The Relationship between Water Availability and Forest Dynamics in Northern Minnesota

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CHAPTER 1. INTRODUCTION

1.1 Long-Term Soil Moisture Dynamics

Forests play a major role in global and local water budgets, returning approximately 40% of total annual precipitation back to the atmosphere in the form of evapotranspiration (ET). In the contiguous U.S., forested watersheds generate about 50% of runoff and management decisions include both afforestation and deforestation to create desired water yields (Furniss et al. 2010; Ellison et al. 2012). Given that climate change is expected to increase evapotranspiration, understanding the intricate role of forested watersheds in the utilization, storage, and supply of water is necessary.

Water stored in the soil profile is a central component of the forest hydrologic cycle and globally accounts for over $120x10^3$ km^3 of water per year (Trenberth et al. 2007). However, current knowledge of how soil water storage dynamics change over time and influence forested processes is limited, particularly due to the lack of long-term *in situ* measurements of soil moisture. Our current understanding of how soil moisture varies across time and space is based on short-term field studies or soil moisture models (Robock et al. 2000). Water movement in forest soils, which are extremely heterogeneous, is difficult to correctly predict even using the most complex models. To help inform theory and models, and to expand our knowledge of soil water dynamics, more *in situ* measurements of soil moisture are needed through the soil profile across broad spatial scales and at small (minutes) and large (decadal) time scales.

Given the importance behind understanding water dynamics, I sought to utilize a unique, 45-year *in situ* network of soil moisture measurements from the Marcell Experimental Forest (MEF) in northern Minnesota. The soil moisture record consists of soil moisture collected seasonally (approximately May, September, and November) at ten permanent sites on the forest. Data were collected using a neutron probe, which allowed for data to be collected across the soil profile. Complete methodology is described in Chapter 2. This unique dataset allowed me to look at long-term trends in soil moisture over time, as well as the dynamics of soil moisture within and across growing seasons.

1.2 Linking Water Availability to Tree Growth

Changes in soil water may alter tree growth, survival, and diversity, with cascading effects through forest ecosystems. Although the general relationships between soil moisture and ecosystem function are implicit, the interactions between moisture and forest productivity across species, soils, and landscape positions are poorly understood. Some northern forest species exploit deeper water (Emerman and Dawson 1996), but few studies have focused on niche diversification and differential exploitation of soil water in northern forests, in which root activity, depth, and lateral extent vary among species to partition soil moisture (Rodriguez-Iturbe et al. 2001). Given that many northern forest landscapes undergo a summer moisture deficit, particularly near the western biome boundary, this niche diversification may be key in sustaining some species and may affect overall forest water use and productivity.

Water is a key determinant of forest structure and ecosystems services in northern forests in general (Robertson 1992), and in Minnesota in particular. In this region, forests are found at the junction of western prairie and eastern mesophytic and boreal forest boundaries, each with distinct patterns of water cycling, use, and outflows (Figure 1-1). Sandy soils and annual summer droughts lead to an annual cycle of saturated and dry soils. Tree growth is dependent upon the volume of annual precipitation, both in the form of spring snowmelt and rainfall, but slight changes in elevation allow long-term storage of deep soil moisture and groundwater and may augment other water sources during summer droughts.

One way to investigate the relationship between climate, water availability, and tree growth is to utilize tree-ring records. Annual tree growth is a function of the surrounding environment and can be estimated using a model of aggregate tree growth (Eqn. 1-1).

$$R_t = f(G_t, C_t, Di_t, Do_t, E_t) \qquad \text{(Eqn. 1-1)}$$

Where R_t is the tree ring width at year t, G_t is the size-related growth trend (which is a function of tree age), C_t includes climatic factors affecting tree growth, Di_t is the within stand disturbance, Do_t quantifies disturbance outside of the stand, and E_t is the error term associated with unidentifiable errors. To isolate climate-growth relationships, one must account for the other model terms. G_t can be removed from the model by standardizing the tree-ring chronologies to remove growth-related trends. Disturbance to the forest can be addressed by sampling numerous trees both within (Di_t) and across (Do_t) stands. This simplifies the growth model to the following (Eqn. 1-2):

$$R_t = f(C_t, E_t) \qquad \text{(Eqn. 1-2)}$$

Despite the fundamental role of water in northern ecosystems, many dendroclimatological studies investigating the relationship between plant available water and tree growth are conducted in arid regions (Cook et al. 2004, Meko et al. 2007). Targeting the majority of dendroclimatological studies on trees that exhibit extreme responses to water stress is of benefit to climate science, where the important questions center on the timing and magnitude of climatic extremes. In doing so, however, a gap of knowledge about the relationship between historical plant available water and tree growth has been created in ecosystems such as the northern forests, where environments are often water-dependent but not necessarily water-stressed.

I investigated primary questions involving the relationship between plant available water and tree growth in the northern forests, specifically at the Marcell Experimental Forest in northern Minnesota. Historical relationships between tree growth and plant available water were done using dendrochronological analysis of dominant tree species and a unique 45-year record of soil water content by depth.

1.3 Dissertation Goals and Objectives

My overarching goal was to understand soil moisture dynamics at the MEF and to explore how these dynamics influence forest productivity. The 45-year record of soil moisture at the MEF allowed me to investigate how soil moisture fluctuates both within and across growing seasons. Additionally, I explored how different climate forcings (e.g. precipitation, temperature, evapotranspiration) influence available soil water at different depths in the soil profile. Because the historical soil moisture network was in aspen-dominated overstory canopies, the goal of Chapter 3 was to understand how cover type influences soil moisture. I compared two soil moisture models that were calibrated using field data under three dominant cover types at the MEF (red pine, aspen, and mixed hardwoods). Lastly, Chapter 4 is a synthesis of the long-term soil moisture record and uses dendrochronological analysis to look at how forest productivity changes with temperature and water availability. The information gleaned from this research will help inform understanding of how soil water changes across time and landscapes. Additionally, understanding how tree growth has responded to climate in the past can help predict how resistant and resilient different trees will be to climate change.

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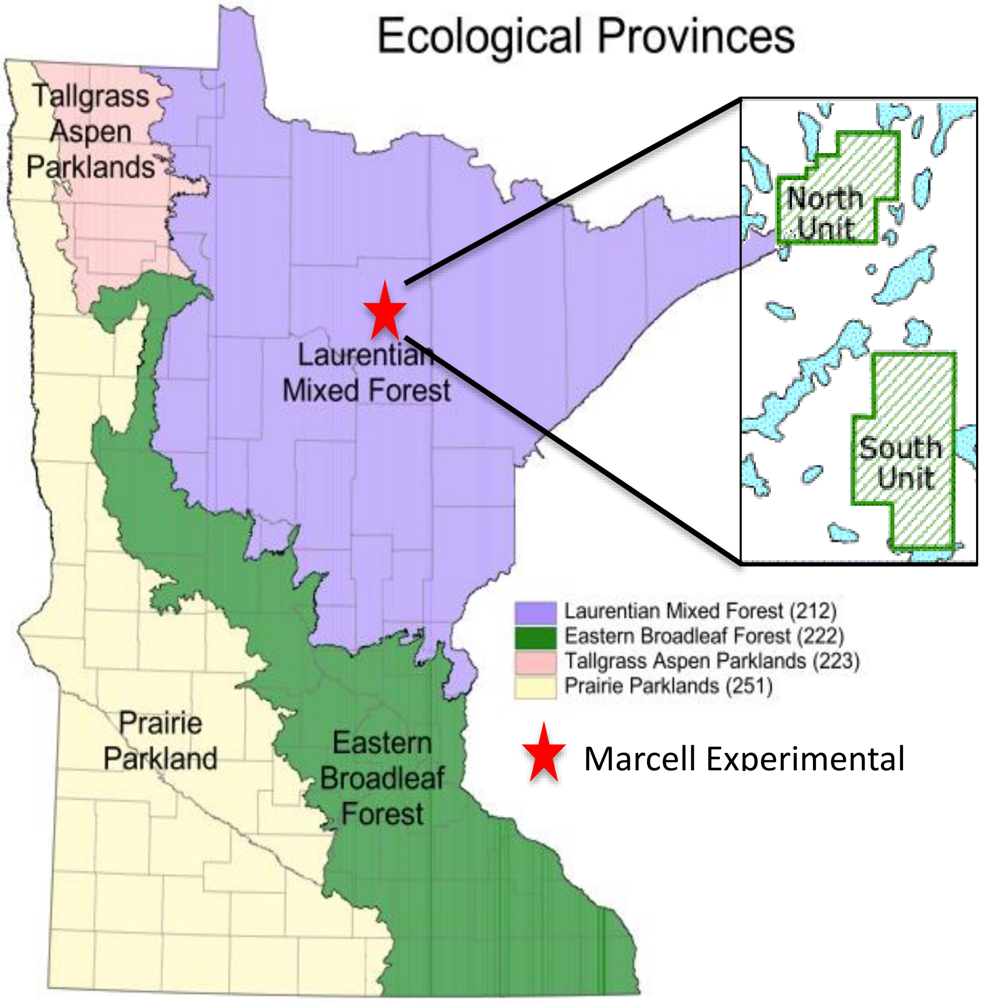

Figure 1-1. The Marcell Experimental Forest is located in the center of the Laurentian Mixed Forest. Image Credit: MN DNR.

CHAPTER 2. LONG-TERM SOIL MOISTURE PATTERNS IN A NORTHERN MINNESOTA FOREST

2.1 Introduction

Soil moisture influences ecosystem processes, including soil pedogenesis, type and abundance of flora and fauna, decomposition, and nutrient availability (Rodriguez-Iturbe, 2000; Porporato et al., 2002, 2004; Eamus, 2003; Jenerette and Lal, 2005). In forested ecosystems, extreme high or low soil moisture conditions can lead to decreased photosynthesis (Chaves et al. 2002) and root (Kuhns et al. 1985) and tree growth (Hinckley et al. 1979), changes in phenology (Borchert 1994), and increased susceptibility to diseases and pathogens (Desprez-Loustau et al. 2006). Soil moisture is so vital to hydrological, biological, and biogeochemical processes that the European Space Agency designated it to be an essential climate variable (Wagner et al., 2012). Soil moisture is also critical to climate forecasting and can impact management decisions regarding future climate scenarios, flood and drought mitigation, and land management policy (Adams et al., 1991; Eltahir, 1998; Norbiato et al., 2008). Despite its important role in forested ecosystems, soil moisture is rarely measured, especially with respect to depth in the soil profile and through time.

Although in-situ measurements of soil moisture are becoming more prevalent, current understanding of in-situ soil moisture dynamics is limited in time, space, and depth (Baker et al., 1979; Passioura, 1982; Adams et al., 1991; Hollinger and Isard, 1994; Stephens, 1995; Western and Grayson, 1998; Robock et al., 2000; Rodriguez-Iturbe, 2000; Kirkham, 2004; Dorigo et al., 2011). Specifically, long-term records of in-situ soil moisture are rare (Adams et al., 1991). The current understanding of soil moisture dynamics is limited in time (Robock et al., 2000), to agricultural ecosystems (Hawley et al., 1983; Robock et al., 2000), or following disturbance events (Adams et al., 1991; Robertson et al., 1993; Guo et al., 2002). In many cases, the understanding of available soil water is based on theoretical models (Huang et al., 1996; Nijssen and Lettenmaier, 2001; Wagner et al., 2003). While modeling approaches are useful, their accuracy can be variable due to the complexity of upscaling from individual plant-water use relationships to larger, heterogeneous landscapes.

Understanding soil moisture dynamics may become increasingly important under changing climates. In the north-central United States, temperatures are expected to increase while precipitation is expected to become more variable (Christensen et al. 2007). The effects of climate change on soil moisture will depend upon the timing and severity of the changes. Globally, soil moisture has increased despite increases in temperature, suggesting that increased precipitation will offset increased plant water demand with warmer temperature (Robock et al. 2000). Regional studies of soil moisture in northern forests have shown increases in soil moisture over time (Vinnikov et al. 1996; Groffman et al. 2012), and some studies have already shown an increase in plant water demand and carbon sequestration due to increasing temperatures, especially in northern forests (Pastor and Post 1988; Hyvönen et al. 2007). In light of anticipated climatic changes, long-term, spatially resolved measurements of *in situ* available soil water, weather (e.g. temperature, precipitation, and humidity), and plant-water use are needed to better understand the mechanisms behind forest growth. Increased knowledge about these mechanisms can help us to better understand the resilience and resistance of these ecosystems under increased water stresses.

To quantify the role of changing climatic regimes on soil moisture in northern hardwood forests, I examined 45 years of *in situ* soil moisture measurements from the Marcell Experimental Forest in north-central Minnesota. This record of soil moisture is among the longest ongoing, continuous record of soil moisture currently available. The relationship between available soil water and climate forcings (e.g. precipitation, temperature, evapotranspiration) was analyzed using a Critical Climate Period (CCP) analysis (Craine et al., 2009). The Critical Climate Period can be defined as the window of time over which a climatic variable explains the maximum variation in a response, in this case, available soil water. CCP has been used to assess the relationship between climate and grass culm production (Craine et al., 2010), bison weights (Craine et al., 2009), and grassland productivity (Craine et al., 2012). CCP has not previously been used to explore the relationship between climate variables, but it allows for general knowledge of how changes in climate variability that occur during one season may influence the available soil water and thus ecosystem processes following the climatic event. Specifically, this study seeks to 1) investigate the trends in climatic patterns, including available soil water, from 1966 – 2011 at the Marcell Experimental Forest; and 2) to identify the critical climate period (CCP) that influences available soil water in these systems.

2.2 Study Site

The Marcell Experimental Forest (MEF) (47.5° N, 93.5° W) is located on the eastern edge of the Chippewa National Forest in north-central Minnesota (Figure 2-1). Established by the USDA Forest Service in the early 1960s, initial research focused on the hydrology of peatlands. Meteorological and hydrological monitoring began in 1961

(Sebestyen et al., 2011; Verry et al., 2011b). The 1100-ha forest is divided into six research watersheds, each of which contains a bog or fen and a surrounding upland ecosystem. Combined, the six watersheds comprise less than 300 ha of the forest. This study focuses on the two control watersheds, S2 and S5, that have not been disturbed since establishment of the experimental forest or harvested since the early 1900s (Table 2-1).

The climate at the MEF is continental with cold, dry winters and warm, moist summers. Mean annual precipitation from 1961 to 2012 was 78.0 cm with approximately 1/3 of the precipitation occurring as snowfall and the remainder as rain (Sebestyen et al., 2011). Mean annual temperature from 1961 to 2012 was -15.1°C in January and 18.9°C in July. Aspen (*Populus tremuloides* and *Populus grandidentata*) dominates the upland landscape with smaller populations of red pine (*Pinus resinosa*) and mixed hardwoods (*Tilia americana*, *Acer saccharum,* and *Acer rubrum*) also common in the uplands. Upland soils are predominately deep glacial tills. Water drains through mineral soils on low-elevation ridges (approximately 20 m relief) through peatlands to ephemeral streams or the regional groundwater system (Sebestyen et al., 2011; Verry et al., 2011a).

2.3 Methods

2.3.1 Climatic Trends

Air temperature at the S2 watershed has been recorded since 1961 while the temperature at the S5 watershed has been recorded since 1962. Daily maximum and minimum temperature were recorded using Belfort model 594-1 Hygrothermographs (Belfort Instruments, Baltimore, Maryland, USA) and were then averaged to calculate mean daily air temperatures at the two meteorological stations (Rosenberg et al. 1983). Daily precipitation data have been collected since 1961. The stations are equipped with Belfort Universal Recording Precipitation Gauges (Belfort Instruments, Baltimore, Maryland, USA); the S2 watershed was updated with an ETI NOAH IV digital rain gauge (ETI Instrument Systems, Fort Collins, Colorado, USA) in 2009. Snow water equivalent was calculated by first equipping the rain gauges with antifreeze to melt snow and then obtaining weekly precipitation measurements using a temperature-compensated spring scale (Sebestyen et al. 2011).

To evaluate trends in climatic data from 1966 – 2012 at the MEF, a non-parametric Mann-Kendall trend test (Mann, 1945) was fitted to temperature and precipitation records. This test is more robust for trend detection than linear regression because it does not require normality of the dataset and the method is insensitive to missing data. Mean annual temperature was calculated by averaging mean daily temperature between the S2 and S5 watersheds and then averaging this value across years. Mann-Kendall trends were then assessed on mean annual temperature, mean maximum annual temperature, mean minimum annual temperature, and mean seasonal temperature. Seasons were defined as the following: Winter (January, February, and March); Spring (April, May, and June); Summer (July, August, and September); and Fall (October, November, and December) and are consistent with seasons previously defined at the MEF (Sebestyen et al., 2011).

Total annual precipitation was calculated by averaging total daily precipitation between watersheds S2 and S5 and then summing the daily precipitation measurements over the calendar year. Mann-Kendall trends were then assessed on total annual precipitation and total seasonal precipitation. Again, seasons were defined as Winter (January, February, and March); Spring (April, May, and June); Summer (July, August, and September); and Fall (October, November, and December). Many studies have found an increase in the severity of droughts and floods over time that are not always reflected in changes in total annual precipitation (Alexander et al., 2006; Dai et al., 1998; Easterling et al., 2000; Meehl and Tebaldi, 2004). To evaluate whether changes in the size, frequency, and severity of rainfall events has changed over time, trend tests were performed on mean annual number of days since last rainfall (used as an index of drought), annual maximum intensity of rainfall (mm hr^{-1}), mean annual total volume of rainfall per storm, and frequency of rainfall events.

Additionally, I applied a Mann-Kendall trend test to modeled potential evapotranspiration (PET) since PET can account for up to 65%-66% of annual precipitation at the MEF (Brooks et al. 2011). Daily PET was calculated using a modified Thornthwaite equation (Pereira and Pruitt, 2004; Thornthwaite, 1948) which corrected for temperatures greater than 26°C and photoperiods greater or less than 12 hours. Daily PET calculations were averaged to obtain seasonal and yearly estimates of PET.

2.3.2 Soil Moisture Trends

Soil moisture has been measured since 1966 at three sites within the two control watersheds (Table 2-2). Measurements typically occurred three times per year: once each at leaf-out, tree senescence, and prior to soil freeze. These times roughly fell in May, September, and November, but exact measurement days and months varied depending on the year, weather, and length of the growing season. Seasonal snow cover and frozen soils prevented measurements during winter months (January – March). Data were measured using the neutron probe technique (Brakensiek et al., 1979) with a Troxler Model 105 depth moisture gage before 1990 and a Series 4300 gage from 1990 to 2012. Data were measured as percent soil moisture and were subsequently converted to cm of available soil water per sampling depth. Soil moisture was measured in 30.4 cm increments from 15.2 cm to the depth of an access tube (Table 2-2). Soil moisture was measured gravimetrically for 0 to 15 cm by soil sampling and drying (Gardner, 1986), as measuring moisture in near-surface soil horizons using the neutron probe technique can lead to spurious measurements due to neutrons escaping from the soil surface (Bell et al., 1987). The neutron probe collected the volumetric water content (θ_v) of the soil, which was subsequently converted to cm of water per horizon by multiplying θ_v by the sampling depth. Values were then converted to cm of available soil water by subtracting the soil permanent wilting point (defined as θ_v at -1500 kPa). The soil field capacity and permanent wilting point for each sampling depth was determined at the time of access tube installation.

A Mann-Kendall trend test was used to assess shifts in soil moisture over time. Because there was inter-annual variation in the sample timing of available soil water measurements, only measurements collected during May, September, and November were used in the analysis; this created minor gaps in the dataset. Total available soil water from each sampling depth was aggregated to obtain total site available water to a depth of 228.6 cm. Data were analyzed at the sites, individual watersheds, and averaged between the two watersheds. To obtain the averaged watershed data, total available soil water was averaged between all months of measurement and the two watersheds to obtain one annual value of soil moisture. Relationships were similar across all sites and subsequent results display data averaged between the control watersheds.

Differences between sites, depths, and months were analyzed using a Tukey-Kramer test (Tukey, 1949; Kramer, 1956) for differences in means. The two control watersheds were included in this analysis, and differences between sites were analyzed at three depth increments (0 – 15.2 cm, 76.2 – 106.7 cm, and 198.1 – 228.6 cm) and three months (May, September, and November). These depths were chosen to represent upper, middle, and lower soil horizons. Analysis included individual Tukey-Kramer tests for each depth increment during each month.

2.3.3 Critical Climate Period

To investigate the relationship between available soil water and climate forcing using CCP, precipitation measurements were taken from the MEF precipitation gauge located nearest to each soil water-sampling site. Precipitation the day prior to the soil moisture measurement date was used as a starting point for analysis. Precipitation was iteratively summed each day back to a period of 750 days. A correlation analysis between soil moisture and the climate variables was performed for each of three depths (0 – 15.2 cm, 76.2 – 106.7 cm, and 198.1 – 228.6 cm) and for three months (May, September, and November) at each depth. Analysis was repeated across all three sampling locations. The optimized CCP was then calculated by minimizing the variation and percent deviation from maximum R^2 across all three sites (within the two watersheds). CCP was calculated for summed daily precipitation, daily potential evapotranspiration (PET), and daily precipitation less PET. For all climate variables, an optimized CCP was determined for the soil depth and month of measurement. All analyses were computed using SAS version 9.3 (SAS Institute, Cary, NC, USA).

2.4 Results

2.4.1 Climatic Trends

Mean annual temperature at the MEF has increased by 0.5° C per decade since 1966 ($p < 0.001$, Figure 2-2). Winter temperatures account for much of the annual increase (0.7°C per decade from January to March), with smaller yet statistically significant increases occurring during the spring (0.3°C per decade from April to June), summer (0.3°C per decade from July to September), and fall (0.04°C per decade from October to December) (Figure 2-2). Mean annual minimum and maximum temperatures followed similar patterns throughout the forty-five year study period.

From 1966-2012, I detected no statistically significant trends in total annual precipitation at the MEF (Figure 2-3). Additionally, seasonal precipitation, frequency of rainfall events, volume of rainfall, and number of consecutive days without rainfall have not changed over the forty-five year study period.

Despite no changes in precipitation, annual available soil water at the MEF has been declining since 1966. Mean annual available soil water from 0.0 – 228.6 cm has decreased at a rate of 0.8 cm per decade (p-value < 0.03) (Figure 2-3). The strongest decline has been in May available soil water (1.3 cm per decade, p-value < 0.0001), and no statistically significant changes in September or November available soil water were detected (Figure 2-3). Some of the highest decreases in mean annual available soil water occurred between 45.7 and 259.0 cm in the soil profile (Table 2-3). No statistically significant changes in mean annual available soil water were found in deeper soils.

While the rate of change in modeled mean annual PET (1966 – 2012) is not statistically significant, the variability around mean annual PET has increased over the same time period (Figure 2-4). Significant increases in PET were found in the summer (July, August, and September: 1.2 cm per decade, $p = 0.02$) and spring (April, May, and June: 1.4 cm per decade, $p = 0.09$). September PET has been increasing at a rate of 1.2 cm per decade ($p = 0.05$), while no changes were found in May and November PET (data not presented).

2.4.2 Seasonal Trends in Soil Moisture

Collected soil moisture data show a marked seasonal pattern in available soil water that is consistent across all three sampling sites (Figure 2-5). The three monthly data points differentiate the spring dry-down period, when evapotranspiration begins and starts to deplete available soil water, as well as the fall recharge phase, when evapotranspiration slows down and precipitation increases available soil water. High inter-annual variability between sites is present within all months of recorded available soil water (Figure 2-5).

2.4.3 Critical Climate Period

At the MEF, precipitation less PET (summed over a period of days prior to the available soil water measurements) was found to explain the variability in mean available soil water more so than precipitation or PET alone (Table 2-4).

The relationship between the summed precipitation less PET and available soil water was found to vary greatly between month, depth, and site (Figure 2-6). Summed precipitation less PET was found to explain as much as 72% of the variation in available soil water in the upper soil layers and 56% of the variation in deeper soil layers. Summed precipitation less PET had difficulties explaining the variation in May available soil water, particularly as depth in the soil profile increased. Overall, relationships between the summed precipitation less PET and available soil water were strongest in September and November.

2.5 Discussion

2.5.1 Declining Soil Moisture

Despite no changes in annual or seasonal precipitation from 1966 – 2012, available soil water at the MEF has decreased significantly since 1966, specifically in May. In northern Minnesota, May soil moisture is a function of precipitation and the preceding snowmelt, as well as antecedent available soil water from the previous fall. While our data suggest that the total precipitation inputs to the system may be unchanging, the timing of these inputs is critical. The observed increase in winter and spring temperatures likely results in snow melting earlier in the season. As a result, snowmelt, runoff, and available soil water levels would peak in April as opposed to May. Additional data are needed to test this hypothesis. If seasonal snowpack is melting earlier in the season, evapotranspiration may be beginning earlier, leading to an additional depletion in May soil moisture. The day of snowmelt centroid (day when the accumulated streamflow exceeds 50% of the total streamflow) is currently 10 - 27 days earlier than it was in the 1960s (Sebestyen et al., 2011). Peak snowmelt at the MEF occurred in the first week of May in 1962 and has become increasingly earlier. In 2011 snowmelt occurred in the first and third weeks of April for watersheds S5 and S2, respectively (Sebestyen et al., 2011). The growing season length, defined as the number of days between spring and fall frosts (Skaggs and Baker, 1985), has been increasing at the MEF. The MEF mean growing season length from 1961 – 1970 was 94 days while the mean growing season length from 2000 – 2010 was 129 days (unpublished data).

2.5.2 Soil Moisture Patterns

The three annual measurements of soil moisture suggest that available soil water at the MEF follows anticipated patterns, with a spring draw-down and subsequent fall recharge of available soil water (Baker et al., 1979; Grayson et al., 1997; Tromp-van Meerveld and McDonnell, 2006). Additional measurements would be needed to determine if these patterns are consistent throughout the year. Annual soil water can vary greatly across months, years, and with depth. Prior to the growing season, soils are recharged via spring snowmelt (Sebestyen et al., 2011). Evapotranspiration and a lack of summer precipitation result in declining available soil water from May until August. Soils begin to recharge in the fall with the cessation of evapotranspiration. Available soil water usually falls below field capacity during the late summer months (average field capacity to a depth of 259.0 cm across the three sites is 31.9 cm).

2.5.3 Critical Climate Period

An analysis of the Critical Climate Period (CCP) of available soil water suggests that soil moisture is not simply a function of the environmental conditions (i.e. precipitation, temperature, PET) on the day of soil moisture measurement, but is instead a signature of precipitation less PET from the 1 – 10 months prior to the time of measurement. Precipitation less PET takes into account precipitation, evapotranspiration, and temperature, all of which are important in determining soil water availability (Robertson et al., 1993). In general, the relationship between precipitation less PET and available soil water in May is weaker than the relationships for September and November. This is likely due to (1) the influx of water to the soil profile via spring snowmelt, which was not included as a variable in precipitation less PET, and (2) the timing of May available soil water measurements. Most of the May measurements occurred before deciduous vegetation has leafed out and would be transpiring water to full capacity, yet the modeled PET that was included in precipitation less PET did not take into account this short period of time in which PET is possible, but trees have not yet started transpiring. In general, optimized CCP (the number of days prior to available soil water measurement in which the summed precipitation less PET accounted for the highest variability in soil moisture) increased with depth. Water that enters the deeper soil horizons must first infiltrate through upper horizons, leading to time lags between precipitation events and deep soil moisture signatures.

Our results suggest that the timing of climate events and interannual variability has lingering impacts on available soil moisture. For instance, a spring drought may significantly influence available soil moisture in the upper soil horizons for the current spring, but may also impact late-summer available soil moisture in the middle soil horizons, as well as deep soil moisture in the fall. Droughts have effects lasting the entire year, even though precipitation may have rebounded from drought conditions. Analyses such as CCP are beneficial, but complex soil-atmosphere feedbacks not considered by the analysis may further enhance variability in soil moisture (Eltahir, 1998; Schar et al., 1999; D'Odorico and Porporato, 2004; Koster et al., 2004).

Trends showing a decrease of available soil water at the MEF contrast with studies conducted in the boreal forests of Russia, which have similar climates to the MEF. These studies have found increases in available soil water despite increases in temperature (Vinnikov et al. 1996; Robock et al., 2000). However, no comparative records of long-term available soil water are known to exist in boreal peatland ecosystems. Results from global soil moisture are similar to those found in Russia, and suggest that increases in precipitation offset increases in evaporative demand (Robock et al., 2000). However, we have found that an increase in mean annual temperature does significantly affect soil moisture even when total annual precipitation remains steady. This finding may have profound implications for available soil water, especially as global temperatures are expected to rise by 1.1 – 6.4°C by 2100 (National Research Council, 2010). Our results are especially important considering that most climate models project decreasing or static summer (June, July, and August) precipitation combined with increasing temperatures over the contiguous United States (Christensen et al., 2007). Such a scenario could result in drastic decreases in available soil water over time, leading to shifts in species, decreases in decomposition rates, and lower water tables.

2.6 Conclusions

I have presented a unique long-term record of seasonal soil moisture that spans forty-five years across three sites and reaches a depth of 2.3 m. Our results show that long-term available soil water in a northern forest has been decreasing at three sites despite no significant changes in precipitation over time and that increases in temperature and PET may be accounting for changes in available soil water. In a CCP analysis, precipitation less PET accounted for greater variability in available soil water than precipitation or PET alone. These results suggest that temperature and precipitation inputs couple to influence available soil water. Temperature at the MEF is predicted to continue to rise, which may contribute to even greater declines in available soil moisture.

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Table 2-1. Characteristics of upland forest management treatments for six established research watersheds at the Marcell Experimental Forest (MEF).

Watershed	Total Area *(ha)*	Maximum Elevation *(m)*	Outlet Elevation *(m)*
S2	9.7	430	420
S5	52.6	438	422

Table 2-2. Characteristics of three historical soil water-monitoring locations at the Marcell Experimental Forest.

Site	Record Start Date	Probe Depth *(m)*	Soil Type	Soil Texture[†]	Drainage Class	Cover Type	Stand Age[‡] *(years)*	Slope *(%)*
S2-E	10/1967	2.3	Haplic Glossudalf	Fine Sandy Loam	Well Drained	Aspen	96	1 to 8
S2-S	04/1968	3.2	Haplic Glossudalf	Fine Sandy Loam	Well Drained	Aspen	96	1 to 8
S5	09/1966	2.3	Typic Udipsamment	Fine Sandy Loam	Poorly Drained	Aspen	92	1 to 10

†Source: Soil Survey Staff
‡As of 2013

Table 2-3. Linear regression variables for mean annual soil moisture against year for each sampling depth at MEF watersheds S2 and S5.

Soil Depth *(cm)*	R^2	p-value	α	β
0.0 - 15.2	0.39	< 0.01	0.024	-45.85
15.2 - 45.7	0.02	0.912	-0.001	6.192
45.7 - 76.2	0.61	< 0.0001	0.028	-52.15
76.2 - 106.6	0.46	< 0.01	-0.018	38.77
106.6 - 137.1	0.17	< 0.01	-0.014	30.78
137.1 - 167.6	0.49	< 0.001	-0.018	38.77
167.6 - 198.1	0.32	0.030	-0.010	22.79
198.1 - 228.6	0.69	< 0.0001	-0.040	82.63
228.6 - 259.0	0.85	< 0.0001	-0.072	145.5
259.0 - 289.5	0.00	0.776	0.001	-0.745
289.5 - 320.0	0.00	0.982	0.000	2.147

Table 2-4. Optimized critical climate period (CCP) duration for each sampling depth and month of measurement. Optimized CCP maximizes the percent variation in available soil water that can be explained by a climate variable precipitation, potential evapotranspiration (PET), and precipitation – PET) for an optimized number of days prior to the sampling date.

		Precipitation		PET		Precipitation – PET	
Depth *(cm)*	Season	Optimized CCP *(days)*	R^2	Optimized CCP *(days)*	R^2	Optimized CCP *(days)*	R^2
0 - 15	May	44	0.226	4	0.450	31	0.452
	Sep	22	0.265	145	0.368	22	0.723
	Nov	84	0.257	44	0.331	84	0.416
76 - 107	May	30	0.123	18	0.313	312	0.254
	Sep	117	0.428	51	0.338	77	0.692
	Nov	109	0.385	107	0.160	109	0.721
198 - 229	May	500	0.240	60	0.269	319	0.233
	Sep	116	0.313	660	0.306	77	0.557
	Nov	147	0.260	295	0.275	109	0.552

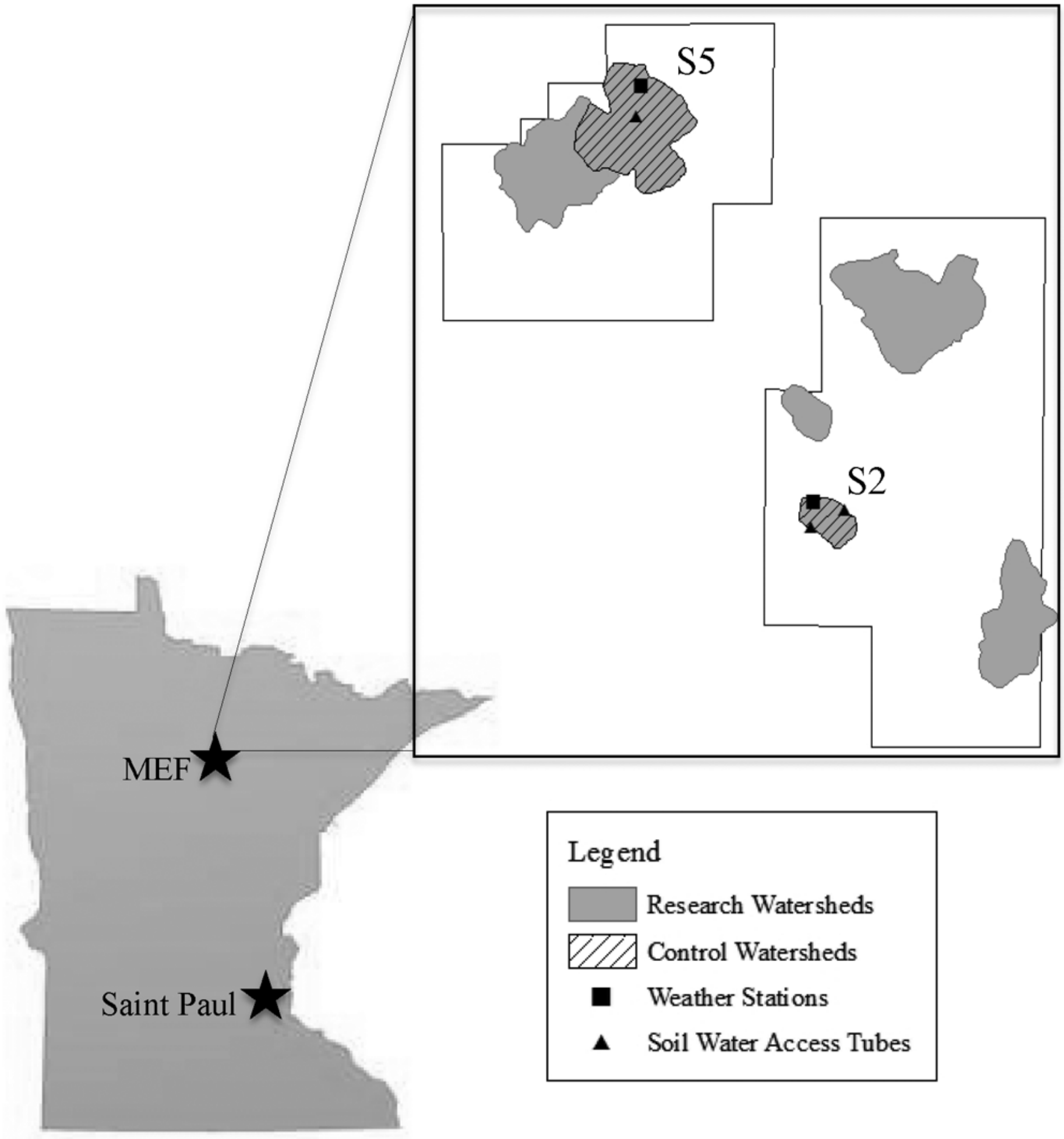

Figure 2-1. The Marcell Experimental Forest (MEF) is located in north-central Minnesota and consists of six research watersheds, two of which are control watersheds that have not undergone any management.

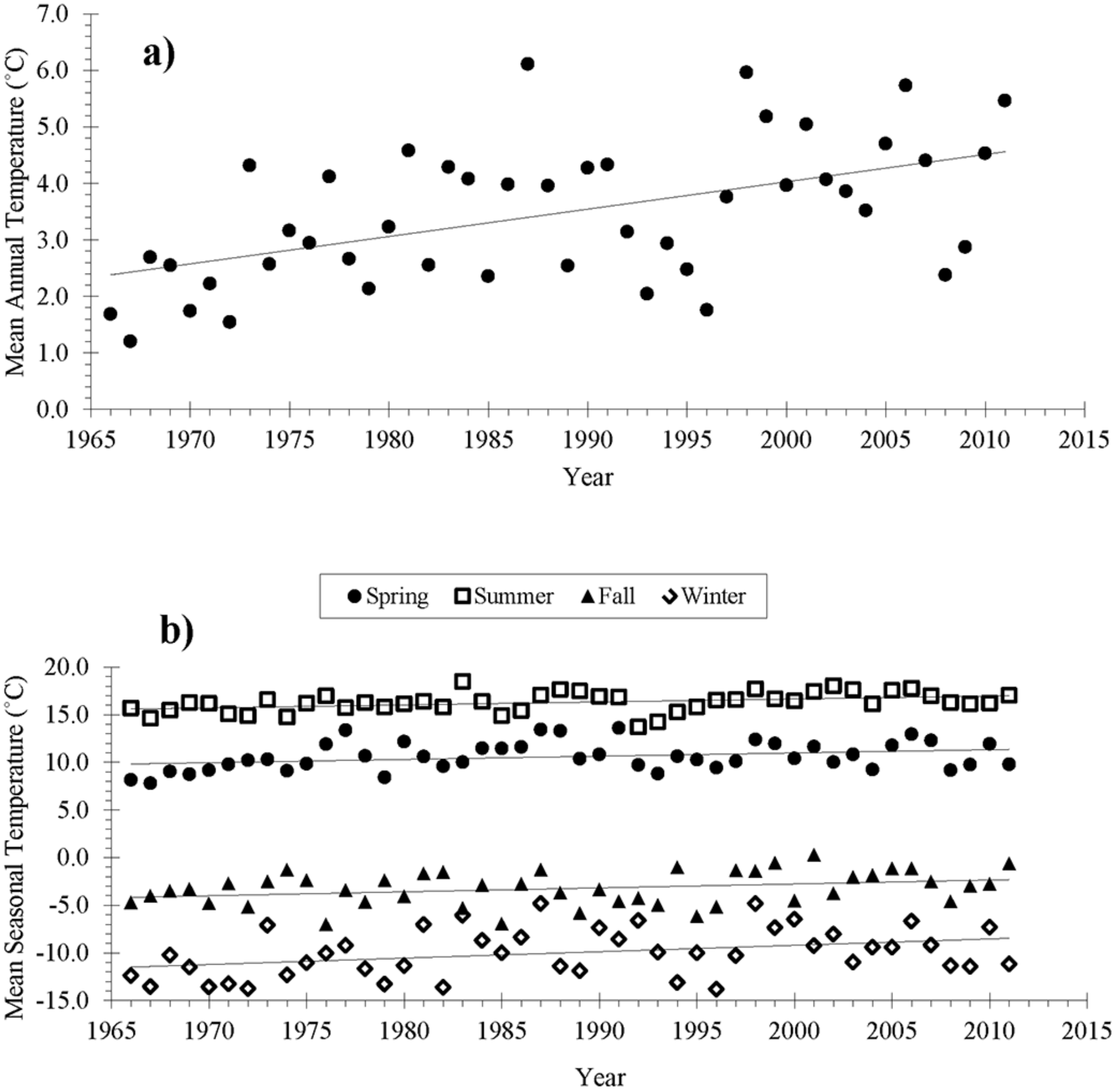

Figure 2-2. Mean annual (a) and mean seasonal (b) air temperature at the MEF from 1966 to 2010. Mean annual air temperature has significantly increased since the start of measurement ($p < 0.001$). Summer air temperature has increased since 1966 ($p < 0.001$), as have winter, spring, and fall air temperature ($p < 0.05$). Lines represent statistically significant linear regressions.

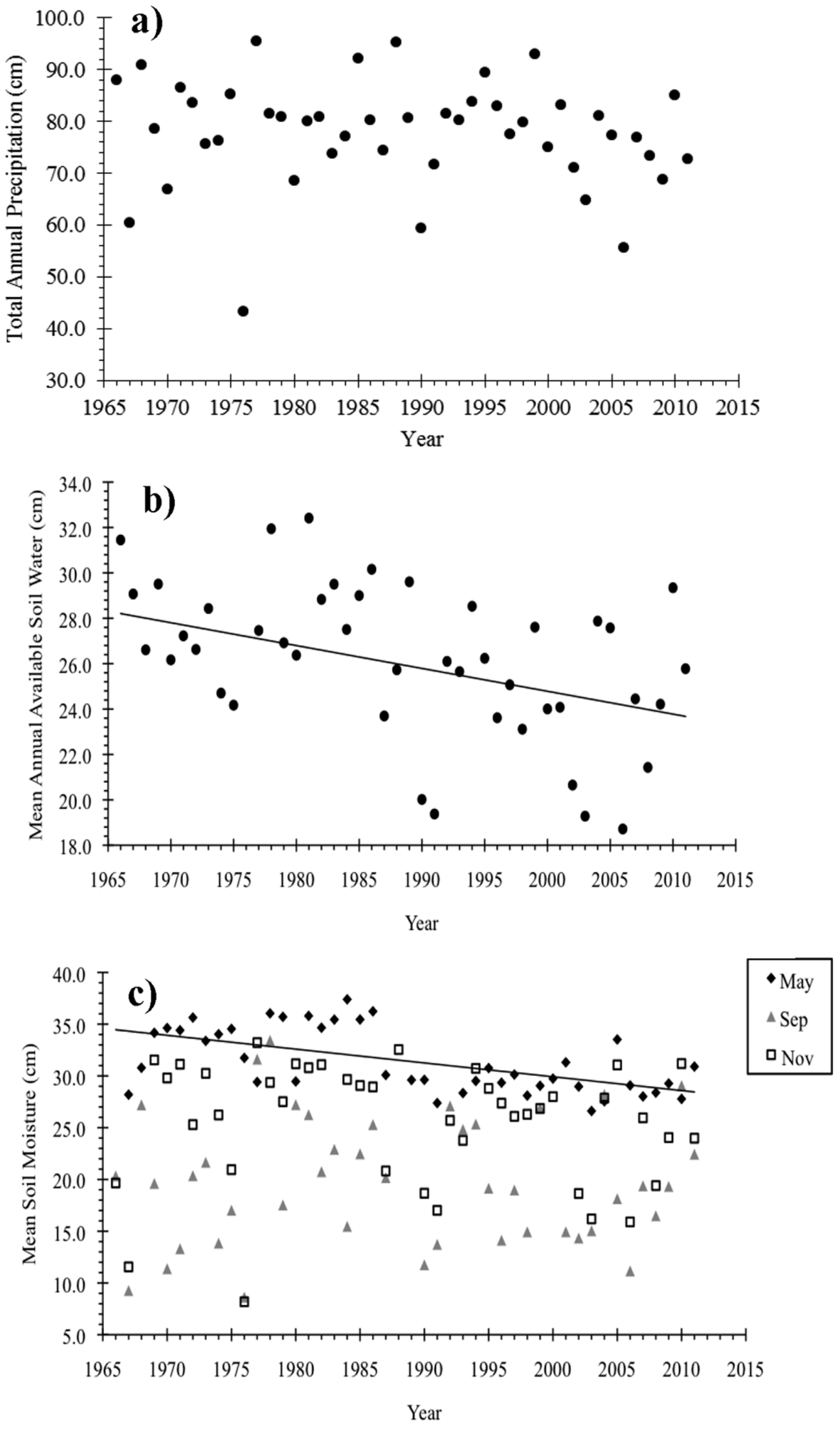

Figure 2-3. Mean annual precipitation (a), mean annual available soil water (b), and seasonal mean available soil water (c) at the MEF. Mean annual soil water has been decreasing at a rate of 0.08 cm per year ($p < 0.03$) and May mean available soil water has been decreasing at a rate of 0.13 cm per year ($p < 0.0001$). Lines represent statistically significant linear regressions.

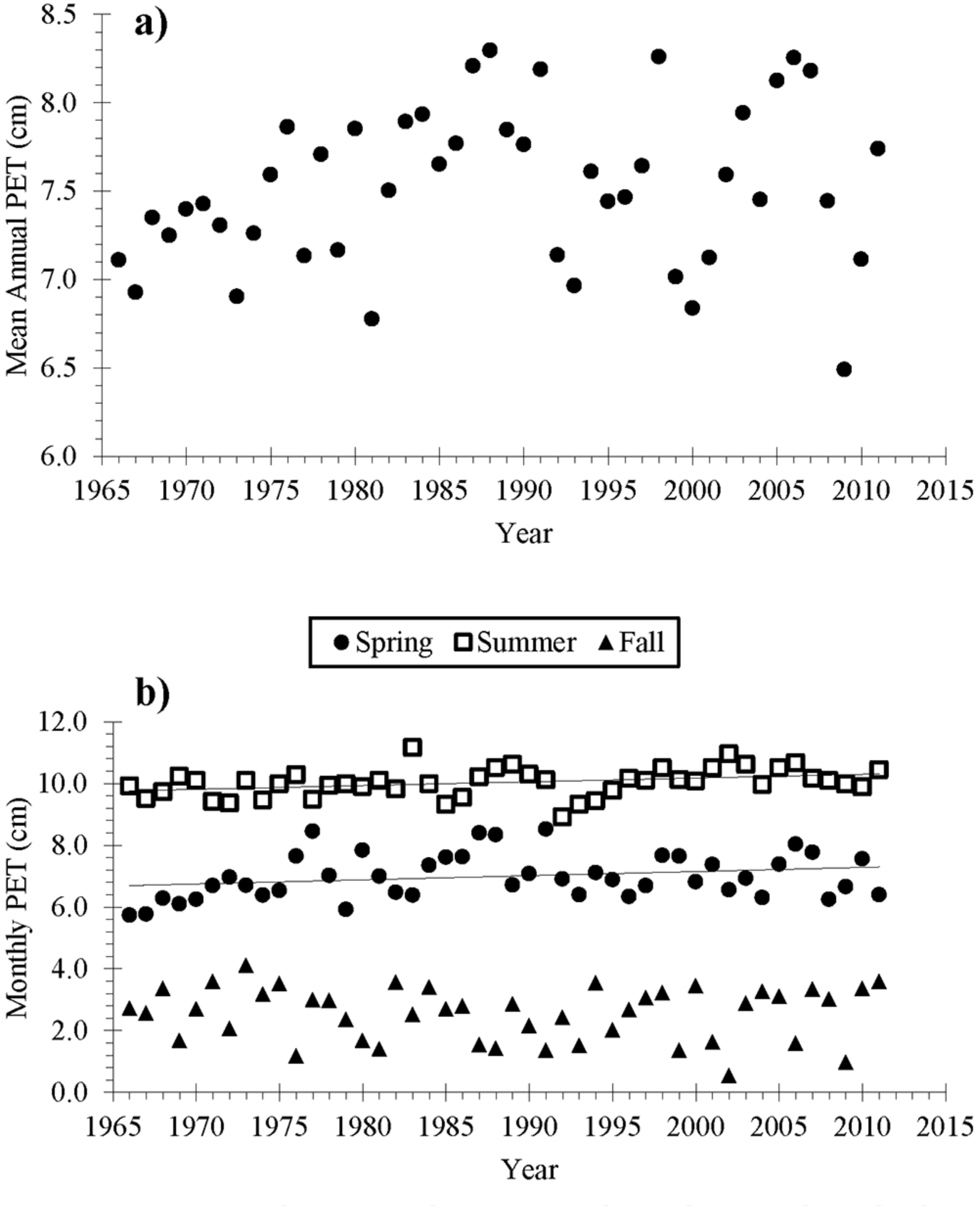

Figure 2-4. Mean annual PET (a) and mean seasonal PET (b). Annual PET has been increasing, albeit not statistically significantly, since 1966. Mean spring PET and mean summer PET have been increasing since 1966. Lines represent statistically significant linear regressions.

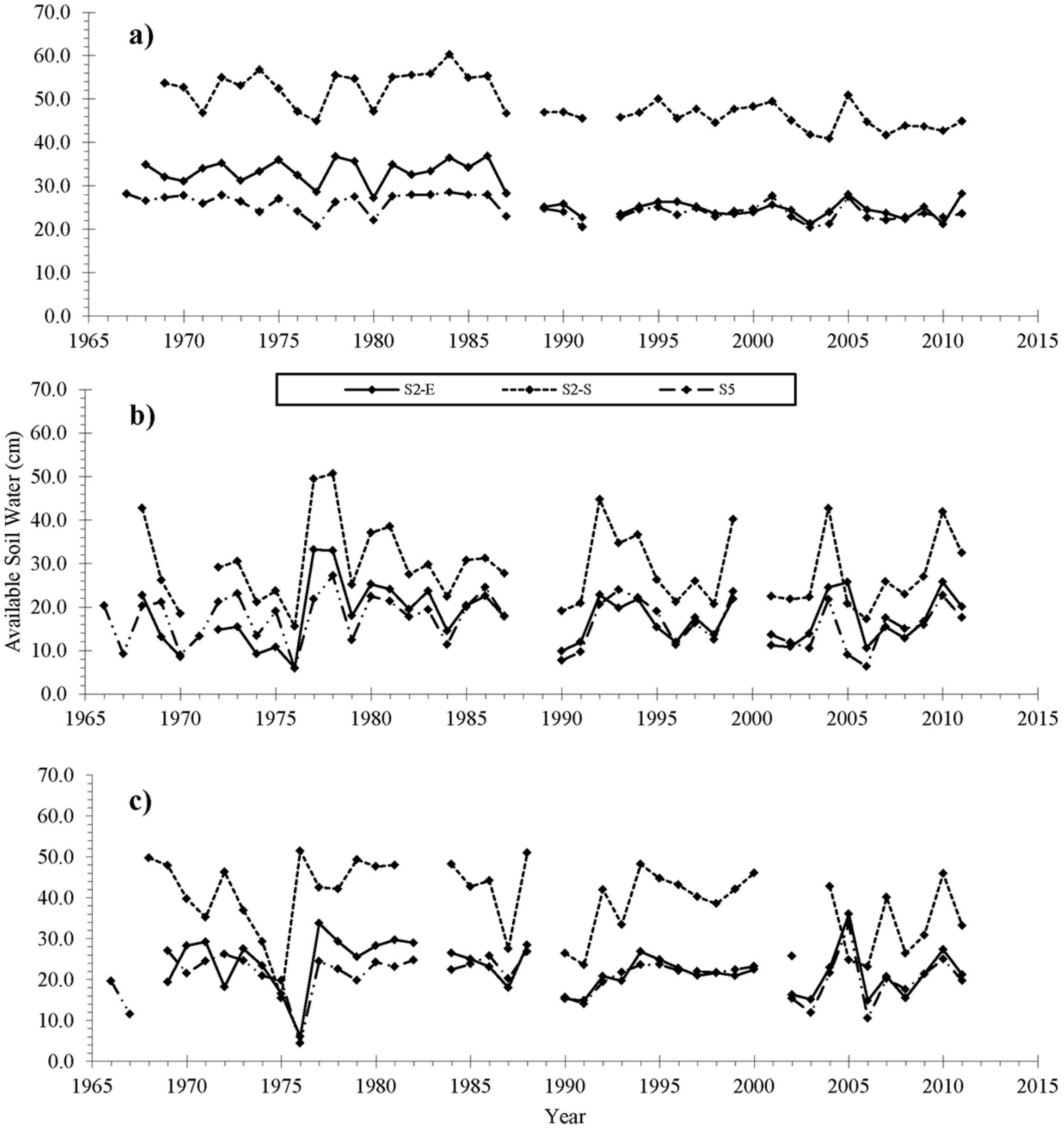

Figure 2-5. Available soil water (0 cm to 229 cm) for three sampling sites during (a) May, (b) September, and (c) November at the MEF, 1966-2011.

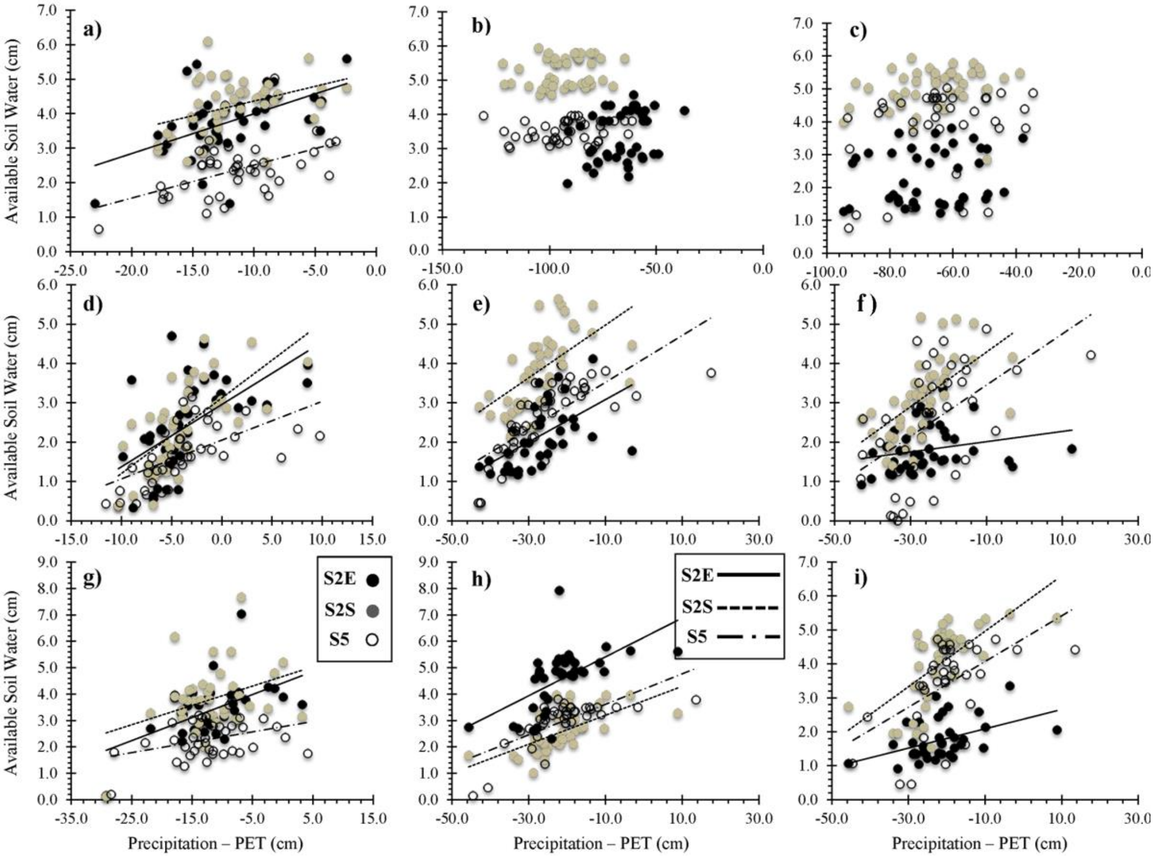

Figure 2-6. Precipitation – PET summed over the optimized CCP duration versus available soil water for three control watersheds at the MEF. Lines are linear relationships significant at $p < 0.01$. (a) 0 – 15 cm sampling depth, May measurements, optimized CCP of 31 days; (b) 76 – 107 cm sampling depth, May measurements, optimized CCP of 312 days; (c) 198 – 229 cm sampling depth, May measurements, optimized CCP of 319 days; (d) 0 – 15 cm sampling depth, September measurements, optimized CCP of 22 days; (e) 76 – 107 cm sampling depth, September measurements, optimized CCP of 77 days; (f) 198 – 229 cm sampling depth, September measurements, optimized CCP of 77 days; (g) 0 – 15 cm sampling depth, November measurements, optimized CCP of 84 days; (h) 76 – 107 cm sampling depth, November measurements, optimized CCP of 109 days; (i) 198 – 229 cm sampling depth, November measurements, optimized CCP of 109 days.

CHAPTER 3. FOREST VEGETATION AND SOIL TEXTURE RELATIONSHIPS TO SOIL MOISTURE

3.1 Introduction

The interactions between soil moisture, plants, landscapes, and climate have been increasingly studied (e.g. Adams et al. 1991; Rodriguez-Iturbe et al. 1999*a*; Detto et al. 2006; Tromp-van Meerveld and McDonnell 2006; Troch et al. 2009; Cavanaugh et al. 2011), yet much is to be learned about the complex mechanisms behind water exchange throughout the soil-plant-atmosphere continuum. Soil moisture is an important component of the water balance in forested ecosystems: evapotranspiration rates (ET), tree growth and carbon assimilation (Bassett 1964; Pastor and Post 1986; Porporato et al. 2004), soil respiration (Davidson et al. 1998; Davidson et al. 2000), and resistance to and resilience following disturbance (Johnstone, et al. 2010) are all influenced by soil moisture. However, at the watershed scale, water storage in the form of soil moisture is heterogeneous and site-driven, leading to variability both within and between sites (Western and Blöschl 1999; Tromp-van Meerveld and McDonnell 2006). Because of intra- and inter-site variability, detailed quantification of soil moisture dynamics are needed both within and across different landscapes.

Within a site, soil moisture is thought to be a function of topography, soil texture, and cover type (Nyberg 1996; Western et al. 1999; Tromp-van Meerveld and McDonnell 2006), yet differences from site to site are complex (Francis et al. 1986). Few studies have looked at the interrelations of soil moisture and landscape-level drivers at depths beyond the near surface (> 0.3 m) (Schulze et al. 1996; Tromp-van Meerveld and McDonnell 2006) and I am not aware of studies of how soil moisture dynamics change with cover type and landscape position over time. The inclusion of time in studying soil moisture dynamics is gaining importance as climate change is causing global temperatures and evapotranspiration rates to rise, as well as increased precipitation and soil moisture variability (Groffman et al. 2012; Dymond et al. 2014).

Studies have found conflicting trends in soil moisture and soil moisture proxies across the past century. A global analysis of the Palmer Drought Severity Index (PDSI) found that very dry portions of the globe increased by 50% in the latter half of the twentieth century; increases in extreme dry conditions were attributed to warming temperatures as opposed to decreases in precipitation (Dai et al. 2004). More recently, these global decreases in soil moisture were re-affirmed using microwave satellite observations, with declines in soil moisture shown to reduce ET (Jung et al. 2010). In contrast, other models and syntheses of *in situ* soil moisture measurements have suggested that global soil moisture is increasing (Robock et al. 2000; Sheffield and Wood 2008) and that increases in precipitation are outweighing any negative effects of increased ET rates. In the United States, soil moisture trends have increased in the East (Groffman et al. 2012) and decreased in the upper Midwest and Southeast (Dorigo et al. 2012; Dymond et al. 2014).

Long-term *in situ* measurements of soil moisture are rare, resulting in soil moisture models that vary in complexity. At the simpler end of the modeling spectrum, models are based on a bucket approach, with changes in soil moisture storage driven by inputs less outputs to the system (Thornthwaite, C.W. and J.R. Mather 1955; Robock et al. 1995; Huang et al. 1996; Kolka and Wolfe 1998; Rodriquez-Iturbe et al. 1999*b*; Laio et al. 2001; Porporato et al. 2004; and others). More complex models couple atmospheric and land-surface processes (Wood et al. 1992; Liang et al. 1994; Robock et al. 1998; Koster and Suarez 2001; Dirmeyer et al. 2004). There are trade-offs to using simple vs. complex models: erroneous results can arise from simple models due to omitted hydrological processes, while complex models may rely on poorly constrained parameters that have not been measured or fully understood. Studies have shown errors resulting from both simple and complex models, and a more accurate representation may result from models that are intermediate in complexity (Meng and Quiring 2008).

This study utilizes a unique long-term soil moisture dataset from the Marcell Experimental Forest (MEF) in northern Minnesota to develop and validate two simple soil moisture model and investigate long-term patterns in soil moisture under varying landscapes. Specifically, this research asks the following questions:

(1) How does soil moisture vary across different cover types and landscape positions (inter-site variability)?

(2) How does soil moisture vary under similar cover types and landscape positions (intra-site variability)?

(3) What are the long-term trends in soil moisture across different forest cover types?

3.2 Methods

3.2.1 Study Area

The 1100 ha MEF (47°52’N, -93°46’W) is located in north-central Minnesota (Figure 3-1). Elevations in the MEF range from 412 m at watershed outlets to 438 m in the uplands. Climate at the MEF is continental with warm, moist summers and cold winters. Mean annual air temperatures range from -15°C in January to 19°C in July. Annual precipitation is dominated by summer rainfall events and averaged 780 mm from 1962-2011 (Sebestyen et al. 2011). The MEF is a landscape with of peatland bogs and fens dominated by spruce and tamarack (*Picea mariana* Mill. B. S. P. and *Larix laricina (Du Roi*) K. Koch) that are surrounded by uplands consisting of pine (*Pinus resinosa* Ait. and *Pinus banksiana* Lamb), aspen (*Populus tremuloides* Michx. and *Populus grandidentata* Michx.), and mixed hardwoods (*Tilia Americana* L., *Acer saccharum* Marsh, and *Acer rubrum* L.). Soils in the forest uplands are predominately Entisols and Alfisols overlying deep (typically > 3 m) glacial tills and sandy outwashes (Sebestyen et al. 2011).

3.2.2 Climate Data

Historical soil moisture data have been collected on the MEF at ten sites (Figure 3-1) approximately three times per year (leaf-out, tree senescence, and prior to soil freeze) starting in 1966. These sites are primarily aspen-dominated ridges (Table 3-1). At all sites, percent soil moisture was determined using a Troxler neutron probe moisture gauge (Model 105 prior to 1990 and Series 4300 from 1990 to the present, Troxler Electronic Laboratories, Inc., Research Triangle Park, North Carolina, USA). Soil moisture has been measured in 30.4 cm increments from 15.2 cm to the depth of the probe (Table 3-1). Soil moisture was measured gravimetrically by sampling and drying from 0 – 15.2 cm in the soil profile, since moisture measured using the neutron probe technique can lead to spurious measurements due to a loss of neutrons from the soil surface (Brakensiek et al. 1979).

Daily maximum and minimum air temperature has been recorded at two watersheds (S2 and S5) since the early 1960’s (1961 and 1962, respectively) using Belfort model 594-1 Hygrothermographs (Belfort Instruments, Baltimore, Maryland, USA). Total daily precipitation has also been recorded at these sites using Belfort Universal Recording Precipitation Gauges (Belfort Instruments, Baltimore, Maryland, USA), which was replaced with an ETI NOAH IV digital rain gauge (ETI Instrument Systems, Fort Collins, Colorado, USA) in 2009.

3.2.3 Expanded Soil Moisture Modeling Network

In June 2011, the long-term soil moisture network was expanded to encompass more cover types and topographic positions. Aluminum access tubes, 3.8 cm in diameter, were installed along topographic transects consisting of a ridge, sideslope, and toeslope position. Transects were replicated three times within each of three cover types: red pine, aspen, and mixed hardwoods (Figure 3-1; Table 3-2). To reduce time and costs associated with installing new access tubes, two sites from the historical soil moisture network were used as sites within the expanded soil moisture network, S4W and S5 are also AB04 and AB07, respectively. Aluminum access tubes were installed to a depth of approximately 300 cm using a compact excavator outfitted with a soil auger. Soil samples were collected during the installation process, which allowed for determination of soil texture at 30.2 cm increments throughout the profile using the hydrometer method for particle size analysis (Gee and Bauder 1986).

Soil moisture measurements were collected bi-weekly at both the historical and expanded soil moisture networks throughout the 2011-2013 growing seasons (approximately May to November). Total annual rainfall was lower than average in 2011 and 2013 (727 and 748 mm, respectively) while mean July temperatures were higher than normal in 2011 and 2012 (21 and 22°C, respectively). Instrument error occurred during all three sampling seasons, creating dataset gaps during August 2011, June-early July 2012, and July 2013.

Calibration measurements for the expanded network were collected in both dry (October 2012) and wet (May 2014) soil conditions. Neutron probe measurements were collected and gravimetric moisture analysis and bulk density were determined for each depth. Calibration curves were created for each site and depth and raw neutron probe measurements were adjusted accordingly.

3.2.4 Inter- and Intra-site Dynamics

Comparisons amongst different sites were done using soil moisture data collected at the 27 plots within the expanded soil moisture monitoring network from 2011-2013. In addition to soil moisture measurements, 1/20th ha circular plots were established around access tubes in the expanded soil moisture network. Within each plot, slope and aspect were recorded. Species, height, diameter at breast height (DBH), crown class, azimuth, and distance from plot center were collected for all within plot trees greater than 10 cm DBH. Stand-level basal area (m^2 ha^{-1}) was calculated to determine the differences in density between each plot (Eqn. 3-1).

$$BA = \frac{0.00007854 * DBH^2}{A} \qquad \text{(Eqn. 3-1)}$$

Where *BA* is the stand-level basal area in m^2, *DBH* is the diameter at breast height in cm, and *A* is the plot area in ha. Community composition at each plot were calculated as Shannon's Diversity Index (H′):

$$H' = \sum_{i=1}^{N} p_i \; x \; ln(p_i) \qquad \text{(Eqn. 3-2)}$$

Where *N* is the number of species within a plot and p_i is the relative proportion of each species.

The influence of landscape-level parameters (cover type, topographic position, dominant species, soil texture, BA, and H′) on percent soil moisture at nine depths (0 – 15.2 cm, 15.2 – 45.7 cm, 45.7 – 76.2 cm, 76.2 – 106.7 cm, 106.7 – 137.2 cm, 137.2 – 167.6 cm, 167.6 – 198.1 cm, 198.1 – 228.6 cm, and 0 – 228.6 cm) was analyzed using repeated measures analysis of variance (ANOVA) via PROC GLIMMIX in SAS Version 9.0 (SAS Institute Inc., Cary, North Carolina, USA). The covariance matrix of the gamma-distributed data was analyzed using an autoregressive model. ANOVAs were run for each depth with plot as a random variable to understand landscape-level dynamics both across and within different cover types. A Tukey test of means was used to determine significant differences in soil moisture.

3.2.5 Model Description: Linear Regression Approach

To get backcasted soil moisture across the different cover types, I applied two simple soil moisture models to the MEF to limit the need of modeled climate, vegetative, and edaphic parameters. First, a linear model was applied on the premise that soil moisture at one site would be highly correlated with soil moisture at a different site, keeping soil depth and time constant. The simplification of this model is only appropriate given the assumption that parameters influencing the water budget (e.g. infiltration rate and evapotranspiration) are similarly scaled across different sites and that these site-level relationships are static across time.

Correlation matrices were run between the expanded and historical monitoring sites. Sites with the highest correlation coefficients were used in linear regression models (3-. 3):

$$ESM_{yjk} = HSM_{xjk} * a + b \qquad \text{(Eqn. 3-3)}$$

Where *ESM* is the percent soil moisture at the expanded site *y*, depth *j*, and time *k*, and *HSM* is the percent soil moisture at the historical site *x*, depth *j*, and time *k*, and *a* and *b* are regression coefficients. Models were created for each of the 25 sites in the expanded monitoring network at 0 – 15.2 cm and downward every 30.5 cm to a depth of 228.1 cm in the soil profile.

Additionally, non-linear regression models were also established at the 25 sites at each of the depth increments. A sigmoidal curve was used based on the assumption that soil moisture would be less than saturation and greater than the hygroscopic coefficient, both of which varied based on soil texture (Eqn. 3-4).

$$ESM_{yjk} = \beta_0 + \frac{(\beta_1 - \beta_0)}{1 + e^{\left[\left(log\beta_2 - HSM_{xjk}\right) * \beta_3\right]}} \qquad \text{(Eqn. 3-4)}$$

Where β_0 is the asymptotic bottom, β_1 is the top of the asymptote, β_2 is a parameter defining the midpoint of the sigmoidal curvature, and β_3 is the steepness of the curve. Model were parameterized using Prism version 6.00 for Mac OS X (GraphPad Software, La Jolla California USA, www.graphpad.com). Selection of the linear versus non-linear models was done using Akaike's Information Criterion (AIC), which was computed using the Prism software. Lower values of AIC were desired; in all cases, the linear models were more appropriate.

The linear model regression coefficients were then used to backcast soil moisture at the expanded monitoring sites through the length of the available historical soil moisture record. The backcasting resulted in an approximately seasonal snapshot of soil moisture at three depths across different cover types and topographic positions at the MEF from 1966 – 2013.

3.2.6 Model Description: Modified Thornthwaite Approach

A simple bucket model was used to predict soil moisture dynamics across the growing season from 0 – 228.6 cm in the soil profile. The Modified-Thornthwaite approach was originally designed assess at actual evapotranspiration (AET) fluxes and was shown to be successful in predicting monthly soil moisture storage and AET at the MEF (Thornthwaite and Mather 1955; Kolka and Wolfe 1996). I utilized only the soil moisture storage component of the approach, and applied it over a daily timestep (Eqn. 3-5).

$$S_t = 10^{\left[logMSW - \left(\frac{0.525}{MSW^{1.0371}}\right) x\ ACPWL_{t-1}\ \right]} \qquad \text{(Eqn. 3-5)}$$

Where S_t is the soil moisture storage at time t (mm), *MSW* is the maximum soil water storage (mm), and $ACPWL_{t-1}$ is the absolute value of accumulated potential water loss from the prior timestep (mm). *MSW* was determined using typical field capacity values based on measured soil texture data (Saxton and Rawls 2006). *ACPWL* is based on the precipitation and potential evapotranspiration (PET). *ACPWL* is null when $P > PET$. *ACPWL* is equal to $P – PET$ when *PET* is greater than *P*. *PET* was calculated using the Thornthwaite approach modified for a daily timestep (Thornthwaite 1948; Pereira and Pruitt 2004).

3.2.7 Model Performance Assessment

Model performance was determined by computing the mean absolute error (MAE) and mean bias error (MBE), both of which express error as a function of observed and modeled soil moisture values (Eqn. 3-6 and Eqn. 3-7):

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|M_i - O_i| \qquad \text{(Eqn. 3-6)}$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N}(M_i - O_i) \qquad \text{(Eqn. 3-7)}$$

where *N* is the number of observations, M_i is modeled percent soil moisture, and O_i is observed percent soil moisture. Lower values of both MAE and MBE indicate better model performance. Additionally, for the Modified-Thornthwaite approach, the Nash-Sutcliffe test was used to look at overall model performance (Eqn. 3-8, Nash and Sutcliffe 1970).

$$NSE = 1 - \frac{\sum_{i=1}^{N}(O_i - M_i)^2}{\sum_{i=1}^{N}(O_i - \bar{O})^2} \qquad \text{(Eqn. 3-8)}$$

Where *NSE* is the Nash-Sutcliffe model efficiency coefficient and $\bar{O}$ is mean of observed soil moisture. Values of *NSE* range from -∞ to 1; values closer to 1 indicate better model performance.

3.3 Results

3.3.1 Landscape Drivers of Soil Moisture

For the three years of collected measurements, percent soil moisture was significantly different ($\alpha = 0.005$) among cover types (Figure 2-2). Soil moisture was above field capacity at the beginning of each growing season for both the northern hardwoods and red pine cover types. Aspen soil moisture was below field capacity but above wilting point at the start of the growing season for all three years in the study. Across the record length, soil moisture was highest under the hardwoods, followed by the aspen and red pine cover types (0 – 228.6 cm depth; $\alpha = 0.05$). Despite small gaps in the dataset, seasonal patterns in soil moisture could still be detected. Percent soil moisture was highest in the early spring, followed by a long drawdown during the summer months. Increases in soil moisture during the growing season could be detected in June 2011 and May 2012 (except in the aspen cover type). In 2011, 7.1 cm of rain had fallen two days prior to the June measurement. The May 2012 measurement occurred in the middle of a 36-hour event that resulted in 4.3 cm of precipitation. In 2012 and 2013, soil moisture levels decreased below wilting point under the aspen and red pine cover types. Hardwood soil moisture remained above wilting point for the entire period of study. This cover type had the largest soil texture variability (Table 3-2), so the average values for field capacity and wilting point might not capture the true site-level moisture conditions. In 2011 and 2012, the beginning of soil moisture recharge can be detected in early autumn. No recharge was detected in 2013, perhaps because observations terminated earlier in the season (August).

There was very little variation in soil moisture across depth when soils were close to or exceeded field capacity (Figure 3-3). When grouped according to site, aspen soil moisture increased slightly from 0 – 45.7 cm, then remained relatively stable throughout the soil profile. In the northern hardwoods, soil moisture was lowest from 0 – 15.2 cm and highest from 15.2 – 45.7 cm. Soil moisture decreased slightly with soil depth in the red pine sites. When soil moisture was closer to field capacity, patterns in soil moisture with depth were similar across cover types. Soil moisture decreased slightly from 15.2 – 45.7 cm and steadily increased from 45.7 – 228.6 cm.

When examined independent of one another, cover type and soil texture were the only landscape variables significantly related to soil moisture ($\alpha < 0.0001$); they were significant across of all of the eight soil depths. Soil texture was not a significant variable when cover type was included in the model and vice versa. Because of their similarities, only differences between cover types will be presented. Differences in cover types changed with depth in the soil profile: northern hardwoods were significantly different from red pine and aspen (which were not significantly different) from 0 – 15.2 cm in the soil profile (Figure 4). At the next depth (15.2 – 45.7 cm), soil moisture in all three cover types differed from one another. From 45.7 to 228.6 cm, red pine was significantly different from aspen and northern hardwoods, which exhibited similar mean soil moisture levels.

3.3.2 Model Performance: Linear Regression Approach

Model results were evaluated by comparing observed percent soil moisture with modeled percent soil moisture throughout the soil profile at each site in the expanded soil moisture network from 2011-2013. Overall, the variability in percent soil moisture at the expanded network sites was related to percent soil moisture from at least one historical network site ($\alpha < 0.05$, Table 3-3). Most of the models had R^2 values greater than 0.60. Of the 200 site/depth combinations, only 11 (5.5%) models did not have significant results ($\alpha < 0.05$) and 78% of the models had highly significant results ($\alpha < 0.0001$). Of the models that did not have significant results, all but one (NH02, 0 – 15.2 cm) occurred at depths below 76.2 cm in the soil profile. Site NH01 did not have any significant models below 137.2 cm in the soil profile and site RP07 did not have any significant models below 167.6 cm in the soil profile. There were no apparent patterns in R^2 values across the different cover types or with depth in the soil profile; model results were site and depth specific.

Results of the linear model approach were also evaluated through comparisons of observed percent soil moisture versus modeled percent soil moisture at each site/depth combination from 2011-2013. MAE and MBE were low for most sites. MAE as a percentage of mean observed mean soil moisture ranged from 1% to 207% while percent MBE ranged from <1% to 170%. The average percent MAE across all 27 sites ranged from a low of 29% at 0 – 15.2 cm in the soil profile to a maximum of 65% at 76.2 –

106.7 cm. Despite a handful of sites where soil moisture models were not adequate, overall the linear models were good predictors of soil moisture.

3.3.3 Model Performance: Modified Thornthwaite Approach

Performance of the Modified Thornthwaite model was evaluated using NSE, MAE, and MBE. This modeling technique gives soil moisture storage in mm of available water per soil horizon (in this case, 0 – 228.6 cm in the soil profile). Overall, the approach did a poor job of modeling soil moisture dynamics (Table 3-4). NSE was close to 0 for almost all of the sites, except RP02, RP05, and RP07, where results were very poor. Two of these site (RP05 and RP07) are ridges, while the other is a sideslope site. All of them have sandy soil textures. In many cases, the Modified Thornthwaite approach was able to properly predict mean soil moisture over the record length, yet was unable to capture the variability in daily soil moisture. Mean MAE as a percent of observed soil moisture was lowest for the aspen and hardwoods (19 and 22%, respectively) and was high for red pine sites (92%).

3.3.4 Back-casted Soil Moisture Dynamics

As exhibited in the 2011-2013 data, mean modeled soil moisture was highest in the hardwoods, followed by the aspen and the pine (Figure 3-5; Table 3-4). Temporally, a period of spring wetness, summer drawdown, and fall recharge is evident. Variability in seasonal soil moisture was lowest in the spring and highest in the summer (Table 3-5).

Annual patterns in modeled soil moisture were consistent across cover types: dry and wet years could be discerned in all cases. Despite having greater percent soil moisture during wet years, the northern hardwood sites dried to moisture levels similar to the aspen sites (Table 3-5). This was true during the summer and fall months but could not be detected during the spring. Within the four driest periods on record, soil moisture patterns across depth were similar across the aspen and hardwood sites. However, for three of the time periods, there was a distinct deviation between soil moisture under the two cover types (Figure 3-6). These occurred deep in the soil profile: from 167.6 – 198.1 cm during Summer 1970 and Fall 1967 and in Fall 1976 the deviation occurred from 106.7 – 137.2 cm in the soil profile. During Summer 1990, soil moisture levels under the aspen and northern hardwood sites were similar, except in the upper and lowest soil layers. There was little change in soil moisture with depth at the red pine sites.

3.3.5 Wetness and Drought at the MEF

In 46 years of modeled soil moisture under three different cover types, seasonal levels (May, September, and November, averaged across 0 – 228.6 cm depth) never fell below the wilting point (Figure 3-5). Despite that the models only present a snapshot of soil moisture at a particular point in time, extreme dry periods could be discerned in the long-term record. Extreme wet periods were harder to detect in the modeled dataset. Based on the Palmer-Drought-Severity Index (PDSI), four extreme droughts (PDSI ≤ -4.00) and two extremely moist periods (PDSI ≥ 4.00) occurred during May, September, and November from 1966-2012. Three of the four extreme droughts were within the top 10% of driest years at the MEF, regardless of cover type (Figure 3-5). The exception was September 1990, which could be discerned as a dry period in the aspen and hardwood cover types, but not in the red pine sites. The two extreme wet periods on record were not within the 10% wettest years at MEF under any cover type. In general, the past decade (2002-2012) has been drier than prior decades (Table 3-5).

3.4 Discussion

3.4.1 Landscape Level Drivers of Soil Moisture

At the landscape scale, I found that cover type and soil texture were the only factors that significantly influenced soil moisture levels. Few studies have quantified disparities in soil moisture under different forested cover types over long time scales and at multiple sites, although it has been well established that soil moisture levels will co-vary with vegetation characteristics (Francis et al. 1986; Adams et al. 1991; Hollinger and Isard 1994). Previous studies have found that topography can significantly influence soil moisture (Burt and Butcher 1985; Tromp-van Meerveld and McDonnell 2006; Voepel et al. 2011), yet there was no evidence of landscape differences at the MEF. Voepel et al. (2011) found that slope and elevation are significant factors in determining the Horton index. Elevations at the MEF only range 20 m and, while these differences may be critical in distinguishing peatlands from the surrounding uplands, it is likely that both the horizontal and vertical distances between ridges and toeslopes were not great enough to generate significant differences in soil moisture. Likewise, while the percent slope across our sites ranged from 0 to 50%, the overall variability in percent slope was not great enough to be detected in our models.

The landscape anomalies could also be explained by problems with spatial scaling. I used point-level estimates as representatives of plot-level soil moisture. There can be difficulty in scaling from point estimates to landscapes, since preferential flow through macropores, the presence of an impeding layer, or proximity to trees can all influence point measurements. Spatial dynamics and scaling of soil moisture remains at the core of understanding hydrological processes at the hillslope scale (Western et al. 1998; Western and Blöschl 1999; Western et al. 2002; Tromp van Meerveld and McDonnell 2005). However, because point-level measurements were collected at the same points over a time series, I still feel that the comparisons amongst different cover types provide insights into ecohydrological dynamics at these sites.

Despite not being a significant predictor of soil moisture when type is also included in the model, soil texture can conceptually describe the soil moisture differences between the hardwood/aspen sites and the red pine sites. Throughout the three year study period, red pine had significantly lower soil moisture than the hardwood and aspen sites. However, the red pine sites stayed above field capacity more often than the hardwood and aspen sites. The red pine sites were almost all classified as sands, which have higher infiltration rates and lower water-holding capacity (Saxton et al. 1986) than the hardwood and aspen sites, which had higher clay contents. Soil moisture remained relatively uniform across the soil profile at the red pine sites, regardless of the antecedent moisture conditions (Figure 3-3). There was a slight increase in soil moisture from 15.2 – 45.7 cm relative to the surface, this was likely caused by plant uptake. Red pine can develop extensive root systems, but lateral roots are typically most prolific in the upper 10-46 cm of the soil profile (Rudolf 1990).

Comparisons between cover types showed that aspen and hardwood sites had similar soil moisture levels at depths > 45.7 cm that were significantly higher than the red pine sites. I anticipated that the hardwood sites would have lower soil moisture than the aspen sites (despite having similar soil textures) due to niche partitioning. Under this theory, different tree species would utilize different rooting zones, reducing competition and thereby accessing soil water throughout the entire soil profile (Jackson et al. 1995; Filella and Peñuelas 2003). In contrast, the aspen sites, which have lower diversity (Table 3-2), would occupy only certain portions of the rooting zone. While niche diversification may be happening at the individual and species level in the hardwoods, the similar soil moisture levels between the aspen sites and hardwood sites suggest that niche diversification may be occurring at the individual level in the aspen stands as well. Aspen can develop extensive heartroot systems that can reach depths of 2.9 m in sandy loam soils (Gifford 1966; Perala 1990).

3.4.2 Modeling Approaches and Applications

I employed a simple linear soil moisture model relating historical soil moisture data to newly collected soil moisture data to backcast soil moisture under different cover types and landscape positions at three soil depths at the MEF. Based on regression parameters, the linear model technique was adequate. Despite using a simplified approach, soil moisture at one site explained 42-90% of the variation in soil moisture at a different site (Table 3-3). In the upper soil horizons, soil moisture dynamics can be highly variable (Famiglietti et al. 1998; Wang et al. 2001), leading to difficulty in modeling soil moisture, yet I had good results in modeling soil moisture in the upper soil horizons. Using a simple linear regression to model soil moisture may not be appropriate for understanding hydrological dynamics at the hillslope scale, although it allowed us to compare long-term soil moisture patterns across different cover types. Similar methods could be utilized to understand soil moisture dynamics across different landscapes in locations where soil moisture has been monitored at a small number of sites over time.

3.4.3 Inter-annual Soil Moisture Dynamics

Despite having a coarse temporal resolution, there was evidence of recharge of spring soil moisture, a summer drawdown, and subsequent fall moisture recharge in the modeled soil moisture dataset. These soil moisture dynamics, which occurred under all forest types, are common for soils in the upper Midwestern U.S. (Baker et al. 1979). Temporal variability was the highest in the spring and in the northern hardwood cover types. The northern hardwood cover types also exhibited the highest species diversity (Table 3-2), which could lead to larger variability amongst sites and across depths. Additionally, there was evidence that northern hardwood sites draw down soil moisture to lower relative levels than aspen and red pine sites. This could be evidence of niche partitioning or hydraulic distribution of deep soil water occurring in the hardwood stands (Dawson 1993).

Soil moisture levels remained high across the growing season at the MEF and did not dip below the wilting point under any of the cover types, suggesting that soils in this region are relatively well watered. In a simulation of soil moisture in northern Minnesota, Pastor and Post (1986) found that levels rarely dipped below wilting point during the growing season. This could be one reason why the modeled soil moisture could not detect wet PDSI levels: the sites are so moist that it is difficult to discern one wet year from another. Severe droughts, however, were easier to detect in the modeled soil moisture data. Droughts of this magnitude were rare during the study period, yet were easy to detect because the drought-level soil moisture was much lower than the mean soil moisture. Despite the rarity of extreme and severe droughts, soil moisture levels during the past decade (2000-2012) were drier than the average conditions across all cover types and study months. This is in concert with recent findings suggesting that overall soil moisture levels have been decreasing at the MEF (Dymond et al. 2014). An increase in dry periods could have profound impacts on ecosystem productivity and health in the region (Graumlich 1993; Briggs and Knapp 1995).

3.5 Conclusions

I present a three-year record of measured soil moisture at twenty-seven sites across three cover types at the MEF, as well as seasonal modeled soil moisture at the same sites from 1966 – 2013. A simple linear regression approach was found to be more adequate at modeling soil moisture than a simple bucket model approach, although modifications to the bucket model might improve its accuracy in modeling variability in soil moisture over time. I found that cover type or soil texture were the only landscape-level variables that influenced soil moisture over time. Because cover type and soil texture covaried in our system, only one or the other was included in the model. Overall, soil moisture under red pine (sandier) sites was lower than both aspen and hardwood sites.

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Table 3-1. Site details for the ten locations within the historical soil moisture monitoring network at the MEF. Two sites, S4W and S5, were also included as sites in the expanded soil moisture-monitoring network.

Site ID	Year of Record Start	Cover Type	Landscape Position	Soil Texture	Probe Depth *(m)*
S1N	1967	Aspen	Ridge	Fine Sandy Loam	3.2
S1S	1966	Aspen	Ridge	Fine Sandy Loam	3.2
S2E	1967	Aspen	Ridge	Fine Sandy Loam	2.3
S2S	1968	Aspen	Ridge	Fine Sandy Loam	3.2
S3	1966	Hardwoods	Ridge	Loamy Sand	3.2
S4S	1966	Aspen	Ridge	Fine Sandy Loam	2.9
S4W†	1968	Aspen	Ridge	Fine Sandy Loam	2.3
S5†	1966	Aspen	Ridge	Fine Sandy Loam	2.3
S6N	1967	Black Spruce	Sideslope	Loamy Sand	3.2
S6S	1985	Black Spruce	Sideslope	Loamy Sand	2.9

†Denotes a site that is located within both the historical and expanded soil moisture.

Table 3-2. Site characteristics for the twenty-seven sites in the expanded soil moisture monitoring network at the MEF. Two sites, AB04 and AB07, were also included as sites in the historical soil moisture-monitoring network.

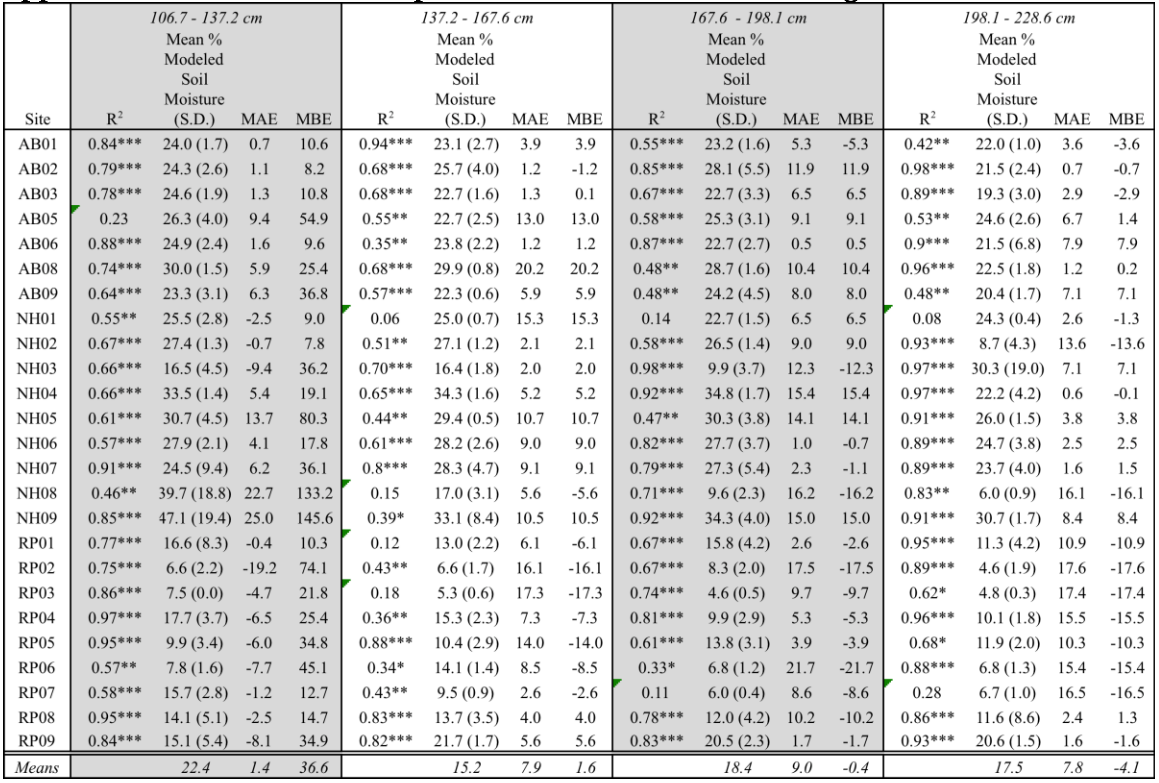
Site ID	Cover Type	Landscape Position	Soil Texture	Maximum Soil Water Storage *(mm)*	Basal Area *(m^2 ha^{-1})*	H'
AB01	Aspen	Sideslope	Sandy Clay Loam	503	11.02	0.08
AB02	Aspen	Ridge	Sandy Clay Loam	543	6.97	0.98
AB03	Aspen	Toeslope	Sandy Clay Loam	544	8.53	0.77
AB04†	Aspen	Ridge	Sandy Loam	589	7.57	0.85
AB05	Aspen	Toeslope	Sandy Clay Loam	549	17.19	0.67
AB06	Aspen	Sideslope	Sandy Clay Loam	513	11.28	0.75
AB07†	Aspen	Ridge	Sandy Loam	495	2.29	0.73
AB08	Aspen	Sideslope	Sandy Clay Loam	594	3.36	0.78
AB09	Aspen	Toeslope	Sandy Clay Loam	494	5.46	0.47
NH01	Hardwoods	Ridge	Sandy Clay Loam	671	6.29	0.97
NH02	Hardwoods	Ridge	Sandy Clay Loam	604	8.62	1.62
NH03	Hardwoods	Sideslope	Sandy Loam	336	6.91	1.11
NH04	Hardwoods	Toeslope	Sandy Loam	671	5.39	1.03
NH05	Hardwoods	Sideslope	Sandy Clay Loam	604	9.05	1.08
NH06	Hardwoods	Toeslope	Sandy Loam	604	12.53	1.44
NH07	Hardwoods	Ridge	Loamy Sand	604	11.44	1.92
NH08	Hardwoods	Sideslope	Loamy Sand	594	7.45	0.63
NH09	Hardwoods	Toeslope	Sandy Loam	617	7.09	1.15
RP01	Red Pine	Ridge	Sandy Loam	302	4.23	0.15
RP02	Red Pine	Sideslope	Sand	302	50.19	0.50
RP03	Red Pine	Sideslope	Sand	336	263.1	0.44
RP04	Red Pine	Toeslope	Sand	302	10.15	0.69
RP05	Red Pine	Ridge	Sand	302	34.62	0.62
RP06	Red Pine	Toeslope	Sand	272	32.47	0.65
RP07	Red Pine	Ridge	Sand	302	14.32	0.00
RP08	Red Pine	Sideslope	Sand	297	17.63	0.76
RP09	Red Pine	Toeslope	Sandy Loam	309	18.93	0.30

†Denotes a site that is located within both the historical and expanded soil moisture-monitoring network

Table 3-3. Model performance results for the linear regression modeling approach for 27 sites in the expanded soil moisture monitoring network at the MEF.

	0 - 15.2 cm				*15.2 - 45.7 cm*				*45.7 - 76.2 cm*				*76.2 - 106.7 cm*			
Site	R^2	Mean % Modeled Soil Moisture (S.D.)	MAE	MBE	R^2	Mean % Modeled Soil Moisture (S.D.)	MAE	MBE	R^2	Mean % Modeled Soil Moisture (S.D.)	MAE	MBE	R^2	Mean % Modeled Soil Moisture (S.D.)	MAE	MBE
AB01	0.90***	11.5 (4.2)	14.1	-14.1	0.88***	11.5 (9.7)	4.9	-4.9	0.90***	24.0 (2.7)	2.7	-2.7	0.85***	25.5 (1.7)	2.5	-2.5
AB02	0.85***	11.4 (3.3)	3.3	-3.1	0.86***	16.2 (11.3)	0.2	-0.2	0.87***	22.1 (6.5)	2.4	1.9	0.87***	25.1 (3.6)	11.0	11.0
AB03	0.72***	23.2 (8.7)	2.5	-2.5	0.91***	19.9 (5.1)	3.2	3.2	0.90***	24.2 (1.3)	2.7	-2.7	0.92***	25.3 (2.2)	2.7	-2.7
AB05	0.79***	20.4 (6.6)	5.3	-5.3	0.89***	16.5 (3.7)	0.8	0.8	0.87***	20.1 (4.5)	4.1	-0.2	0.68***	24.6 (2.7)	13.9	13.9
AB06	0.69***	22.3 (8.0)	3.4	-3.4	0.88***	14.9 (5.0)	2.7	-2.7	0.88***	21.7 (3.1)	4.3	-4.3	0.85***	24.7 (2.6)	16.9	16.9
AB08	0.72***	18.8 (5.3)	6.9	-6.9	0.65***	13.6 (6.8)	3.2	-2.8	0.91***	17.8 (5.7)	5.0	-5.0	0.73***	26.0 (3.0)	15.3	15.3
AB09	0.67***	20.4 (7.9)	5.2	-5.2	0.85***	20.2 (5.1)	3.3	3.3	0.43**	27.3 (8.1)	1.4	0.7	0.69***	22.1 (2.9)	3.4	-3.4
NH01	0.14***	20.3 (4.4)	5.9	5.9	0.90***	19.5 (9.1)	1.2	-0.3	0.93***	26.6 (3.0)	1.0	-1.0	0.78***	25.1 (4.8)	1.1	-0.3
NH02	0.54***	26.3 (7.7)	1.8	0.6	0.91***	21.0 (1.5)	3.2	3.2	0.32*	23.4 (0.7)	11.5	11.5	0.73***	27.7 (1.1)	1.9	0.1
NH03	0.74***	23.0 (12.0)	4.9	-4.9	0.52**	17.6 (6.9)	3.1	1.2	0.81***	28.8 (11.8)	2.1	2.1	0.87***	16.9 (3.0)	8.3	-8.3
NH04	0.49**	25.8 (7.5)	6.7	-2.1	0.75***	28.6 (9.4)	15.7	15.7	0.68***	31.6 (0.9)	2.2	2.2	0.74***	32.7 (1.8)	5.1	5.1
NH05	0.67***	23.5 (2.6)	4.5	4.5	0.92***	22.6 (1.3)	4.3	4.3	0.33*	29.3 (0.9)	16.4	16.4	0.56**	28.3 (1.1)	0.7	-0.7
NH06	0.71***	13.8 (1.8)	11.6	-10.9	0.57***	18.5 (10.1)	5.6	5.6	0.85***	16.7 (11.5)	6.5	-6.1	0.79***	23.2 (3.0)	4.1	-4.1
NH07	0.77***	16.7 (5.5)	9.0	-9.0	0.76***	15.3 (5.4)	3.8	-3.8	0.86***	14.2 (6.3)	1.3	1.3	0.88***	17.8 (9.8)	10.1	10.1
NH08	0.77***	18.8 (10.5)	9.1	-9.1	0.65***	25.4 (18.8)	9.0	9.0	0.40*	22.2 (7.9)	2.0	2.0	0.36*	28.8 (6.0)	18.1	18.1
NH09	0.62***	19.1 (1.7)	8.1	-5.6	0.81***	23.5 (15.9)	7.1	7.1	0.67***	21.5 (13.9)	9.3	8.7	0.8***	27.8 (18.2)	20.0	20.0
RP01	0.71***	12.6 (5.0)	1.9	-1.9	0.89***	8.4 (1.5)	5.5	-5.5	0.93***	9.0 (4.7)	13.8	-13.8	0.82***	9.1 (3.5)	18.5	-18.5
RP02	0.92***	9.5 (3.0)	4.9	-4.9	0.76**	5.8 (6.4)	10.6	-10.6	0.67***	9.9 (4.9)	16.7	-16.7	0.79***	6.8 (1.6)	16.5	-16.5
RP03	0.80***	7.9 (4.2)	16.8	-16.8	0.97***	8.8 (4.8)	4.1	-4.1	0.86***	15.0 (2.3)	8.9	-8.9	0.54**	15.2 (1.9)	9.4	-9.4
RP04	0.83***	10.2 (2.9)	4.2	-4.2	0.88***	12.7 (5.0)	2.2	2.2	0.79***	13.3 (7.8)	13.3	-13.3	0.82***	10.1 (3.0)	2.3	2.3
RP05	0.79***	10.3 (2.9)	2.3	-2.1	0.76***	7.1 (2.8)	10.7	-10.7	0.79***	6.7 (2.1)	0.4	-0.1	0.87***	7.3 (2.5)	1.5	-0.4
RP06	0.85***	9.7 (3.1)	2.7	-2.7	0.90***	7.1 (3.7)	5.8	-5.8	0.81***	9.6 (4.4)	17.0	-17.0	0.13	8.2 (0.4)	3.7	-0.5
RP07	0.68***	13.2 (4.9)	12.5	-12.5	0.91***	6.4 (4.1)	6.5	-6.5	0.77***	6.8 (1.3)	2.3	-2.3	0.69***	9.2 (5.1)	16.3	-16.3
RP08	0.74***	13.9 (4.7)	11.8	-11.8	0.88***	10.4 (1.0)	3.8	-3.8	0.81***	11.0 (2.0)	3.5	3.5	0.91***	9.9 (4.1)	15.6	-15.6
RP09	0.79***	9.1 (3.6)	3.2	-3.2	0.89***	7.3 (5.5)	9.1	-9.1	0.78***	8.1 (2.6)	1.1	1.1	0.89***	10.8 (5.7)	0.5	0.1
Means		*16.5*	*6.5*	*-5.2*		*20.7*	*5.2*	*-0.6*		*18.4*	*6.1*	*-1.7*		*19.5*	*8.8*	*0.5*

Table 3-3. (cont.) Model performance results for the linear regression modeling approach for 27 sites in the expanded soil moisture monitoring network at the MEF.



	106.7 - 137.2 cm				*137.2 - 167.6 cm*				*167.6 - 198.1 cm*				*198.1 - 228.6 cm*			
Site	R^2	Mean % Modeled Soil Moisture (S.D.)	MAE	MBE	R^2	Mean % Modeled Soil Moisture (S.D.)	MAE	MBE	R^2	Mean % Modeled Soil Moisture (S.D.)	MAE	MBE	R^2	Mean % Modeled Soil Moisture (S.D.)	MAE	MBE
AB01	0.84***	24.0 (1.7)	0.7	10.6	0.94***	23.1 (2.7)	3.9	3.9	0.55***	23.2 (1.6)	5.3	-5.3	0.42**	22.0 (1.0)	3.6	-3.6
AB02	0.79***	24.3 (2.6)	1.1	8.2	0.68***	25.7 (4.0)	1.2	-1.2	0.85***	28.1 (5.5)	11.9	11.9	0.98***	21.5 (2.4)	0.7	-0.7
AB03	0.78***	24.6 (1.9)	1.3	10.8	0.68***	22.7 (1.6)	1.3	0.1	0.67***	22.7 (3.3)	6.5	6.5	0.89***	19.3 (3.0)	2.9	-2.9
AB05	0.23	26.3 (4.0)	9.4	54.9	0.55**	22.7 (2.5)	13.0	13.0	0.58***	25.3 (3.1)	9.1	9.1	0.53**	24.6 (2.6)	6.7	1.4
AB06	0.88***	24.9 (2.4)	1.6	9.6	0.35**	23.8 (2.2)	1.2	1.2	0.87***	22.7 (2.7)	0.5	0.5	0.9***	21.5 (6.8)	7.9	7.9
AB08	0.74***	30.0 (1.5)	5.9	25.4	0.68***	29.9 (0.8)	20.2	20.2	0.48**	28.7 (1.6)	10.4	10.4	0.96***	22.5 (1.8)	1.2	0.2
AB09	0.64***	23.3 (3.1)	6.3	36.8	0.57***	22.3 (0.6)	5.9	5.9	0.48**	24.2 (4.5)	8.0	8.0	0.48**	20.4 (1.7)	7.1	7.1
NH01	0.55**	25.5 (2.8)	-2.5	9.0	0.06	25.0 (0.7)	15.3	15.3	0.14	22.7 (1.5)	6.5	6.5	0.08	24.3 (0.4)	2.6	-1.3
NH02	0.67***	27.4 (1.3)	-0.7	7.8	0.51**	27.1 (1.2)	2.1	2.1	0.58***	26.5 (1.4)	9.0	9.0	0.93***	8.7 (4.3)	13.6	-13.6
NH03	0.66***	16.5 (4.5)	-9.4	36.2	0.70***	16.4 (1.8)	2.0	2.0	0.98***	9.9 (3.7)	12.3	-12.3	0.97***	30.3 (19.0)	7.1	7.1
NH04	0.66***	33.5 (1.4)	5.4	19.1	0.65***	34.3 (1.6)	5.2	5.2	0.92***	34.8 (1.7)	15.4	15.4	0.97***	22.2 (4.2)	0.6	-0.1
NH05	0.61***	30.7 (4.5)	13.7	80.3	0.44**	29.4 (0.5)	10.7	10.7	0.47**	30.3 (3.8)	14.1	14.1	0.91***	26.0 (1.5)	3.8	3.8
NH06	0.57***	27.9 (2.1)	4.1	17.8	0.61***	28.2 (2.6)	9.0	9.0	0.82***	27.7 (3.7)	1.0	-0.7	0.89***	24.7 (3.8)	2.5	2.5
NH07	0.91***	24.5 (9.4)	6.2	36.1	0.8***	28.3 (4.7)	9.1	9.1	0.79***	27.3 (5.4)	2.3	-1.1	0.89***	23.7 (4.0)	1.6	1.5
NH08	0.46**	39.7 (18.8)	22.7	133.2	0.15	17.0 (3.1)	5.6	-5.6	0.71***	9.6 (2.3)	16.2	-16.2	0.83**	6.0 (0.9)	16.1	-16.1
NH09	0.85***	47.1 (19.4)	25.0	145.6	0.39*	33.1 (8.4)	10.5	10.5	0.92***	34.3 (4.0)	15.0	15.0	0.91***	30.7 (1.7)	8.4	8.4
RP01	0.77***	16.6 (8.3)	-0.4	10.3	0.12	13.0 (2.2)	6.1	-6.1	0.67***	15.8 (4.2)	2.6	-2.6	0.95***	11.3 (4.2)	10.9	-10.9
RP02	0.75***	6.6 (2.2)	-19.2	74.1	0.43**	6.6 (1.7)	16.1	-16.1	0.67***	8.3 (2.0)	17.5	-17.5	0.89***	4.6 (1.9)	17.6	-17.6
RP03	0.86***	7.5 (0.0)	-4.7	21.8	0.18	5.3 (0.6)	17.3	-17.3	0.74***	4.6 (0.5)	9.7	-9.7	0.62*	4.8 (0.3)	17.4	-17.4
RP04	0.97***	17.7 (3.7)	-6.5	25.4	0.36**	15.3 (2.3)	7.3	-7.3	0.81***	9.9 (2.9)	5.3	-5.3	0.96***	10.1 (1.8)	15.5	-15.5
RP05	0.95***	9.9 (3.4)	-6.0	34.8	0.88***	10.4 (2.9)	14.0	-14.0	0.61***	13.8 (3.1)	3.9	-3.9	0.68*	11.9 (2.0)	10.3	-10.3
RP06	0.57**	7.8 (1.6)	-7.7	45.1	0.34*	14.1 (1.4)	8.5	-8.5	0.33*	6.8 (1.2)	21.7	-21.7	0.88***	6.8 (1.3)	15.4	-15.4
RP07	0.58***	15.7 (2.8)	-1.2	12.7	0.43**	9.5 (0.9)	2.6	-2.6	0.11	6.0 (0.4)	8.6	-8.6	0.28	6.7 (1.0)	16.5	-16.5
RP08	0.95***	14.1 (5.1)	-2.5	14.7	0.83***	13.7 (3.5)	4.0	4.0	0.78***	12.0 (4.2)	10.2	-10.2	0.86***	11.6 (8.6)	2.4	1.3
RP09	0.84***	15.1 (5.4)	-8.1	34.9	0.82***	21.7 (1.7)	5.6	5.6	0.83***	20.5 (2.3)	1.7	-1.7	0.93***	20.6 (1.5)	1.6	-1.6
Means		*22.4*	*1.4*	*36.6*		*15.2*	*7.9*	*1.6*		*18.4*	*9.0*	*-0.4*		*17.5*	*7.8*	*-4.1*

Table 3-4. Model performance results from the Modified-Thornthwaite approach for 27 sites in the expanded soil moisture-monitoring network at the MEF. Soil moisture storage units are in mm of available water from 0 – 228.6 cm in the soil profile.

Site	Mean Observed Soil Moisture Storage (S.D.) *(mm)*	Mean Modeled Soil Moisture Storage (S.D.) *(mm)*	NSE	MAE	MBE
AB01	461.7 (120.1)	498.3 (2.7)	-0.107	74.2	36.6
AB02	516.7 (83.8)	538.1 (2.7)	-0.070	67.5	21.3
AB03	490.6 (128.9)	538.6 (2.7)	-0.157	82.4	48.0
AB04	424.1 (185.5)	584.5 (2.8)	-0.787	170.8	160.5
AB05	497.1 (63.7)	544.6 (2.8)	-0.563	62.1	47.4
AB06	504.1 (88.7)	508.4 (2.8)	0.007	74.5	4.3
AB07	403.2 (165.5)	490.8 (2.9)	-0.293	96.3	87.6
AB08	520.7 (119.0)	589.8 (2.8)	-0.340	75.8	69.1
AB09	421.3 (65.0)	489.1 (2.8)	-1.141	74.7	67.8
NH01	499.9 (182.6)	666.2 (2.6)	-0.878	174.9	166.3
NH02	558.2 (44.5)	598.3 (2.6)	-0.900	47.9	40.2
NH03	288.5 (114.9)	330.7 (2.8)	-0.164	82.0	42.2
NH04	627.2 (209.9)	666.4 (2.8)	-0.047	103.9	39.2
NH05	640.1 (57.5)	598.6 (2.8)	-0.564	58.2	-41.5
NH06	579.2 (100.8)	598.6 (2.8)	-0.047	75.2	19.4
NH07	505.4 (125.2)	597.8 (2.2)	-0.589	116.6	92.4
NH08	435.1 (141.9)	588.6 (2.2)	-1.250	192.0	153.5
NH09	683.0 (179.0)	611.5 (2.2)	-0.175	164.0	-71.5
RP01	293.3 (69.4)	296.9 (2.6)	-0.011	56.0	3.6
RP02	175.7 (43.7)	598.1 (2.2)	-99.317	422.4	422.4
RP03	210.5 (51.3)	330.5 (2.6)	-5.741	120.0	120.0
RP04	261.1 (46.2)	296.9 (2.6)	-0.669	48.8	35.8
RP05	227.6 (55.5)	598.1 (2.2)	-47.525	370.5	370.5
RP06	164.1 (76.0)	266.3 (2.4)	-1.896	102.2	102.2
RP07	186.7 (47.5)	597.8 (1.6)	-99.898	411.1	411.1
RP08	315.7 (77.4)	292 (2.6)	-0.098	67.7	-23.7
RP09	323.1 (98.5)	303.4 (2.6)	-0.041	73.0	-19.6
Means	*415.3*	*504.4*	*-9.750*	*128.3*	*89.1*

Table 3-5. Mean, maximum, and minimum modeled soil moisture for different landscape cover types during three seasons at the MEF. Data are averaged over the soil profile, 0 – 228.6 cm.

Cover Type	Season	Mean % SM (S.D.)	Max. % SM	Min .% SM	# Years Wetter than Mean†	# Years Drier than Mean†
Aspen	May	26.2 (1.4)	28.7	22.8	3	10
	September	21.9 (2.1)	26.4	17.0	2	11
	November	23.5 (2.1)	26.6	18.1	3	10
Hardwoods	May	29.4 (1.6)	32.5	26.2	4	9
	September	23.6 (2.8)	29.4	18.4	2	11
	November	25.8 (2.7)	29.3	18.7	4	9
Red Pine	May	14.0 (1.2)	16.3	11.4	4	9
	September	10.8 (1.9)	15.2	6.8	2	11
	November	12.0 (1.8)	15.2	7.7	2	11

SM = soil moisture; S.D. = standard deviation

†From 2000-2012

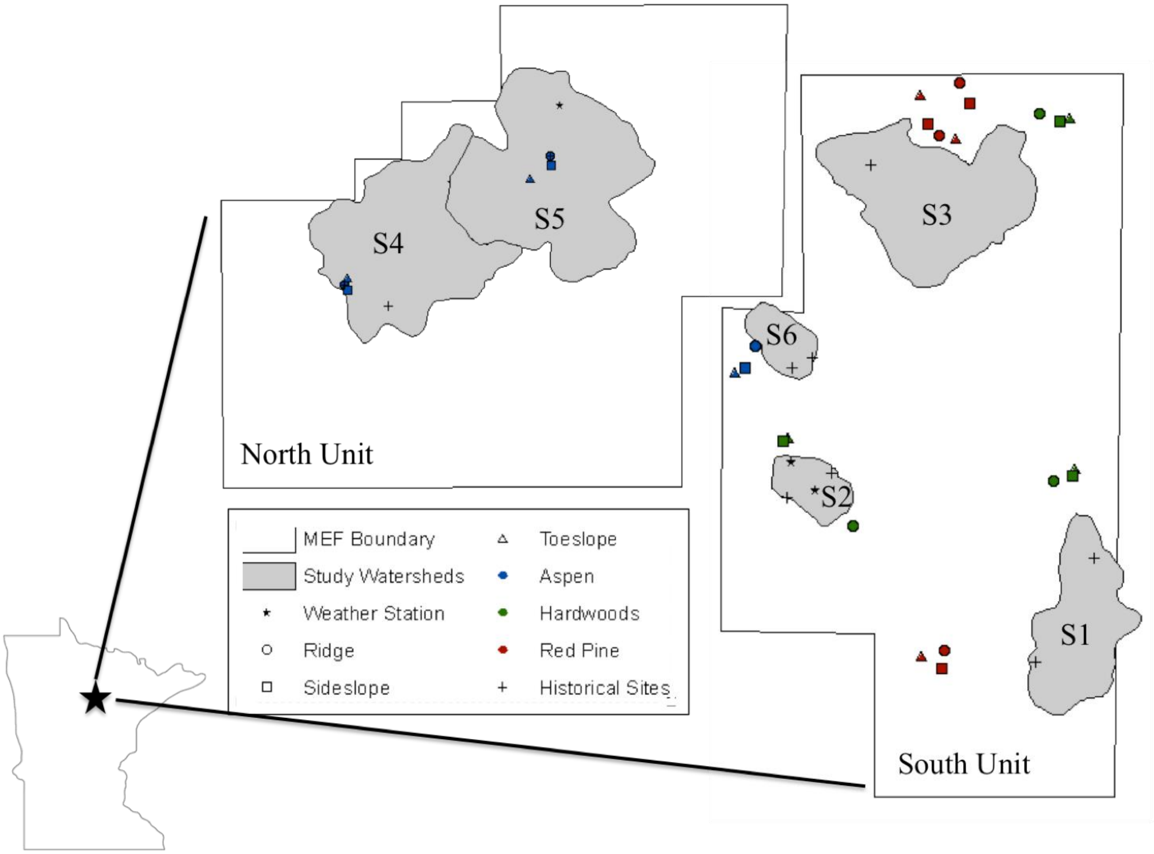


Figure 3-1. The MEF is located in north-central Minnesota. The forest has 10 historical soil moisture-monitoring sites and 27 sites in the expanded soil moisture monitoring network (two sites are part of both networks: S4W = AB04 and S5 = AB07).

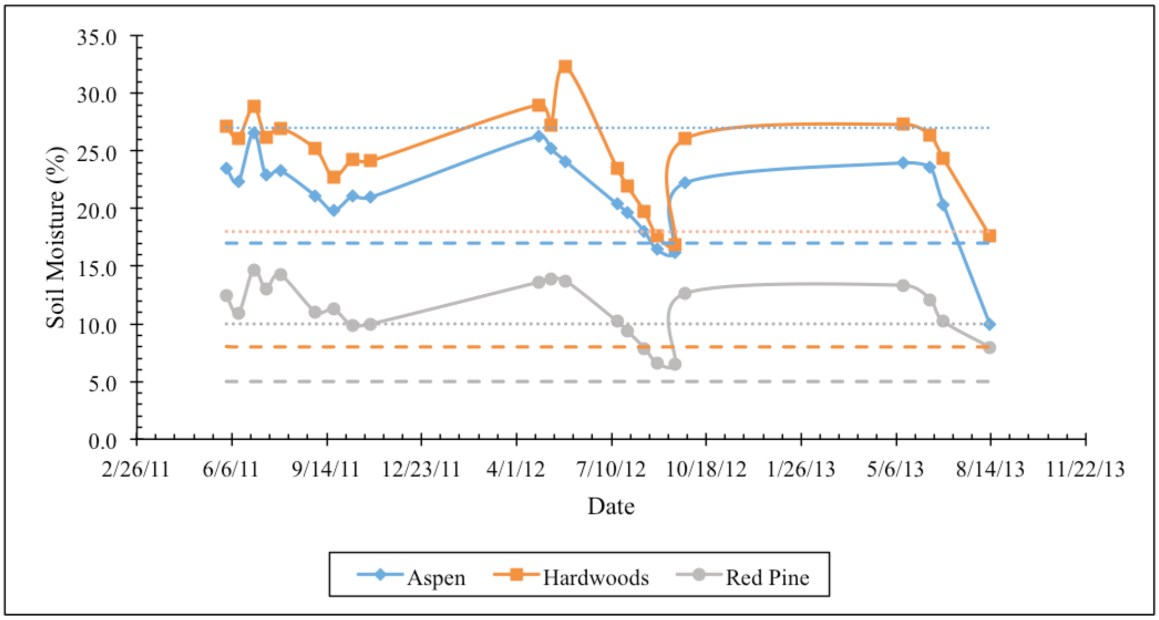


Figure 3-2. Observed percent soil moisture at the MEF expanded soil moisture monitoring network (0 – 228.1 cm depth) averaged across cover types over the 2011-2013 study period. Dotted lines indicate field capacity and dashed lines indicate wilting point (based on soil texture averaged over the soil profile, Saxton and Rawls 2006).

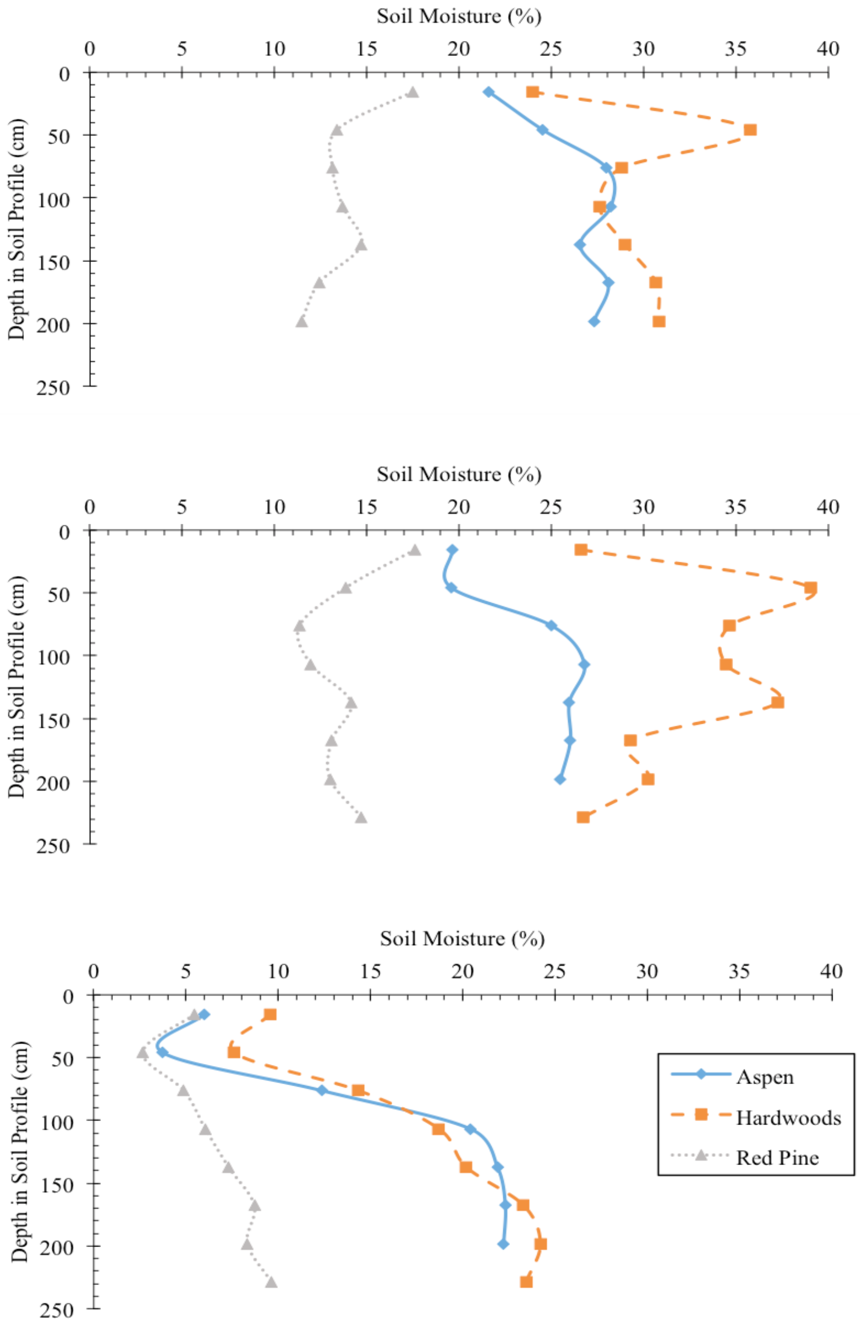


Figure 3-3. Representative soil moisture depth profiles for three cover types at the MEF expanded soil moisture monitoring network at the beginning of the growing season (top, measurements occurred on 4/24/12), following a spring rainstorm (middle, measurements occurred on 5/23/12), and during the summer drawdown (bottom, measurements occurred on 8/27/12).

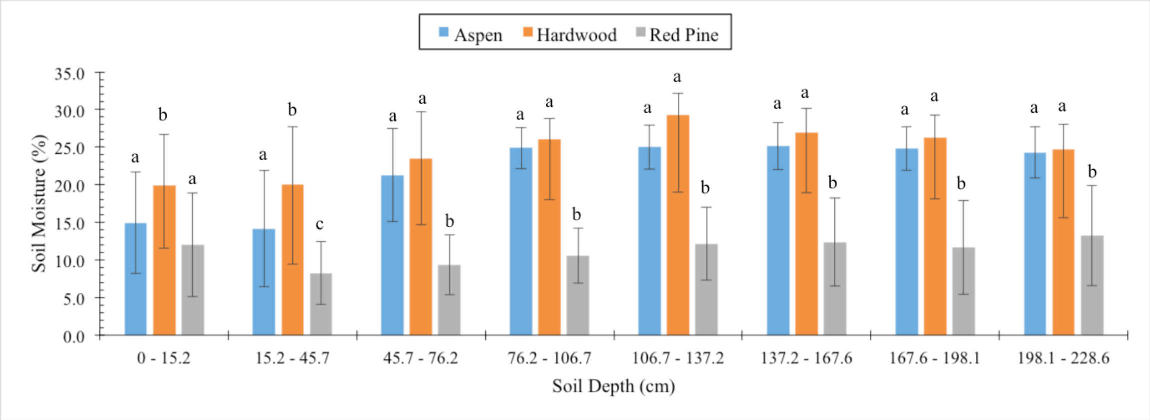


Figure 3-4. Differences between mean observed soil moisture at the MEF expanded soil moisture network under different cover types at different depths within the soil profile. Different letters denote significant differences in soil moisture within each depth increment (α = 0.01).

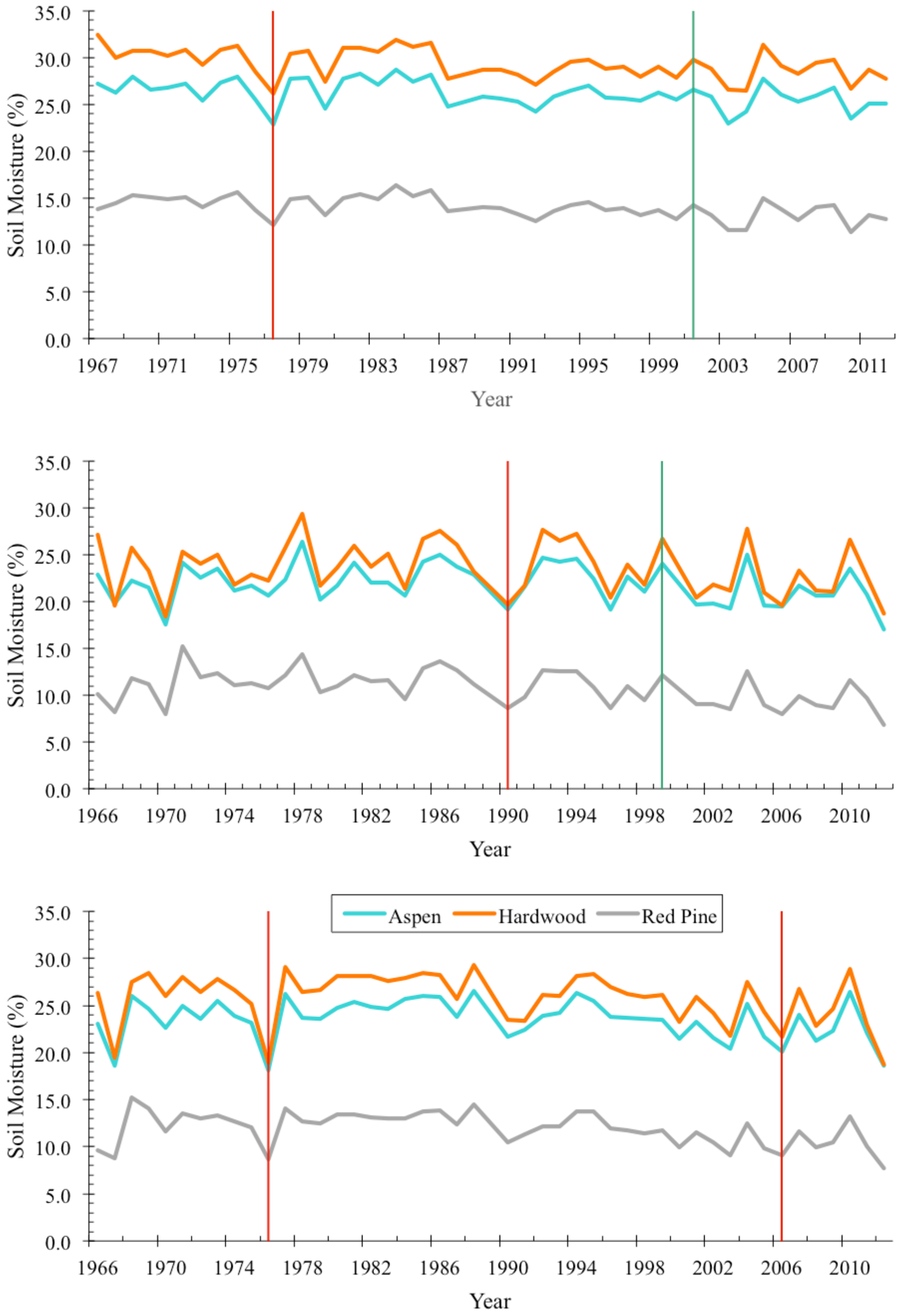


Figure 3-5. Mean modeled percent soil moisture (0 – 228.6 cm) for aspen, hardwood, and red pine cover types from 1967-2013 during the spring (top), summer (middle), and fall (bottom). Vertical red lines indicate years of extreme drought (PDSI < -4.00) and vertical green lines indicate years of extreme wetness (PDSI > 4.00).

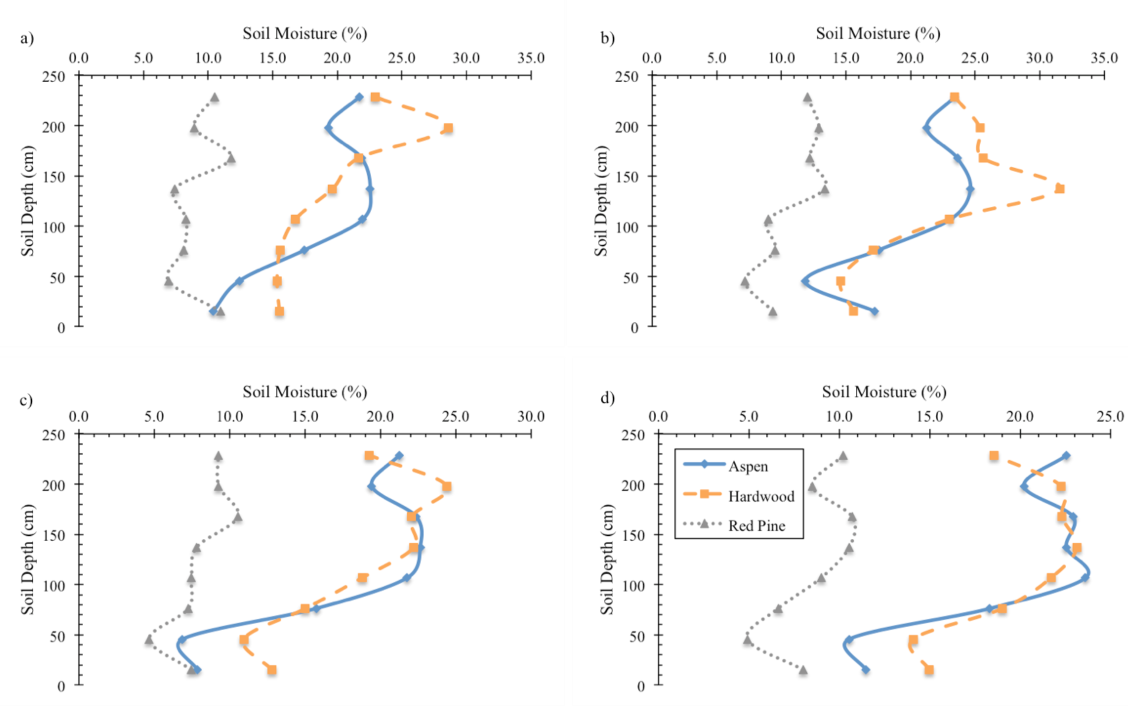


Figure 3-6. Percent modeled soil moisture with depth for four dry periods: a) Summer 1970; b) Summer 1990; c) Fall 1967; d) Fall 1976.

CHAPTER 4. GROWTH-CLIMATE RELATIONSHIPS FOR THREE TREE SPECIES IN THE NORTHERN GREAT LAKES

4.1 Introduction

Globally, the distribution and productivity of forests is strongly influenced by water availability (Whittaker 1975; Churkina et al. 1999). In the Great Lakes region, climate is known to be an important factor in regulating annual tree growth and stand dynamics (Graumlich 1993; Hogg et al. 2002; Hogg et al. 2008). Dendroclimatalogical analysis has shown that precipitation and temperature alone can explain over 50% percent of annual tree growth. However, using precipitation as a proxy for tree growth can invite error, since plant available water is not always directly associated with precipitation (Loik et al. 2004; Reynolds et al. 2004; Schwinning et al. 2004; Dymond et al. 2014). For instance, the same amount of precipitation may fall on two adjacent stands, one that is fine-textured with a deep-rooted species and one that is coarse-textured with a shallow rooted species. Despite having identical water inputs, the plant available water in these two systems would be very different, given their differences in infiltration rates, hydraulic conductivity, antecedent moisture conditions, species physiology, and other factors. As such, using precipitation as a proxy for plant available water in dendroclimatological analyses may greatly oversimplify complex ecohydrological processes.

Given that climate in the Great Lakes region is expected to warm with more extreme precipitation events (Christensen et al. 2007), a thorough understanding of how the annual growth of different species responds to climatic variables is necessary. These climate-growth relationships can then be used to assess the sensitivity, resilience, and resistance of different tree species to changes in climate. The goal of this study was to understand how different hydrologic parameters interact with temperature to influence annual tree growth in three species that are dominant in the Great Lakes region. The specific objectives of this study were:

1) to develop tree-ring chronologies for dominant species in northern Minnesota;
2) to identify the climate factors, including soil moisture, that determine the growth of different tree species;

   and
3) to identify differences between climate-growth relationships for different tree species and landscape positions.

4.2 Methods

4.2.1 Study Site

The sites for this study were all located within the Marcell Experimental Forest (MEF) (47°52’N, -93°46’W) in north-central Minnesota (Figure 4-1). The MEF is located near the boundary of the forest-prairie tension zone. Vegetation across this tension zone shifts from deciduous and coniferous trees to prairie grasses, a transition primarily driven by moisture availability (Curtis 1971). Upland forested vegetation in this portion of northern Minnesota consists primarily of mixed hardwoods and pines, with quaking aspen (*Populus tremuloides* Michx.) and red pine (*Pinus resinosa* Sol.) dominating the landscape. Smaller quantities of bigtooth aspen (*Populus grandidentata* Michaux), red maple (*Acer rubrum* L.), sugar maple (*Acer saccharum* Marshall), American basswood (*Tilia americana* L.), paper birch (*Betula papyrifera* Marshall), Eastern white pine (*Pinus strobus* L.) and jack pine (*Pinus banksiana* Lamb.) are also common. Lowland peatlands, which occur frequently across the region, have black spruce (*Picea mariana* Mill.), eastern tamarack (*Larix laricina* Du Roi), and northern white cedar (*Thuja occidentalis* L.) in the overstory (Aaseng 2003; Sebestyen et al. 2011).

The climate at the MEF is continental and strongly influenced by arctic air moving southward out of Canada. Summers are warm and moist and winters are cold and dry with abundant sunshine. Mean temperature (1966-2013) is lowest in January (-15°C) and highest in July (19°C). Mean annual precipitation (1966-2013) is 78 cm, with the majority of precipitation falling during the summer months (Figure 4-2). Topographic relief on the forest is low, with elevations from the watershed outlets to upland ridges spanning less than 20 m. Soils developed after glaciers retreated over 10,000 years ago and are generally well mixed and deep (> 3 m) sandy loam tills and outwashes (Johnson 1994).

4.2.2 Climate Data

Climate data used in the dendroclimatological analyses were collected at two weather stations on the MEF (one in each of the North and South units) from 1961 - 2011. Daily mean air temperature (°C) and total daily precipitation (cm) were aggregated to determine mean monthly air temperature and total monthly precipitation. Other climate variables included monthly potential evapotranspiration (PET), a simplified water balance (precipitation minus PET), and soil moisture storage. PET was modeled using the

Thornthwaite equation (Thornthwaite and Mather 1955); these PET values were subsequently used in the water balance equation.

Monthly soil water storage from 0 – 228.6 cm in the soil profile was modeled at twenty-seven different forested plots across the MEF using a modified Thornthwaite equation (Kolka and Wolf 1998). Soil water storage was calculated as

$$S_t = 10^{\left[logMSW - \left(\frac{0.525}{(MSW^{1.0371})}\right) x\ ACPWL_{t-1}\right]} \qquad \text{(Eqn. 4-1)}$$

where *S* is soil water storage in month *t*, *MSW* is the maximum soil water (mm) that a particular soil can hold, and *ACPWL* is the absolute value of accumulated potential water loss. The *MSW* for each site was obtained using the relationship between soil texture and percent volumetric water at field capacity. Soil texture values were found using the hydrometer method for particle size analysis (Gee and Bauder 1986). Maximum soil water storage was estimated based on the average soil texture across the soil profile (Saxton and Rawls 2006); percent volumetric water was multiplied by soil depth to obtain the maximum soil water storage at field capacity in mm. *ACPWL* is the amount of water lost from the soil when PET exceeds precipitation. Details of *ACPWL* calculations can be found in Kolka and Wolf (1998).

4.2.3 Field and Laboratory Methods

During the 2010 and 2011 growing seasons, 27 1/20th ha circular plots were established on the MEF. Nine plots were located within each of three cover types: aspen/birch, northern hardwoods, and red pine. Within each cover type, transects consisting of one plot within each of three topographic positions (ridge, sideslope, and toeslope) were installed. Transects were replicated three times within each cover type (Table 4-1).

Within each plot, trees greater than 10 cm diameter-at-breast height (DBH) were recorded for species, height, DBH, and crown class. Additionally, two perpendicular increment cores were collected at DBH from each tree. Cores that were rotten, broken, or otherwise unreadable were removed from the analysis, resulting in a total of 1017 cores from 594 trees.

Tree cores were mounted and prepared using standard dendrochronological procedures (Stokes and Smiley 1968). Rings were visually aged and cross-dated using the list method (Speer 2010). Ring widths were then measured to the nearest 0.001 mm using a VELMEX measuring system (Velmex, Inc., Bloomfield, New Jersey, USA) outfitted with MeasureJ2X measuring software (VoorTech Consulting, Holderness, New Hampshire, USA). Accuracy of measurements and cross-dating techniques were statistically verified using COFECHA software (Holmes 1983).

Individual tree ring series were detrended and converted to dimensionless ring-width indices using a two-thirds cubic smoothing spline with a 50% frequency response. The technique of detrending removes any growth patterns that may be a function of geometrically adding radial growth to an increasing tree diameter (Cook and Peters 1981). Additionally, each series was prewhitened to remove temporal autocorrelation using autoregression. Residual chronologies from single trees were subsequently aggregated into one chronology per cover type and topographic combination. All standardization techniques were applied using package dplR in the R v. 3.1.1 statistical program (R Core Development Team, Vienna, Austria).

4.2.4 Analyses

Relationships between annual growth and climate were analyzed using partial correlation analysis applied over the dendrochronological year via seascorr in R (Meko et al. 2011). Confidence intervals at the 95% level were obtained using Monte Carlo simulation. Seascorr assesses the partial relationship between two climate variables. To compare the accuracy of different water metrics, seascorr was run using air temperature as the secondary climate variable while substituting various water-related primary climate variables. The primary water climate variables included total monthly precipitation, total monthly PET, total monthly water balance (precipitation minus Thornthwaite-modeled PET), and monthly soil water storage. To determine which water parameter most effectively explains variability in tree-rings, significant variables from seascorr were used to construct linear regression models predicting standardized ring width as a function of the climate variables using the PROC MIXED procedure in SAS Version 9.0 (SAS Institute Inc., Cary, North Carolina, USA). Models were compared using the corrected Akaike information criterion (AIC; Akaike 1974) and the squared correlation between predicted and observed values used as a measure of goodness of fit.

4.3 Results

4.3.1 Cross-dating and Growth Patterns

Trees included in this sample were relatively young: the mean age of red pine, aspen, and sugar maple was 38, 32, and 61 years, respectively (Table 4-1). The total mean series intercorrelation ranged from 0.012 to 0.537, with the sugar maple having much lower R_{bar} values than red pine and quaking aspen. There was some difficulty in cross-dating sugar maple, since sugar maple are prone to dropping rings during times of stress. Additionally, the red pine and quaking aspen were collected from almost pure stands, while the sugar maple were sampled from stands of mixed northern hardwood species. This resulted in a much smaller sample size for sugar maple than for red pine and quaking aspen.

The mean annual basal area increment was significantly different ($p < 0.0001$) amongst species (Figure 4-3). Red pine had the highest mean annual growth rates (709.0 mm^2 yr^{-1}), followed by quaking aspen (372.5 mm^2 yr^{-1}) and sugar maple (251.9 mm^2 yr^{-1}). There were no significant differences in growth rates across topographic positions both within and across cover types. Because of no statistical differences with topographic position, all further results are averaged across topographic positions within each cover type.

Periods of higher than mean annual growth and lower than mean annual growth were evident across species (Figure 4-4). Periods of low growth occurred from 1979-1980 and 1989. Growth was slightly lower than normal in 2001 for red pine and sugar maple, while 2001 and 2002 were extremely low years of growth for aspen trees. Periods of higher growth for all species occurred in the mid-1970s and early 1990s. The low growth periods for quaking aspen all corresponded to periods of forest tent caterpillar insect outbreaks in the region (Albers et al. 2014).

4.3.2 Climate Analyses

The variation in growth of the three dominant tree species sampled was significantly correlated with water availability and air temperature (Table 4-2). The direction (positive or negative) and months in which correlations were significant ($\alpha = 0.05$) varied with species and models. In general, quaking aspen growth was positively associated with prior season September and current season March moisture, yet was negatively associated with prior season November moisture. Growth of quaking aspen was negatively correlated with air temperature. Overall, sugar maple growth was positively associated with current season September moisture as well as warm temperatures early in the growing season (March and April). Red pine growth was most strongly correlated with current season moisture and early season temperatures.

Using AIC, best-approximating bioclimate models of annual tree ring growth were found for quaking aspen, sugar maple and red pine at the MEF (Table 4-3; Appendix A). The best-approximating models explained a relatively small amount (14% to 33%) of the annual variation in tree-ring growth, yet were all significant ($p < 0.001$). The significant climate variables varied depending on tree species and none of the tree species exhibited the same significant water metric. Quaking aspen and red pine growth were best explained by a generalized water budget (precipitation less PET) while sugar maple growth was explained by soil moisture storage (Figure 4-5).

4.4 Discussion

4.4.1 Forest Productivity and Topography

Many studies have suggested that tree productivity is a function of topography (Whittaker 1975; Oberhuber and Kofler 2000; Fekedulegn et al. 2003; Tsujino et al. 2006), yet we found that topography did not play a role in determining mean basal area increment over time for three species (quaking aspen, sugar maple, and red pine) at the MEF. From a hydrologic standpoint, vegetation distribution and productivity will disperse along topographic gradients due to topography's influence on plant available water. At the MEF, where elevational gradients vary only on the order of 20 m between toeslopes and ridges and are largely reflective of depositional features, soil moisture dynamics across depth are a function of forest cover type and soil texture as opposed to topography (Chapter 3). This is consistent with patterns in tree growth across the study landscape; if soil moisture does not vary across a landscape, growth patterns will not differ either.

4.4.2 Tree Growth in Response to Climate

Quaking aspen, sugar maple, and red pine exhibited different responses in annual tree growth to climate. Quaking aspen had the strongest climatic response; 33% of the variability in annual growth could be explained by a simple water budget (precipitation less PET) and temperature. Tree growth was positively correlated with precipitation minus potential evapotranspiration (P-PET) for the September prior to the growing season and current season January, as well as their interaction. Quaking aspen growth declined with warm temperatures late in the growing season (August). Previous studies have also found quaking aspen growth to be sensitive to January precipitation and freeze-thaw events (Hogg et al. 2002; Lapointe-Garant et al. 2010). Because PET is near zero in winter months at the MEF, P-PET simplifies to precipitation. A large winter snowpack is thought to protect fine roots from freeze-thaw cycles, thus increasing growth in the following growing season (Frey et al. 2004). Additionally, other studies have also found quaking aspen growth to decline following droughts during the prior growing season, suggesting a lag effect of water availability on quaking aspen growth and mortality (Hogg et al. 2008; Lapointe-Garant et al. 2010). At the MEF, quaking aspen growth was also negatively correlated with late-season temperatures. Quaking aspen reaches the southern end of its range in Minnesota (in non-mountainous regions), and trees in this region may be more sensitive to the warmer climatic condition than their northern counterparts.

While not part of the climate analysis, the three lowest ring-width years for aspen were all associated with forest tent caterpillar (*Malacosoma disstria*) outbreaks in northern Minnesota (Albers et al. 2014). Forest tent caterpillar preferentially feeds on aspen, birch, basswood, and oak leaves, and many studies have also found that defoliating insects largely influence quaking aspen productivity and stand dynamics (Hogg et al. 2002; Hogg et al. 2008; Huang et al. 2008; Lapointe-Garant et al. 2010; Reinikainen et al. 2012). There is also evidence that defoliating insect outbreaks can be exacerbated by regional droughts (Worrall et al. 2013). The short (40 year) MEF quaking aspen chronology had no overlap between droughts and insect outbreaks, so this could not be explicitly tested in our dataset. Other studies have also found that site factors such as nutrient availability, pH, soil texture, and soil organic layer thickness can significantly contribute to quaking aspen growth (Pinno et al. 2009; Gewehr et al. 2014).

Climate explained a low but significant percentage of growth for red pine and sugar maple, indicating that individual tree, juvenile growth patterns, edaphic parameters, and stand dynamics may be more important in determining growth for these species. Additionally, red pine and sugar maple growth tended to be more complacent than quaking aspen during the period of overlapping climate and chronology data (1966 – 2011) and may respond to extreme climatic events not covered in our climate data (Hughes and Graumlich 1996).

Despite the data limitations, there were significant growth-climate relationships for red pine and sugar maple. Red pine growth increased with warm early season temperature and water availability (March and May, respectively) yet decreased with warm summer (July) temperatures. These results are in concert with previous studies that have found that red pine growth responded most to warm early growing season temperatures and cool July temperatures (Graumlich 1993; Kilgore and Telewski 2004; Kipfmueller et al. 2010; Magruder et al. 2013). There is some evidence that red pine growth is a function of June and July precipitation (Kipfmueller et al. 2010). Other studies have found no association between red pine growth and water availability, yet these studies have been conducted in the middle of the red pine range (Graumlich 1993; Magruder et al. 2013). In Minnesota, red pine is at the western edge of its range; trees cannot grow beyond the western range due to limited moisture availability.

Recently it has been shown that red pine management regimes may influence growth-climate relationships (D'Amato et al. 2014; Magruder et al. 2013). Of the nine red pine sites included in this study, five were from thinned stands and four were from un-thinned stands (average basal area = 13.1 and 35.9 m^2 ha^{-1}, respectively). These sites were placed into groups according to stocking status and the growth-climate relationships were re-analyzed. Despite a difference in mean annual basal area between the thinned and un-thinned stands, the growth-climate relationships did not change according to management regime. However, this could be a result of the young stand age of the trees sampled, as tree size (and age) in managed red pine stands has been shown to affect growth-climate relationships (D’Amato et al. 2014).

Sugar maple growth at the MEF was negatively associated with prior December soil moisture and positively associated with current season September soil moisture, indicating that sugar maple is susceptible to drought. Previous sugar maple growth-climate relationships have found that sugar maple growth is positively correlated with growing season temperature (Graumlich 1993; Lane et al. 1993; Payette et al. 1996). Correlation between sugar maple growth and water availability is more site dependent and varies from negatively correlated with prior December and summer precipitation in the current growing season (Lane et al. 1993; Payette et al. 1996) to positive associations with current growing season temperature (Graumlich 1993). The sugar maple growth-climate relationships at the MEF were weak, which may be a result of poor cross-dating due to dropped rings and a low sample size. Despite these potential dating issues, our results indicate that sugar maple growth is more responsive to moisture availability than to temperature. Previous studies have also found that sugar maple can be vulnerable to nutrient anomalies and defoliating insects, such as forest tent caterpillar (Payette et al. 1996; St. Clair et al. 2008).

4.4.3 Water Availability Metrics

Many dendroclimatological studies use temperature and precipitation as the primary climate metrics (D’Arrigo and Jacoby 1991; Graumlich 1993; Salzer and Kipfmueller 2005; Liang et al. 2014; and others); measurements of these climate variables are geographically widespread and long-term records (100+ years) are often available. However, the use of precipitation as a proxy for tree growth can be misleading, since monthly precipitation does not always directly correlate to plant available water (Loik et al. 2004; Reynolds et al. 2004; Schwinning et al. 2004; Dymond et al. 2014). Because of this, more dendroclimatological studies are incorporating the use of Palmer Drought Severity Index (PDSI), soil moisture, and P-PET or P/PET as surrogates for moisture stress in their analyses (Kagawa et al. 2003; Li et al. 2007). In our climate analyses, we found that P-PET and soil moisture were better predictors of tree growth than precipitation (when combined with temperature). These metrics give a more accurate portrayal of how ecosystems are responding to the influence of climate on plant available water. Since PET can easily be modeled from available temperature data, it is recommended that more dendroclimatological studies incorporate additional metrics of water availability into their analyses to provide an independent representation of soil moisture availability.

4.5 Conclusions

I present tree ring series for three dominant species at the MEF: quaking aspen, red pine, and sugar maple. Dendroclimatological analysis showed that each species responded differently to climate metrics and that water availability metrics such as soil moisture and P – PET were more important in determining annual growth than precipitation. The significant water availability metrics varied by species, indicating the importance of species and stand dynamics in determining how trees response to climate. The response of tree growth to climate is becoming increasingly important as the climate in northern Minnesota is expected to become warmer with more extreme periods of wetness and drought. In the past 45 years alone, mean annual temperature at the MEF has increased by 2.5 °C while mean available soil water in May (0 – 228.6 cm depth) has declined by 2.8 cm (Dymond et al. 2014). While all species could exhibit lower growth given less water, red pine may be particularly susceptible to decreased May soil water, since its growth is positively associated with May water availability.

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Table 4-1. Site information and statistics for different cover types at the MEF. Each cover type and landscape position consisted of three plots.

Cover Type	Dominant Species	Landscape Position	No. of Cores	No. of Trees	Mean Tree Ring Width (S.D.) *(mm)*	R_{BAR}†
Aspen	Quaking aspen	Ridge	127	70	2.224 (1.043)	0.507
		Sideslope	44	44	2.003 (0.990)	0.492
		Toeslope	83	45	1.914 (0.811)	0.537
Hardwoods	Sugar maple	Ridge	11	6	1.076 (0.614)	0.028
		Sideslope	40	21	1.199 (0.669)	0.164
		Toeslope	27	14	1.595 (0.792)	0.012
Red Pine	Red pine	Ridge	210	112	2.607 (1.769)	0.402
		Sideslope	275	173	2.299 (1.468)	0.379
		Toeslope	200	109	2.480 (1.568)	0.407

†Total mean series intercorrelation; the average correlation of individual series with the master chronology (Holmes 1983).

Table 4-2. Monthly correlations with various water availability metrics for three dominant tree species at the MEF and partial correlations with mean monthly temperature. Blue squares indicate significant positive correlations while red squares indicate significant negative correlations (alpha = 0.01). *Indicates month prior to year of growth.

		Primary Correlations														*Secondary Partial Correlations***													
Species	Water Variable	Aug*	Sep*	Oct*	Nov*	Dec*	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Aug*	Sep*	Oct*	Nov*	Dec*	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Quaking Aspen	PPT		🟦		🟥														🟥		🟥					🟥			🟥
	PET						🟥		🟦			🟦	🟦											🟥		🟥			
	P - PET		🟦		🟥		🟦		🟦			🟥									🟥							🟥	
	Storage		🟦		🟥																🟥							🟥	🟥
Sugar Maple	PPT				🟥										🟦		🟥							🟦			🟥	🟥	
	PET																		🟥	🟥			🟦						
	P - PET														🟦					🟥			🟦	🟦					
	Storage				🟥	🟥									🟦		🟥						🟦	🟦		🟥			🟥
Red Pine	PPT										🟦		🟦									🟦	🟦			🟥			
	PET		🟥									🟦	🟦																
	P - PET									🟦	🟦		🟦									🟦	🟦			🟥	🟥		
	Storage						🟥		🟥		🟦											🟦	🟦			🟦			🟥

Table 4-3. Models of annual tree-ring growth using different water metrics and mean monthly temperature for three dominant tree species at the MEF. Best-approximating models were determined using AIC and all top models were significant ($p < 0.001$).

Species	Water Availability Metric	Best-approximating Model	AIC	k	Weight	R^2
Quaking Aspen	P - PET	$y = W_{pSep} + W_{Jan} + T_{Aug} + W_{pSep}*W_{Jan}$	-22.9	6	0.275	0.325
Sugar Maple	Storage	$y = S_{pDec} + S_{Sep}$	-100.6	4	0.013	0.138
Red Pine	PET	$y = W_{May} + T_{Mar} + T_{Jul}$	-68.6	5	0.028	0.250

W = P – PET (cm), T = temperature (°C), S = soil moisture storage (mm)

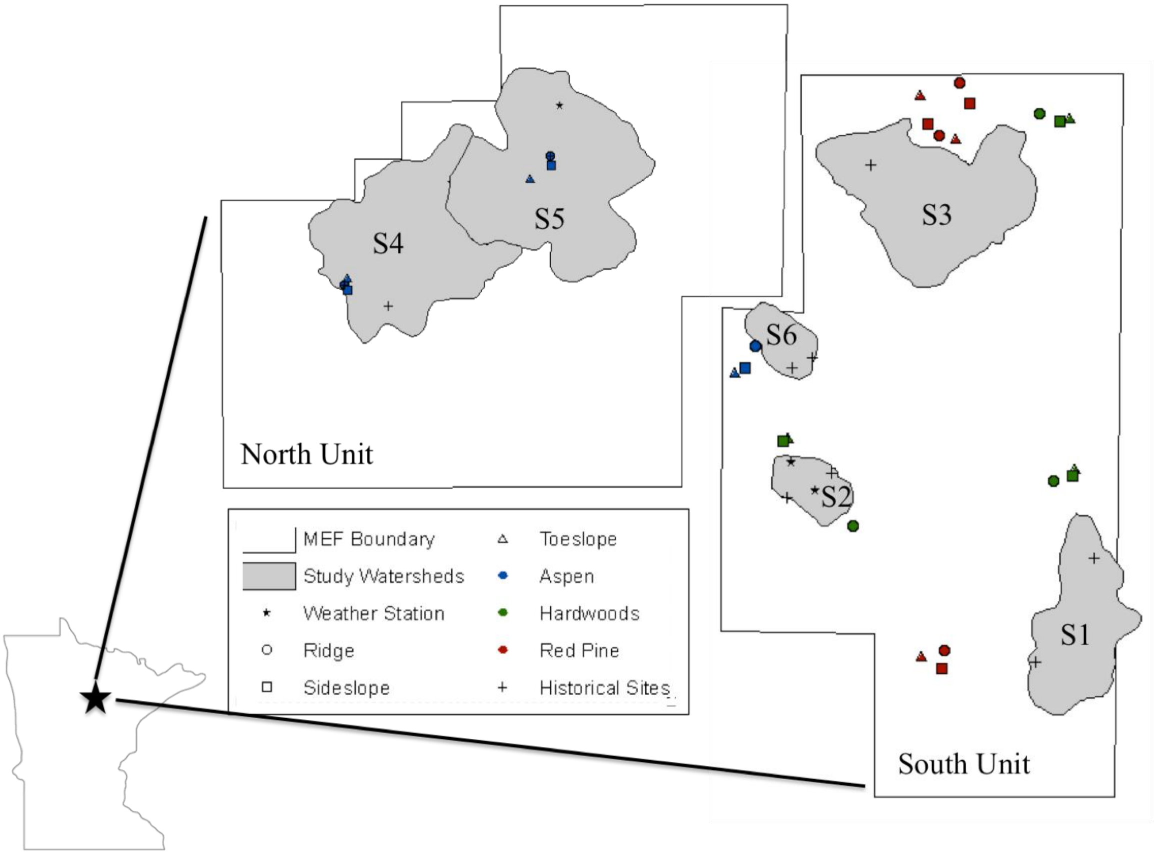

Figure 4-1. The MEF is located in north-central Minnesota. From 2010-2011, nine sites in each of three cover types (aspen, hardwoods, and red pine) were cored for dendroclimatological analysis.

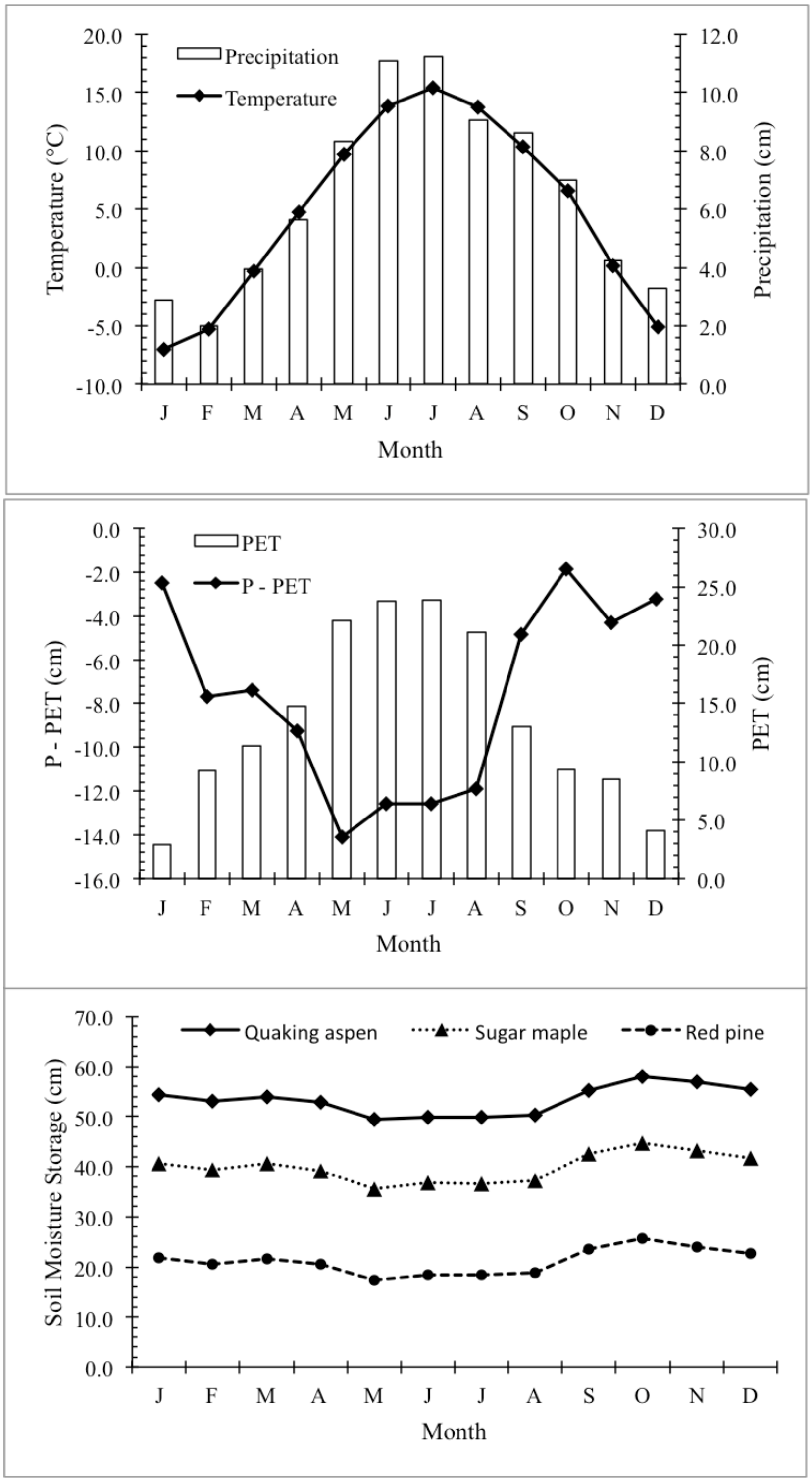

Figure 4-2. Mean monthly temperature, precipitation (top), PET, P-PET (middle), and soil moisture storage under three different cover types (bottom) from 1966 – 2011 at the MEF.

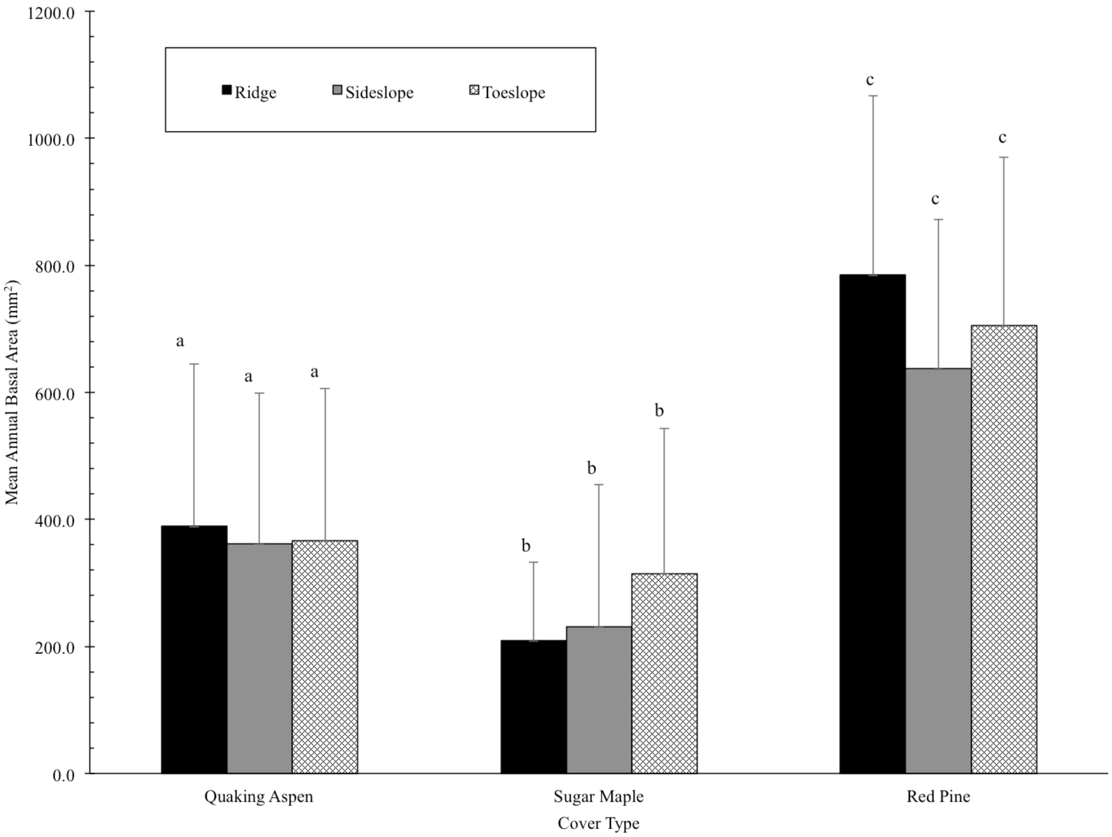

Figure 4-3. Mean annual basal area increment for three species across three different topographic positions at the MEF. Error bars indicate one standard deviation from the mean. Different letters indicate significantly different mean annual basal area ($\alpha < 0.0001$).

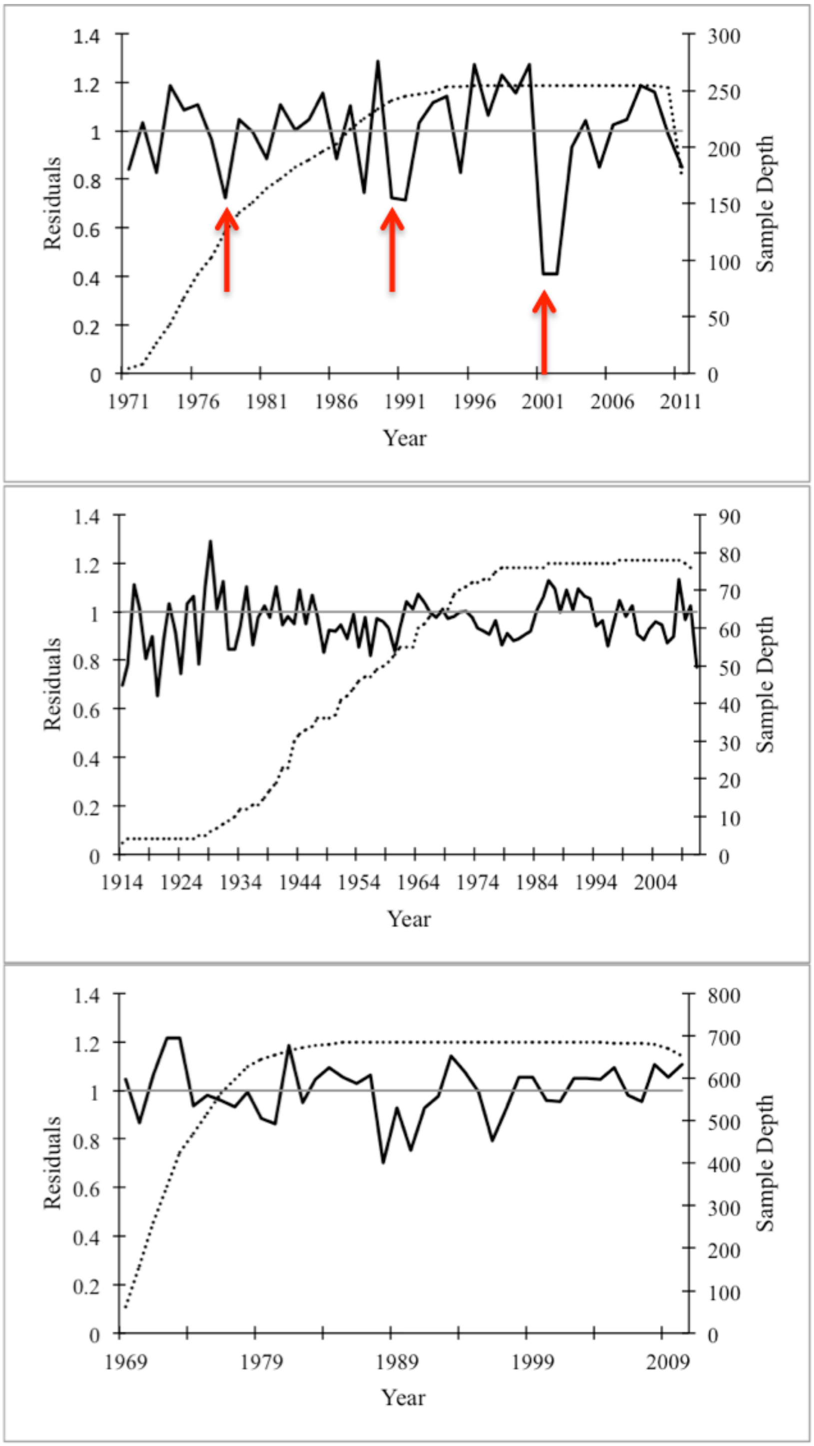

Figure 4-4. Standardized residual tree ring index (solid black line) for three species (top: Quaking Aspen, Middle: Sugar Maple, Bottom: Red Pine) at the MEF. Dotted lines indicate the sample depth. Red arrows indicate periods of forest tent caterpillar outbreak.

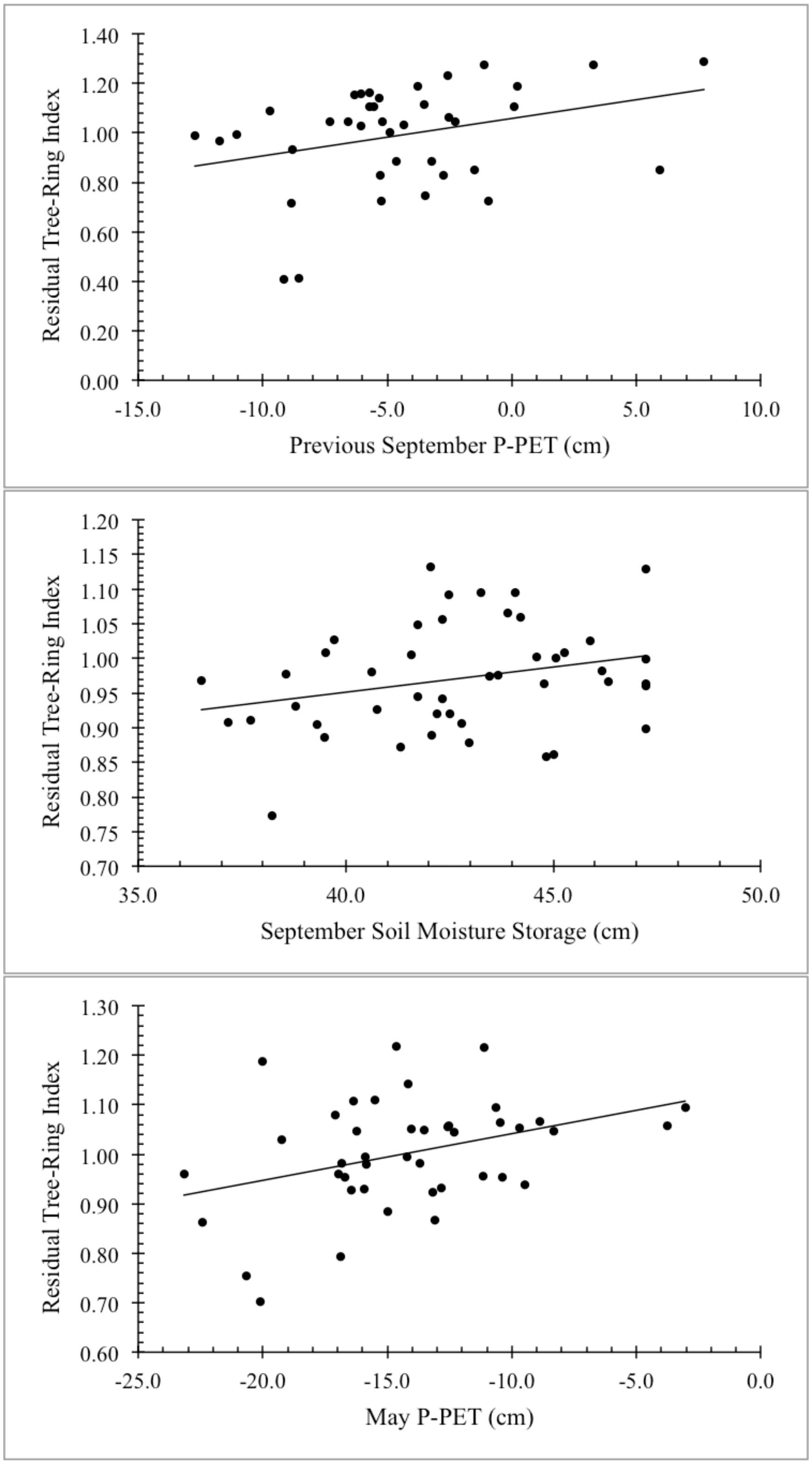

Figure 4-5. Scatterplots of residual tree ring chronologies and most significant climate variables from the top models (Table 4-3) for quaking aspen (top), sugar maple (middle), and red pine (bottom) at the MEF.

CHAPTER 5. CONCLUSIONS

5.1 Declining Soil Moisture

Forest productivity is expected to increase given rising temperatures and CO_2 levels attributable to climate change (Cao and Woodward 1992; Norby et al. 1999; Latta et al. 2010). However, upturns in forest productivity may be offset by changes in water availability. It is uncertain how water availability will change with climate, but models predict that the timing and variability of water will shift (Christensen et al. 2007). Therefore, my primary goal was to understand how water availability has changed over time and how tree productivity has responded to these changes. Results from this research can be used to predict changes in forest productivity and the resistance and resilience of different tree species to a changing climate. Understanding these relationships and future forest productivity can help inform management adaptation to climate change.

The first major finding of this dissertation is that despite no changes in the timing, magnitude, or variability in precipitation at the MEF, plant available water is decreasing (Chapter 2). The decrease in May available soil water was attributed to increases in potential evapotranspiration due to increased temperature. The increase in temperature creates a larger gradient between soil water potential and atmospheric water potential. As a result, more water is transferred from the soil back to the atmosphere via trees. Despite significant increases in Thornthwaite-modeled PET over time, forests have not been responding by increasing growth rates (Chapter 3). As such, soil moisture at the MEF is declining without any positive influences on forest productivity.

Waning soil moisture stores should be of concern to forest landowners and managers in the region, who rely on soil to provide water for healthy and productive forests. Since temperature in northern Minnesota is expected to increase as much as 3.5 °C by the end of the 21st Century (Christensen et al. 2007), I expect PET and soil moisture to decline even further. Chapter 3 results show that while forest productivity has not been increasing with an increase in PET, it has not been decreasing with decreased water availability. It remains to be seen whether or not future reductions in soil moisture will have detrimental effects on forests and productivity.

5.2 Soil Moisture and Topography

Topography has often been thought to play a significant role in water availability (Western and Blöschl 1999; Tromp-van Meerveld and McDonnell 2006), yet topographic position had no effect on soil moisture at the MEF (Chapter 2). Soil moisture is generally highest at the toe of a slope due to deep soils that can store an abundance of water as well as the accumulation of runoff and subsurface flow from upslope. Ridges can still be moist, but have shallower soils than toeslopes and thus cannot store as much water. Sideslopes are often the driest position of the landscape due to shallow soils and steep slopes that allow water to runoff quickly.

At the MEF, many slopes are short and gradual with grades less than 10%. Forest communities are similar across topographic gradients; yet change drastically in the lagg zones, which are the confluence between peatlands and uplands. The bogs and fens contain deep, moist organic material that supports very different plant communities than the upland mineral soil.

5.3 Forest Productivity in Response to Climate

Typical dendroclimatology studies sample trees at the fringes of their ranges and studies are targeted to include severely climate-stressed trees (LaMarche 1973; D'Arrigo and Jacoby 1993; Espter et al. 2003; Liang et al. 2014). The species sampled at the MEF are at the edges, but not the fringes of their ranges. Quaking aspen, sugar maple, and red pine tree-ring chronologies show significant responses to climate. However, climate was only able to explain 10-30% of annual growth. In looking at the chronologies, large droughts can be detected by decreased ring widths. However, the lowest periods of growth for all three species did not align with extreme climatic events. This suggests that disturbance at the plot and landscape scale greatly influences forest productivity and that the sampling scheme did not adequately account for these factors. For instance, quaking aspen trees all responded much more strongly to forest tent caterpillar outbreaks than to climatic events.

Results suggest that trees at the MEF are climate sensitive yet not climate stressed. They respond to large drought events yet are able to recover and resume growth quickly. In turn, this means that the trees would be susceptible to large drought events as are expected under different climate change projections.

5.4 Shift in the Forest-Prairie Tension Zone

The forest-prairie tension zone approximately follows the 100th meridian, and is an area in which soil moisture can no longer sustain trees (Weaver and Thiel 1917; Pool et al. 1918). Results from Chapter 2 show that soil moisture under three different cover types at the MEF never fell to the permanent wilting point. For the aspen and northern hardwoods plots, soil moisture over the 45-year record was never in jeopardy of falling too low to severely limit plant growth. However, the sandy red pine sites were close to drying to the wilting point on numerous occasions.

If, as predicted, precipitation inputs change in their timing and magnitude, sandy soils in the region could be in jeopardy of losing tree cover. Sandy sites have a lower water-holding capacity and greater hydraulic conductivity than finer-textured soils. If a large rainstorm were to fall on sandy soils, the water will infiltrate into the soil quickly, yet it will also be quickly lost to groundwater and subsurface flow pathways. Trees on the sandy sites would be able to access this water only temporarily during wet periods. Since water cannot be held tightly in these systems, periods of prolonged drought could lead to decreased productivity and increased tree mortality in these systems.

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APPENDIX A. DENDROCLIMATOLOGIAL MODELS

Table A-1. Dendroclimatological models and model statistics for annual ring-width growth for quaking aspen at the MEF. W = P-PET, T = temperature, S = soil moisture storage, P = precipitation

Model Number	Model	AICC	k	Weight
1	pSepP	-10	3	0.0006
2	pNovP	-7.1	3	0.0001
3	pNovT	-10.2	3	0.0007
4	JanT	-9.9	3	0.0006
5	JunT	-13.5	3	0.0035
6	SepT	-6.7	3	0.0001
7	pSepP pNovP	-9.1	4	0.0004
8	pSepP pNovT	-11.6	4	0.0013
9	pSepP JanT	-11.5	4	0.0013
10	pSepP JunT	-15.6	4	0.0100
11	pSepP SepT	-9.2	4	0.0004
12	pNovP pNovT	-7.9	4	0.0002
13	pNovP JanT	-7.6	4	0.0002
14	pNovP JunT	-11.5	4	0.0013
15	pNovP SepT	-5.1	4	0.0001
16	pNovT JanT	-9.7	4	0.0005
17	pNovT JunT	-13.7	4	0.0038
18	pNovT SepT	-8.2	4	0.0003
19	JanT JunT	-13.3	4	0.0032
20	JanT SepT	-8	4	0.0002
21	JunT SepT	-11	4	0.0010
22	pSepP pNovP pNovT	-8.9	5	0.0004
23	pSepP pNovP JanT	-9.3	5	0.0004
24	pSepP pNovP JunT	-13.8	5	0.0042
25	pSepP pNovP SepT	-7.9	5	0.0002
26	pSepP pNovT JanT	-11.1	5	0.0011
27	pSepP pNovT JunT	-15.5	5	0.0098
28	pSepP pNovT SepT	-10.5	5	0.0008
29	pSepP JanT JunT	-15.4	5	0.0089
30	pSepP JanT SepT	-10.6	5	0.0008
31	pSepP JunT SepT	-13.4	5	0.0034
32	pNovP pNovT JanT	-7.5	5	0.0002
33	pNovP pNovT JunT	-11.2	5	0.0011

Table A-1. (cont.)

Model Number	Model	AICC	k	Weight
34	pNovP pNovT SepT	-5.8	5	0.0001
35	pNovP JanT JunT	-10.7	5	0.0009
36	pNovP JanT SepT	-5.5	5	0.0001
37	pNovP JunT SepT	-8.9	5	0.0003
38	pNovT JanT JunT	-12.3	5	0.0019
39	pNovT JanT SepT	-7.7	5	0.0002
40	pNovT JunT SepT	-11.1	5	0.0010
41	JanT JunT SepT	-10.7	5	0.0009
42	pSepP pNovP pNovT JanT	-8.4	6	0.0003
43	pSepP pNovP pNovT JunT	-12.8	6	0.0024
44	pSepP pNovP JanT JunT	-12.8	6	0.0025
45	pSepP pNovT JanT JunT	-14.1	6	0.0048
46	pNovP pNovT JanT JunT	-9.9	6	0.0006
47	pSepP pNovP pNovT SepT	-7.8	6	0.0002
48	pSepP pNovP JanT SepT	-8.1	6	0.0002
49	JanT pNovT JanT SepT	-7.7	5	0.0002
50	pNovP pNovT JanT SepT	-5.4	6	0.0001
51	pSepP pNovP JunT SepT	-11.4	6	0.0013
52	pSepP pNovT JunT SepT	-13.3	6	0.0031
53	pNovP pNovT JunT SepT	-8.5	6	0.0003
54	pSepP JanT JunT SepT	-13.1	6	0.0029
55	pNovP JanT JunT SepT	-8	6	0.0002
56	pNovT JanT JunT SepT	-9.6	6	0.0005
57	pSepP pNovP pNovT JanT JunT	-11.2	7	0.0011
58	pSepP pNovP pNovT JanT SepT	-7.2	7	0.0002
59	pSepP pNovP pNovT JunT SepT	-10.3	7	0.0007
60	pSepP pNovP JanT JunT SepT	-10.4	7	0.0008
61	pSepP pNovT JanT JunT SepT	-11.8	7	0.0015
62	pNovP pNovT JanT JunT SepT	-7	7	0.0001
63	pSepP pNovP pNovT JanT JunT SepT	-8.7	8	0.0003
64	JanPET	-10.5	3	0.0008
65	MarPET	-8.4	3	0.0003
66	JunPET	-9.8	3	0.0006
67	JulPET	-9	3	0.0004
68	AprT	-6.4	3	0.0001
69	JanPET MarPET	-10	4	0.0006
70	JanPET JunPET	-10.9	4	0.0010
71	JanPET JulPET	-9.2	4	0.0004
72	JanPET AprT	-8.1	4	0.0002

Table A-1. (cont.)

Model Number	Model	AICC	k	Weight
73	JanPET JunT	-14.8	4	0.0067
74	MarPET JunPET	-9.3	4	0.0004
75	MarPET JulPET	-9.1	4	0.0004
76	MarPET AprT	-6	4	0.0001
77	MarPET JunT	-12.7	4	0.0024
78	JunPET JulPET	-8.2	4	0.0002
79	JunPET AprT	-7.5	4	0.0002
80	JunPET JunT	-11	4	0.0010
81	JulPET AprT	-6.5	4	0.0001
82	JulPET JunT	-11.4	4	0.0012
83	AprT JunT	-11	4	0.0010
84	JanPET MarPET JunPET	-10	5	0.0006
85	JanPET MarPET JulPET	-8.8	5	0.0003
86	JanPET MarPET AprT	-7.5	5	0.0002
87	JanPET MarPET JunT	-13.6	5	0.0037
88	JanPET JunPET JulPET	-8.4	5	0.0003
89	JanPET JunPET AprT	-8.3	5	0.0003
90	JanPET JunPET JunT	-12.3	5	0.0019
91	JanPET JulPET AprT	-6.6	5	0.0001
92	JanPET JulPET JunT	-12.1	5	0.0018
93	JanPET AprT JunT	-12.2	5	0.0018
94	MarPET JunPET JulPET	-7.8	5	0.0002
95	MarPET JunPET AprT	-6.9	5	0.0001
96	MarPET JunPET JunT	-10.1	5	0.0006
97	MarPET JulPET AprT	-7.2	5	0.0002
98	MarPET JulPET JunT	-10.7	5	0.0008
99	MarPET AprT JunT	-10.8	5	0.0009
100	JunPET JulPET AprT	-5.6	5	0.0001
101	JunPET JulPET JunT	-8.9	5	0.0004
102	JunPET AprT JunT	-8.4	5	0.0003
103	JulPET AprT JunT	-8.8	5	0.0003
104	JanPET MarPET JunPET JulPET	-7.5	6	0.0002
105	JanPET MarPET JunPET AprT	-7.5	6	0.0002
106	JanPET MarPET JulPET AprT	-6.7	6	0.0001
107	JanPET JunPET JulPET AprT	-5.6	6	0.0001
108	MarPET JunPET JulPET AprT	-5.6	6	0.0001
109	JanPET MarPET JunPET JunT	-10.9	6	0.0010
110	JanPET MarPET JulPET JunT	-10.8	6	0.0009
111	JulPET JunPET JulPET JunT	-8.9	5	0.0004

Table A-1. (cont.)

Model Number	Model	AICC	k	Weight
112	MarPET JunPET JulPET JunT	-8	6	0.0002
113	JanPET MarPET AprT JunT	-11.8	6	0.0015
114	JanPET JunPET AprT JunT	-9.6	6	0.0005
115	MarPET JunPET AprT JunT	-8.1	6	0.0002
116	JanPET JulPET AprT JunT	-9.4	6	0.0004
117	MarPET JulPET AprT JunT	-9	6	0.0004
118	JunPET JulPET AprT JunT	-6.1	6	0.0001
119	JanPET MarPET JunPET JulPET AprT	-5.1	7	0.0001
120	JanPET MarPET JunPET JulPET JunT	-8	7	0.0002
121	JanPET MarPET JunPET AprT JunT	-9.1	7	0.0004
122	JanPET MarPET JulPET AprT JunT	-9	7	0.0004
123	JanPET JunPET JulPET AprT JunT	-6.6	7	0.0001
124	MarPET JunPET JulPET AprT JunT	-6.4	7	0.0001
125	JanPET MarPET JunPET JulPET AprT JunT	-6.2	8	0.0001
126	pSepW	-10.2	3	0.0007
127	pNovW	-9	3	0.0004
128	JanW	-11.3	3	0.0012
129	MarW	-7.2	3	0.0002
130	JunW	-9.7	3	0.0005
131	AugT	-9.1	3	0.0004
132	pSepW pNovW	-10.8	4	0.0009
133	pSepW JanW	-13.4	4	0.0034
134	pSepW MarW	-10.2	4	0.0007
135	pSepW JunW	-12.4	4	0.0020
136	pSepW JanT	-11.5	4	0.0013
137	pSepW AugT	-11.1	4	0.0011
138	pNovW JanW	-9.7	4	0.0005
139	pNovW MarW	-7.5	4	0.0002
140	pNovW JunW	-9.4	4	0.0004
141	pNovW JanT	-8.8	4	0.0003
142	pNovW AugT	-9.3	4	0.0004
143	JanW MarW	-9.6	4	0.0005
144	JanW JunW	-10	4	0.0006
145	JanW JanT	-9.4	4	0.0005
146	JanW AugT	-11.9	4	0.0016
147	MarW JunW	-7.6	4	0.0002
148	MarW JanT	-8.1	4	0.0002
149	MarW AugT	-7	4	0.0001
150	JunW JanT	-9.9	4	0.0006

Table A-1. (cont.)

Model Number	Model	AICC	k	Weight
151	JunW AugT	-9.8	4	0.0006
152	JanT AugT	-8.5	4	0.0003
153	pSepW pNovW JanW	-11.7	5	0.0015
154	pSepW pNovW MarW	-10.6	5	0.0008
155	pSepW pNovW JunW	-12	5	0.0017
156	pSepW pNovW JanT	-10.4	5	0.0008
157	pSepW pNovW AugT	-11.4	5	0.0012
158	pSepW JanW MarW	-12.9	5	0.0027
159	pSepW JanW JunW	-12.6	5	0.0023
160	pSepW JanW JanT	-11.3	5	0.0012
161	pSepW JanW AugT	-14.5	5	0.0057
162	pSepW MarW JunW	-11.1	5	0.0011
163	pSepW MarW JanT	-10.8	5	0.0009
164	pSepW JunW JanT	-12.3	5	0.0020
165	pSepW JunW AugT	-12.8	5	0.0025
166	pSepW JunW AugT	-12.8	5	0.0025
167	pSepW JanT AugT	-10.3	5	0.0007
168	pNovW JanW MarW	-7.8	5	0.0002
169	pNovW JanW JunW	-8.3	5	0.0003
170	pNovW JanW JanT	-7.5	5	0.0002
171	pNovW JanW AugT	-10	5	0.0006
172	pNovW MarW JunW	-7.1	5	0.0001
173	pNovW MarW JanT	-6.8	5	0.0001
174	pNovW MarW AugT	-7	5	0.0001
175	pNovW JunW JanT	-8.4	5	0.0003
176	pNovW JunW AugT	-9.2	5	0.0004
177	pNovW JanT AugT	-7.5	5	0.0002
178	JanW MarW JunW	-7.8	5	0.0002
179	JanW MarW JanT	-7.5	5	0.0002
180	JanW MarW AugT	-9.5	5	0.0005
181	JanW JunW JanT	-8.1	5	0.0002
182	JanW JunW AugT	-10.2	5	0.0007
183	JanW JanT AugT	-9.3	5	0.0004
184	MarW JunW JanT	-7.5	5	0.0002
185	MarW JunW AugT	-7.2	5	0.0002
186	MarW JanT AugT	-6.2	5	0.0001
187	JunW JanT AugT	-8.4	5	0.0003
188	MarW JunW JanT AugT	-5.6	6	0.0001
189	JanW JunW JanT AugT	-7.4	6	0.0002

Table A-1. (cont.)

Model Number	Model	AICC	k	Weight
190	JanW MarW JanT AugT	-6.7	6	0.0001
191	JanW MarW JunW JanT	-5.6	6	0.0001
192	JanW MarW JunW JanT	-5.6	6	0.0001
193	pNovW JunW JanT AugT	-6.9	6	0.0001
194	pNovW MarW JanT AugT	-5	6	0.0001
195	pNovW MarW JunW AugT	-6.5	6	0.0001
196	pNovW MarW JunW JanT	-5.8	6	0.0001
197	pNovW JanW JanT AugT	-7.3	6	0.0002
198	pNovW JanW JunW AugT	-8.2	6	0.0003
199	pNovW JanW JunW JanT	-6	6	0.0001
200	pNovW JanW MarW AugT	-7.4	6	0.0002
201	pNovW JanW MarW JanT	-5.4	6	0.0001
202	pNovW JanW MarW JunW	-5.9	6	0.0001
203	pSepW JunW JanT AugT	-11	6	0.0010
204	pSepW MarW JanT AugT	-8.8	6	0.0003
205	pSepW MarW JunW AugT	-10.6	6	0.0008
206	pSepW MarW JunW JanT	-10.6	6	0.0008
207	pSepW JanW JanT AugT	-11.7	6	0.0015
208	pSepW JanW JunW AugT	-13.2	6	0.0030
209	pSepW JanW JunW JanT	-10.5	6	0.0008
210	pSepW JanW MarW AugT	-12.7	6	0.0024
211	pSepW JanW MarW JanT	-10.5	6	0.0008
212	pSepW JanW MarW JunW	-11.3	6	0.0012
213	pSepW pNovW JanT AugT	-9.4	6	0.0004
214	pSepW pNovW JunW AugT	-12.2	6	0.0018
215	pSepW pNovW JunW JanT	-10.8	6	0.0009
216	pSepW pNovW MarW AugT	-9.9	6	0.0006
217	pSepW pNovW MarW JanT	-9.5	6	0.0005
218	pSepW pNovW MarW JunW	-10.6	6	0.0008
219	pSepW pNovW JanW AugT	-12.5	6	0.0021
220	pSepW pNovW JanW JanT	-9.3	6	0.0004
221	pSepW pNovW JanW JunW	-10.8	6	0.0009
222	pSepW pNovW JanW MarW	-11	6	0.0010
223	JanW MarW JunW JanT AugT	-4.5	7	0.0000
224	pNovW MarW JunW JanT AugT	-4	7	0.0000
225	pNovW JanW JunW JanT AugT	-5.2	7	0.0001
226	pNovW JanW MarW JanT AugT	-4.5	7	0.0000
227	pNovW JanW MarW JunW AugT	-5.3	7	0.0001
228	pNovW JanW MarW JunW JanT	-3.4	7	0.0000

Table A-1. (cont.)

Model Number	Model	AICC	k	Weight
229	pSepW MarW JunW JanT AugT	-8.7	7	0.0003
230	pSepW JanW JunW JanT AugT	-10.2	7	0.0007
231	pSepW JanW MarW JanT AugT	-9.8	7	0.0005
232	pSepW JanW MarW JunW AugT	-10.9	7	0.0009
233	pSepW JanW MarW JunW JanT	-8.8	7	0.0003
234	pSepW pNovW JunW JanT AugT	-9.6	7	0.0005
235	pSepW pNovW MarW JanT AugT	-7.6	7	0.0002
236	pSepW pNovW MarW JunW AugT	-9.8	7	0.0006
237	pSepW pNovW MarW JunW JanT	-8.9	7	0.0004
238	pSepW pNovW JanW JanT AugT	-9.6	7	0.0005
239	pSepW pNovW JanW JunW AugT	-11.1	7	0.0010
240	pSepW pNovW JanW JunW JanT	-8.3	7	0.0003
241	pSepW pNovW JanW MarW AugT	-10.5	7	0.0008
242	pSepW pNovW JanW MarW JanT	-8.3	7	0.0003
243	pSepW pNovW JanW MarW JunW	-9.3	7	0.0004
244	pNovW JanW MarW JunW JanT AugT	-2.1	8	0.0000
245	pSepW JanW MarW JunW JanT AugT	-7.7	8	0.0002
246	pSepW pNovW MarW JunW JanT AugT	-7	8	0.0001
247	pSepW pNovW JanW JunW JanT AugT	-7.9	8	0.0002
248	pSepW pNovW JanW MarW JanT AugT	-7.4	8	0.0002
249	pSepW pNovW JanW MarW JunW AugT	-8.5	8	0.0003
250	pSepW pNovW JanW MarW JunW JanT	-6.4	8	0.0001
251	pSepW pNovW JanW MarW JunW JanT AugT	-5.2	9	0.0001
252	pSepS	-9	3	0.0004
253	pNovS	-8.5	3	0.0003
254	pSepS pNovS	-8.8	4	0.0003
255	pSepS JanT	-10.2	4	0.0007
256	pSepS AugT	-9.7	4	0.0005
257	pSepS SepT	-7.4	4	0.0002
258	pNovS JanT	-8.4	4	0.0003
259	pNovS AugT	-8.6	4	0.0003
260	pNovS SepT	-6.3	4	0.0001
261	JanT SepT	-8	4	0.0002
262	AugT SepT	-7	4	0.0001
263	pSepS pNovS JanT	-8.6	5	0.0003
264	pSepS pNovS AugT	-9	5	0.0004
265	pSepS pNovS SepT	-6.7	5	0.0001
266	pSepS JanT AugT	-8.9	5	0.0003
267	pSepS JanT SepT	-8.6	5	0.0003

Table A-1. (cont.)

Model Number	Model	AICC	k	Weight
268	pSepS AugT SepT	-7.8	5	0.0002
269	pNovS JanT AugT	-6.9	5	0.0001
270	pNovS JanT SepT	-6.1	5	0.0001
271	pNovS AugT SepT	-6.1	5	0.0001
272	JanT AugT SepT	-6.3	5	0.0001
273	pSepS pNovS JanT AugT	-7.2	6	0.0001
274	pSepS pNovS JanT SepT	-6.5	6	0.0001
275	pSepS pNovS AugT SepT	-6.6	6	0.0001
276	pSepS JanT AugT SepT	-6.9	6	0.0001
277	pNovS JanT AugT SepT	-4.4	6	0.0000
278	pSepS pNovS JanT AugT SepT	-4.7	7	0.0000
279	pSepP JunT pSepP*JunT	-15.4	5	0.0091
280	pSepP JanT JunT pSepP*JanT	-15.6	7	0.0102
281	pSepP pNovT JunT pSepP*pNovT	-13.5	6	0.0035
282	pSepP JanT JunT pSepP*JunT	-12.5	7	0.0021
283	pSepP pNovT JunT pSepP*JunT	-14.4	6	0.0057
284	pSepP JanT JunT pSepP*JunT JanT*JunT pSepP*JanT	-13.8	8	0.0040
285	JanPET JunT JanPET*JunT	-12.6	5	0.0023
286	pSepW JanW AugT pSepW*JanW	-22.9	6	0.3878
287	pSepW JanW AugT pSepW*AugT	-12.9	6	0.0027
288	pSepW JanW AugT JanW*AugT	-14.5	6	0.0057
289	pSepW JanW AugT pSepW*JanW JanW*AugT	-20.4	7	0.1134
290	pSepW JanW AugT pSepW*JanW pSepW*AugT	-20.9	7	0.1437
291	pSepW JanW AugT pSepW*AugT JanW*AugT	-13.6	7	0.0037
292	pSepW JanW AugT pSepW*AugT JanW*AugT pSepW*JanW	-18.6	8	0.0461

Table A-2. Dendroclimatological models and model statistics for annual ring-width growth for sugar maple at the MEF. W = P-PET, T = temperature, S = soil moisture storage, P = precipitation

Model Number	Model	AICC	k	Weight
1	pNovP	-98.1	3	0.0039
2	SepP	-98.6	3	0.0049
3	pSepT	-97.7	3	0.0032
4	AprT	-98.2	3	0.0041
5	JulT	-98.4	3	0.0046
6	AugT	-96.9	3	0.0021
7	pNovP SepP	-98.1	4	0.0038
8	pNovP pSepT	-97.5	4	0.0028
9	pNovP AprT	-97.7	4	0.0031
10	pNovP JulT	-97.4	4	0.0027
11	pNovP AugT	-96.2	4	0.0015
12	SepP pSepT	-97.4	4	0.0028
13	SepP AprT	-97.9	4	0.0035
14	SepP JulT	-98.6	4	0.0049
15	SepP AugT	-96.6	4	0.0018
17	pSepT AprT	-97.8	4	0.0034
18	pSepT JulT	-96.3	4	0.0016
19	pSepT AugT	-100	4	0.0098
20	AprT JulT	-96.8	4	0.0020
21	AprT AugT	-96.2	4	0.0015
22	JulT AugT	-97.2	5	0.0025
23	pNovP SepP pSepT	-97.4	5	0.0026
24	pNovP SepP AprT	-97.6	5	0.0029
25	pNovP SepP JulT	-95.8	5	0.0012
26	pNovP SepP AugT	-97.1	5	0.0023
27	pNovP pSepT AprT	-97.1	5	0.0023
28	pNovP pSepT JulT	-95.8	5	0.0012
29	pNovP pSepT AugT	-98.7	5	0.0052
30	pNovP AprT JulT	-95.9	5	0.0013
31	pNovP AprT AugT	-95	5	0.0008
32	pNovP JulT AugT	-96.8	5	0.0020
33	SepP pSepT AprT	-97.8	5	0.0033
34	SepP pSepT JulT	-95.6	5	0.0011
35	SepP pSepT AugT	-99.9	5	0.0096
36	SepP AprT JulT	-96.1	5	0.0014
37	SepP AprT AugT	-96.1	5	0.0014
38	SepP JulT AugT	-99.8	5	0.0089

Table A-2. (cont.)

Model Number	Model	AICC	k	Weight
39	pSepT AprT JulT	-96.4	5	0.0017
40	pSepT AprT AugT	-95.7	5	0.0011
41	pSepT JulT AugT	-97.7	5	0.0031
42	AprT JulT AugT	-96.5	6	0.0017
43	pNovP SepP pSepT AprT	-96.9	6	0.0022
44	pNovP SepP pSepT JulT	-98.6	6	0.0050
45	pNovP SepP AprT JulT	-98.7	6	0.0053
46	pNovP pSepT AprT JulT	-99.5	6	0.0076
47	SepP pSepT AprT JulT	-95.1	6	0.0009
48	pNovP SepP pSepT AugT	-95.2	6	0.0009
49	pNovP SepP AprT AugT	-96.4	5	0.0017
50	AprT pSepT AprT AugT	-95.4	6	0.0010
51	SepP pSepT AprT AugT	-94.9	6	0.0008
52	pNovP SepP JulT AugT	-94.7	6	0.0007
53	pNovP pSepT JulT AugT	-95.2	6	0.0009
54	SepP pSepT JulT AugT	-96.2	6	0.0015
55	pNovP AprT JulT AugT	-97.3	6	0.0026
56	SepP AprT JulT AugT	-97.7	6	0.0031
57	pSepT AprT JulT AugT	-98.4	7	0.0044
58	pNovP SepP pSepT AprT JulT	-94.8	7	0.0007
59	pNovP SepP pSepT AprT AugT	-94.3	7	0.0006
60	pNovP SepP pSepT JulT AugT	-95.9	7	0.0013
61	pNovP SepP AprT JulT AugT	-96.5	7	0.0017
62	pNovP pSepT AprT JulT AugT	-97	7	0.0022
63	SepP pSepT AprT JulT AugT	-95.7	8	0.0012
64	pNovP SepP pSepT AprT JulT AugT	-100	3	0.0099
65	pNovT	-97.5	3	0.0029
66	pDecT	-99.9	3	0.0095
67	MarT	-98.1	4	0.0039
68	pNovT pDecT	-100.5	4	0.0127
69	pNovT MarT	-98.2	4	0.0041
70	pDecT MarT	-98.2	5	0.0041
71	pNovT pDecT MarT	-98.9	3	0.0057
73	SepW	-98.6	4	0.0050
74	pDecT	-98.6	4	0.0049
75	SepW pDecT	-98.2	4	0.0041
76	SepW MarT	-98.2	4	0.0041
77	SepW AprT	-96.6	4	0.0019
78	pDecT MarT	-97.8	4	0.0034

Table A-2. (cont.)

Model Number	Model	AICC	k	Weight
79	pDecT AprT	-97.4	5	0.0028
80	MarT AprT	-97.3	5	0.0026
81	SepW pDecT MarT	-96.6	5	0.0018
82	SepW pDecT AprT	-95.9	5	0.0013
83	SepW MarT AprT	-95.2	6	0.0009
84	pDecT MarT AprT	-98.2	3	0.0041
85	SepW pDecT MarT AprT	-100.3	3	0.0115
86	pNovS	-99.8	3	0.0091
88	pDecS	-96.5	3	0.0017
89	SepS	-97	3	0.0022
90	pSepT	-100.4	4	0.0121
91	JunT	-99.1	4	0.0064
92	SepT	-97.4	4	0.0027
93	pNovS pDecS	-99.1	4	0.0062
94	pNovS SepS	-98.2	4	0.0040
95	pNovS pSepT	-95.8	4	0.0012
96	pNovS MarT	-96.2	4	0.0015
97	pNovS AprT	-100.6	4	0.0135
98	pNovS JunT	-99.4	4	0.0073
99	pNovS SepT	-100.5	4	0.0127
100	pDecS SepS	-99.1	4	0.0062
101	pDecS pSepT	-99.1	4	0.0063
102	pDecS MarT	-98.7	4	0.0053
103	pDecS AprT	-98.8	4	0.0055
104	pDecS JunT	-99.1	4	0.0063
105	pDecS SepT	-98.9	4	0.0059
106	SepS pSepT	-98	4	0.0036
107	SepS MarT	-97.9	4	0.0035
108	SepS AprT	-99.8	4	0.0092
109	SepS JunT	-97.4	4	0.0027
110	SepS SepT	-95.5	4	0.0011
111	pSepT MarT	-96.5	4	0.0017
112	pSepT AprT	-97.7	4	0.0031
113	pSepT JunT	-98.1	4	0.0039
114	pSepT SepT	-96.2	4	0.0015
115	MarT JunT	-96.8	4	0.0020
116	MarT SepT	-94.6	4	0.0007
117	AprT JunT	-100.4	5	0.0119
118	AprT SepT	-99.6	5	0.0080

Table A-2. (cont.)

Model Number	Model	AICC	k	Weight
119	JunT SepT	-100.1	5	0.0103
120	pNovS pDecS SepS	-99.4	5	0.0075
121	pNovS pDecS pSepT	-98.2	5	0.0041
122	pNovS pDecS MarT	-98.4	5	0.0044
123	pNovS pDecS AprT	-98.2	5	0.0040
124	pNovS pDecS JunT	-98.1	5	0.0038
125	pNovS pDecS SepT	-98.6	5	0.0048
126	pNovS SepS pSepT	-96.7	5	0.0019
127	pNovS SepS MarT	-96.9	5	0.0021
128	pNovS SepS AprT	-99	5	0.0061
129	pNovS SepS JunT	-97.4	5	0.0028
130	pNovS SepS SepT	-94.8	5	0.0007
131	pNovS pSepT MarT	-95.7	5	0.0011
132	pNovS pSepT AprT	-97.1	5	0.0024
133	pNovS pSepT JunT	-96.5	5	0.0017
134	pNovS pSepT SepT	-96.5	5	0.0017
135	pNovS MarT AprT	-96.9	5	0.0021
136	pNovS MarT JunT	-95.7	5	0.0012
137	pNovS MarT JunT	-96.3	5	0.0015
138	pNovS MarT SepT	-93.7	5	0.0004
139	pNovS AprT JunT	-99.6	5	0.0080
140	pNovS AprT SepT	-99.3	5	0.0070
141	pNovS JunT SepT	-99.1	5	0.0062
142	pDecS SepS pSepT	-99.9	5	0.0095
143	pDecS SepS MarT	-98.8	5	0.0054
144	pDecS SepS AprT	-100.3	5	0.0114
145	pDecS SepS JunT	-98.1	5	0.0039
146	pDecS SepS SepT	-98.2	5	0.0041
147	pDecS pSepT MarT	-98.3	5	0.0043
148	pDecS pSepT AprT	-98.1	5	0.0039
149	pDecS pSepT JunT	-99	5	0.0061
150	pDecS pSepT SepT	-98.7	5	0.0053
151	pDecS MarT AprT	-98	5	0.0037
152	pDecS MarT JunT	-97.6	5	0.0030
153	pDecS MarT SepT	-97	5	0.0022
154	pDecS AprT JunT	-98.7	5	0.0051
155	pDecS AprT SepT	-98	5	0.0036
156	pDecS JunT SepT	-97	5	0.0022
157	SepS pSepT MarT	-97.3	5	0.0026

Table A-2. (cont.)

Model Number	Model	AICC	k	Weight
158	SepS pSepT AprT	-97.1	5	0.0023
159	SepS pSepT JunT	-97	5	0.0023
160	SepS pSepT SepT	-97.1	5	0.0023
161	SepS MarT AprT	-97.3	5	0.0026
162	SepS MarT JunT	-97.2	5	0.0024
163	SepS MarT SepT	-95.7	5	0.0012
164	SepS AprT JunT	-97.6	5	0.0029
165	SepS AprT SepT	-97.6	5	0.0030
166	SepS JunT SepT	-98.6	5	0.0050
167	pSepT MarT AprT	-95.3	5	0.0010
168	pSepT MarT JunT	-96.5	5	0.0017
169	pSepT MarT SepT	-94	5	0.0005
170	pSepT AprT JunT	-95.6	5	0.0011
171	pSepT AprT SepT	-96	5	0.0014
172	pSepT JunT SepT	-94.4	5	0.0006
173	MarT AprT JunT	-99.4	6	0.0074
174	MarT AprT SepT	-98.7	6	0.0051
175	AprT JunT SepT	-99	6	0.0061
176	pNovS pDecS SepS pSepT	-98.5	6	0.0047
177	pNovS pDecS SepS MarT	-98.1	6	0.0038
178	pNovS pDecS SepS AprT	-99.9	6	0.0095
179	pNovS pDecS SepS JunT	-98.6	6	0.0050
180	pNovS pDecS SepS SepT	-97.4	6	0.0027
181	pNovS pDecS pSepT MarT	-97.9	6	0.0035
182	pNovS pDecS pSepT AprT	-97.8	6	0.0033
183	pNovS pDecS pSepT JunT	-97.8	6	0.0033
184	pNovS pDecS pSepT SepT	-97.9	6	0.0034
185	pNovS pDecS MarT AprT	-97.3	6	0.0026
186	pNovS pDecS MarT JunT	-97.4	6	0.0028
187	pNovS pDecS MarT SepT	-95.9	6	0.0013
188	pNovS pDecS AprT JunT	-97.7	6	0.0031
189	pNovS pDecS AprT SepT	-97.7	6	0.0031
190	pNovS pDecS JunT SepT	-95.6	6	0.0011
191	pNovS SepS pSepT MarT	-96.2	6	0.0015
192	pNovS SepS pSepT AprT	-96.3	6	0.0016
193	pNovS SepS pSepT JunT	-95.5	6	0.0010
194	pNovS SepS pSepT SepT	-95.7	6	0.0012
195	pNovS SepS MarT AprT	-96.1	6	0.0014
196	pNovS SepS MarT JunT	-96.4	6	0.0016

Table A-2. (cont.)

Model Number	Model	AICC	k	Weight
197	pNovS SepS MarT SepT	-96.9	5	0.0021
198	pNovS SepS AprT JunT	-96.9	6	0.0021
199	pNovS SepS AprT SepT	-96.4	6	0.0016
200	pNovS SepS SepT SepT	-97.3	6	0.0026
201	pNovS pSepT MarT AprT	-94.8	6	0.0007
202	pNovS pSepT MarT JunT	-96	6	0.0013
203	pNovS pSepT MarT SepT	-93	6	0.0003
204	pNovS pSepT AprT JunT	-94.5	6	0.0006
205	pNovS pSepT AprT SepT	-95	6	0.0008
206	pNovS pSepT JunT SepT	-94.2	6	0.0006
207	pNovS MarT AprT JunT	-93.6	6	0.0004
208	pNovS MarT AprT SepT	-98.7	6	0.0053
209	pNovS MarT JunT SepT	-98	6	0.0037
210	pNovS AprT JunT SepT	-99	6	0.0059
211	pDecS SepS pSepT MarT	-98.2	6	0.0040
212	pDecS SepS pSepT AprT	-96.9	6	0.0021
213	pDecS SepS pSepT JunT	-98.2	6	0.0040
214	pDecS SepS pSepT SepT	-97.3	6	0.0025
215	pDecS SepS MarT AprT	-98.5	6	0.0047
216	pDecS SepS MarT JunT	-97.3	6	0.0025
217	pDecS SepS AprT SepT	-97.5	6	0.0029
218	pDecS SepS AprT JunT	-97.7	6	0.0032
219	pDecS SepS AprT SepT	-98.9	6	0.0057
220	pDecS SepS JunT SepT	-99.1	6	0.0065
221	pDecS pSepT MarT AprT	-97.2	6	0.0024
222	pDecS pSepT MarT JunT	-97.3	6	0.0026
223	pDecS pSepT MarT SepT	-96.5	6	0.0017
224	pDecS pSepT AprT JunT	-96.7	6	0.0019
225	pDecS pSepT AprT SepT	-96.3	6	0.0016
226	pDecS pSepT JunT SepT	-96.8	6	0.0020
227	pDecS MarT AprT JunT	-96	6	0.0013
228	pDecS MarT AprT SepT	-96.4	6	0.0017
229	pDecS MarT JunT SepT	-96.6	6	0.0018
230	pDecS AprT JunT SepT	-97.2	6	0.0024
231	SepS pSepT MarT AprT	-96.3	6	0.0016
232	SepS pSepT MarT JunT	-96.7	6	0.0019
233	SepS pSepT MarT SepT	-95	6	0.0008
234	SepS pSepT AprT JunT	-95.1	6	0.0009
235	SepS pSepT AprT SepT	-95.1	6	0.0009

Table A-2. (cont.)

Model Number	Model	AICC	k	Weight
236	SepS pSepT JunT SepT	-94.7	6	0.0007
237	SepS MarT AprT JunT	-95.1	6	0.0008
238	SepS MarT AprT SepT	-95.3	6	0.0009
239	SepS MarT JunT SepT	-96	5	0.0014
240	SepS AprT JunT SepT	-93.5	6	0.0004
241	pSepT MarT AprT JunT	-94	6	0.0005
242	MarT MarT AprT SepT	-93.5	6	0.0004
243	AprT MarT JunT SepT	-93.7	7	0.0004
244	pSepT AprT JunT SepT	-92.7	7	0.0003
245	MarT AprT JunT SepT	-94.5	7	0.0006
246	pSepT MarT AprT JunT SepT	-94.6	7	0.0007
247	SepS MarT AprT JunT SepT	-95	7	0.0008
248	SepS pSepT AprT JunT SepT	-94.4	7	0.0006
249	SepS pSepT MarT JunT SepT	-94.4	7	0.0006
250	SepS pSepT MarT AprT SepT	-95.6	7	0.0011
251	SepS pSepT MarT AprT JunT	-97.1	7	0.0024
252	pDecS MarT AprT JunT SepT	-96.6	7	0.0018
253	pDecS pSepT AprT JunT SepT	-96.3	7	0.0016
254	pDecS pSepT MarT JunT SepT	-96.1	7	0.0014
255	pDecS pSepT MarT AprT SepT	-95.7	7	0.0011
256	pDecS pSepT MarT AprT JunT	-94.9	7	0.0008
257	pDecS SepS AprT JunT SepT	-96	7	0.0013
258	pDecS SepS MarT JunT SepT	-96.8	7	0.0020
259	pDecS SepS MarT AprT SepT	-96.8	7	0.0020
260	pDecS SepS MarT AprT JunT	-97.6	7	0.0030
261	pDecS SepS pSepT JunT SepT	-97.3	7	0.0026
262	pDecS SepS pSepT AprT SepT	-97.7	7	0.0031
263	pDecS SepS pSepT AprT JunT	-96.1	7	0.0015
264	pDecS SepS pSepT MarT SepT	-92.2	7	0.0002
265	pDecS SepS pSepT MarT JunT	-93.1	7	0.0003
266	pDecS SepS pSepT MarT AprT	-94.5	7	0.0006
267	pNovS MarT AprT JunT SepT	-95.2	7	0.0009
268	pNovS pSepT AprT JunT SepT	-95.2	7	0.0009
269	pNovS pSepT MarT JunT SepT	-93.7	7	0.0004
270	pNovS pSepT MarT AprT SepT	-92.9	7	0.0003
271	pNovS pSepT MarT AprT SepT	-95.7	6	0.0012
272	pNovS SepS AprT JunT SepT	-95.5	6	0.0010
273	pNovS SepS MarT JunT SepT	-93.4	7	0.0004
274	pNovS SepS MarT MarT SepT	-95.8	7	0.0012

Table A-2. (cont.)

Model Number	Model	AICC	k	Weight
275	pNovS SepS MarT MarT JunT	-95.1	7	0.0009
276	pNovS SepS pSepT JunT SepT	-95.7	7	0.0012
277	pNovS SepS pSepT AprT SepT	-95	7	0.0008
278	pNovS SepS pSepT AprT JunT	-95.6	7	0.0011
279	pNovS SepS pSepT MarT SepT	-95	7	0.0008
280	pNovS SepS pSepT MarT JunT	-95.3	7	0.0010
281	pNovS SepS pSepT MarT AprT	-95.6	7	0.0011
282	pNovS pDecS AprT JunT SepT	-95.5	7	0.0010
283	pNovS pDecS MarT JunT SepT	-95.4	7	0.0010
284	pNovS pDecS MarT AprT SepT	-97.1	7	0.0024
285	pNovS pDecS MarT AprT JunT	-96.5	7	0.0017
286	pNovS pDecS pSepT JunT SepT	-98.2	7	0.0041
287	pNovS pDecS pSepT AprT SepT	-97.6	7	0.0030
288	pNovS pDecS pSepT AprT JunT	-97.4	7	0.0028
289	pNovS pDecS pSepT MarT SepT	-95.9	7	0.0013
290	pNovS pDecS pSepT MarT JunT	-96.8	7	0.0020
291	pNovS pDecS pSepT MarT AprT	-97.2	7	0.0024
292	pNovS pDecS SepS JunT SepT	-96.3	7	0.0015
293	pNovS pDecS SepS AprT SepT	-96.6	7	0.0018
294	pNovS pDecS SepS AprT JunT	-96.5	7	0.0017
295	pNovS pDecS SepS MarT SepT	-97.5	7	0.0029
296	pNovS pDecS SepS MarT JunT	-97.5	7	0.0029
297	pNovS pDecS SepS MarT AprT	-98.1	7	0.0038
298	pNovS pDecS SepS pSepT JunT	-98.2	7	0.0040
299	pNovS pDecS SepS pSepT JunT	-92.4	8	0.0002
300	pNovS pDecS SepS pSepT AprT	-94.5	8	0.0006
301	pNovS pDecS SepS pSepT MarT	-93.4	8	0.0004
302	SepS pSepT MarT AprT JunT SepT	-95.6	7	0.0011
303	pDecS pSepT MarT AprT JunT SepT	-96.8	6	0.0020
304	pDecS SepS MarT AprT JunT SepT	-96.3	6	0.0016
305	pDecS pSepT pSepT AprT JunT SepT	-96.7	6	0.0019
306	pDecS MarT MarT MarT JunT SepT	-92.2	8	0.0002
307	pDecS AprT AprT MarT AprT SepT	-91	8	0.0001
308	pDecS JunT JunT MarT AprT JunT	-93	8	0.0003
309	pNovS pSepT MarT AprT JunT SepT	-92.8	8	0.0003
310	pNovS SepS MarT AprT JunT SepT	-93.7	8	0.0004
311	pNovS SepS pSepT AprT JunT SepT	-92.9	8	0.0003
312	pNovS SepS pSepT MarT JunT SepT	-92.9	8	0.0003
313	pNovS SepS pSepT MarT AprT SepT	-94.6	8	0.0007

Table A-2. (cont.)

Model Number	Model	AICC	k	Weight
314	pNovS SepS pSepT MarT AprT JunT	-95.5	8	0.0011
315	pNovS pDecS MarT AprT JunT SepT	-95.7	8	0.0012
316	pNovS pDecS pSepT AprT JunT SepT	-95	8	0.0008
317	pNovS pDecS pSepT MarT JunT SepT	-94.5	8	0.0006
318	pNovS pDecS pSepT MarT AprT SepT	-93.8	8	0.0005
319	pNovS pDecS pSepT MarT AprT JunT	-94	8	0.0005
320	pNovS pDecS SepS AprT JunT SepT	-94.4	8	0.0006
321	pNovS pDecS SepS MarT JunT SepT	-95.2	8	0.0009
322	pNovS pDecS SepS MarT AprT SepT	-96.3	8	0.0015
323	pNovS pDecS SepS MarT AprT JunT	-96.3	8	0.0015
324	pNovS pDecS SepS pSepT JunT SepT	-96.2	8	0.0015
325	pNovS pDecS SepS pSepT AprT SepT	-96	8	0.0014
326	pNovS pDecS SepS pSepT AprT JunT	-95.7	8	0.0012
327	pNovS pDecS SepS pSepT MarT SepT	-93	9	0.0003
328	pNovS pDecS SepS pSepT MarT JunT	-90.6	9	0.0001
329	pNovS pDecS SepS pSepT MarT AprT	-92.9	9	0.0003
330	pDecS SepS pSepT MarT AprT JunT SepT	-91.5	9	0.0001
331	pNovS SepS pSepT MarT AprT JunT SepT	-93.9	9	0.0005
332	pNovS pDecS pSepT MarT AprT JunT SepT	-93.6	9	0.0004
333	pNovS pDecS SepS MarT AprT JunT SepT	-93.7	9	0.0004
334	pNovS pDecS SepS pSepT AprT JunT SepT	-93.6	9	0.0004
335	pNovS pDecS SepS pSepT MarT JunT SepT	-91	10	0.0001
336	pNovS pDecS SepS pSepT MarT AprT SepT	-98.2	5	0.0041
337	pNovS pDecS SepS pSepT MarT AprT JunT	-98.2	5	0.0040
338	pNovS pDecS SepS pSepT MarT AprT JunT SepT	-98.4	5	0.0045
339	pDecS SepS pDecS*SepS	-100.6	5	0.0134
340	pNovS pDecS SepS pNovS*pDecS	-100	6	0.0098
341	pNovS pDecS SepS pNovS*SepS	-100.2	6	0.0109
342	pNovS pDecS SepS pDecS*SepS	-97.7	6	0.0032
343	pNovS pDecS SepS pNovS*pDecS pDecS*SepS	-97.2	7	0.0024
344	pNovS pDecS SepS pNovS*pDecS pNovS*SepS	-100.3	7	0.0119
345	pNovS pDecS SepS pNovS*SepS pDecS*SepS	-97.4	7	0.0027
346	pNovS pDecS SepS pNovS*SepS pDecS*SepS pNovS*pDecS	-97.5	8	0.0028

Table A- 3. Dendroclimatological models and model statistics for annual ring-width growth for red pine at the MEF. W = P-PET, T = temperature, S = soil moisture storage, P = precipitation

Model Number	Model	AICC	k	Weight
1	MayP	-63.4	3	0.0021
2	JulP	-64.3	3	0.0033
3	FebT	-62.4	3	0.0013
4	MarT	-62.8	3	0.0015
5	JunT	-63.7	3	0.0025
6	MayP JulP	-64	4	0.0028
7	MayP FebT	-63	4	0.0017
8	MayP MarT	-63.5	4	0.0022
9	MayP JunT	-63.5	4	0.0022
10	JulP FebT	-64.3	4	0.0032
11	JulP MarT	-64.5	4	0.0036
12	JulP JunT	-65	4	0.0047
13	FebT MarT	-61.9	4	0.0010
14	FebT JunT	-64.2	4	0.0031
15	MarT JunT	-64.7	4	0.0039
16	MayP JulP FebT	-63.4	5	0.0021
17	MayP JulP MarT	-63.7	5	0.0025
18	MayP JulP JunT	-63.7	5	0.0024
19	MayP FebT MarT	-62.1	5	0.0011
20	MayP FebT JunT	-63.3	5	0.0019
21	MayP MarT JunT	-63.8	5	0.0026
22	JulP FebT MarT	-63.3	5	0.0020
23	JulP FebT JunT	-65.1	5	0.0048
24	JulP MarT JunT	-65.4	5	0.0056
25	FebT MarT JunT	-63.7	5	0.0025
26	MayP JulP FebT MarT	-62.2	6	0.0011
27	MayP JulP FebT JunT	-63.2	6	0.0019
28	MayP JulP MarT JunT	-63.6	6	0.0023
29	MayP FebT MarT JunT	-62.5	6	0.0013
30	JulP FebT MarT JunT	-64.2	6	0.0031
31	MayP JulP FebT MarT JunT	-62.1	7	0.0011
32	pSepPET	-60.3	3	0.0004
33	JunPET	-67.1	3	0.0130
34	JulPET	-68.9	3	0.0325
35	pSepPET JunPET	-65.3	4	0.0055
36	pSepPET JulPET	-66.7	4	0.0106
37	JunPET JulPET	-68.5	4	0.0268

Table A-3. (cont.)

Model Number	Model	AICC	k	Weight
38	pSepPET JunPET JulPET	-66.3	5	0.0088
39	AprW	-60.4	3	0.0005
40	MayW	-65.7	3	0.0067
41	JulW	-61.9	3	0.0010
42	JulT	-64.1	3	0.0029
43	AprW MayW	-63.8	4	0.0026
44	AprW JulW	-60.6	4	0.0005
45	AprW FebT	-62.7	4	0.0015
46	AprW MarT	-61.4	4	0.0008
47	AprW JunT	-61.5	4	0.0008
48	AprW JulT	-61.9	4	0.0010
49	MayW JulW	-64.6	4	0.0038
50	MayW FebT	-65.1	4	0.0049
51	MayW MarT	-66.5	4	0.0100
52	MayW JunT	-65.8	4	0.0069
53	MayW JulT	-67.4	4	0.0155
54	JulW FebT	-62.1	4	0.0011
55	JulW MarT	-62.2	4	0.0012
56	JulW JunT	-63.4	4	0.0021
57	JulW JulT	-64.1	4	0.0030
58	FebT JulT	-64.8	4	0.0042
59	MarT JulT	-65.2	4	0.0050
60	JunT JulT	-63.3	4	0.0020
61	AprW MayW JulW	-62.9	5	0.0016
62	AprW MayW FebT	-64.7	5	0.0040
63	AprW MayW MarT	-65	5	0.0046
64	AprW MayW JunT	-63.5	5	0.0021
65	AprW MayW JulT	-65	5	0.0047
66	AprW JulW FebT	-63.2	5	0.0019
67	AprW JulW MarT	-61.2	5	0.0007
68	AprW JulW JunT	-61.3	5	0.0007
69	AprW JulW JulT	-62.1	5	0.0011
70	AprW FebT MarT	-62.2	5	0.0012
71	AprW FebT JunT	-63.3	5	0.0020
72	AprW MarT JunT	-62.6	5	0.0014
73	AprW MarT JulT	-63.2	5	0.0018
74	AprW MarT JulT	-63.2	5	0.0018
75	AprW JunT JulT	-60.9	5	0.0006
76	MayW JulW FebT	-63.9	5	0.0026

Table A-3. (cont.)

Model Number	Model	AICC	k	Weight
77	MayW JulW MarT	-65	5	0.0047
78	MayW JulW JunT	-64.6	5	0.0038
79	MayW JulW JulT	-66.4	5	0.0092
80	MayW FebT MarT	-64.9	5	0.0043
81	MayW FebT JunT	-65.3	5	0.0054
82	MayW FebT JulT	-67.1	5	0.0133
83	MayW MarT JunT	-66.7	5	0.0111
84	MayW MarT JulT	-68.6	5	0.0281
85	MayW JunT JulT	-65.6	5	0.0062
86	JulW FebT MarT	-61.2	5	0.0007
87	JulW FebT JunT	-63.6	5	0.0023
88	JulW FebT JulT	-64.7	5	0.0039
89	JulW MarT JunT	-63.9	5	0.0026
90	JulW MarT JulT	-64.7	5	0.0041
91	JulW JunT JulT	-63.1	5	0.0018
92	FebT MarT JulT	-64.5	5	0.0036
93	FebT JunT JulT	-63.9	5	0.0027
94	MarT JunT JulT	-64.4	5	0.0034
95	FebT MarT JunT JulT	-63.5	6	0.0022
96	JulW MarT JunT JulT	-63.7	6	0.0024
97	JulW FebT JunT JulT	-63.5	6	0.0022
98	JulW FebT MarT JunT	-62.8	6	0.0016
99	JulW FebT MarT JunT	-62.8	6	0.0016
100	MayW MarT JunT JulT	-66.7	6	0.0109
101	MayW FebT JunT JulT	-65.2	6	0.0051
102	MayW FebT MarT JulT	-67	6	0.0128
103	MayW FebT MarT JunT	-65	6	0.0047
104	MayW JulW JunT JulT	-64.4	6	0.0034
105	MayW JulW MarT JulT	-67.2	6	0.0136
106	MayW JulW MarT JunT	-65.1	6	0.0049
107	MayW JulW FebT JulT	-66	6	0.0075
108	MayW JulW FebT JunT	-63.9	6	0.0027
109	MayW JulW FebT MarT	-63.2	6	0.0019
110	AprW MarT JunT JulT	-62	6	0.0010
111	AprW FebT JunT JulT	-62.7	6	0.0015
112	AprW FebT MarT JulT	-63.9	6	0.0026
113	AprW FebT MarT JunT	-62.9	6	0.0016
114	AprW JulW JunT JulT	-60.7	6	0.0005
115	AprW JulW MarT JulT	-63	6	0.0017

Table A-3. (cont.)

Model Number	Model	AICC	k	Weight
116	AprW JulW MarT JunT	-62	6	0.0010
117	AprW JulW FebT JulT	-64.7	6	0.0039
118	AprW JulW FebT JunT	-63.3	6	0.0020
119	AprW JulW FebT MarT	-62.3	6	0.0012
120	AprW MayW JunT JulT	-63	6	0.0017
121	AprW MayW MarT JulT	-66.4	6	0.0094
122	AprW MayW MarT JunT	-64.6	6	0.0037
123	AprW MayW FebT JulT	-65.9	6	0.0073
124	AprW MayW FebT JunT	-64	6	0.0029
125	AprW MayW FebT MarT	-64.5	6	0.0036
126	AprW MayW JulW JulT	-64.1	6	0.0029
127	AprW MayW JulW JunT	-62.3	6	0.0012
128	AprW MayW JulW MarT	-63.7	6	0.0024
129	AprW MayW JulW FebT	-64	6	0.0029
130	JulW FebT MarT JunT JulT	-62.7	7	0.0015
131	MayW FebT MarT JunT JulT	-65	7	0.0047
132	MayW JulW MarT JunT JulT	-65.1	7	0.0048
133	MayW JulW FebT JunT JulT	-63.9	7	0.0026
134	MayW JulW FebT MarT JulT	-65.5	7	0.0059
135	MayW JulW FebT MarT JunT	-63.3	7	0.0020
136	AprW FebT MarT JunT JulT	-62.3	7	0.0012
137	AprW JulW MarT JunT JulT	-61.4	7	0.0008
138	AprW JulW FebT JunT JulT	-62.8	7	0.0015
139	AprW JulW FebT MarT JulT	-63.9	7	0.0027
140	AprW JulW FebT MarT JunT	-62.5	7	0.0013
141	AprW MayW MarT JunT JulT	-64.2	7	0.0031
142	AprW MayW FebT JunT JulT	-63.6	7	0.0023
143	AprW MayW FebT MarT JulT	-65.8	7	0.0069
144	AprW MayW FebT MarT JunT	-63.8	7	0.0025
145	AprW MayW JulW JunT JulT	-61.8	7	0.0009
146	AprW MayW JulW MarT JulT	-65.1	7	0.0048
147	AprW MayW JulW MarT JunT	-63	7	0.0017
148	AprW MayW JulW FebT JulT	-65.2	7	0.0052
149	AprW MayW JulW FebT JunT	-63.1	7	0.0018
150	AprW MayW JulW FebT MarT	-63.4	7	0.0021
151	MayW JulW FebT MarT JunT JulT	-63.3	8	0.0019
152	AprW JulW FebT MarT JunT JulT	-61.9	8	0.0010
153	AprW MayW FebT MarT JunT JulT	-63.3	8	0.0020
154	AprW MayW JulW MarT JunT JulT	-62.6	8	0.0014

Table A-3. (cont.)

Model Number	Model	AICC	k	Weight
155	AprW MayW JulW FebT JunT JulT	-62.7	8	0.0014
156	AprW MayW JulW FebT MarT JulT	-64.7	8	0.0040
157	AprW MayW JulW FebT MarT JunT	-62.4	8	0.0013
158	AprW MayW JulW FebT MarT JunT JulT	-62	9	0.0010
159	JanS	-60.7	3	0.0006
160	MarS	-63.1	3	0.0018
161	MayS	-65	3	0.0045
162	SepT	-60.2	3	0.0004
163	JanS MarS	-61.7	4	0.0009
164	JanS MayS	-63.7	4	0.0024
165	JanS FebT	-60.5	4	0.0005
166	JanS MarT	-60.6	4	0.0005
167	JanS JunT	-62	4	0.0010
168	JanS SepT	-58.9	4	0.0002
169	MarS MayS	-65.5	4	0.0059
170	MarS FebT	-63.4	4	0.0021
171	MarS MarT	-65.2	4	0.0052
172	MarS JunT	-64.1	4	0.0030
173	MarS SepT	-60.7	4	0.0005
174	MayS FebT	-64.4	4	0.0034
175	MayS MarT	-65.7	4	0.0067
176	MayS JunT	-65.1	4	0.0048
177	MayS SepT	-63.6	4	0.0023
178	FebT SepT	-60.9	4	0.0006
179	MarT SepT	-60.7	4	0.0005
180	JunT SepT	-61.4	4	0.0008
181	JanS MarS MayS	-64.1	5	0.0030
182	JanS MarS FebT	-61.4	5	0.0007
183	JanS MarS MarT	-62.9	5	0.0016
184	JanS MarS JunT	-62.4	5	0.0012
185	JanS MarS SepT	-59.2	5	0.0003
186	JanS MayS FebT	-62.5	5	0.0013
187	JanS MayS MarT	-63.5	5	0.0022
188	JanS MayS JunT	-63.4	5	0.0021
189	JanS MayS SepT	-62.3	5	0.0012
190	JanS FebT MarT	-59.5	5	0.0003
191	JanS FebT JunT	-61.9	5	0.0010
192	JanS MarT JunT	-62.2	5	0.0011
193	JanS MarT SepT	-58.5	5	0.0002

Table A-3. (cont.)

Model Number	Model	AICC	k	Weight
194	JanS MarT SepT	-58.5	5	0.0002
195	JanS JunT SepT	-59.6	5	0.0003
196	MarS MayS FebT	-64.9	5	0.0044
197	MarS MayS MarT	-67.7	5	0.0178
198	MarS MayS JunT	-65.1	5	0.0050
199	MarS MayS SepT	-63.2	5	0.0019
200	MarS FebT MarT	-64	5	0.0029
201	MarS FebT JunT	-64.5	5	0.0036
202	MarS FebT SepT	-61.1	5	0.0006
203	MarS MarT JunT	-66.4	5	0.0094
204	MarS MarT SepT	-62.7	5	0.0014
205	MarS JunT SepT	-61.6	5	0.0008
206	MayS FebT MarT	-64.1	5	0.0029
207	MayS FebT JunT	-64.6	5	0.0039
208	MayS FebT SepT	-63.3	5	0.0020
209	MayS MarT JunT	-66	5	0.0077
210	MayS MarT SepT	-64.1	5	0.0029
211	MayS JunT SepT	-62.9	5	0.0016
212	FebT MarT SepT	-60	5	0.0004
213	FebT JunT SepT	-61.9	5	0.0010
214	MarT JunT SepT	-62.1	5	0.0011
215	FebT MarT JunT SepT	-61.2	6	0.0007
216	MayS MarT JunT SepT	-63.6	6	0.0023
217	MayS FebT JunT SepT	-62.6	6	0.0014
218	MayS FebT MarT JunT	-64.4	6	0.0034
219	MayS FebT MarT JunT	-64.4	6	0.0034
220	MarS MarT JunT SepT	-63.8	6	0.0026
221	MarS FebT JunT SepT	-61.8	6	0.0009
222	MarS FebT MarT SepT	-61.4	6	0.0008
223	MarS FebT MarT JunT	-65.2	6	0.0051
224	MarS MayS JunT SepT	-62.5	6	0.0013
225	MarS MayS MarT SepT	-65.1	6	0.0048
226	MarS MayS MarT JunT	-67.4	6	0.0154
227	MarS MayS FebT SepT	-62.8	6	0.0015
228	MarS MayS FebT JunT	-64.6	6	0.0039
229	MarS MayS FebT MarT	-65.8	6	0.0068
230	JanS MarT JunT SepT	-59.5	6	0.0003
231	JanS FebT JunT SepT	-59.5	6	0.0003
232	JanS FebT MarT SepT	-57.5	6	0.0001

Table A-3. (cont.)

Model Number	Model	AICC	k	Weight
233	JanS FebT MarT JunT	-61	6	0.0006
234	JanS MayS JunT SepT	-61.2	6	0.0007
235	JanS MayS MarT SepT	-61.9	6	0.0010
236	JanS MayS MarT JunT	-63.5	6	0.0022
237	JanS MayS FebT SepT	-61.4	6	0.0008
238	JanS MayS FebT JunT	-62.3	6	0.0012
239	JanS MayS FebT MarT	-61.6	6	0.0008
240	JanS MarS JunT SepT	-59.6	6	0.0003
241	JanS MarS MarT SepT	-60.2	6	0.0004
242	JanS MarS MarT JunT	-63.8	6	0.0025
243	JanS MarS FebT SepT	-58.9	6	0.0002
244	JanS MarS FebT JunT	-62.1	6	0.0011
245	JanS MarS FebT MarT	-61.4	6	0.0008
246	JanS MarS MayS SepT	-61.8	6	0.0010
247	JanS MarS MayS JunT	-63.4	6	0.0020
248	JanS MarS MayS MarT	-65.2	6	0.0052
249	JanS MarS MayS FebT	-62.9	6	0.0016
250	MayS FebT MarT JunT SepT	-62	7	0.0010
251	MarS FebT MarT JunT SepT	-62.3	7	0.0012
252	MarS MayS MarT JunT SepT	-64.5	7	0.0036
253	MarS MayS FebT JunT SepT	-61.9	7	0.0010
254	MarS MayS FebT MarT SepT	-63.2	7	0.0018
255	MarS MayS FebT MarT JunT	-65.5	7	0.0059
256	JanS FebT MarT JunT SepT	-58.3	7	0.0002
257	JanS MayS MarT JunT SepT	-61	7	0.0006
258	JanS MayS FebT JunT SepT	-60.3	7	0.0004
259	JanS MayS FebT MarT SepT	-60.1	7	0.0004
260	JanS MayS FebT MarT JunT	-61.6	7	0.0008
261	JanS MarS MarT JunT SepT	-61	7	0.0006
262	JanS MarS FebT JunT SepT	-59.2	7	0.0003
263	JanS MarS FebT MarT SepT	-58.6	7	0.0002
264	JanS MarS FebT MarT JunT	-62.3	7	0.0012
265	JanS MarS MayS JunT SepT	-60.6	7	0.0005
266	JanS MarS MayS MarT SepT	-62.5	7	0.0014
267	JanS MarS MayS MarT JunT	-64.7	7	0.0039
268	JanS MarS MayS FebT SepT	-60.7	7	0.0005
269	JanS MarS MayS FebT JunT	-62.2	7	0.0011
270	JanS MarS MayS FebT MarT	-63	7	0.0017
271	MarS MayS FebT MarT JunT SepT	-62.4	8	0.0013

Table A-3. (cont.)

Model Number	Model	AICC	k	Weight
272	JanS MayS FebT MarT JunT SepT	-59.1	8	0.0002
273	JanS MarS FebT MarT JunT SepT	-59.3	8	0.0003
274	JanS MarS MayS MarT JunT SepT	-61.6	8	0.0008
275	JanS MarS MayS FebT JunT SepT	-59.4	8	0.0003
276	JanS MarS MayS FebT MarT SepT	-60.3	8	0.0004
277	JanS MarS MayS FebT MarT JunT	-62.5	8	0.0013
278	JanS MarS MayS FebT MarT JunT SepT	-59.2	9	0.0003
279	MayW MarT JulT MayW*MarT	-66	6	0.0078
280	MayW MarT JulT MayW*JulT	-66.4	6	0.0093
281	MayW MarT JulT MarT*JulT	-66.4	6	0.0093
282	MayW MarT JulT MayW*MarT MarT*JulT	-63.7	7	0.0025
283	MayW MarT JulT MayW*MarT MayW*JulT	-63.6	7	0.002279111
284	MayW MarT JulT MayW*JulT MarT*JulT	-64.1	7	0.002938209
285	MayW MarT JulT MayW*JulT MarT*JulT MayW*MarT	-61.2	8	0.000678367
286	JunPET JulPET JunPET*JulPET	-66	5	0.007805798
287	MarS MayS MarT MarS*MayS	-66.3	6	0.008860441
288	MarS MayS MarT MarS*MarT	-67.9	6	0.0193757
289	MarS MayS MarT MayS*MarT	-65	6	0.004526512
290	MarS MayS MarT MarS*MayS MayS*MarT	-63.5	7	0.00217929
291	MarS MayS MarT MarS*MayS MarS*MarT	-66	7	0.007625133
292	MarS MayS MarT MarS*MarT MayS*MarT	-65	7	0.004559452
293	MarS MayS MarT MarS*MarT MayS*MarT MarS*MayS	-63	8	0.001689438
294	JulPET MarT	-69.5	4	0.043509674
295	JulPET MarT JulPET*MarT	-67.2	5	0.013892624