Using the Penman-Monteith framework, the fluctuation of ET throughout the study period was considered to be controlled by five environmental factors: incoming solar radiation (a surrogate for available energy), VPD, air temperature, wind speed (turbulence), and water table depth.

Preliminary attempts to assess the relative influence of each of the five environmental variables on ET using linear regression provided generally weak relationships. Linear regression modeling suggested ET was mainly driven by incoming solar radiation, which was the only variable significantly related to ET (Figure 4.11 and Table 4.4). Previous studies in wetlands also found ET to predominantly driven by radiative energy (Humphreys et al. 2006; and Kellner, 2001); however the relationship at the cells was considerably weaker ( $r = 0.47$  for pooled data) than previous studies. The other environmental variables exhibited few significant relationships with ET (Figures 4.12 through 4.15).

### ***5.3.1 Multiple Linear Regression Models***

To explore the complex interactions among environmental variables that may act to control ET, multiple linear regression models were created. Initial multiple linear regression analysis considered the additive effects of each individual environmental variables operating at the same time. Generally, these models were able to provide

improved correlations with ET than the simple one-to-one regression equations. However, after insignificant ( $p > 0.05$ ) variables were removed, many of the resulting models were reduced to the original one-to-one relationships between incoming solar radiation and ET. The inability of the multiple linear regression models to explain ET using only additive individual relationships between environmental variables and ET suggested that complex interactions among variables are important.

The addition of interaction terms to the multiple linear regression models greatly improved the ability to explain ET. Substantial increases in correlation were observed with coefficients of determination ( $r^2$ ) as high as  $\sim 0.98$  and RMSE values as low as  $\sim 0.023$  (Figure 4.17). In many cases, individual variables did not have a significant relationship with ET, but new variables created that were composed of two or more previously insignificant variables exhibited significant relationships with ET. Many of the interaction terms were considered significant, and new models contained a far greater number of variables than the previous ones. Also, each new model was composed of a unique combination of individual and/or interaction terms reflecting the complex nature of the relationship between the environmental variables and ET. Because the new models were considerably more complex, uncertainty existed in their ability to explain data and predict ET and gap fill missing data. Curiously, some models contained nearly as many significant terms as data points – surpassing statistical considerations and resulting in the possibility of over-fitting the data. Consequently, some models were susceptible to producing extreme outliers, and were assumed to be poor at gap-filling ET on days with no observations. While some models produced reasonable gap filled data, the production of extreme outliers resulted

in water balance estimates that were highly biased, reducing the credibility of this method for interpolation data.

Multiple regression models that used pooled data from the cells reduced the tendency to over-fit the data due to higher numbers of observations and a reduction in the number of significant terms. However the reduction in complexity came at the cost of a reduction in the strength of the correlations and of increases to the RMSE. The tendency of multiple linear regression models to over-fit the data is likely amplified in small data groups and/or when predicting ET for small data groups where limited observations exist for calibration (e.g. rainy days).

Results from the multiple regression modeling suggest that the interactions between any two or more of the five controlling environmental variables explain more of the variability in ET than the sum of the individual relationships of those same variables with ET. While mediocre at gap-filling, the models do provide some indication of which interaction variables (two or more environmental variables working concurrently) play an important role in controlling ET at this site.

### ***5.3.2 Recursive Partitioning Models***

Recursive partitioning models implicitly include interactions between environmental variables. Any numerical model output is a result of a series of decisions at nodes along the branches of the tree. Because most outputs are a result of different variables at each node, the potential for interaction between variables is created in the model. In addition, the inclusion of thresholds identifies not only potentially important interactions but also the range of values under which these interactions become important.

Recursive partitioning models were better at predicting and thus more useful for gap filling. Because tree models work with branches containing specific variables and threshold values, predictions are stratified and change by fixed intervals to as input variables change. This stratification occurs as predictions for situations of similar environmental conditions often result in the same value of ET. However, this tendency to produce tiered predictions of ET keeps the models from over-fitting the data and reduces their propensity to generate extreme outliers.

By analyzing the recursive partitioning models, it was possible to identify important environmental factors and important interactions on controlling ET. Solar radiation was the most important individual variable, as shown by the number of times it is repeated in the models. Additionally, these models reveal other environmental factors that become important depending on the value of solar radiation. For example, in many cases wind speed and, to a lesser extent air temperature, became important explanatory variables during times of relatively low solar radiation. Conversely, VPD was often important during periods of high solar radiation. Other similar dependencies between environmental variables appear further down the tree; however they may be less significant. The recurrence of these patterns throughout many of the models underscores the potential that interactions between environmental variables have significant influence on ET.

Future analysis using recursive partitioning could focus on the value and composition of threshold values that work to control the complex process of northern wetland ET. Tree models show promise in helping to identify the dominant controls, and their thresholds values at specific sites and may hold the potential to be expanded

over large areas when used in combination with remote sensing techniques. However, tree models are often not optimal upon creation and so further study should also consider validation techniques such as bootstrapping and random forest analysis.

#### **5.4 Effects of Treatments**

Placement period of the soil and, to a lesser extent, the depth of soil medium significantly affected ET. Winter placement cells had higher growing season ET rates than summer placement which is likely explained by the nature of the soil medium, particularly for live transplanted peat. During winter installation, soils were frozen and moved in a series of blocks from the disturbed wetland or stockpiled storage area. These frozen soils had a tendency to fracture upon placement, degrading the overall soil structure and creating large cracks at the surface throughout the cells, which were then filled with loose peat. The impact of these fractures became apparent in the following spring during thaw when cracks became preferential pathways for channelization and erosion, redistributing loose decomposed organic material to the cell edges. As the growing season progressed, degraded material throughout the cells remained wet after continual irrigation due to its greater near-surface storage capacity, enhancing evaporation. This process was more pronounced in the shallow cells where the surface peat and vegetation had dies and degradation was considerable. As soils were artificially irrigated, degraded cells were much wetter near the surface and ET was enhanced.

Soil depth also influenced ET rates and the water balance. The shallowest cells (15 cm) had significantly higher ET than the 50 cm and 100 cm cells. However, these

deeper cells did not display significant differences in ET with each other. Given that only the 15 cm depth cells were significantly different, it is possible that there is a depth threshold, beyond which the placement depth has limited influence on ET. Shallower soil cells (S-P-15 cm, S-S-15 cm, W-P-15 cm, W-S-15 cm) were prone to flooding during irrigation or rain events, and often had free water at the surface that enhanced ET. Deeper soils provided for increased storage, reducing the frequency of ponding compared with the shallower cells. Additionally, vegetation in the shallow cells was often dead or dying, due to disturbances to its rooting zone upon transplant. However, transpiration was likely small compared with evaporation due to the cells near continually-saturated conditions.

There were no significant differences in ET based on soil type (stockpiled mixture vs. live peat transplant). While there were strong visual differences between live and stockpiled mixture cells in terms of plant species, there were no significant differences despite stockpiled soil mixture cells having much greater LAI's.

The implication of these results on future reclamation techniques is important, as future wetland construction projects, in some cases, have actively managed water use systems that provide water to the wetland during initial stages of development. Management of freshwater resources in northern Alberta is of great importance as it relates to mining, and any opportunity for a reduction in freshwater use is significant. Construction techniques that reduce ET rates, such as deeper soil placements, have the potential for long-term savings in water use despite higher initial placement costs associated with the movement of more material.

From this research, it is not possible to evaluate the long-term sustainability of wetland placement techniques due to the highly managed nature of the cells. It is unclear how keeping the cells at near-saturation impacts their long term performance, and also masks the true evaporative dynamics associated with lowering water tables in organic soils (Nicholas and Brown, 1980; Ingram, 1983; Lafleur et al. 2005). Future research at the cells may assess how ET varies under conditions where cells are not artificially watered, and how vegetation change is linked to water balance components.

From the water balances, four cells (S-P-15 cm, S-S-50 cm, W-S-100 cm, S-S-100 cm) appear to have leakages through the cell base, which is likely due to degraded liners. Cracks and punctures in geosynthetic liners are generally related to installation techniques and degradation over time. Natural wetlands in the boreal region typically form above impermeable clay soils, and comparison of water balances between leaking and non-leaking cells leads to equivocal conclusions based on the extra water applied to the leaking systems.

### **5.5 Context – Comparison with Other Natural and Constructed Sites**

Despite being a pilot study to assess the effect of construction techniques on the water balance (and vegetation/carbon dynamics not discussed in this thesis), it is clear that the cells are distinct from natural wetlands in terms of size, setting, physical properties and hydrology through the irrigation regime. Regardless, the comparative nature of this study does allow construction techniques such as soil depth and placement strategy to be assessed.

Table 5.1 summarizes the relative growing season ET rates based on construction technique whereas Table 5.2 summarizes values presented in the literature for undisturbed boreal and constructed wetlands. Placement period was the greatest factor that distinguished ET among the cells, and was greater than ET rates reported in the literature for other wetlands in similar regions. This is an important consideration; that soil placement period may be the most important factor in controlling water balance dynamics by strongly affecting soil properties (which in general are more degraded in winter cells). ET rates from these cells approach those more typically found in southern climates, although it must be noted again that cells were maintained artificially wet.

Table 5.1 Summary of ET rates according to construction techniques that caused statistically significant differences. Data reported are mean and maximum values for the 2010 growing season.

<b>Construction Technique</b>	<b>Mean ET Rate (mm day<sup>-1</sup>)</b>	<b>Maximum ET Rate (mm day<sup>-1</sup>)</b>
All Cell Pooled	3.2	8.2
Winter Placement Cells	3.6	8.2
Summer Placement Cells	2.7	6.3
15 cm Soil Depth Cells	3.4	7.6
Pooled 50 and 100 cm Soil Depth Cells	3.0	8.2

Table 5.2 Summary of ET rates from previous wetland studies. Data are reported mean and maximum values for the growing season period. Wetland type is as reported by the authors. (adapted from Lafleur et al. 2005)

Study	Wetland Type	Location	Mean ET (mm day <sup>-1</sup> )	Maximum ET (mm day <sup>-1</sup> )
Lafleur (1990)	Natural rich fen sedge dominated	James Bay, Ontario (51°07' N, 79°51' W)	2.9	5.0–6.0 <sup>a</sup>
Lafleur and Roulet (1992)	Natural poor fen sphagnum dominated	Hudson's Bay Lowlands, Ontario (50°20' N, 80°05' W)	2.5	n/a
Moore et al. (1994)	Natural rich Fen sphagnum/sedge dominated	Schefferville, Quebec (54° 52' N, 66° 40' W)	2.7 <sup>b</sup>	n/a
Price (1996)	Disturbed limited sphagnum cover	Toubiere Fafard Peatland, Quebec (48°47'N, 72°10'W)	2.9	5.0–5.5 <sup>a</sup>
Lafleur et al. (1997)	Natural Poor Fen sedge/tamarack dominated	BOREAS northern study area, Manitoba (55.9°N, 98.4°W)	1.8 <sup>b</sup>	n/a
Joiner et al. (1999)	Natural Poor Fen sedge/tamarack dominated	BOREAS northern study area, Manitoba (55.9°N, 98.4°W)	n/a	3.0–3.5 <sup>a</sup>
Lott and Hunt (2001)	Constructed shrub/sedge dominated	Monroe County, Wisconsin (43.29°N, 90.83°W)	3.5	6.0–6.5 <sup>a</sup>
Van Seters and Price (2001)	Disturbed limited sphagnum cover	Cacouna Peatland Quebec (47°53'N, 69°27'W)	2.9	6.0–6.5 <sup>a</sup>
Petrone et al. (2001)	Restored Fen sphagnum/straw mulch	Bois-des-Bel Peatland, Quebec (47° 53'N, 69° 27'W)	n/a	4.5–5.0 <sup>a</sup>
Lafleur et al. (2005)	Natural Bog shrub covered	Mer Blue Bog, Ontario (45.40°N, 75.50 °W)	2.2 - 3.3 <sup>c</sup>	4.0–5.0
Raddatz et al. (2009)	Natural Poor Fen sedge dominated	Churchill Tundra Sedge Fen, Manitoba (58°40' N, 93°50' W)	n/a	3.0–3.5

<sup>a</sup> estimated from figure

<sup>b</sup> computed from seasonal total ET

<sup>c</sup> Range of values from more than one year of observations

The shallowest cells (15cm) had a slightly higher mean ET rates, whereas the deeper soil depths (50 cm and 100cm) had higher maximum ET rates. Mean ET in the 15 cm cells still fell within the range of values observed in previous studies, but they were closer to the upper range likely due to wetter than normal conditions. Maximum ET was also higher than previously reported.

Mean ET at the site was generally within the range of values found in comparable wetlands, although at the upper range. At times ET exceeded values reported elsewhere. Again, the relatively high ET, particularly maximum rates, are influenced by many factors including the maintenance of saturated conditions, altered soil/vegetation properties, and a potential “oasis” effect caused by the cells being surrounded by relatively dry mine soils. While direct comparison is difficult, Roulet et al. (1997) and Lafleur (2008) suggest that bogs and poor fens should have relatively low ET rates compared to other wetland types. In contrast, construction techniques and management practices indicate that these cells are hydrologically distinct from the natural systems they were designed to replicate.

## **5.6 Implications for Future Research**

The results of this research have implications for the understanding of how ET is controlled in northern wetlands, the relationship between wetland construction technique and ET, and subsequently, the hydrologic behaviour of these constructed wetlands. This understanding should contribute to the long-term success of future reclamation and/or construction of wetlands in relation to oil sands mining. Further study with technical improvements and more complex modeling could lead to more

accurate results and thus create a better understanding of the processes involved in controlling ET. Several suggestions to improve future studies are identified below.

#### *Number of Observations*

The number of ET measurements should be increased. The low number of measurements in this study increased uncertainty in the results and created problems when performing statistical testing and empirical modeling. An increase in the number of observations would increase data robustness, improve models and help guide recommendations with more confidence. This is especially true for situations of low ET (inclement weather), as models tended to have difficulty in these situations given the lack of calibration data points.

#### *Increased Sample Variability*

Future studies at this site would benefit from diversifying the measurement locations within the cells to find more representative locations. The cells in this study contained only one measurement location (lysimeter) and its location was determined by space availability and/or its proximity to the board walks (accessibility). Increasing the diversity of measurement locations would help ensure that observations are truly representative of each cell as a whole.

#### *Statistical Models vs Physical Models*

Physically based models (Penman-Monteith) often have a difficult time operating at scales as small as the cells and would have required cell specific measurements of every input variable. In the past, statistical models were often unable to incorporate complex physical processes – the foundations of physically based models. However, this study has shown that specific multivariate statistical modeling approaches can, in

fact, identify complex interactions on the micro-scale and without the need for more complicated and expensive data collection. Future studies could compare these newer multivariate statistical models with physically based models with in order to establish if the complex interactions revealed by these models hold any physical foundations in known scientific processes. If this calibration is successful statistical models such as the multiple linear regression models used in this study could be fit to different land surface types and then used to estimate/model ET over large areas where measurements are not available

#### *Irrigation and Water Table Effects*

In this study, all cells were watered so extensively that water tables rarely fell much below the surface. Future studies should focus on quantifying irrigation volumes and determining the effects of irrigation regimes given their possible impact on the sustainability of wetlands once they have been constructed. For example, future research could attempt to establish the effect of lower, more natural water tables that experience greater fluctuations than those in this study. This could be achieved through pairing cells of the same construction technique and providing regular irrigation to one and only periodic irrigation to the other. A better understanding of how the cells respond to drier conditions could help increase the success of constructed wetlands and even determine a minimum water table threshold. Such a threshold could likely save vast quantities of water.

## 6.0 Conclusions

Oil sands mining can be particularly destructive to terrestrial ecosystems, as much of the land cover must be removed in order to access the bitumen below. Because of the shallow yet expansive nature of the deposits, large areas of northern Alberta are being disturbed or completely destroyed. As stipulated in the producers' agreement with the provincial government, lands where mining has occurred must be returned to a capability and function similar to those in place before mining began.

This thesis analyzed a series of 12 test plots containing potential wetland reclamation techniques. Each cell was designed to replicate natural boreal wetlands by adding liners that limited deep percolation or lateral flow. Frequent irrigation using a pipe network meant that the cells were hydrologic distinct from natural wetlands, with water tables near the surface and ponded water for extended periods. Cells were composed of different combinations of construction strategies, which resulted in unique individual cell characteristics and considerable variation in ET and water balances.

ET varied considerably both spatially and temporally at the study site. Highest ET was observed in June, averaging  $3.6 \text{ mm day}^{-1}$  compared with  $3.4 \text{ mm day}^{-1}$  in July and  $2.0 \text{ mm day}^{-1}$  in August. Among all cells, ET ranged from  $\sim 0.6 \text{ mm day}^{-1}$  to over  $8.2 \text{ mm day}^{-1}$  with an average of  $3.2 \text{ mm day}^{-1}$ . ET was moderately correlated with incoming solar radiation ( $r = 0.47$ ) but weakly correlated with all other individual environmental variables. Multiple linear regression models revealed that ET at the site was more strongly influenced by complex interactions between environmental variables than by the effects of individual variables. However, these models had a

tendency to over-fit the data due to their high level of complexity and a relatively low number of observations. Recursive partitioning models also captured environmental variable interaction but without a strong tendency to over-fit the data due the stratified method for generating predictions.

Different combinations of construction techniques created distinctive hydrologic and vegetative characteristics and were therefore considered to be the main cause of variation in ET among the cells. Of the three construction techniques assessed, placement period and, to a lesser extent, soil depth were found to have significant effects on ET.

Total water input depths (irrigation and precipitation) ranged from ~200 to 475 mm the bulk of which was contributed in June, even with very little precipitation in the month. Total outputs (ET) for the growing season varied widely among the cells, ranging between ~175 and ~325 mm. June and July had similarly large losses while August was substantially lower.

Cumulative water balances indicate that the cells had a distinct hydrology compared with natural wetlands they were designed to replicate. ET rates were generally higher than what has been previously reported in literature, for both natural and constructed wetlands. Additionally, the water balances of several cells suggest the presence of leaks in their liners. Approximate leakage estimates are substantial ranging from  $1.9 \text{ mm day}^{-1}$  to  $3.4 \text{ mm day}^{-1}$ .

The following five conclusions can be drawn from the examination of the magnitude and variation of ET the site, effects of construction techniques and controlling factors on ET, and the cumulative water balance components for each of the 12 cells in the study.

(1) Construction techniques had a significant effect on ET. Constructing in winter and/or with only a shallow (15 cm) soil depth may have adverse effects on the sustainability of constructed wetlands because of their potential for increased ET rates.

(2) The highly managed nature of the cells, including the possibility that the geosynthetic liners were not impermeable, may have masked their true evaporative dynamics, making it difficult to evaluate the long-term sustainability of the construction techniques used.

(3) The hydrologic behaviour of the cells was considerably different from the wetlands they were designed to replicate. Additional work is necessary in order to develop improved wetland reclamation techniques that can create systems with hydrologic behaviour comparable to those that existed before mining. Future research should attempt to evaluate the impact of lowering the water table on hydrologic behaviour by removing much of the additional water added and thus creating more realistic growing season wetland conditions in the cells.

(4) Direct relationships between individual environmental variables and ET at the site appear weaker than at natural wetlands. Instead, controls on ET in the cells are closely linked to incoming solar radiation and/or to the resultant effects of complex interactions between two or more of five environmental variables.

(5) Multivariate statistical modeling techniques, specifically multiple linear regression, hold considerable promise for furthering our understanding of ET controls in environments where traditional physical models are not appropriate. Their ability to assess complex interactions among environmental factors may provide new insight into wetland ET dynamics.

## 7.0 References

- Alberta Environment. 1994. A Guide for Oil Production Sites, Pursuant to the Environmental Protection and Enhancement Act and Regulations. Queen's Printer.
- Alberta Environment. 2003. Regulatory Perspective – Oil Sands Reclamation. Presented at CONRAD/OSERN Symposium, May 12 & 13 2003, Edmonton, Alberta.
- Alberta Environment. 2005. State of the Environment. Available from: [http://www3.gov.ab.ca/env/soe/land\\_indicators/41\\_oilsands\\_reclamation.html](http://www3.gov.ab.ca/env/soe/land_indicators/41_oilsands_reclamation.html)
- Baldocchi, D.D., Vogel, C.A., Hall, B. 1997. Seasonal variation of energy and water vapor exchange rates above and below a boreal jack pine forest canopy. *Journal of Geophysical Research*, 102(D24): 28 939- 28 951.
- Baldocchi, D.D., Kelliher, F.M., Black, T.A., Jarvis, P., 2000. Climate and vegetation controls on boreal zone energy exchange. *Global Change Biology* 6: 69-83.
- BGC Engineering. 2009. Final Report: Syncrude Canada EIP Instrumented Watershed U-Shaped Cell As-Built Report and Operational Guidelines.
- Blanken, P.D., Black, T.A., Neumann, H.H., den Hartog, G., Yang, P.C., Nesic, Z., and Lee, X. 2001. The seasonal water and energy exchange above and within a boreal aspen forest. *Journal of Hydrology*, 245: 118-136.
- Bridgman, S.D., Pastor, J., Updegraff, K., Malterer, T.J., Johnson, K., Harth, C., and Chen, J. 1999. Ecosystem control over temperature and energy flux in northern peatlands. *Ecological Applications* 9, no. 4: 1345-1358.
- Breiman, L., Friedman, J., Olshen, R., and Stone, C. 1984. *Classification and Regression Trees*. Wadsworth.
- Brown, S.M., Petrone, R.M., Mendoza, C., Devito, K.J. 2010. Surface vegetation controls on evapotranspiration from a sub-humid Western Boreal Plain wetland. *Hydrological Processes* 24: 1072- 1085.
- Cagampan, J.P., and Waddington, J.M. 2008. Moisture dynamics and hydrophysical properties of a transplanted acrotelm on a cutover peatland. *Hydrological Processes* 22, 1776-1787.
- Carey, S.K., 2008. Growing season energy and water exchange from an oil sands overburden reclamation soil cover, Fort McMurray, Alberta, Canada. *Hydrological Processes*, 22: 2847-2857.

- Carter, V. 1986. An overview of the hydrologic concerns related to wetlands in the United States. *Canadian Journal of Botany* 64: 364–374.
- Cowardin, L.M., Carter, V., Golet, F.C., LaRoe, E.T. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service Publication FWS/OBS-79/31: Washington, DC; 103.
- Crawley, M. J. 2005. *Statistics: An Introduction Using R*. Wiley, London.
- Cross, H. 1936. Analysis of flow in networks of conduits or conductors. Bulletin 286, University of Illinois Engineering Experiment Station.
- Crown, P.H., and Twardy, A.G., 1975. Soils of the Fort McMurray region, Alberta (Townships 88-89, Ranges 8-11) and their relations to agricultural and urban development. Alberta Institute of Pedology, University of Alberta.
- Devito K.J., Creed, I.F., Fraser, C.J.D. 2005. Controls on runoff from a partially harvested aspen-forested headwater catchment, Boreal Plain, Canada. *Hydrological Processes* 19: 3–25.
- Dingman, S.L. 2002. *Physical Hydrology*. Waveland Press, Long Grove Illinois.
- Drexler, J.Z., Snyder, R.L., Spano, D, and, Kyaw, T.P.U. 2004. A review of models and micrometeorological methods used to estimate wetland evapotranspiration. *Hydrological Processes* 18: 2071-2101.
- Ellies, A., Hartge, K.H., MacDonald, R., Ramirez, C. 2003. Organische bodensubstanz und benetzbarkeit von bodenproben-eine interpretation. *J. Plant Nutr. Soil Sci.* 166: 120–123.
- Elshorbagy, A., Jutla, A., Barbour, L., and Kells, J., 2005. System dynamics approach to assess the sustainability of reclamation of disturbed watersheds. *Canadian Journal of Civil Engineering*, 32: 144-158.
- Gavin, H. and Agnew, C.T., 2003. Evaluating the reliability of point estimates of wetland reference evaporation. *Hydrology and Earth systems Science*, 7: 3-10.
- Golchin, A., Oades, J.M., Skjemstad, J.O., Clarke, P. 1994. Soil structure and carbon cycling. *Aust. J. Soil Res.* 32: 1043–1068.
- Heijmans, M., Arp, W.J., Chapin, F.S. III. 2004. Carbon dioxide and water vapour exchange from understory species in boreal forest. *Agricultural and Forest Meteorology* 123: 135–147.

- Hassink, J. 1995. Decomposition rate constants of size and density fractions of soil organic matter. *Soil Sci. Soc. Am. J.* 59: 1631–1635.
- Holden, J. 2005. Peatland hydrology and carbon release: why small-scale process matters. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences* 363, no. 1837: 2891–913.
- Humphreys, E.R., Lafleur, P.M., Flanagan, L.B., Hedstrom, N., Syed, K.H., Glenn, A.J., and, Granger, R. 2006. Summer carbon dioxide and water vapor fluxes across a range of northern peatlands. *Journal of Geophysical Research* 111, no. 4.
- Ingram, H.A.P. 1978. Soil layers in mires – function and terminology. *Journal of soil Science.* 29: 224–227.
- Ingram, H.A.P. 1983. Hydrology. *Ecosystems of the World 4A—Mires: Swamp, Bog Fen and Moor*, Gore APJ (ed.). Elsevier: Amsterdam.
- Joiner, D.W., Lafleur, P.M., McCaughey, J.H., Bertlett, P.A. 1999. Interannual variability in carbon dioxide exchanges at a boreal wetland in the BOREAS northern study area. *Journal of Geophysical Research* 104(D22): 27663–27672.
- Keshta, N., Elshorbagy, A., Carey, S., and Barr, A. 2009. A generic system dynamics model for simulating and evaluating the hydrological performance of reconstructed watersheds. *Hydrol. Earth Syst. Sci. Discuss.*, 5: 1441–1478.
- Kellner, E. 2001. Surface energy fluxes and control of evapotranspiration from a Swedish Sphagnum mire. *Agricultural and Forest Meteorology*, 110: 101–123.
- Kim, J., Verma, S.B., 1996. Surface exchange of water vapour between an open Sphagnum fen and the atmosphere. *Boundary-Layer Meteorology*, 79: 243–264.
- Ladd, J.N., Foster, R.C., Nannipieri, P. 1995. Soil structure and biological activity. *Soil Biochem.* 9: 128–129.
- Lafleur, P. and Rouse, W.R. 1988. The influence of surface cover and climate on energy partitioning and evaporation in a subarctic wetland. *Boundary Layer Meteorology*, 44: 327–347.
- Lafleur, P.M. 1990. Evapotranspiration from sedge-dominated wetland surfaces. *Aquatic Botany*, 37: 341–353.
- Lafleur, P.M. and Roulet, N.T. 1992. A comparison of evaporation rates from two fens of the Hudson Bay Lowland. *Aquatic Botany*, 44: 59–69.

- Lafleur, P.M. and Schreder, C. P. 1994. Water loss from the floor of a subarctic forest. *Arct. Alp. Res.*, 26: 152–158
- Lafleur, P.M., McCaughey, J.H., Joiner, D.W., Bartlett, P.A., Jelinski, D.E. 1997. Seasonal trends in energy, water and carbon dioxide fluxes at a northern boreal wetland. *Journal of Geophysical Research*, 102: 29009–29020.
- Lafleur, P.M., 2008. Connecting Atmosphere and Wetland: Energy and Water Vapour Exchange. *Journal of Geography Compass*, 2: 1027-1057.
- Linacre, E.T. 1976. Swamps. *Vegetation and the Atmosphere*, Vol. 2 – Case Studies, Monteith JL (ed.). Academic Press: London; 329–347.
- Lopes, A.M.G. 2003. Implementation of the Hardy-Cross Method for the solution of piping networks. *Computer Applications in Engineering Education* 12-2: 117-125.
- Lott, R. B., and Hunt, R. J. 2001. Estimating evapotranspiration in natural and constructed. *Wetlands*, 21(4): 614-628.
- Lucchese, M., Waddington, J.M., Poulin, M., Pouliot, R., Rochefort, L., Strack, M. 2009. Organic matter accumulation in a restored peatland: Evaluating restoration success. *Ecological Engineering*, 36: 482–488.
- McNeil, P., Waddington, J.M. 2003. Moisture controls on Sphagnum growth and CO<sub>2</sub> exchange on a cutover bog. *Journal of Applied Ecology*, 40: 354–367.
- Monteith, J.L., 1965. *Evaporation and environment*. Symp. Soc. Exp. Biol. XIX., Cambridge University Press.
- Monteith, J.L., 1981. Evaporation and surface temperature. *Quart. J. Roy. Meteorolog. Soc.*, 107: 1–27.
- Moore, K.E., Fitzjarrald, D.R., Wofsy, S.C., Daube, B.C., Munger, W.J., Bakwin, P.S., Crill, P. 1994. A season of heat, water vapor, total hydrocarbon, and ozone fluxes at a sub-arctic fen. *Journal of Geophysical Research* 99: 1937–1952.
- Moore. Paul, M. 2008. *Micrometeorological Fluxes and Controls on Evapotranspiration for a Jack Pine Stand Growing on Reclamation Soil Cover, Fort McMurray, Alberta*. M.Sc. Thesis. Unpublished. Department of Geography and Environmental Studies, Carleton University, Ottawa.
- National Wetlands Working Group. 1997. *The Canadian Wetland Classification System*. 2<sup>nd</sup> edition. Wetlands Research Centre, University of Waterloo, Waterloo, Canada.

- Natural Resources Canada (NRC). 2004-2009. Boreal Forest. Date accessed: October 2010. Available:  
[http://atlas.nrcan.gc.ca/site/english/learningresources/theme\\_modules/borealforest/index.html](http://atlas.nrcan.gc.ca/site/english/learningresources/theme_modules/borealforest/index.html).
- Nichols, D.S., Brown, J.M. 1980. Evaporation from a Sphagnum moss surface. *Journal of Hydrology*, 48: 289–302.
- Oke, T.R. 1987. *Boundary layer climates* (2nd edition). New York, NY: Routledge.
- Okruszko, H. 1995. Influence of hydrological differentiation of fens on their transformation after dehydration and on possibilities for restoration. *Restoration of Temperate Wetlands*. Chichester, UK: John Wiley and Sons, 113-120.
- Petrone, R.M., Waddington, J. M., and, Price, J.S. 2001 Ecosystem scale evapotranspiration and net CO<sub>2</sub> exchange from a restored peatland. *Hydrological Processes* 15: 2839-2845.
- Petrone, R.M., Price, J., Waddington, M.J., and Vonwaldow, H. 2004. Surface moisture and energy exchange from a restored peatland, Québec, Canada. *Journal of Hydrology*, 295,1-4: 198-210.
- Petrone, R.M., Waddington, M.J., and Price, J.S. 2003. Ecosystem-scale flux of CO<sub>2</sub> from a restored vacuum harvested peatland. *Wetlands Ecology and Management*, 11: 419-432.
- Piquard, T. 2010. Species colonization in a reclaimed fen prototype using a peat-mineral mix substrate near Fort McMurray, Alberta. B.A.Sc. Thesis. Unpublished. Department of Environmental Science, Lakeland College, Vermillion
- Price, J. S. 1991. Evaporation from a blanket bog in a foggy coastal environment. *Boundary-Layer Meteorology*, 57: 391-406
- Price, J. S. 1994. Evaporation from a lakeshore Typha marsh and adjacent open water systems. *Aquatic Botany*, 48: 261-272.
- Price, J.S. 1996. Hydrology and Microclimate of Partly Restored Cutover Bog, Quebec. *Hydrological Processes*, 10: 1263-1272.
- Price, J.S., Schlotzhauer, S.M. 1999. Importance of shrinkage and compression in determining water storage changes in peat: The case of a mined peatland. *Hydrological Processes*, 13: 2591–2601.

- Price, J.S., Waddington, J.M. 2000. Advances in Canadian wetland hydrology and biogeochemistry. *Hydrological Processes*, 14: 1579–1589.
- Price, J.S., Whitehead, G.S. 2001. Developing hydrological thresholds for *Sphagnum* recolonization on an abandoned cutover bog. *Wetlands*, 21: 32–40.
- Price, J.S., 2003. The role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands. *Water Resour. Res.*, 39: 9, 1241.
- Price, J.S., Branfireun, B, Waddington, J.M., and Devito, K., 2005. Advances in Canadian Wetland Hydrology, 1999-2003. *Hydrological Processes*, 18: 201-214.
- Price, J.S., Edwards, T.W.D., Yi, Y., Whittington, P.N. 2009. Physical and isotopic characterization of evaporation from *sphagnum* moss. *Journal of Hydrology*, 369: 175-182
- Qualizza, C., Chapman, D., Barbour, S.L., and Purdy, B. 2004. Reclamation research at Syncrude Canada's mining operation in Alberta's Athabasca oil sands region. Proceedings, International Conference on Ecological Restoration SER2004, Victoria, B.C., Canada, August 24-26.
- R Development Core Team. 2009. R: A language and environment for statistical computing. R Foundation for Statistical Computing.
- Raddatz, R.L., Papakyriakou, T.N., Swystun, K.A., and M. Tenuta. 2009. Evapotranspiration from a wetland tundra sedge fen: Surface resistance of peat for land-surface schemes. *Agricultural and Forest Meteorology*, 149, 5: 851-861.
- Rosenberry, D.O., Winter, T.C. 1997. Dynamics of water-table fluctuations in an upland between two prairie–pothole wetlands in North Dakota. *Journal of Hydrology* 191: 266–289.
- Roulet, N.T., Crill, P.M., Comer, N.T., Dove, A., and Boubonniere, R. A. 1997. CO<sub>2</sub> and CH<sub>4</sub> flux between a boreal beaver pond and the atmosphere. *Journal of Geophysical Research*, 102:29, 313–329.
- Rouse, W. R. 2000. The energy and water balance of high-latitude wetlands: controls and extrapolation. *Global Change Biology* 6, no. S1: 59-68. .
- Schlotzhauer, S. M. and Price, J.S. 1999. Soil water flow dynamics in a managed cutover peat field, Quebec: 1. Field and laboratory investigations. *Water Resources Research*, 35: 3675-3684.

- Skopp, J.M. 2000. Physical properties of primary particles. In: M.E. Summer, Editor. Handbook of soil science. CRC Press, Boca Raton, pp. A3–A17.
- Shantz, M.A., and Price, J.S., 2006. Hydrological changes following restoration of the Bois- des-Bel Peatland, Quebec, 1999–2002. *Journal of Hydrology*, 331: 543–553.
- Smerdon, B.D., Devito, K.J., Mendoza, C.A. 2005. Interaction of groundwater and shallow lakes on outwash sediments in the sub-humid Boreal Plains region. *Journal of Hydrology*, 314: 246–262.
- Souch, C., Wolfe, C.P., Grimmond, C.S.B. 1996. Wetland evaporation and energy partitioning: Indiana Dunes National Lakeshore. *Journal of Hydrology*, 184: 189–208.
- Van Seters, T.E. 1999. Linking the past to the present: the hydrological impacts of peat harvesting and natural regeneration on an abandoned cutover bog, Quebec. MES Thesis, Department of Geography, University of Waterloo, Canada,
- Van Seters, T.E., and Price, J.S. 2001. The impact of peat harvesting and natural regeneration on the water balance of an abandoned bog, Quebec. *Hydrology Processes*, 15: 233–248.
- Vitt, D.H. and Chee, W.L. 1990. Relationships of vegetation to surface water chemistry and peat chemistry in fens of Alberta, Canada. *Vegetation*, 89: 87-106, 1990.
- Vitt, D.H. 1990. Growth and production dynamics of Boreal mosses over climatic, chemical and topographic gradients. *Botanical Journal of the Linnean Society* 104: 35–39.
- Vitt, D.H., Halsey, L.A., Bauer, I.E. and, Campbell. 2000. Spatial and temporal trends of carbon sequestration in peatlands of continental western Canada through the Holocene. *Canadian Journal of Earth Sciences*, 37: 683-693
- Waddington, J.M., Price, J.S. 2001. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography* 21: 433–451.
- Wever, L.A., Flanagan, L.B., Carlson, P.J. 2002. Seasonal and interannual variation in evapotranspiration, energy balance and surface conductance in a northern temperate grassland. *Agric. For Meteorol.* 112:31-49
- Williams, T.G., and Flanagan, L.B. 1996. Effect of changes in water content on photosynthesis, transpiration and discrimination against CO<sub>2</sub> and C<sup>18</sup>O<sup>16</sup>O in *Pleurozium* and *Sphagnum*. *Oecologia*, 108: 38–46.

Woynillowicz, D., Severson-Baker, C., Reynolds, M. 2005. Oil sands fever the environmental implications of Canada's oil sands rush. The Pembina Institute. [www.pembina.org](http://www.pembina.org)

Young, J.L., and Spycher, G. 1979. Water-dispersible soil organic-mineral particles: I. Carbon and nitrogen distribution. *Soil Sci. Soc. Am. J.* 43: 324–328