EFFECTS OF FOREST AGE AND TOPOGRAPHY ON BOREAL FOREST EVAPOTRANSPIRATION AND WATER BALANCE

BY

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ABSTRACT

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The boreal forest forms a band that stretches across the continents of the northern hemisphere. Wildfire disturbances have helped transform this forest into stands of varying ages with varying soil drainage. It is well known that the boreal forest contributes greatly to the global water cycle, but less is known as to how variable these water fluxes are throughout the forest mosaic. Throughout the growing seasons of 2006 and 2007, meteorological measurements were taken during the growing season from three different aged black spruce stands near Thompson, MB. The stands that were burned in 1930 and 1964 each included upland and lowland sites with independent measurements. The stand burned in 1850 had measurements taken only from an upland site. Evapotranspiration (ET) was calculated from the residual energy after net radiation (Rn), sensible heat flux (H) and ground heat flux were measured. We sought to investigate whether ET varied with stand age and topographic location.

Results indicate that there is a significant increase in Rn, H, and ET as forests age. ET levels range from being 4% to 19% lower for younger stands. It is assumed that the depth of the organic layer at older sites allows for mosses to more effectively wick up available moisture through capillary rise, and have higher transpiration levels. The larger tree density at the 1964 sites compared to the 1930 sites may account for a portion of the observed increase in ET for these ages. Differences in drainage between the 1930 and 1850 sites may also account for a portion of the increase in ET observed between these two ages.

Wetland sites had H and ET that were significantly less than for the upland sites. ET rates were 11 to 20% higher at the upland sites than the wetland sites; part of this difference is thought to be due to the presence of larger trees, with an increased capacity to transpire water at upland sites.

As the number of forest fires has been predicted to increase substantially in the future, the prospect of the boreal forest average stand age being younger would affect the boreal's water and energy budgets. Our data helps to describe water and energy budgets for forest stands with different drainage capabilities, for stands between the ages of 45 and 160 years. This knowledge will be used to help predict the degree and speed of climate change that will be experienced in the boreal forest.

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1 INTRODUCTION

1.1 The Boreal Forest

The boreal forest covers a huge expanse of land in the northern hemisphere, and accounts for approximately one third of the world's forested land. Forming a broad ring between 50 and 70 degrees north in the northern hemisphere, it covers a large portion of North America, Russia and Scandinavia. The vegetation inhabiting the boreal forest is extremely diverse, and varies from deciduous forests in the southern reaches of the zone, to sparse coniferous vegetation on permafrost in the north.

The majority of land now covered by the boreal forest was formerly glaciated, and therefore these ecosystems are relatively young. This region is characterized by the presence of long winters with up to six months of freezing temperatures, and short growing seasons of 50 to 100 frost-free days. In North America, black and white spruce, tamarack, pine and balsam fir are commonly found in coniferous stands. Spruce trees are well-adapted to low-lying areas and high water tables, and pines occur in areas with sandy, well-drained soils. Throughout the boreal zone, deciduous trees such as aspen, alder, and birch are often found during early periods of forest succession (Bonan and Schugart, 1989). A common thread linking all areas of the boreal forest is the presence of innumerable water bodies; marshes, fens, lakes, bogs, wetlands, and rivers are scattered throughout. The soils found in the boreal forest are diverse, but most are slightly acidic with high water tables (Bonan and Schugart, 1989).

The amount of solar energy that is incident on the surface of the earth controls much of the biological activity in ecosystems. The physiological functioning of the vegetation is affected by factors such as precipitation, radiation, and temperature. In response, the type of vegetation influences the climate through its influence on soil moisture, albedo, and surface roughness (Betts et al., 1996). The depth of the planetary boundary layer is controlled by the interaction between the biosphere and the atmosphere. The entrainment of dry air increases the vapour pressure deficit and promotes evaporation from the ecosystem. There can, however, be a negative feedback loop for evaporation (Raupach, 1998), because the entrainment of dry air can also inhibit transpiration by forcing the closure of stomata (Baldocchi et al., 2000).

Global climate change is occurring due to rapid increases in greenhouse gas levels during the most recent decades (Solomon et al., 2007). The boreal forest and peatlands are extremely important global carbon sinks, as they absorb a large amount of CO_2 through photosynthesis, and store a large amount of carbon in the thick organic soil deposits. Disturbances such as forest fire, harvesting, and insects have a large impact on the boreal zone, and often affect large areas of forest (Kurz and Apps, 1999). Following disturbances, regeneration occurs, and the succession of vegetation results in patches of stands of different ages (Murphy et al., 2000; Stocks et al., 2002), which has a huge impact on the energy and water budgets of these forests. It has been predicted that climate change will result in an increased area burned by forest fires in Canada, due to the increase in warm and dry conditions (Flannigan et al., 2005). It is not known to what extent increase in forest fires in the boreal forest will affect global energy and water cycles.

1.2 The Canadian Carbon Progam and Fluxnet Canada

The international Fluxnet network is a group of more than 400 flux towers has been assembled since 1994 in order to study energy, water vapour and CO_2 fluxes worldwide (Fluxnet, 2001). Fluxnet-Canada developed 22 sites throughout Canada that are maintained by universities and government agencies, and are present in many different ecosystem types. The objectives of Fluxnet-Canada were i) to study the effects of forest fires and climate on the sequestration of carbon in forests, ii) to study the effects of peatlands on the climate and on the carbon cycle, and iii) to use modelling, remote sensing, and scaling in order to extrapolate carbon fluxes in time and space (Fluxnet-Canada, 2006). Fluxnet-Canada has since evolved to become the Canadian Carbon Program (CCP), with the goal of furthering our knowledge of carbon and energy cycling in Canadian ecosystms.

Before Fluxnet, the Boreal Ecosystem-Atmosphere Study (BOREAS) network was formed in order to study the boreal forest in a 1000 x 1000 km area in Saskatchewan and Manitoba. The majority of sites included were mature sites, and the study consisted of continuous meteorological measurements, aircraft measurements, and intensive field campaigns between 1994 and 1996 (Sellers et al., 1997). In 1996, the Boreal Ecosystem Research Monitoring Sites (BERMS) group was formed, which included three sites that had been included in BOREAS. Younger sites of different composition were also included for comparison (BERMS, 2003).

1.3 Energy Balance in the Boreal Forest

In the boreal forest, the surface radiation budget is determined by the season, the latitude, aerosols present in the atmosphere, cloud cover, surface albedo, near-surface temperature, and moisture (Betts et al., 2001). Boreal wildfires tend to cover large expanses of forest, and are high-intensity, which has resulted in the forest being composed of large patches of even-aged stands of varying ages. A given site's species composition will vary depending on what stage it is at in secondary succession and its drainage. Sites of different species composition are known to have differences in water and energy balances. Coniferous trees retain their needles year-round, and are therefore able to begin photosynthesizing and transpiring water earlier in the growing season than deciduous trees, which lose their leaves during the winter months (Pejam et al., 2006). The aerodynamic roughness and low albedo of coniferous species allows them to easily exchange energy and mass with the atmosphere, and absorb solar radiation (Baldocchi et al., 2000).

Net radiation (Rn) is equal to the total difference between the amount of shortwave and longwave radiation incident on the surface and the amount leaving the surface. Surface albedo is the ratio of up-welling to down-welling shortwave radiation, and is determined by the physical properties of the earth's surface. Albedo has a large effect on the available energy for an ecosystem (Pejam et al., 2006). During the growing season when Rn is at its highest, the largest amount of energy is being partitioned into heating of the air (sensible heat flux (H)) and the evaporation of water in the boreal forest ecosystem (latent heat flux (LE)). This partitioning is controlled by the availability of water, which is affected by the cycle of soil freezing and controls on transpiration during the summer (Betts et al., 2001). The amount of radiation reaching the forest floor peaks at the solar maximum and decreases throughout the growing season, as the sun angle becomes lower (Baldocchi et al., 1997). Rn is partitioned into H, LE, ground heat flux (G), and storage within the system (S):

$$Rn = H + LE + G + S$$

It is generally assumed that S in the black spruce forests is small, and averages out to zero over the growing season (Arain et al., 2003). For a boreal black spruce forest in central Saskatchewan, Arain et al. (2003) found that G was small during the spring and summer seasons. The presence of a deep peat layer on the soil resulted in small G values, with slightly positive values during the day and slightly negative values during the night. Values of G were found to range from an average of +6 W/m^2 during the month of July when the soil is storing energy, down to -5 W/m^2 during the winter months when energy is lost from the soil. The observed loss of energy from the soil during late summer to fall partially accounts for the decrease in Rn, and helps to continue the heating of the air and evaporation of water in boreal systems (Baldocchi et al., 1997).

LE is the amount of energy partitioned into the vaporization of liquid water from the system, which is also represented as evapotranspiration (ET). Evapotranspiration is a function of a forest's ability to take up and utilize moisture, and therefore is extremely variable throughout the boreal forest. Within Canada, during the growing season ET often ranges from 2 mm/day for a jack pine forest (Baldocchi et al., 1997) to 3.25 mm/day for a deciduous aspen forest (Black et al., 1996). Swedish pine forests have shown ET rates up to 4 mm/day (Grelle et al., 1999), and Siberian larch forests have been found to have lower ET rates of 1.1 to 1.9 mm/day (Ohta et al., 2001).

1.4 Previous Studies on Boreal Water and Energy Balance

Our study is one component of a larger research initiative at chronosequence sites in northern Manitoba. The focus of this larger project is to gain a greater understanding of water and energy partitioning, and to see if they differ among forest stands of different ages and different topographic position. Other studies have examined the energy and water balances of boreal forest stands (Amiro, 2001; Amiro, Orchansky et al., 2006; Amiro, Barr et al., 2006; Barr et al., 2006; Betts et al., 2001; Chambers and Chapin, 2001; Cienciala et al., 1998; Jarvis et al, 1997; McCaughey et al., 2006;), either for single forest stands, stands of different ages, or stands of different topographic position. Our study is unique in the fact that it examines these factors for chronosequence sites that are in close proximity to each other, and each stand age has well- and poorly-drained areas.

Baldocchi et al. (1997) studied a boreal jack pine stand in Saskatchewan, and found that due to a combination of low albedo, longer days, and clearer skies, this stand absorbed more radiation than a temperate broad-leaf forest in a given 24-hour period. It was also found that for jack pines, the amount of energy partitioned into LE peaks during early summer after soils begin to thaw, water becomes available and temperatures are high (Baldocchi et al., 1997).

Arain et al. (2003) found that for black spruce in central Saskatchewan, 90% of annual Rn was partitioned into H and LE, with soil heat flux (G) and storage (S) being very small. G was found to be positive during the day and negative at night. This amplitude is smaller than for S because of the bryophyte layer and peat, which have low thermal conductivity. LE for black spruce was found to respond mainly to vapour pressure deficit (VPD), and to a lesser extent, Rn. During the spring, the majority of available energy was partitioned into H, while during the summer this changed to H and LE becoming equal. Jarvis et al. (1997) also measured energy and CO_2 fluxes over a black spruce site in Saskatchewan, and found that H and LE accounted for 93% of the total net radiation for the growing season.

Amiro, Barr et al. (2006) examined carbon, energy and water fluxes at previous fire and harvested forest sites in Saskatchewan. The site ages were between 8 and 150 years of age, and the dominant tree species ranged from aspen, jack pine, black spruce, and a combination of these. The youngest sites were found to be carbon sources, and older sites were carbon sinks. There was a gap of information for forests between the ages of 10 and 50 years. Evapotranspiration levels were found to be largely dependent on age and forest composition.

Chambers and Chapin (2002) performed a study on the energy balance of a young Alaskan fire chronosequence. Results were compared to unburned sites, and demonstrated that following fire changes in albedo, G and Rn occurred. Albedo for black spruce stands was found to increase from approximately 0.06 following fire, up to 0.13 twelve years after fire. G as a percentage of Rn decreased from 12% in the first year following fire, down to 9% after 12 years. The first years following fire showed the greatest change in these factors, as the sites became re-vegetated. They predicted that due to the potential increase in forest fire occurrence and severity, the changes in energy balance over recently burned fire sites may have an effect on local and regional climates.

Amiro, Orchansky et al. (2006) proposed that if forest fire frequency is going to increase, a cooling effect could result due to the change in energy balance. Albedo for sites 10 years following fire was found to be approximately 0.13 and decreased to 0.07 by the time forests reach 150 years. LE was found to increase sharply for young sites, peaking at about 60% of Rn between 10 and 25 years of age. Manitoba sites were also found to have lower levels of LE than Saskatchewan sites, thought to be due to differences in hydrology, water status, and soil type. Liu et al. (2005) examined the energy and ET fluxes over a fire chronosequence in Alaska that included a 3-year, 5-year and 80-year site. Annual Rn and ET were found to significantly decrease following a fire disturbance for this chronosequence.

1.5 Studies in Northern Manitoba

The northern old black spruce (NOBS) site was established in 1994, and is the oldest flux tower present in the boreal zone. The NOBS site was included in the BOREAS group of sites in Saskatchewan and Manitoba, and subsequently was included in the Fluxnet international network of meteorological towers. Due to the fact that there are historical measurements for this site, it has been included in a number of other studies, and compared to other boreal forest stands.

Gower et al. (1997) looked at NPP and root mass for six boreal forest sites in Saskatchewan and Manitoba, and included jack pine, aspen and black spruce stands. The NOBS site was included as the Manitoba black spruce stand. The patterns of carbon allocation in evergreen forests were found to differ from patterns found for deciduous forests.

A study by Bergeron et al. (2007) compared NOBS to other black spruce sites in Canada, including a southern old black spruce site in Saskatchewan, and an old black spruce site in Quebec. Springtime air temperatures were found to have a stronger relationship with gross ecosystem production than air temperatures later in the growing season. This research found support for the hypothesis that springtime conditions are extremely significant when examining the impact of climate change on C budgets of coniferous boreal forest forests on a regional scale.

Dunn et al. (2007) examined CO_2 flux at NOBS between 1994 and 2004. It was found that the ecosystem shifted between being a C source to a C sink over this period. Ecosystem C exchange was found to respond strongly to moisture status, air temperature, potential ET, and summertime solar radiation. Soil thaw and the depth of the water table were found to predict 64% of the daily respiration rate, with wetter conditions decreasing respiration.

1.6 Research on Our Chronosequence

A chronosequence is a group of sites that represent a type of ecosystem throughout a range of ages, or different stages in succession. The boreal black spruce forest chronosequence sites included in our study have been used in various other research projects during the past ten to fifteen years. Bond-Lamberty, Wang, Gower and Norman (2002) measured leaf area index (LAI) for the understory and overstory of well and poorly-drained stands. Overstory LAI was found to be significantly higher for well-drained stands than for poorly-drained stands. The 70-year-old stand (1930) had the highest overstory LAI, the 150-year-old stand (NOBS) was found to be 30-50% lower, and the 40-year-old stand (1964) was approximately 75% lower. There was an inverse relationship found between understory LAI and overstory LAI, as high overstory LAI was found to limit light availability for the understory.

Bond-Lamberty, Wang and Gower (2002) examined the distribution of woody debris, and the evolution of CO_2 from the debris at our chronosequence sites and more recently burned sites. Downed dead wood (DDW) was found to be the highest at the 1964 site, followed by the NOBS site, and then the 1930 site. This "u-shaped" temporal curve for DDW levels is typical for similar forest sites. Initial debris levels are high following fire, and this declines with age as the stand regenerates and the debris decomposes. The debris level increases in much older stands, due to natural senescence of the mature trees. Well-drained sites always showed significantly higher levels of DDW than poorly-drained sites, as the higher moisture levels at the poorly-drained sites aides in the decomposition of DDW. Wang et al. (2003) quantified C distribution for the same chronosequence, and found that C pools increased with stand age in the overstory and bryophyte components. Understory, bryophyte and forest floor C pools were found to be significantly larger at the poorly-drained sites than at the well-drained sites. Net primary production (NPP) was measured for three years at these sites as well (Bond-Lamberty et al., 2004), and it was found that the youngest sites were moderate C sources, the middle-aged stands were strong C sinks, and the oldest stands were roughly neutral.

Litvak et al. (2003) used eddy covariance to directly measure CO_2 and energy exchanges above five different-aged well-drained boreal stands in northern Manitoba, including the three forest age sites included in our study, during the growing seasons of 1999 and 2000. Measurements were taken at NOBS throughout both years, and portable towers were moved between the younger sites during the growing seasons. The younger sites have limited data, and measurements for these sites were not taken during the same time periods, but were compared to continuous baseline measurements taken at NOBS.

Results demonstrated that the 11 year-old site was a small C sink, the 19 year-old site was a modest sink, and the 36 year-old site (1964) was a large sink. The 70 year-old site was found to be a modest sink, while the 130 year old stand (NOBS) was close to zero.

Goulden et al. (2006) measured CO_2 for a chronosequence in northern Manitoba including the same sites mentioned above. Growing season length was seen to increase with stand age, due to a shift from young deciduous stands to older coniferous stands. CO_2 exchange rates at midday were found to recover within four years of a fire disturbance.

Canopy transpiration was measured by Ewers et al. (2005) for a northern Manitoba chronosequence that included our three sites. Stands younger than 70 years old were found to be composed of jack pine, trembling aspen and black spruce. Jack pine and trembling aspen have higher transpiration rates per unit leaf area than black spruce, which contributed to higher transpiration rates at a given leaf area index at the stand level for the younger sites. Stands older than 70 years were composed solely of black spruce, and as a result had lower stand-level transpiration rates for a given leaf area index.

The larger research project being conducted at our sites include transpiration (sap flux) measurements by Dr. Brent Ewers and Julia Angstmann from the University of Wyoming. These measurements are being used to explore spatial and temporal sap flux distribution, and relate sap flux measurements to remote sensing images. This will help expand on existing knowledge of tree water use for various species in the northern boreal forest. Work done on dissolved organic carbon at the 1930 and 1964 sites by Cyr (2005) included the monitoring of various environmental factors such as soil temperatures, and involved the installation of thermistors at depth. The measurement of these soil temperatures using the installed thermistors has continued in order to gain further insight into any long-term changes, but these data are not included in this thesis (Cyr, 2005). Some work on the spatial dependencies of soil temperature and moisture has been done on our research sites as well (Bond-Lamberty et al., 2006).

1.7 Objectives

The aim of this study is to gain a greater understanding of the variability in water and energy balance in the boreal forest. In the past, assumptions have been made regarding how the boreal forest may be impacted with changes in C or water cycles. It must be noted that there are intricacies and complexities in these cycles that may vary with conditions including age and topography. Our objectives are to measure energy balance components and evapotranspiration throughout a northern Manitoba black spruce chronosequence, and assess whether differences exist among sites of different ages, and areas with different topography. These differences were investigated in order for us to have an accurate picture of the boreal forest system as a whole. Our study includes three forest stands of different ages that were burned in 1850, 1930, and 1964. The 1930 and 1964 forest ages each have both upland and wetland research sites. Information gained through this study will be extremely valuable for developing ecosystem process models, which include a level of detail that would allow predictions of climate change impacts on northern boreal forests (Bergeron et al., 2007).

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2 INDIRECT ENERGY BALANCE MEASUREMENT OF EVAPOTRANSPIRATION FOR A BOREAL FOREST CHRONOSEQUENCE

2.1 Introduction

The boreal zone has a significant global footprint, and 40% of Canada is covered by boreal forests and peatlands (Kurz and Apps, 1999). Throughout the boreal forest there is a high diversity of vegetation, soils and environmental conditions, and as a result, energy and water balances may vary greatly. It is important for us to better understand and quantify variability in water and energy balances, which will further enable researchers to assess the impact that the boreal forest has on the global climate. Measurements of these fluxes are difficult, and errors are only beginning to be well understood. It is known, however, that differences in forest composition (Baldocchi et al. 2000), forest age (Amiro, Orchansky et al. 2006), and disturbances (Amiro, Barr, et al. 2006) have a significant effect on local and global energy and water cycles. The boreal forest is a complex and ever-changing mosaic**.** In order to project future climates using global and regional climate models, it is necessary to understand how different surface characteristics affect energy balance in these forests (McCaughey et al., 2006), ecotonal forests (Hollinger et al., 1999), and old-growth types of environments.

The boreal forest is variable not only on the regional scale, but marked differences in topography and stand composition exist on much smaller scales. Forest stands in upland positions contrast greatly with neighbouring wetland stands that may be of the same age. Another unique aspect to our study is the comparison of ET for same-aged stands with varying topographic position. If water and energy use differs greatly between sites of different topographic position, this may increase the level of detail necessary in regional water and energy models.

Numerous studies have measured ET and energy balance over varying types of boreal forests, including deciduous (Black et al., 1996), mixed-wood coastal forests (Morgenstern et al., 2004), Scandinavian forests (Cienciala et al., 1999, Grelle et al., 1999), black spruce forests (Chambers and Chapin, 2002) and Siberian taiga (Ohta et al., 2001; Meroni et al., 2002). One of the earlier studies that compared energy balance residual ET to catchment water balance was done in southern Manitoba by Amiro and Wuschke in 1987. Top-down and bottom-up (Cienciala et al., 1999) methods have been used to measure forest ET, and some studies have incorporated both methods (Barbour et al., 2005; Wang et al., 2004). Our ET research is a part of a larger study with the University of Wyoming and the University of Wisconsin, where individual components of boreal forest water use such as bryophyte ET and tree sap-flux (transpiration) measurements are also being made.

The chronosequence approach has previously been used to investigate how energy balance partitioning changes with age (Amiro, Orchansky et al., 2006). Unfortunately, researchers are often unable to construct a chronosequence with sites that are as representative as those used in our study. Our study is unique in that all the chronosequence sites are in close proximity, have experienced stand renewing fire disturbances, possess similar environmental and site characteristics, and are at various stages of succession in black spruce peatland ecosystems. The chronosequence approach allows us to identify any changes that may occur in energy and water use as forests age, effectively replacing the need for time with space, and avoiding the need to perform long-term research at a single site.

The first objective of this study was to determine whether differences in ET exist among boreal black spruce stands of different ages. If changes do occur, this may have important implications on regional water and energy budgets if the average stand age becomes younger due to climate change- induced increase in the area burned by forest fires (Flannigan et al., 2005). The second objective of this study is to assess if differences in ET exist between boreal black spruce stands of the same age, but of different topographic position.

Data from this study were collected during the growing season period, which allowed us to examine differences that existed while the trees were actively growing and photosynthesizing. Various field measurements combined with data obtained via the eddy covariance technique were used in order to quantify the energy budgets for these forest stands.

2.2 Methods

2.2.1 Site Descriptions

The chronosequence ages are located in the northern boreal forest near Thompson, Manitoba. The ages were chosen due to their similar topography and relative proximity to each other (<15 km). Each site includes study areas that were representative of both upland and lowland topography.

The oldest age, known as Northern Old Black Spruce (NOBS), was a previously established research site that was included in the Boreal Ecosystem-Atmosphere Study

(BOREAS). This site was burned in approximately 1850, and the main tower has been in operation since 1994. The access trail is located 52.9 km west of Thompson, MB on highway 391. The forest is composed of black spruce (*Picea mariana*) (Table 2.1) with moss groundcover. The dominant moss types in the upland areas are feather mosses (*Pleurozium schreberi* and *Hylocomium splendens)*, with sphagnum mosses (*Sphagnum* spp.) in the lowland bog areas. The understory includes Labrador tea (*Ledum groenlandicum*), wild rose (*Rosa* spp.), and green alder (*Aldus crispa)* (Bond-Lamberty et al., 2002). The dominant soil series is the Sipewesk series; an Orthic Gray Luvisol with a fine-medium subangular blocky Bt horizon. The dominant soil texture is clay and silty clay (Cyr, 2005).

The second age of the chronosequence was burned in 1930, and is located about 54 km west of Thompson on highway 391. The forest of the lowland site area is composed of stunted black spruce with a groundcover of mosses (Table 2.1). The vegetation at the upland site consists of black spruce, with a few trembling aspen (*Populus tremuloides*) and birch (*Betula papyrifera*), and a groundcover of feather mosses (Bond-Lamberty et al., 2002). The dominant soil texture is clay and silty clay. The soil at the 1930 site is similar to that at NOBS (Cyr, 2005).

The youngest age included in this chronosequence was burned in 1964, and is located about 40 km west of Thompson, MB on highway 391. The lowland tower is located closest to the highway, and the present vegetation is black spruce trees, with a sphagnum moss groundcover (Table 2.1). The upland tower site has a canopy of black spruce, jack pine (*Pinus banksiana*), trembling aspen and a small number of birch, with a groundcover of feather mosses (Bond-Lamberty et al., 2002). The dominant soil texture at the 1964 sites is clay, and the soil series is Wabowden, an Orthic Gray Luvisol with a columnar or coarse-medium blocky Bt horizon (Cyr, 2005).

TABLE 2.1: Site characteristics of five northern boreal forest sites located near Thompson, Manitoba. Tree density and DBH provided by J. Angstmann (Univ. Wyoming)

Site	1964 Wet	1964 Dry	1930 Wet	1930 Dry	NOBS
GPS location	N55.91369° W98.38176°	N55.92033° W98.38986°	N55.90442° W98.52043°	N55.90795° W98.38209°	N55.87962° W98.48081°
Year burned	1964	1964	1930	1930	~1850
Msmt. height (m)	4.5	9	4.5	12	30
Soil Series	Wabowden	Wabowden	Sipewesk	Sipewesk	Sipewesk
Soil Classification	Orthic Gray Luvisol	Orthic Gray Luvisol	Orthic Gray Luvisol	Orthic Gray Luvisol	Orthic Gray Luvisol
Tree Density (trees/ha)					
Black Spruce	3537	7215	4951	6225	5164
Aspen	0	2546	0	354	0
Jack Pine	0	3183	0	0	0
Birch	0	424	0	71	0
Total	3537	13793	4951	6649	5164
Diameter at Breast Height (DBH) in cm					
Black Spruce	2.67	3.34	4.09	8.74	9.34
Aspen	0.00	3.81	0.00	7.38	0.00
Jack Pine	0.00	5.33	0.00	0.00	0.00
Birch	0.00	3.47	0.00	8.45	0.00
Mean	2.67	3.89	4.09	8.69	9.34
Total Basal Area (m^2/ha)					
Black Spruce	2.28	10.77	7.39	42.81	38.29
Aspen	0.00	3.19	0.00	1.89	0.00
Jack Pine	0.00	5.76	0.00	0.00	0.00
Birch	0.00	0.17	0.00	1.98	0.00
Total	2.28	15.39	7.39	45.09	39.29

2.2.2 Field Measurements

Measurements at the research sites were taken from instruments installed on either scaffold or triangular towers above the canopy. The data from the instruments were collected by data loggers, and data were manually downloaded on a regular basis during the growing season. Data loggers were powered by 12 V batteries, which in turn were charged by solar panels (MSX20, Campbell Scientific Inc., Logan, UT, U.S.A.). CR1000 data loggers (Campbell Scientific Inc) were used for all sites, with the exception of the NOBS site where data were stored on a desktop computer. High frequency data were recorded and then averaged by the data loggers or computer over 30-minute periods. The upland tower at NOBS was the largest tower, measuring approximately 30 m. The 2007 data for NOBS had not been compiled and gap-filled as of March 2008, and therefore these data were not included in the study.

The 1930 site used scaffold-type towers for both the upland and lowland sites, which measured approximately 12 and 4.5 meters in height, respectively. The 1964 lowland site also used a scaffold-type tower, which was 4.5 m in height. The upland tower for 1964 was a triangular tower, and measured 9 m high.

All sites were functioning and data were being recorded as of June 15, 2006, and data collection continued until October 31st. In 2007, all sites were operational as of May 14th and data were collected until October 15th.

2.2.3 Meteorological Measurements

Air temperature and relative humidity were measured at both the top of the towers (Table 2.1) and approximately 2 m above ground, using HMP45C probes (Campbell Scientific). A tipping-bucket type precipitation gauge measures precipitation in 0.1 mm increments (TE525M, Texas Electronics, Inc., Dallas, Texas, U.S.A.), and was installed above the canopy for each of the lowland sites. In 2007 a manually read precipitation gauge was installed for comparative purposes.

Soil temperature was measured at each site using four replicate thermocouples (copper constantan) at 5 cm depth, as well as a wooden dowel with thermocouples inserted at 5, 10, 30 and 50 cm depths below the live moss layer. Theta probe soil moisture sensors (ML2x, Delta-T Devices, Ltd., Cambridge, UK) were used to measure soil moisture levels at the peat surface, as well as at 15 and 30 cm depths.

Incoming and outgoing photosynthetically active radiation was measured above the canopy (Table 2.1) at each site using LI-190 PAR sensors (LICOR Inc., Lincoln, NE, U.S.A.). SR50 ultrasonic distance sensors (Campbell Scientific) were installed at approximately 2 m above ground in order to measure snow depth during the winter, but these data were not used here.

2.2.4 Energy Balance Components

At each of the towers, sensible heat flux (H), three-dimensional wind velocity and air temperature were measured at the top of the towers (Table 2.1) with a CSAT3 sonic anemometer (Campbell Scientific) at most sites, and a K-Style anemometer at the NOBS site (Applied Technologies Inc., Longmont, CO, U.S.A.). The CSAT3 took 10 measurements every second, and the cross-products were saved by the CR1000 every 30 minutes. Sensible heat flux was calculated using the eddy covariance method, with the cross-products being used to calculate covariance. The sensible heat flux that is given is the virtual heat flux, which must be adjusted using the actual vapour pressure from the HMP 45C. A MATLAB (Version 7.0.0.19920(R14) The MathWorks Inc., Natick, MA, U.S.A.) function was used to correct for any coordinate rotation that was needed, in order to ensure that for any given 30 minute period the mean vertical velocity was zero, following Tanner and Thurtell (1969).

Net radiation was measured above the canopy (Table 2.1) using a NR-Lite thermopile-sensor net radiometer (Kipp and Zonen, Celft, The Netherlands) and a Q7 net radiometer (REBS, Campbell Scientific) at the NOBS site. Ground heat flux (G) was also measured at each site, using HFT3 Heat Flux Transducers (Campbell Scientific). Four soil heat flux sensors were installed horizontally 2 cm below the active moss and litter layers, within the non-living organic layer at all sites. The results from the four sensors were averaged at each site, in order to gain an understanding of energy flux into the soil. We did not measure energy storage in the shallow layer above the heat flux plates.

2.2.5 Soil Moisture Measurements

In order to monitor soil moisture at depth, a Troxler Neutron Moisture Gauge was used on a monthly basis throughout the growing season (Model 4300, Troxler Electronic Laboratories, NC, U.S.A.). Five aluminium access tubes measuring 157 x 5 cm were installed in July of 2006 at all three forest ages, on a transect at roughly 5-m intervals at the upland sites only. Measurements were made down to depths of 90 cm at most sites, with the exception of permafrost (discontinuous) areas, or extremely wet areas, where the tubes were installed to more shallow depths. Monthly measurements were taken at 20, 40, 60, 80 and 90 cm depths during the growing seasons of 2006 and 2007.

The neutron moisture meter gives a neutron "count", which is then converted into a volumetric moisture (m^3 water / m^3 soil) measurement using a calibration equation. Volumetric moisture measurements were recorded at a series of depths within each column. The volumetric moisture measurements were multiplied by the depth of each column measured (m), which would give m^3 water /m^2 soil, or meters of water. If the soil was frozen at depth when the access tubes were installed (July, 2006), the depth to which the tube was installed was limited. In some locations the tube would reach the depth of 1 m, and in some locations due to frozen soils the tube was installed to a depth of 60 cm. The amount of water in each column was converted to mm water, and for each site this was averaged for the five access tubes for each measurement date.

Bulk density measurements for the soils at the sites were taken in August, 2006, and volumetric moisture measurements were taken when the tubes were installed in July, 2006. The soils from the research sites were then compared to other Manitoba soils with calibration curves for the neutron probe measurements. Gordon Finlay (U of M) designed a calibration curve for the neutron moisture probe that included soils of varying textures in southern Manitoba and Saskatchewan. Using our volumetric soil moisture measurements and the corresponding neutron probe measurements, we were able to determine that our soil type followed the calibration curve for all these soils (Finlay, personal communication 2006) very well.

2.2.6 Data Quality Control and Gap Filling

Instruments may give false or inaccurate data during periods of precipitation, or if a malfunction occurs. Quality control for data was done for various instruments by setting threshold limits for acceptable data. Photosynthetically active radiation (PAR) was found to be acceptable if it was over 0, or under 2000 μmol/m^2/s. The lower threshold for Rn was -500 W/m^2 and the upper limit was 1000 W/m^2. The thresholds for both air and soil temperatures were set at -50°C and +50°C.

The sonic anemometer performs poorly during adverse weather conditions, and therefore data during these conditions were excluded if the CSAT3 missed more than one sample in a 30 minute period. If measured sensible heat flux was greater than 500 W/m^2 or less than -200 W/m^2, data were also excluded. H was not used below the friction velocity (u*) cut-off of 0.25 m/s, due to poor energy balance closure that has been found during these periods at other boreal forest sites (Barr et al., 2006).

In order to ensure that the data sets had no missing data, data gaps were filled using two methods. The first method filled small gaps of less than 2 hours via linear interpolation. To fill gaps in sensible heat flux that were larger than 2 hours, a 240 point moving-window was used, which used a linear regression between Rn-G and H, and moved in 48-point increments (Amiro, Barr et al., 2006).

In 2006, the 1964 upland site experienced multiple complications that resulted in little data being recorded for this year. The small amount of data that was recorded for this site was not used, as it was not sufficient to compare against the other sites. Data for 1964 upland were used from the year 2007. The data from the net radiometer had a large gap from June 29th to July 19th, because the cable was cut. In order to calculate ET during this period, the net radiation for 64D was filled by using a regression relationship between half-hourly Rn data at 64D and 64W.

2.2.7 Calculation of Evapotranspiration (ET)

The method by which ET is calculated assumes that it is driven by a positive value of net radiation minus soil heat flux (Rn-G). Storage is assumed to be minimal, and is not included, and closure is assumed to be perfect. Latent energy (LE) is calculated as the difference between "Rn-G" and H (Amiro, 2008):

$$LE = Rn - G - H$$

LE was set to zero at night, due to low u-star values (insufficient turbulent) and other complicating factors that occur at night, such as the accumulation of dew on the sensors of the sonic anemometers. It is not felt that this has a large impact on our calculations, as it is generally assumed that LE is zero at night, regardless.

The energy balance residual method of measuring ET has been compared to the direct measurement of ET by eddy covariance. The agreement between the two methods was found to be very close, with less than 5% difference for longer-term averaging. It was found that this relationship was especially close during the growing season period of May 1st to September 30th, with the exception that calculated ET may be overestimated during the early spring due to energy stored by the system during snow melt (Amiro, 2008). Our data, however, commenced on May 14th at the earliest, and does not include the period of snowmelt. Based on this relationship, and the fact that our research has focused on the growing season period, it may be assumed that our estimations of ET are accurate.

2.2.8 Calibration of Instruments

During the 2007 season, two separate pairs of CSAT3 sonic anemometers and CNR1 net radiometers (Kipp & Zonen) were used in order to check calibration between instruments at the 1930 and 1964 sites. The 'calibration' sets were installed side-by-side with the existing instruments first at the 1930 upland and lowland sites on July 15, 2007. On August 16th these two sets were removed from the 1930 sites and were installed at the 1964 upland and lowland sites, where they remained until September 20th, 2007. Two types of radiometers were compared; the existing instruments at all sites were NR-lite radiometers, and the calibration instruments were CNR1 net radiometers. The CSAT3 sonic anemometers used for calibration were identical to those previously installed at all of the sites.

2.2.9 Statistical Analysis

All of the regression relationships shown in this thesis for H, Rn, and ET, have had statistical analysis performed on these data to determine the r-squared value for their relationship. Analysis of covariance was also performed for all of our comparisons in order to determine if the slope of the regression was equal to a 1:1 slope. This comparison was done using the MATLAB computing language, and involved comparing a “perfect” data set (identical data) to the existing data set. If the resulting P-value for this comparison is less than 0.05, the slope of the relationship between the two variables was found to be significantly different from the 1:1 line. Root Mean Square Error (RMSE) was also calculated, which gives an idea of how much an estimated value differs from the actual value being estimated (the larger the RMSE, the more imprecise the estimated value).

2.3 Results

2.3.1 Age Effect Experiments

Rn, H and ET were compared between stands of different ages with similar topographic position. Over the growing seasons of 2006 and 2007, four experimental comparisons were possible for the age effect: 1930 wetland (30W) vs. 1964 wetland (64W) (2006 and 2007), NOBS vs. 1930 upland (30D) (2006), and 30D vs. 1964 upland (64D) (2007). The data have been presented in the form of x-y plots in order to demonstrate any differences visually. The slopes of the regressions indicate a fractional difference between the results at the two sites.

2.3.1.1 Net Radiation.

All four age-effect experiments showed lower daily Rn at younger sites than older sites (Figure 2.1). These regressions had slopes that are significantly different from a 1:1 slope ($P < 0.001$). In 2007, the regression between 64D and 30D showed the daily Rn at 64D to be 7% lower ($R^2 = 0.96$, RMSE = 9.2)(Figure 2.1.a), with growing season averages for 64D at 89.8 W/m^2 and 93.8 W/m^2 at 30D (Table 2.2). For the year 2006, 30D was found to have 17% lower Rn than the NOBS site ($R^2 = 0.89$, RMSE = 19.6) (Figure 2.1.b). It must be noted however, that the NOBS site measures Rn with a REBS Q*7.1 net radiometer, while all other sites use NR-lite net radiometers. The average Rn at NOBS for the 2006 growing season was 109.8 W/m^2, compared to 82.7 W/m^2 at 30D (Table 2.2). 64W had daily Rn that was 8% (2006, $R^2 = 0.97$, RMSE = 9.2) (2007, $R^2 = 0.99$, RMSE = 6.8) smaller than Rn at the 30W site (30W) (Figure 2.1 c,d). Average Rn for 64W was 78.2 W/m^2 in 2006 and 87.5 W/m^2 in 2007, while 30W was 82.1 W/m^2 and 94.7 W/m^2 during the same periods, respectively (Table 2.2).

In Table 2.2, Rn, G, and H are averages that include night-time data. LE is a modelled value and as a result, is set to zero at night. Due to this difference, the energy balance components do not exactly sum to Rn. The impact is that energy balance closure can differ by up to 4%.

Figure 2.1: Age-effect regression comparison of daily Rn (W/m^2) for a) 64D vs. 30D (2007), b) 30D vs. NOBS (2006), c) 64W vs. 30W (2006), d) 64W vs. 30W (2007). The 1:1 line is shown.

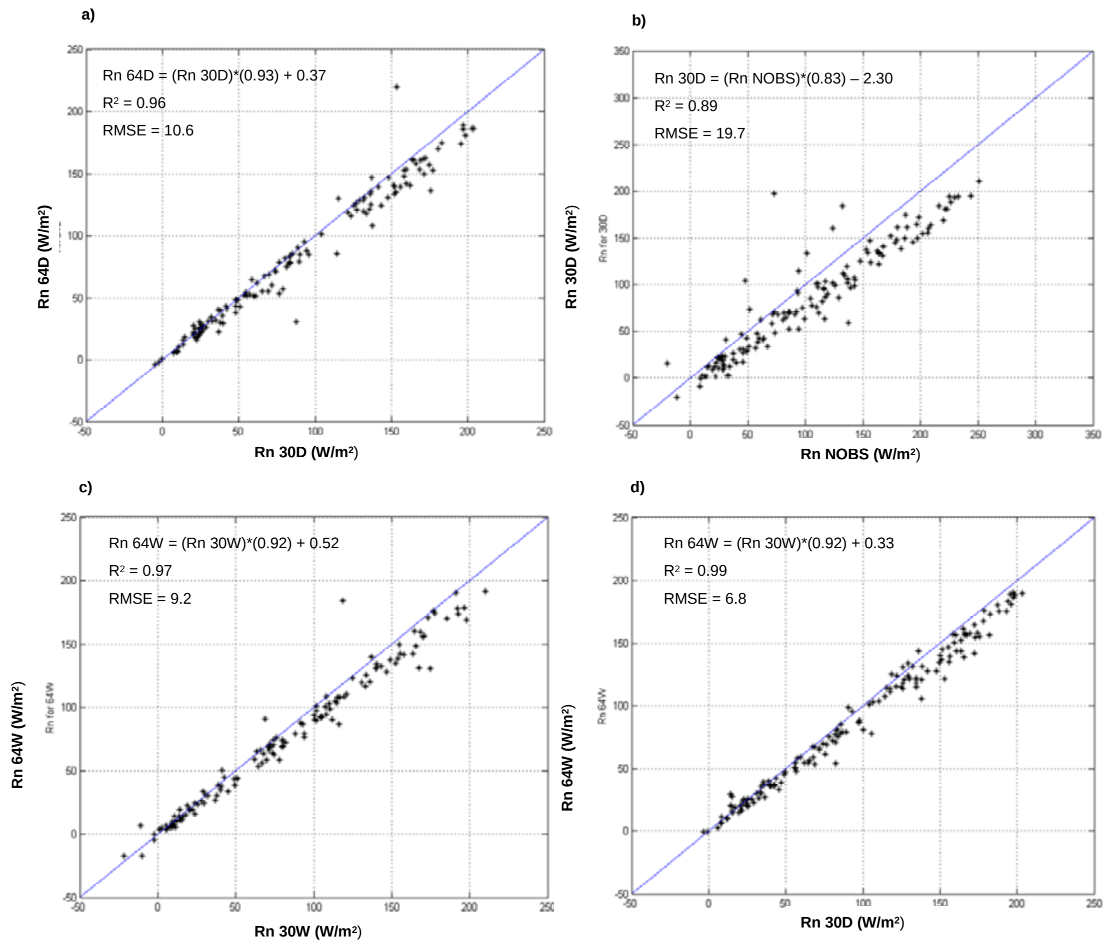


Table 2.2 Growing season averages for energy balance components (W/m^2) at northern boreal forest sites

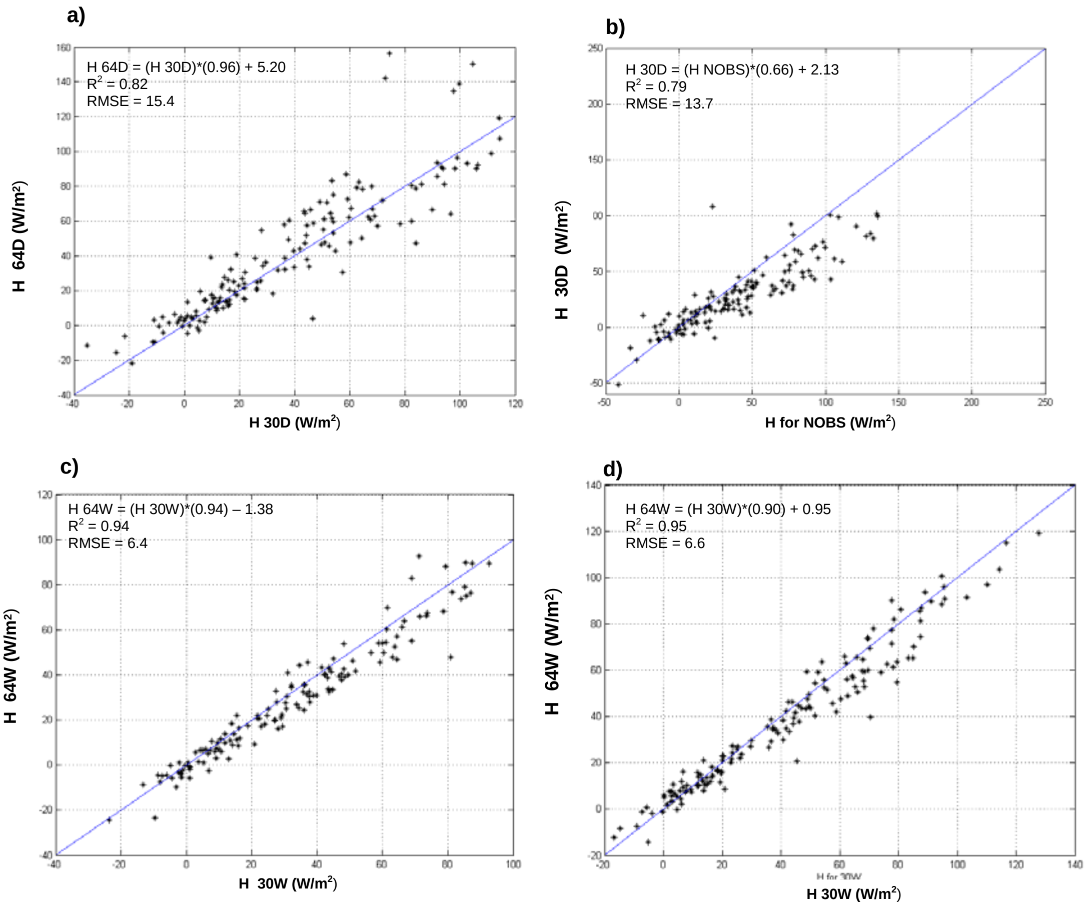
Sites	Rn	H (% of Rn)	G (% of Rn)	LE (% of Rn)	(ET (mm/day))
2006					
1964 W	78.2	29.9 (38)	5.2 (7)	40.1 (51)	1.41
1930 W	82.1	31.5 (38)	3.2 (4)	45.1 (55)	1.61
1930 D	82.7	27.7 (34)	2.7 (3)	52.6 (64)	1.85
NOBS	109.8	44.6 (41)	n/a	65.0 (59)	2.29
2007					
1964 W	87.5	37.9 (43)	5.7 (7)	43.3 (49)	1.53
1964 D	89.8	41.2 (46)	5.0 (6)	47.0 (52)	1.66
1930 W	94.7	41.1 (43)	4.7 (5)	48.0 (51)	1.69
1930 D	93.8	37.5 (40)	2.9 (3)	56.9 (61)	2.01

2.3.1.2 Sensible Heat Flux.

The four age-effect experiment pairs showed that daily H values were generally larger during the growing season at older sites than at younger sites (Figure 2.2). The smallest difference in H between sites of different ages was shown during 2007 between 64D and 30D, where H at 64D was 4% less than 30D (R^2 = 0.82, RMSE = 15.4) (Figure 2.2 a). This difference was not found to be significant (P = 0.245). The largest difference in H between sites was for NOBS and 30D, where 30D was 33% less (R^2 = 0.79, RMSE = 13.7) than the H at NOBS. This slope was significantly different from the 1:1 slope (P < 0.001). It should be noted, however, that different types of sonic anemometers were used at NOBS (Applied Technologies, Longmont CO, U.S.A.) and 30D (CSAT3, Campbell

Scientific). 64W was found to have 10% lower H than 30W in 2007 ($R^2 = 0.95$, RMSE = 6.6), with a smaller difference of 6% in 2006 ($R^2 = 0.94$, RMSE = 6.4). Both slopes were found to be significantly different from 1 ($P < 0.001$) (Figures 2.2 c,d).

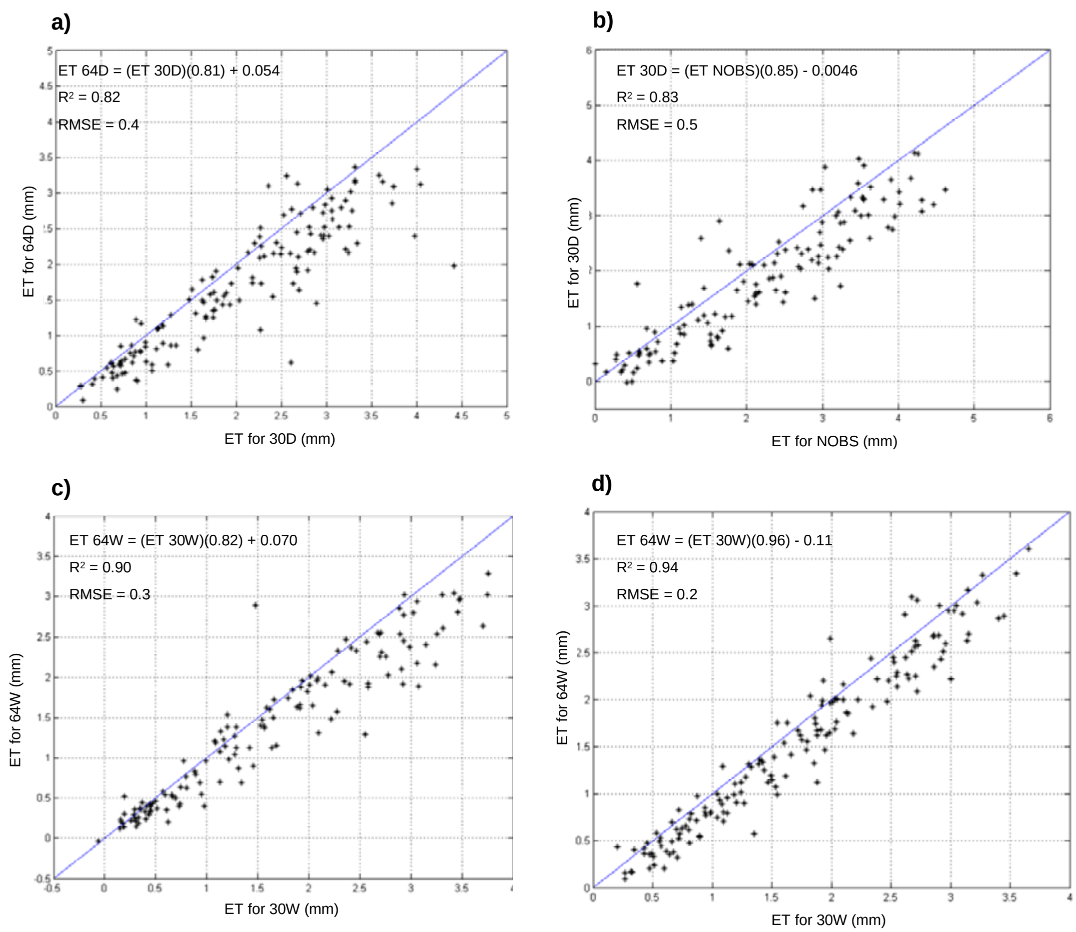
Figure 2.2: Age-effect regression comparison of daily H (W/m^2) for a) 64D vs. 30D (2007), b) 30D vs. NOBS (2006), c) 64W vs. 30W (2006), d) 64W vs. 30W (2007). The 1:1 line is shown



2.3.1.3 Evapotranspiration

As with both Rn and H, daily ET was found to be lower at younger sites. These differences were all found to be significant ($P < 0.001$). The largest difference in ET between sites was 64D and 30D in 2007, where ET at 64D was 19% less than 30D ($R^2 = 0.82$, RMSE = 0.4) (Figure 2.3 a). The 2006 data for 30D and NOBS (Figure 2.3.b) shows ET for 30D is 15% less than at NOBS (R^2 = 0.83, RMSE = 0.5). In 2006, ET at 64W was 18% lower than 30W (R^2 = 0.90, RMSE = 0.3), and in 2007 this difference was smaller, at 4% (r^2 = 0.94, RMSE = 0.22) (Figures 2.3 c,d).

Figure 2.3: Age-effect regression comparison of daily ET (mm) for a) 64D vs. 30D (2007), b) 30D vs. NOBS (2006), c) 64W vs. 30W (2006), d) 64W vs. 30W (2007). The 1:1 line is shown



2.3.2 Topographic Effect Experiments

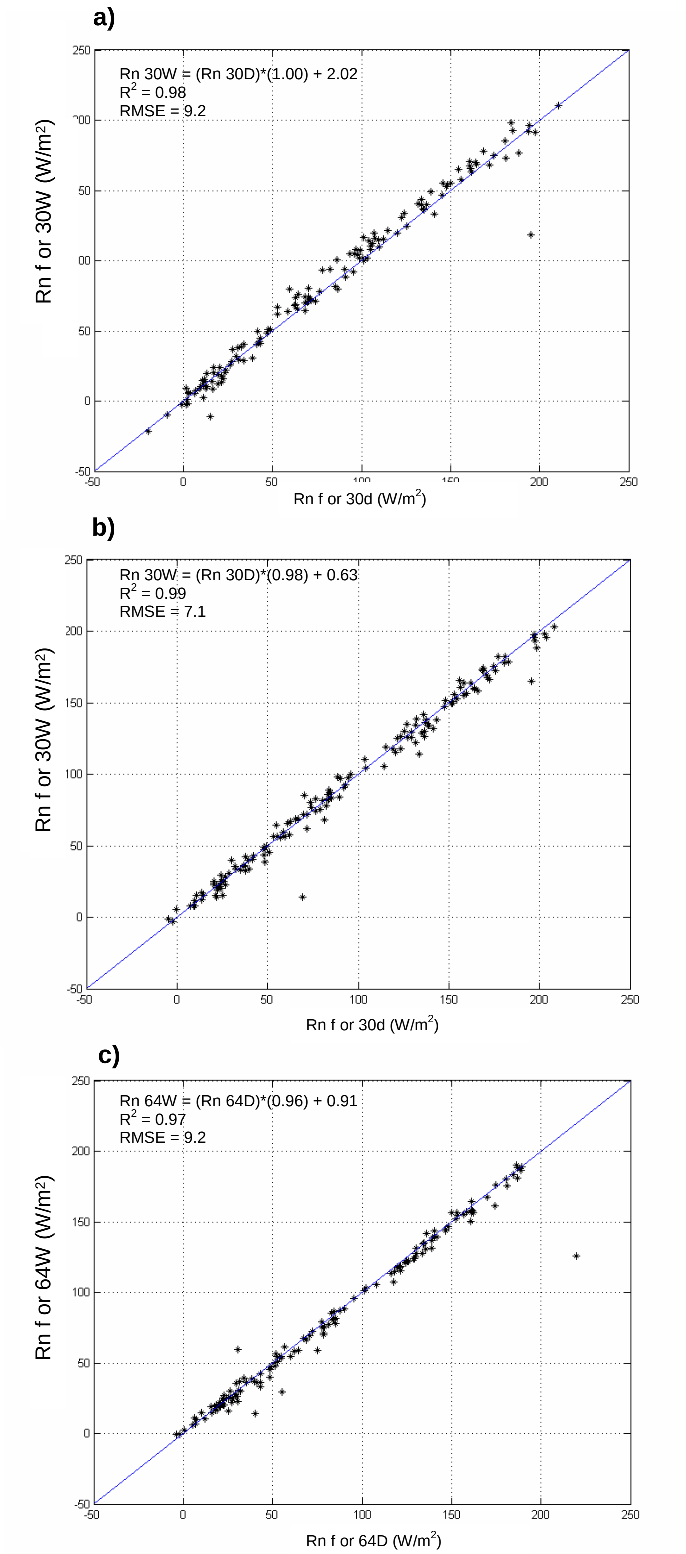
The effect of topographic location on Rn, H, and ET was assessed by comparing these variables for the same time period at sites of the same age with different topographic position. Three comparisons were possible; 30D vs. 30W for 2006 and 2007, and 64D vs. 64W for 2007. Data are presented in the same way that the age-effect experiments were shown, and statistical significance was also determined in the same way.

2.3.2.1 Net Radiation

For both 2006 and 2007, Rn was found to be not significantly different between the two 1930 sites (Figure 2.4.a,b) ($P = 0.76$ for 2006, $P = 0.10$ for 2007). The slopes of the relationship between Rn at these sites showed that for 2006, 30W was equal to 30D ($R^2 = 0.98$, RMSE = 9.2). In 2007, 30W was only 2% less than 30D ($R^2 = 0.99$, RMSE = 7.1). At 1964 sites, Rn was found to be 4% lower at 64W than 64D ($R^2 = 0.97$, RMSE = 9.2) (Figure 2.4.c). This slope of this relationship was found to be significantly different from unity ($P < 0.001$).

A CNR1 net radiometer was set up at the 30D and 30W site during July of 2007 for a period of roughly one month. These net radiometers were then moved to the 64D and 64W sites for one month during August. This setup was performed in order for us to be able to compare the Rn values for the CNR1s to the existing in-situ NR-lite net radiometers at each site. This setup also allowed us to compare differences in shortwave and longwave radiation fluxes between the upland and wetland sites during the same time periods.

Figure 2.4: Topographic-effect regression comparison of daily Rn (W/m^2) for a) 30D vs. 30W (2006), b) 30D vs. 30W (2007), c) 64D vs. 64W (2007). The 1:1 line is shown.

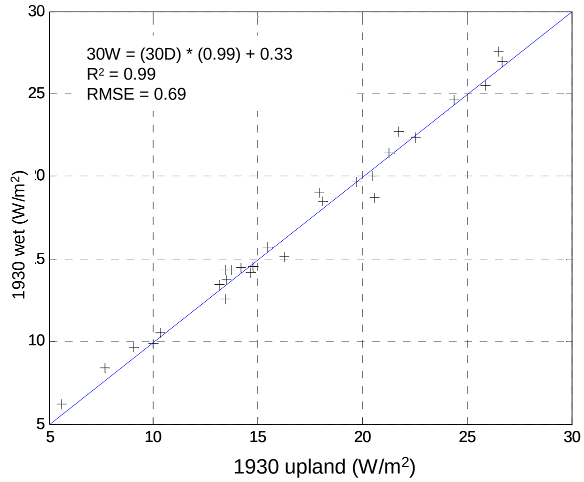


Net radiation is the net amount of energy retained within an ecosystem, and considers incoming shortwave and longwave radiation minus the outgoing shortwave and longwave radiation. Important factors that influence the amount of energy that is available to the system include surface characteristics such as surface albedo. Darker coloured surfaces absorb more incident radiation, and lighter coloured surfaces reflect a larger proportion of this energy. For the 30 age, the difference between the upland and wetland sites was found to be 1% for daily averaged incoming shortwave radiation (R^2 = 0.99), and this was found to be statistically significant (P = 0.0007). There was a 4% difference between the incoming shortwave radiation at the 64 age sites, however this difference was not found to be statistically significant (P = 0.157). Incoming longwave radiation showed only a difference of 1% for both the 30 (R^2 = 0.99, P = 0.79) and 64 ages (R^2 = 0.98, P = 0.61). The amount of reflected shortwave radiation was similar at both the 1964 and 1930 ages, showing only a 1% difference between upland and lowland sites (Figure 2.5) (P = 0.58 for 30 age, P = 0.56 for 64 age).

Outgoing longwave radiation indicates how much energy a system is losing in the form of heat. For both ages, the regression figures showed that the wetland sites had similar daily averages of outgoing longwave radiation than the upland sites (Figure 2.6). Differences were not found to be statistically significant (P = 0.275, 0.106, respectively).

Figure 2.5: Daily average data for surface-reflected shortwave radiation at a) 30W vs. 30D, b) 64W vs. 64D during one month periods in summer 2007. 1:1 line shown for reference.

a)



b)

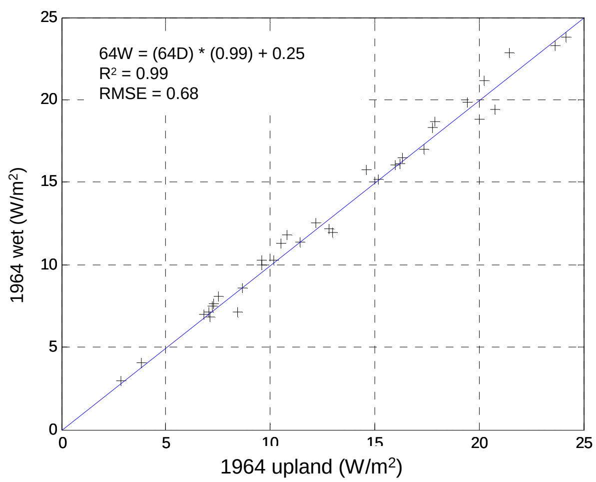
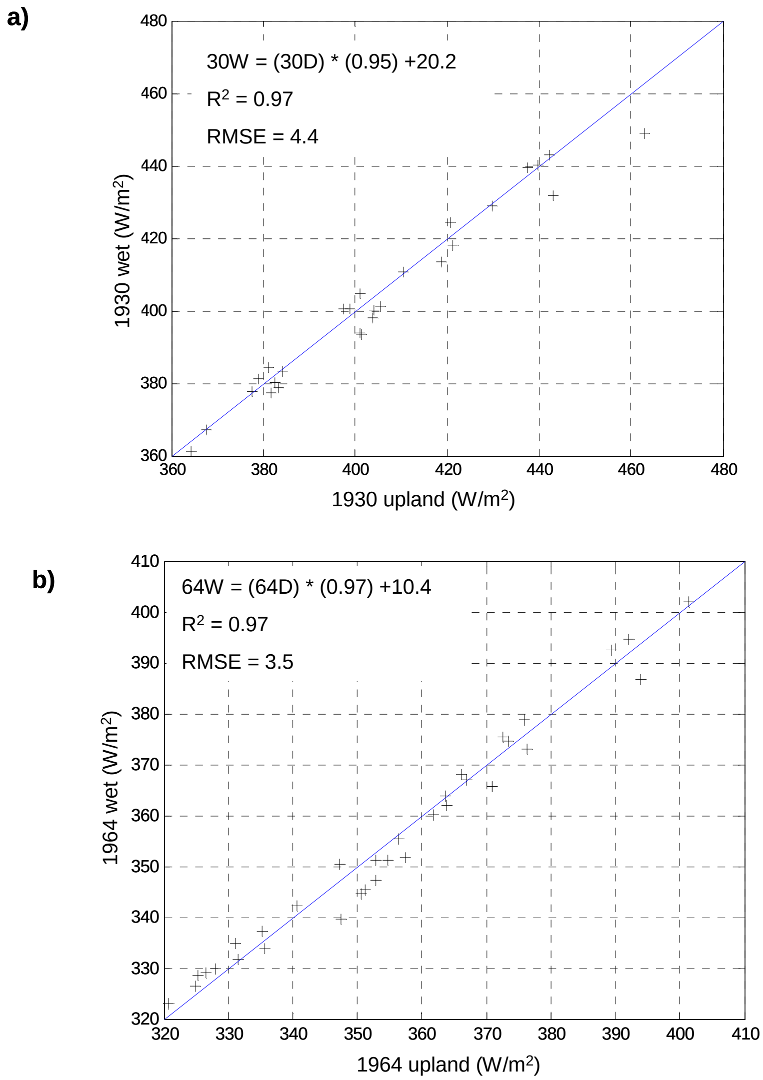


Figure 2.6 : Daily average data for outgoing longwave radiation at a) 30W vs. 30D, b) 64W vs. 64D during one month periods in summer 2007. 1:1 line shown for reference.



2.3.2.2 Sensible Heat Flux

For all three of the paired experiments, H was found to be lower at the wetland sites than upland sites (Figure 2.7), and the slope of these relationships were found to be significantly different from unity (P< 0.0001). During 2006, H at 30W was 12% lower than at 30D (R^2 = 0.90, RMSE = 8.8) (Figure 2.7 a). The relationship between 30W and 30D was similar in 2007, with 30W being 12% lower than 30D (R^2 = 0.92, RMSE = 9.1)

(Figure 2.7 b). At the 1964 site in 2007, the wetland site had 28% lower H than the upland site (R^2 = 0.81, RMSE = 13.1) (Figure 2.7 c), and the group of outliers to the right of the figure are due to one week in particular in mid July. The slopes for all of these relationships were found to be significantly different from unity (P< 0.0001).

2.3.2.3 Evapotranspiration

ET was consistently found to be lower at lowland sites than upland sites (Figure 2.8). For the year 2006, 30W was found to have ET that was 11% lower than 30D (R^2 = 0.90, RMSE = 0.32) (Figure 2.8a). In 2007, 30W as also lower than 30D, but this difference had increased to 20% (R^2 = 0.82, RMSE = 0.37) (Figure 2.8b). At the 1964 burn site in 2007, ET at 64W was found to be 14% lower than at 64D (R^2 = 0.76, RMSE = 0.43) (Figure 2.8c). All of the slopes explaining these relationships were found to be significantly different from unity (P < 0.0001).

2.3.3 Cumulative Evapotranspiration

For the year 2006, cumulative ET was calculated for the growing season period of June 15th to October 31st. As this was the year the research sites were established, the data were not available in the early part of the growing season. The trees had already begun transpiring as of June 15th, and therefore the cumulative growing season ET is not considered complete. Figure 2.9 illustrates the cumulative ET for NOBS, 30D, 30W and 64W. NOBS had the largest cumulative ET for this year, at 304 mm, which was a larger amount than 30D, which had cumulative ET of 258 mm. The 1930 site had larger ET at the upland site than at the wetland site, with 30W at 227 mm. The 64W site had the lowest cumulative ET at 195 mm. The same general patterns were seen for cumulative

ET during 2007 as were seen for 2006 (Figure 2.10). Even though the measurements started on May 14th, ET was already at a relatively high rate. The wetland sites consistently had lower cumulative ET than the upland sites. The 30D site had the highest cumulative ET, at 284 mm for the period of May 14th to Oct 31st, 2007. 30W and 64D had extremely close cumulative ET for this period, at 239 mm and 238 mm, respectively. The 64W site had the smallest cumulative ET for 2007, at 215 mm. The steepest slopes for the cumulative ET occur during the period before approximately day 260, followed by a period where the rate of daily ET decreases.

Figure 2.7: Topographic-effect regression comparison of daily H (W/m^2) for a) 30D vs. 30W (2006), b) 30D vs. 30W (2007), c) 64D vs. 64W (2007). The 1:1 line is shown.

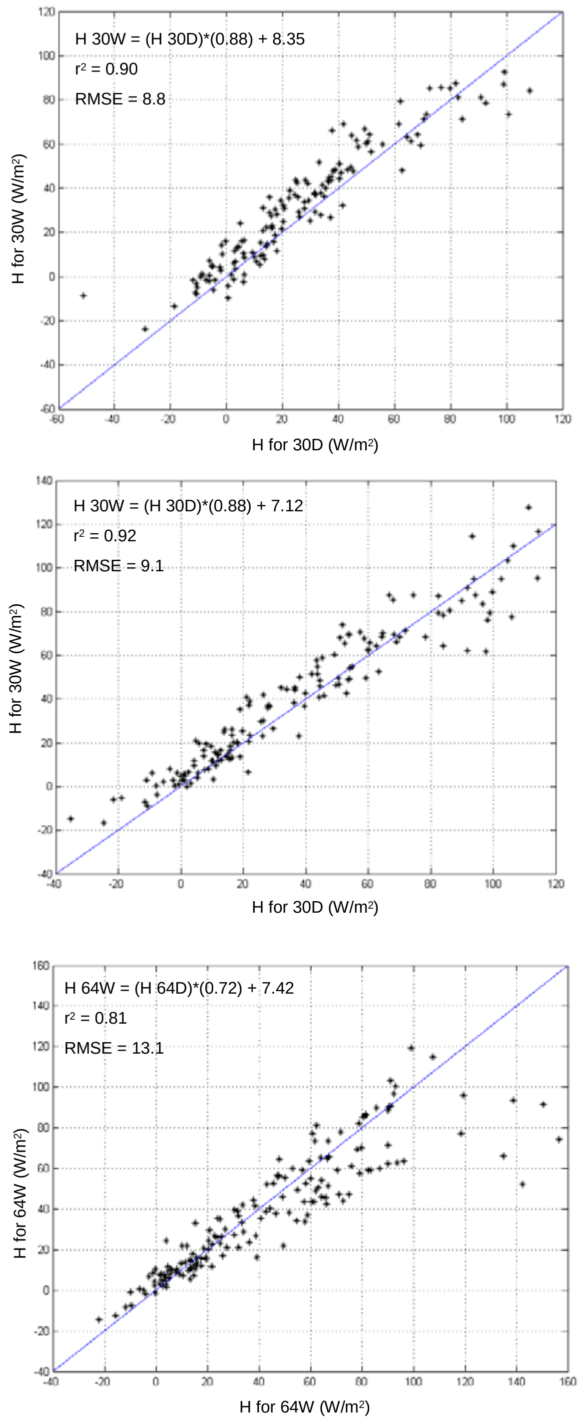


Figure 2.8: Topographic-effect regression comparison of daily ET (mm) for a) 30D vs. 30W (2006), b) 30D vs. 30W (2007), c) 64D vs. 64W (2007). The 1:1 line is shown.

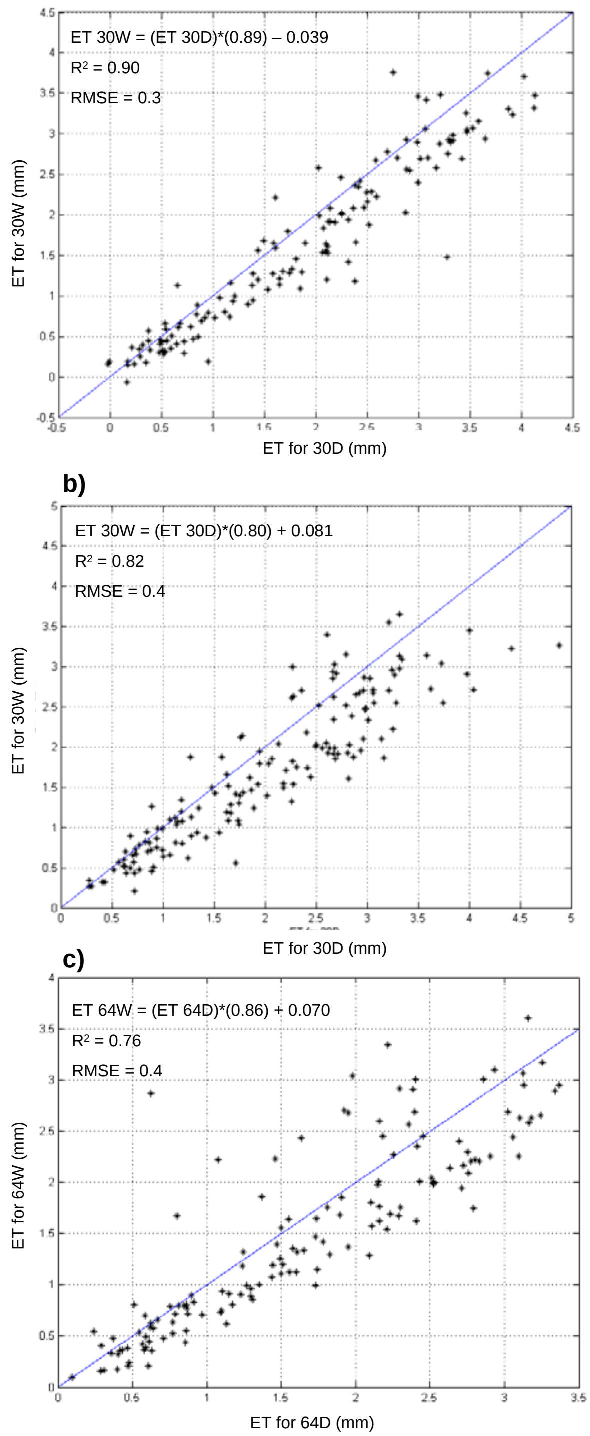


Figure 2.9: Cumulative growing season ET (2006) for northern MB chronosequence sites

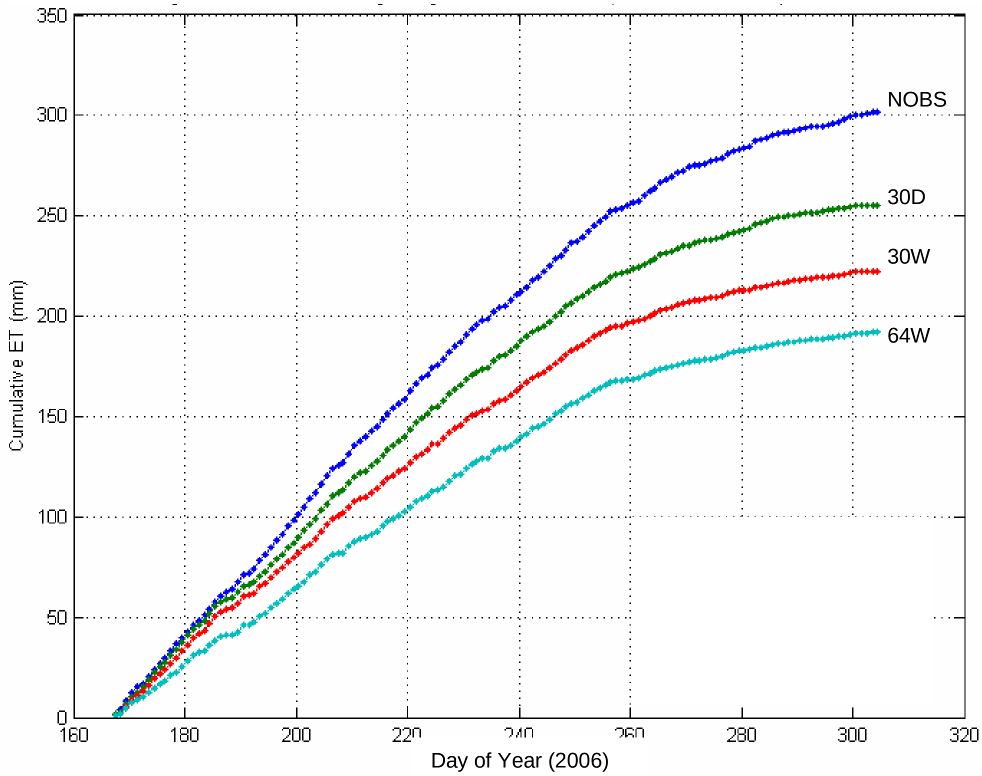
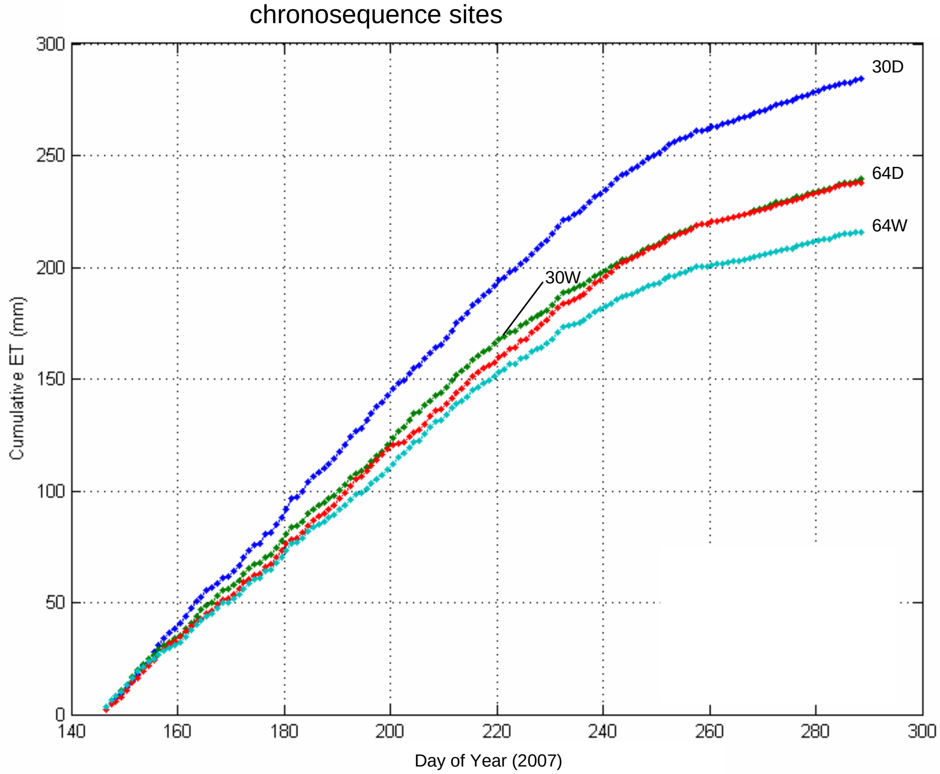


Figure 2.10: Cumulative growing season ET (2007) for northern MB chronosequence sites



2.3.4 Water Balance

In order to assess whether the years 2006 and 2007 were considered wet or dry years at our sites, precipitation and temperature data from the Thompson airport was compared to 30-year normals (Table 2.3). The Thompson airport is approximately 75 km from our research sites, but this is the closest site with historic data for comparison.

The year 2006 had temperatures that were only slightly above the 30-year normals (Table 2.3). The growing season precipitation was above normal for 2006 as well, with the month of May being 47.1 mm above normal, and July being 40.3 mm above normal. For the months of August and September, precipitation was below normal.

The year 2007 had some months that were above normal temperature (May, July, October, and some months that were below normal (June, August, September) (Table 2.3). Precipitation for the spring of 2007 was close to normal, while precipitation for August was 32.9 mm above normals.

The access tubes for the neutron moisture probe were installed in July 2006, and there are a limited number of measurements for this year. At the NOBS site in 2006, there were only two sampling dates; one in July and one in September (Figure 2.11). Figure 2.11 represents the depth of water in centimetres in the top one meter of soil. Both the 64 and 30 sites show an increase in the soil moisture from July to August, followed by a decrease during the August to September period. The NOBS site experienced a decrease in soil moisture between the months of July to September, 2006. The 64 site had the highest soil moisture level for all periods, including the 2007 dates.

Table 2.3: 2006 and 2007 temperature and precipitation data (Thompson airport) compared to 30 year normals (Environment Canada, 2006)

Temperature data (°C)

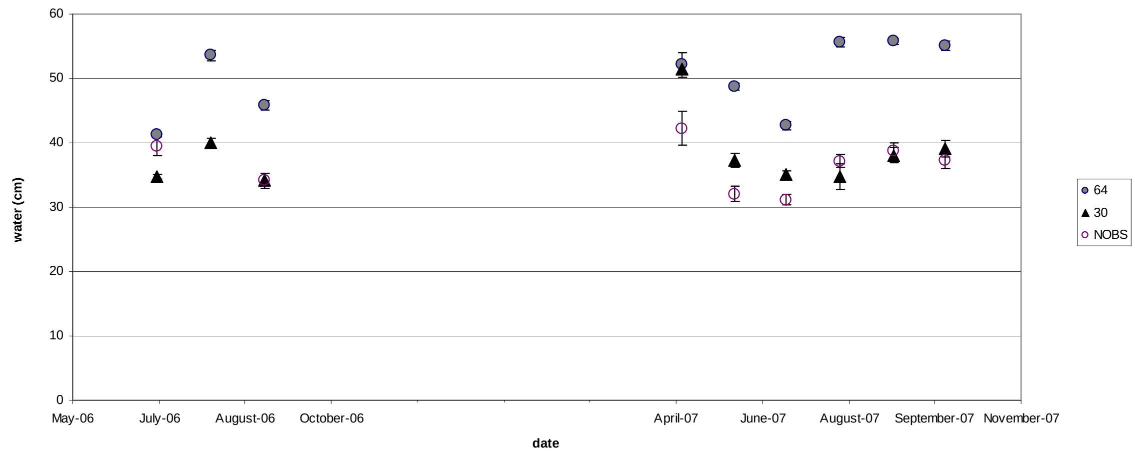
Month	airport normals	Airport 2006	2007
May	6.5	6.5	7.7
June	12.6	14.8	11.9
July	15.8	16	17.7
August	14.1	14.9	12.5
September	7.2	8.9	6
October	0	0.3	2.2

Precipitation data

Month	airport normals	Airport 2006	2007
May	44.4	91.5	48.4
June	69.4	57.9	45.2
July	86.1	126.4	75.5
August	73.9	54.4	106.8
September	62.4	26.8	75
October	41.4	49.4	54.8
Total	377.6	406.4	405.7

April 2007 showed soil moisture that was higher than the September 2006 soil moisture for all sites (Figure 2.11). All sites showed a decrease in soil moisture from April to July. The 64 site and the NOBS site experienced a large jump in soil moisture from July to August, and little change for the remainder of the season. The 64 site experienced higher soil moisture than both the 30 and NOBS site for all periods. The 30 site began the growing season with soil moisture similar to that of the 64 site, and then experienced a large drop. The NOBS site experienced soil moisture that was lower than that of the 30 site during the spring, followed by similar values to the 30 site during August to October.

Figure 2.11: Soil moisture measurements (cm water in 1m soil) for 64 age, 30 age, NOBS site, near Thompson, MB, during 2006 and 2007. Error bars represent standard error.



2.3.5 Soil Temperatures

During the month of July 2006, the ages 30 and 64 had thermocouples installed at depth in the soil at both the upland and wetland sites. This allowed us to look at the change in soil temperatures at 5 cm, 10 cm, 30 cm and 50 cm at each of the sites during the whole of the growing season 2007. Some difficulties were encountered due to wildlife disturbing the dowels, with either mice damaging or severing the thermocouple wires, or larger wildlife extracting the thermocouples from their proper depths. The 1930 site experienced the most problems, with no useable data available for the 10 cm and 50 cm depths, and the remaining 2 depths being disturbed as of approximately day 230. All the depths at 30W were disturbed at approximately day 250. Despite these difficulties, comparisons are still possible, and differences between the sites are evident.

Figure 2.12: 2007 growing season soil temperatures (°C) at 30W, 30D, 64W and 64D at a)5, b) 10, c) 30 and d) 50 cm below the peat surface.

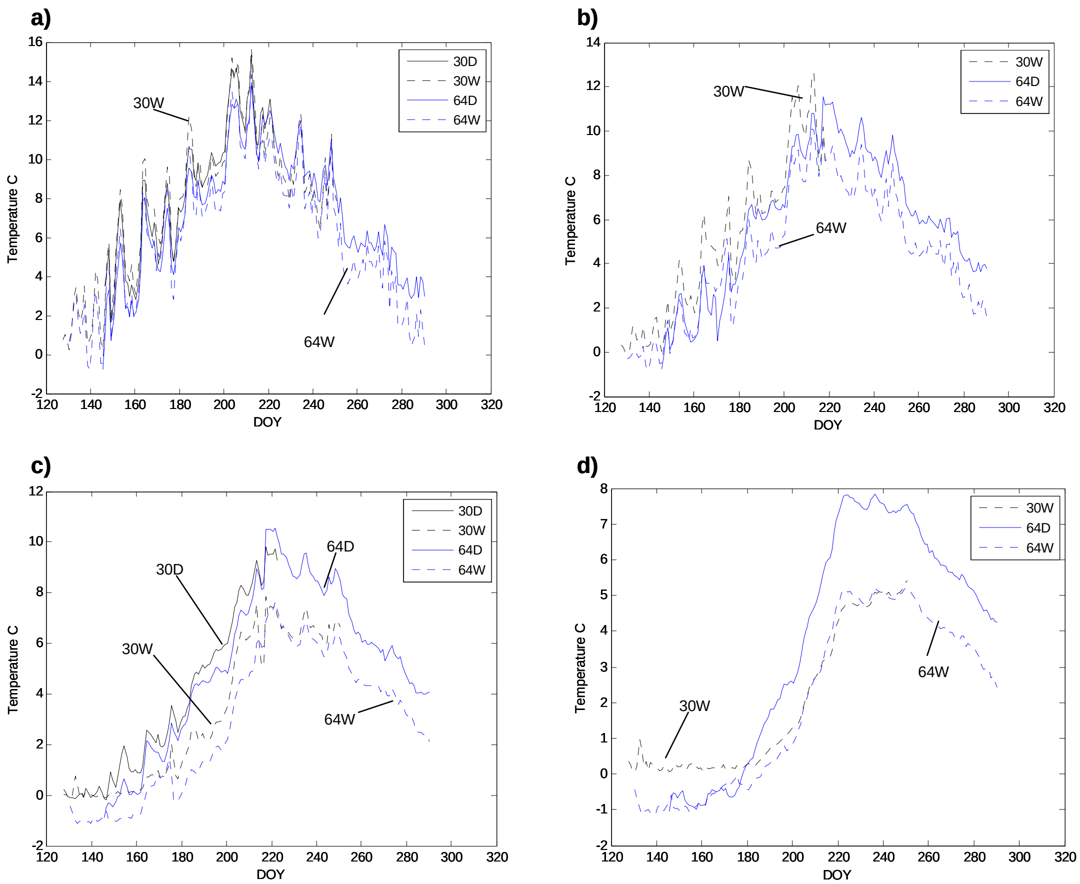


Figure 2.12a shows the growing season temperature fluctuations at the 5cm depth for all sites. All four sites had thawed before data collection began, and all follow each other quite closely with differences becoming more pronounced towards approximately day 190. The 30W and 30D sites follow very closely, and are consistently slightly warmer than the 64 sites. Towards the end of the growing season, the differences between 64D and 64W become more evident, with 64D having significantly higher temperatures than 64W.

The 10cm depth follows a similar pattern to the 5cm depth, with temperatures not becoming as warm (Figure 2.12b). Figure 2.12b shows the soil temperatures at all sites going above zero around approximately day 145. 30W was consistently warmer than both 64W and 64D. Following the peak temperature at approximately day 210, the difference between 64D and 64W is very obvious, with 64D being much warmer.

The 30 cm depth shows the sites thawing at different times; the 30D site thawed first at day 145, followed by 30W at day 155. The 30W site thawed shortly after day 160, with 64W rising above zero approximately 2 days later. The temperature peak occurs later and is less pronounced at the 30cm depth (Figure 2.12c), at around day 220. At this depth the differences between upland and wetland sites become much more pronounced. 64D and 30D follow each other closely, and are consistently warmer than the wetland sites. At the 50 cm depth the distinction between upland and wetland sites is also quite obvious (Figure 2.12d). The 64D site thaws first, around day 180, followed by 30W and lastly 64W. We note that the wetland soils are much slower to warm than the upland soils, and the wetland sites reach peak temperatures that are substantially lower than at the upland sites.

2.3.6 Instrument Uncertainty

Differences in Rn between calibration instruments and the instruments present at our sites were assessed using regression graphs of half-hourly data. The calibration CNR1s consistently gave Rn readings that were 10 to 24% higher than our existing NR-lite net radiometers (see example in Figure 2.13).

The differences in H between our site instruments and the calibration instruments were assessed in the same way as Rn, but the differences were found to be much smaller.

A range of 1 to 3% differences in readings were found for the CSAT3 sonic anemometers (see example in Figure 2.14).

Figure 2.13: Half-hourly Rn data (W/m^2) for 1930 upland site (30D) and Calibration "A" CNR1 net radiometer

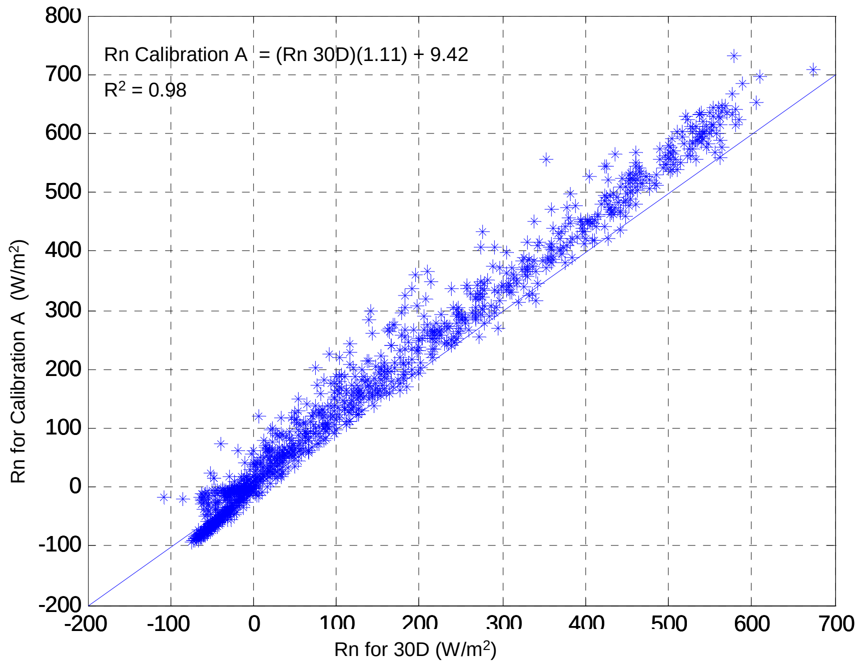
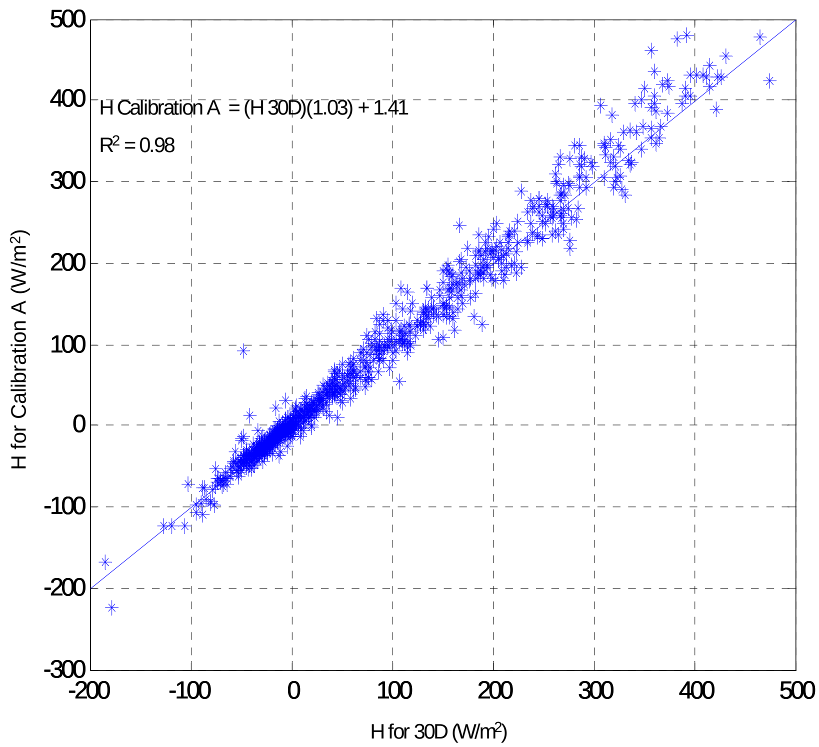


Figure 2.14: Half-hourly H data (W/m^2) for 1930 upland site (30D) and Calibration "A" sonic anemometer. 1:1 line shown.



2.4 Discussion

2.4.1 Uncertainty

The net radiometers deployed at the 1930 and 1964 sites (upland and wetland) were pyrradiometers / all-wave radiometers. These instruments (K&Z NR-lite) measure both solar and thermal/longwave radiation. Pyrradiometers utilize a thermopile with a high thermal conductivity, with one side exposed to down-welling radiation, and the other side to up-welling radiation. The NR-lite does not have a dome filter, which makes it more of a practical instrument that is easier to maintain and use in remote locations. The pyrradiometer used at the NOBS site utilizes a rigid polyethylene dome to protect the sensors from environmental influences (Strangeways, 2000).

In order to look at accuracy of the instruments we were using, calibration instruments were installed for one-month periods at both the 1930 and 1964 sites. The net radiometer used was a Kipp & Zonen CNR1, which consists of two pyranometers and two pyrgeometers incorporated into one instrument. This net radiometer outputs all the individual components of net radiation as well as the total net radiation. It was determined that the CNR1 calibration net radiometers gave readings that were 10 to 24% higher than the NRlite radiometers (R^2 = 0.95 - 0.98) (see example in Figure 2.13).

Brotzge and Duchon (2000) compared the CNR1, NR-lite, and REBS Q*7.1 net radiometers, and found inherent differences between their measurements. Daily averages of net radiation were found to vary by as much as 20% among model types. It was also noted that when 7 different NR-lite instruments were compared to each other, daily estimates varied by up to 5%. When considering the study by Brotzge and Duchon

(2000), and applying this knowledge to our data, we must assume that part of the differences between the 'calibration' net radiometers and our sites' net radiometers were due to the instruments' differences in sensitivity. It is impossible to say which instrument is "correct" in its measurement of net radiation, as there is no standard for this measurement in the industry. The NR-Lite has a higher sensitivity to cooling from wind than the CNR1. The NR-lite was also found to have a significant cosine-response error when the solar elevation angle is less than 20 degrees (Brotzge & Duchon, 2000). All of the sources of error mentioned above, the presence of any debris, precipitation or dew on the sensors, as well as any small errors in levelling may account for a portion of these differences. For this reason, differences of less than 5% in net radiation between sites with the same model net radiometers may lead us to believe that the difference may not be "real", or is negligible.

The CSAT3 sonic anemometers showed extremely good agreement when calculating sensible heat flux. The calibration CSAT3's varied between 1% less and 3% higher than those installed at the sites (R^2 = 0.95 – 0.98) (see example in Figure 2.14). We are therefore able to say that our measurements of H are precise, and any differences that were found between sites were true if they were larger than the inter-instrument variability of 3%.

2.4.2 The Age Effect

For all experiments, Rn was higher at older sites than at younger sites. This difference ranged between 7 and 17% for sites of different ages, as shown in Figure 2.1. Average daily Rn during the growing season at older sites was also larger than for the younger sites in all cases for 2006 and 2007 (Table 2.2). It is felt that species composition contributes to the differences in Rn with stand age. Due to natural succession of boreal forest stands, older stands have a larger proportion of coniferous trees. In boreal black spruce ecosystems, early-succession deciduous trees are replaced by black spruce. At 50 to 60 years of age, it has been found that the understory thins dramatically, and feather-mosses become thick and well-established (Bond-Lamberty et al., 2006). Coniferous trees have a lower albedo than deciduous trees, due to their dark needles, and therefore absorb more solar radiation. In a study that included data from the NOBS site in its chronosequence, Amiro, Orchansky et al. (2006) found that summertime albedo decreases with age for boreal forests.

Coniferous trees retain their needles year-round, which enable them to start photosynthesizing and transpiring water earlier in the growing season, as soon as soil water becomes available. It has been found that coniferous trees are able to begin photosynthesis almost immediately following above-zero nocturnal temperatures (Goulden et al., 2006). Deciduous trees are not able to transpire until they experience leaf-out, when they become able to photosynthesize (Pejam et al., 2006). Deciduous trees experience senescence upon the arrival of colder weather, which occurs in our study area in late August (Goulden et al., 2006). The upland sites have a deciduous component of 21% at the 1964 site, 5% at 1930 and 0% at NOBS (Table 2.1).

The regression figures for H (Figure 2.2) illustrate that in all cases, H is lower at younger sites than at older sites. The comparison of H at 64D vs. 30D in 2007 (Figure 2.2 a) is the only age effect comparison that was found to have a relationship whose slope was not significantly different from the 1:1 slope. There is a fair amount of scatter in this figure, and the RMSE is high at 15.4, which may account for the non-significance. There are some outliers present in the top right corner that may be indicative of a period of water-related stress, when H is much higher at 64D than at 30D. These data points occur during a short period in early July, when solar radiation is strong. Due to the fact that these outliers have such high values, the average growing season H at 64D is skewed so that it is higher than H at 30D. This indicates that for the majority of the growing season, H is higher at 30D than 64D.

Figure 2.2b shows H at NOBS and 30D in 2006. This relationship shows the largest difference in H levels found between sites at 33%. The average growing season H (Table 2.3) is 27.7 W/m^2 at 30D, and 44.6 W/m^2 at NOBS. If this is converted as a percentage of Rn, H at 30D is 34%, and at NOBS is 41%. This indicates that not only is the average growing season H larger, more energy proportionally is going into the heating of the air at NOBS than 30D. We are unsure as to why H differs so greatly at these sites. These two sites are the most similar of all the comparisons in terms of tree density, DBH and total basal area. The NOBS site is composed completely of black spruce trees, while 30D has a deciduous component of only 5%. The NOBS site has undergone some self-thinning as the canopy has aged, and therefore the tree density is slightly lower than for 30D (Table 2.1). The most noticeable difference between these two sites is that the bryophytes at NOBS are more well-established. The bryophyte hummocks are more pronounced, and the organic peat layer is thicker at the NOBS site. Different anemometers were used at these sites, but it must be assumed that both are accurate, and that these differences are true.

The 30W vs. 64W sites demonstrated higher H at 30W for both years, according to the regression equations (Figure 2.2). When we look at the average growing season values for H, it is larger at 30W for both 2006 and 2007. The percent of Rn used for H, however, is similar for these comparisons. Although the amount (W/m^2) of energy being partitioned into H is larger at the older sites, the percentage of Rn that goes into H is very similar for these comparisons. At 64W and 30W, both sites have 38% of Rn partitioned into H in 2006, and 43% in 2007. We note that although the proportion of energy being used for H at these sites are similar, the proportion (and amount) of energy partitioned into G decreases with age in all instances. The increase in canopy coverage with age is assumed to be the reason for the decrease in G with stand age; a denser canopy intercepts more energy and leaves less available for G. Amiro, Orchansky et al. (2006) found that this pattern is not the case for very young (<10 year) sites, but our sites are much further along the successional trajectory.

Although the growing season for deciduous trees is shorter, forests that include deciduous species have been found to have higher evapotranspiration (Pejam et al., 2006). This was not the case in this study, as the regression graphs indicate that for all age-effect comparisons (Figure 2.3), ET was greater for older sites. As mentioned previously, the deciduous component of the stands decreased with stand age. This would indicate that for this study, the presence of deciduous trees is low enough (20%, 5% and 0%) that it does not have a large impact on overall stand ET. It is also possible that the growing season in this area is short enough that any potential increases of ET due to the presence of deciduous trees are relatively small. The regression equations indicate that ET levels range from being 4% to 19% lower for younger stands (Figure 2.3).

The average growing season ET values were larger for older stands in all age-effect comparisons. The regression equation for this comparison indicates that ET at 64W was 18% lower than 30W (Figure 2.3c). In 2007, the same comparison shows a larger average (W/m^2) growing season ET for 30W (Table 2.3), and the regression showed that ET at 64W was only 4% lower (Figure 2.3d). We hypothesize that the higher density of larger trees at 30W (Table 2.1) gives this site an increased capacity to transpire water once available in the spring. The bryophytes at 30W are more established, and therefore perhaps have an increased capability to extract and transpire water.

The NOBS site has a lower total tree density than 30D (Table. 2.1) due to self-thinning, and the stand is at least 70 years older. The average size of the trees present is slightly larger at NOBS, with a diameter at breast height (DBH) of 9.34 cm, compared to a DBH of 8.69 at 30D. We are uncertain as to the reasons for the higher ET levels at the older sites, but assume that it may be closely linked to the efficiency of these older trees, and perhaps bryophyte evaporation levels. This is a curious finding, as it has generally thought that older trees tend to have a reduced capacity to transpire water as they age (Ewers, 2008, personal correspondence). However, the roots of trees in these forests are found in the upper-most organic layer, and it has been found that changes in soil moisture and precipitation have large impacts on the growth of the forest (Pejam et al., 2006). The organic peat layer becomes deeper at older sites, which may allow for the mosses to more effectively wick up available moisture through capillary rise, and have resulting higher transpiration levels. If this layer is able to start extracting water from depth, this would also make water available in the organic layer for the trees. Therefore, the presence of a more established bryophyte component in this ecosystem would benefit the trees by enabling them to commence transpiring earlier than sites with less-developed bryophytes. Constantin et al. (1999) found that for a Scandinavian boreal spruce-pine forest, soil evaporation increased with Rn, and forest floor evaporation and transpiration contributed 10 – 15% of total forest evaporation. It is also possible that these older trees have adapted to the climatic conditions and therefore their roots are able to more efficiently extract water from this organic layer.

According to Figure 2.3.a, 30D has daily ET levels that are 19% higher than for 64D. The average growing season value for LE is also substantially larger at 30D than 64D (Table 2.3). The percent of Rn that is partitioned into LE is also larger at 30D, by approximately 8%. This increased partitioning of energy into LE at 30D results in the average daily growing season ET being 2.01 mm/day, compared to 1.66 mm/day at 64D. Although 64D has a higher density of trees (Table 2.1) than 30D, the trees at 64D are markedly smaller, and the basal area is lower as a result. The proportion of deciduous trees is 15% higher at 64D than at 30D. We propose that the larger coniferous trees at 30D are able to begin transpiring earlier in the growing season than the trees present at 64D. The trees at 30D must also be more efficient at extracting water from a more highly-developed organic layer.

All sites showed a larger proportion of energy partitioned into LE than H, and older sites had larger average growing season LE for all age-effect experiments. This indicates that at all sites, more energy is used to evaporate water than is dissipated as heat.

The insulating properties of the organic layer of soil increase with its thickness, and as a result less energy is able to be lost from the soil surface (Baldocchi et al., 2000). Our sites showed a decrease in the average growing season G with stand age (Table 2.3), which is consistent with these findings. Jarvis et al. (1997) looked at energy partitioning in a 115-year black spruce stand in Saskatchewan and found that G accounted for approximately 3% of total net radiation for the growing season. For our study sites, the amount of Rn partitioned into G ranged from the highest at 6.6% for a 44 year-old wetland stand, to 3.1% for a 78 year-old upland stand. These numbers are in line with the proportion found by Jarvis et al. (1997).

Overall we have found older stands experience higher rates of ET. Some of this may be caused by an increased amount of available energy at older stands (Rn), and the fact that the amount partitioned into G decreases with age. Bond-Lamberty et al. (2006) found that gravimetric soil moisture was much higher and had greater variability at the NOBS site, at 0.72 (+/- 0.53) g H_20/g soil, compared to values of 0.37 (+/- 0.04) g H_20/g soil at 1930 and 0.30 (+/- 0.03) g H_20/g soil at 1964. It was stated that this differences was due to NOBS having areas with poorer drainage than the two younger sites, and therefore water was much more available for ET at NOBS than the younger sites (Bond-Lamberty et al., 2006). We acknowledge that our findings using the neutron moisture probe (Figure 2.11) showed the 64D having substantially higher soil moisture than both 30D and NOBS, but propose that our findings differ from those of Bond-Lamberty et al. (2006) due to differences in sampling location. The area chosen at NOBS for the neutron probe measurements is an upland area, and soil moisture measurements here would differ greatly from the NOBS wetland area. Lower G at older sites is due to a thicker organic soil layer, and we have proposed that this thicker organic layer contributes to the increased ability of older tree roots to take up soil moisture and transpire. ET is higher at older sites, and the difference in average growing season ET was found to range from 0.15 mm/day (64W vs. 30W, 2007) up to 0.44 mm/day (30D vs. NOBS, 2006) (Table 2.3). These differences compound over the entire growing season, giving cumulative differences that range from 23.2 mm (30W vs. 64W, 2007), up to 46.4 mm (30D vs. NOBS, 2006) (Figures 2.7 and 2.8).

2.4.3 The Effect of Topography

Topography has been found to have a significant effect on both H and ET. For Rn, significant differences due to topography were not consistently found. For the comparison of 30D and 30W, Rn for both upland and lowland sites were found to be approximately equal, with the regression equation showing that for both 2006 and 2007 the slope was not significantly different from unity. The 64 age found a small (4%) difference in Rn with topography, but this is within the margin of possible instrument error discussed in section 2.3.6, and therefore should not be considered ‘real’.

Species composition is similar at both 1930 upland and wetland sites. 30W has only black spruce trees, with a smaller tree density, DBH and basal area than the upland site (Table 2.1). All of the wetland sites have lower growing season H than upland sites for the regression relationships (Figure 2.7). For the comparison of 64D and 64W, the regression graph shows a group of outliers in the lower right side (Figure 2.7c), where H is much higher at 64D than 64W. These outliers occur during a short period in early July, where we suspect that 64D may have experienced a brief period of water stress. 64W has a lower average growing season H than 64D (Table 2.2), and a lower fraction of Rn is partitioned into H when compared to 64D. The outliers discussed above, with higher H at 64D than 64W, skew the seasonal average at 64D so that it is higher than it would otherwise have been without this short period. Therefore, for the majority of the growing season, 64W has slightly higher H than 64D, but for a short period in mid summer, 64D has extremely high H values.

For both years, average growing season H was higher at 30W than 30D (Table 2.2), which is contrary to the slope of the regression graphs (show a difference of 12% for both years) (Figure 2.7). These figures demonstrate that there are a large number of points where H at 30W is higher than at 30D, but these usually occur during days with relatively low H values. This pattern seems to shift once the daily H values exceed approximately 80 W/m^2, and H at 30D becomes higher than 30W. This indicates to us that for days with high H, such as early spring before water becomes available, more energy is partitioned into heating the air at the upland site than the wetland sites. We propose that during these periods, more energy is needed to warm the upper soil organic layer at the wetland sites than at the upland sites (as soil moisture levels are higher at the poorly-drained wetland sites). The ground temperatures shown in Figure 2.12 demonstrate a distinct lag behind atmospheric temperatures (not shown), and this lag is more pronounced at the wet sites. Soils at the wetland sites also do not reach temperatures as high as at the upland sites at depth (Betts et al., 2001); most notably at the 30 cm and 50 cm depths (Figure 2.12c,d). Therefore, due to the fact that upland sites have better drainage than wetland sites, upland sites are able to warm up faster in the spring. Tree roots in upland areas are able to begin their uptake of water earlier, effectively ‘waking up’ the trees. In wetland areas there are sometimes small areas of open water, and the water table is higher than at the upland sites. It takes a larger amount of energy to warm the often saturated soils, and therefore the wetland sites take longer to warm up during this period. It is known that once a system has reached temperatures above zero and water is available, transpiration and evaporation will occur freely and LE will increase. Vapour pressure deficit (VPD) represents the demand for water by the atmosphere, and largely influences LE. If volumetric soil water content is low, water is not available to the system for either evaporation or transpiration, and LE will remain low. It has been found that ET levels reach their maximum in July for boreal forests (Arain et al., 2003).

For all topographic-effect comparisons, ET has been found to be higher at upland sites (Figure 2.8). If we look at expected transpiration by trees, we would assumed that the upland sites would have higher levels than wetland sites due to higher LAI and tree density (Table 2.1). Evaporation from wetland sites would be expected to be higher than for upland sites, as there are sometimes small areas with open water, and water is more readily available at the surface. Understory and bryophyte transpiration is thought to contribute greatly to ET (Constantin et al., 1999), as previous studies have found that depending on the type of forest, they can contribute up to 50% (Siberian larch forest) of total ecosystem evaporation. Overall, upland sites have higher transpiration rates due to a larger number of bigger trees. Upland sites have lower water tables than wetland sites, which allow soils to thaw and transpiration by bryophytes to begin earlier in the growing season. A larger proportion of available energy is used for melting soil water at wetland sites compared to upland sites, which results in lower ET rates.

2.4.4 Water Balance

Using the neutron probe, we were able to track slow changes in soil water levels at the 30D, 64D, and NOBS sites. Comparing the changes in soil water levels (Figure 2.11) to precipitation levels in the area for the same time periods (Table 2.3) allow us to draw simplified conclusions regarding the conditions during a particular time period. For example, during July 2007 the Thompson area experienced above-average temperatures (+1.7 °C above normals), and below-average rainfall (10.6 mm below normals) (Table 2.3). At the same time, our neutron probe measurements indicate that all of our research sites experienced a loss of soil water (Figure 2.11), which is similar to what one would expect due to the conditions. August 2007 experienced above-average rainfall (32.9 mm above normals), and below average temperatures (1.6 °C below normals), which would indicate that the area would have experienced a substantial increase in soil moisture. Figure 2.11 indicates that for all sites, with the exception of 30D, a large jump in soil moisture was seen between July and August, 2007.

The neutron probe soil moisture measurements also allow comparisons to be drawn between sites throughout the year. Figure 2.11 demonstrates how the 30D site and the NOBS site experience similar monthly fluctuations in soil moisture, while 64D is consistently wetter. Differences in drainage may account for a portion of this difference, however it should be noted that the 64D site has a different soil type than both the 30D and NOBS sites (Table 2.1).

It is generally thought that the neutron probe is not ideally suited for soils with thick organic layers, especially those that may experience discontinuous permafrost, or those that remain frozen until late summer.

Bond-Lamberty et al. (2006) found that soil temperature and moisture have high spatial variability, and samples that are less than 5 m apart are generally spatially correlated. Young stands were found to need a larger number of samples in order to be representative. Therefore, it is possible that our five-tube transects were not representative of the flux footprint for our sites, especially the youngest 1964 site, which was found to be considerably wetter than the other two sites.

Fruhauf et al. (1999) found good agreement between the eddy covariance energy balance ET water balance and water catchment water budget (inputs – outputs) using stream weirs. Better agreement for our sites perhaps could be reached using this method, however a number of other environmental factors would need to be measured, and increased knowledge regarding drainage and runoff at our sites would be necessary.

Canopy interception of precipitation is also an important part of the boreal forest ecosystem water balance (Toba and Ohta, 2005), but was a factor that was not measured at our research sites. Due to the lack of interception data, a comparison of change in soil moisture measurements taken using the neutron probe to a precipitation (P) – ET water balance was not performed. The energy used to evaporate intercepted rainfall is considered included in calculations of LE/ET in the P-ET water balance method, however the amount is not known. Because the amount of precipitation intercepted and evaporated within the canopy is unaccounted for, the water data are incomplete and do not explain the distribution of water following a precipitation event. A direct comparison between the neutron probe water balance method and the P-ET method is not possible, as the amount of P that contributes to soil water is unknown.

Cuenca et al. (1997) investigated soil water balance for various types of boreal forest systems, including sites in central Saskatchewan, and sites that were also in our study area. Some discrepancies between soil moisture measurements and ET flux measurements were found, including differences in calculated ET rates of up to 60%. At one site in particular, ET flux measurements were consistently larger than ET rates calculated using soil-moisture-based measurements. They proposed that perhaps spatial differences and different sampling volumes were responsible for these differences, or there was a possibility that ET was overestimated due to underestimated negative H at night. These same conclusions may apply to our study sites.

2.4.5 Implications

Our findings may have implications on both regional and global energy and water balances. The number of forest fires has been predicted to increase by as much as two-fold in the future, which would renew stands at an increasing rate (Flannigan et al., 2005). If these predictions are true, the boreal forest as a whole would be younger (Chapin et al., 2000). This may change the boreal forest's contribution to the global water vapour cycle. We would also see a change in both the radiation balance of these stands, and how energy is partitioned within them. It has been suggested that this may cause a cooling feedback, which would counteract the warming that would be encountered due to increased CO_2 release by forest fires (Randerson et al., 2006). Early succession boreal forests often have a large proportion of deciduous trees, and an overall younger boreal forest would see a great change in water use, especially in more southern boreal stands (Chapin et al., 2000).

We have determined that for north-central Manitoba boreal black spruce stands, real differences in ET, Rn and H exist between stands of different ages, and stands of different topographic position. Our data help to describe water and energy budgets for forest stands between the ages of 45 and 150 years, as well as stands that have vastly different drainage capabilities. This knowledge will aid in the development of regional and global climate models, which will be used to help predict the speed and degree of climate change that will be experienced in the boreal forest. Overall, it is unknown whether positive or negative feedbacks will occur with the predicted increase in forest fires (Amiro, Orchansky et al. 2006), but the knowledge gained by this study may help answer this question.

2.5 Conclusions

Our research has found that significant differences in energy and water budgets exist between stand of different ages and topographic position. Wetland sites are shown to have lower H and LE than upland sites of the same age, with resulting lower cumulative growing season ET. Younger sites (~ 40 years old) have been found to have lower Rn, daily ET and cumulative growing season ET than older sites with similar topographic position.

The proportion of deciduous trees decreases with age in boreal black spruce ecosystems, which usually results in single-species coniferous stands. Coniferous trees have relatively low albedo, and therefore Rn is higher for coniferous stands. Deciduous trees experience a shorter growing season, as they experience a lag in photosynthesis once air temperatures rise above zero in spring, and drop their leaves in early fall

(Goulden et al., 2006). The bryophyte layer becomes more established as stands age and the organic soil layer becomes thicker (Wang et al., 2003), which has a large effect on G. As a result, older stands have an increased capacity to transpire water compared to younger stands, which results in higher ET.

Differences in drainage have a huge impact on energy and water balances of boreal forest stands. Organic soils at wetland sites remain frozen much longer into the growing season (Wang et al., 2003), and once thawed are often completely saturated. As a result, fewer trees are present at wetland sites, and those trees that are able to survive are often stressed and have stunted growth. Upland sites have higher tree density, larger trees, better drainage, and increased ET levels as a result.

The distinct seasonality of temperatures and water availability in the boreal zone has an enormous effect on ET and energy partitioning (Betts et al., 2001). The significant energy necessary to melt snow and thaw soils results in a marked difference in energy partitioning and energy budgets for forest stands of different topographic position and age. Our study has helped clarify the changes in energy and water use for boreal black spruce forests in the later stages of succession following fire. Fire changes the canopy density, which determines the amount of radiation that reaches the ground, which controls soil temperature, air temperature, and various other factors (Amiro, Barr et al., 2006). Energy balance partitioning is greatly altered by disturbances such as forest fires, and partitioning changes throughout succession following the disturbance. Other disturbances such as harvesting, insects and windthrow are also very important in boreal forest systems (Amiro, Barr et al., 2006). Possible large increases in the amount of area burned annually (Flannigan et al., 2005) have the potential to have a significant impact on regional climate patterns (Chambers and Chapin, 2003).

2.6 References

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3 GENERAL SYNTHESIS

3.1 General Considerations

The boreal forest covers an enormous amount of the earth's land base, and therefore the cycling of water and energy in this region has a large effect on a global scale. Disturbances such as forest fires are predicted to increase (Flannigan et al., 2005), which will renew the boreal forest zone at a greater rate, and decrease the average age of these forests over time. It is known that changes in hydrology or ET due to disturbances such as fires or harvesting can affect available moisture, and will therefore affect species composition, soil respiration, boreal peatland health and regional climate (Petrone et al., 2006). Knowing how forests of different ages use water and energy gives researchers the ability to develop more precise global climate models.

Water and energy cycles are interconnected with other biogeochemical cycles in boreal forest ecosystems, such as the C cycle. Boreal forests have been found to contain up to 25% of global terrestrial C stores, the majority of which are held in the organic peat soils (Dixon et al., 1994). Dunn et al. (2007) found that soil temperatures and depth to water table predicted 57% of the variation seen in half-hourly respiration values at the NOBS site. High water tables are necessary to maintain anoxic conditions in organic soils, which prevent their decomposition. If water tables drop to unprecedented lows, this brings old organic matter into a position where it is able to be decomposed. Dunn et al. (2007) concluded that the increase in water availability at the NOBS site was responsible for the decrease in overall respiration. This reinforces the need for an increased understanding of slow-changing parameters such as water balance, as it is necessary in order to accurately predict the response of these ecosystems to climate change.

Flux tower research allows us to study changes in energy and water cycles for forest systems and these data enable us to develop ecosystem process models in order to extrapolate to larger spatial and longer temporal scales. It is unknown to scientists how water use for boreal black spruce forests will change with climate change. If the growing season is extended due to warmer temperatures, total growing season ET could increase. If precipitation were to remain the same, and this resulted in a decrease in the water table over years or decades, would wetland areas begin to behave more like upland areas? Would upland areas behave differently due to decreased water availability? Will species composition in these forests change? Large changes in hydrology will affect the level of runoff from these systems, which would result in lower stream flow. This is of great importance globally, and of economic importance here in Manitoba as hydroelectric power is an important product for this province. If seasonal precipitation levels changed, or rainfall intensity shifted, this could also greatly affect the water balance. A more in-depth understanding of the variations between forest ages and areas with different topography will help answer these questions.

3.2 Energy and Water Balance Findings

This study has demonstrated differences in energy balance and ET levels exist among boreal black spruce stands of different ages. Older stands were found to have higher Rn and H. Bryophytes at older sites are more established, and it is thought that this increased organic layer accounts for lower G measured at older sites. Older forests were found to have higher levels of ET (daily and cumulative growing season) than younger sites of similar topographic position. The change in species composition as black spruce ecosystems stands age impacts both growing season length and albedo, which in turn affects energy balance partitioning and ET. Older black spruce trees have an increased capacity to transpire water, and are perhaps more efficient at extracting water from these systems, which results in higher ET for older stands.

Upland sites have been found to have higher ET than wetland sites of the same age. The reduced drainage at wetland sites results in a higher water table, and saturated organic soils require a higher energy input in the spring to melt frozen soil water. The upland sites have sufficient drainage that a larger number of trees are able to establish compared to wetland sites. The small number of trees that are able to establish at wetland sites are often stunted and stressed due to excess soil water, and as a result ET is lower at these sites.

3.3 Implications

This research project is one component of a large NSF funded hydrology project titled "Effects of wildfire disturbance on water budgets of boreal black spruce". Scientists from the University of Manitoba, the University of Wisconsin, and the University of Wyoming are all studying components of the northern Manitoba chronosequence, including the energy and water balances, tree physiology and transpiration levels, as well as bryophyte physiology and transpiration.

The insight gained through the energy and water balance component of this study will aid in further developing an understanding of the black spruce ecosystem. Sap flux measurements of tree transpiration in combination with bryophyte transpiration will detail the partitioning of ET within this ecosystem. The ability of these other scientists to perform "bottom-up" measurements of these factors, in combination with our "top-down" ecosystem-level measurements, gives us the ability to cross reference these measurements in the future. In order to assess whether accurate measurements of ecosystem processes are being made, these multi-level studies are necessary. Knowledge of this type also allows comparisons to be made between these ecosystem types and others throughout the boreal zone.

3.4 Future Work

Further examination of the data collected throughout this study will occur in the near future, and may help to answer some of the questions raised above. Components of this study to be analysed include discovering what is responsible for the differences in tree transpiration levels, including addressing whether differences are genetic or physiological. The bryophyte component of this study is extremely important, and future work will include estimates for bryophyte contribution to ET.

More information is also needed regarding these sites, which may be difficult to measure, but would help explain the discovered differences in ET and energy balance. Water table measurements and measures of subsurface flow would give us an increased understanding of the sites' hydrology. Measures of canopy interception would also be beneficial, as they would allow us to understand the proportion of precipitation that reaches the soil. These measures would greatly increase our capacity to perform water balance calculations for these sites. Other measurements that would be of interest would include soil fertility measurements, which would indicate whether there are other factors that may be affecting forest growth.

Long term research is extremely beneficial, but often due to the nature of research funding, proves to be difficult. Each additional year of measurements allows scientist to gain a greater understanding of inter-annual variability. One or two- year studies are beneficial, but often it is not clear whether the years chosen are representative or are anomalies. Short term research does not allow us to view long term trends, which of course is extremely pertinent now due to climate change. More knowledge is also needed for forests of certain ages, as there seems to be a "gap" of knowledge regarding intermediate-aged boreal forests.

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