Impacts of Black Ash Stand Transpiration on the Hydrology of Wetland Forests in
Northern Minnesota, U.S.A.

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Abstract

The possibility that the emerald ash borer (*Agrilus planipennis*) will spread to northern Minnesota and cause widespread mortality of black ash is an issue of concern for land managers. Northern Minnesota contains many wetland forests dominated by black ash (*Fraxinus nigra*). Given the importance of evapotranspiration of overstory tree species, such as black ash, to the hydrologic budgets of forest systems, transpiration was approximated at multiple ash forests of northern Minnesota. In 2012, sap flux rates were monitored at three stands of black ash with differing moisture regimes within the Chippewa National Forest, Minnesota, USA. Sap flux rates for black ash were within the expected range of values. Black ash exhibited small sapwood area across all of the trees monitored. When sap flux was converted to sap flow and scaled from the sample trees to site level estimates of transpiration, transpiration values were low due to small sapwood area. Results were compared to soil moisture and potential evapotranspiration data to determine the efficacy of the methodology employed for estimating sap flux and to corroborate transpiration results. In the summer of 2012, transpiration by black ash only accounted for 16% to 21% of total potential evapotranspiration. Despite the common flooded status of black ash wetland forests, moisture regime and moisture limitation did impact sap flux and transpiration in black ash stands as there was variability in sap flux and sap flow among sites of varying moisture regime. Potential evapotranspiration and vapor pressure deficit were only important when moisture was not limited spatially or temporally. Belowground impacts to sap flux from soil moisture only became perceivable during periods of moisture limitation. Sources of error associated with the transpiration determination process were explored and while the results of this study indicate trends in transpiration of black ash forests, the multiple stages of transpiration determination contain error that needs to be acknowledged when considering implications of transpiration results. Black ash mortality caused by emerald ash borer could be problematic in terms of hydrologic influence, impacts on vegetation community structure and composition, and alterations to forest management regimes; however, black ash contribution to total evapotranspiration was less than expected and indicates that loss of

black ash may result in fewer alterations to hydrologic processes than previously anticipated.

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1   Introduction

There are many wetland forests dominated by black ash (*Fraxinus nigra*) across the upper Great Lakes region of North America. For example, ash is the second most dominant hardwood genus in the state of Minnesota; there are currently over one million acres dominated by black ash in the state (MN DNR, 2010a). The possibility that the emerald ash borer (*Agrilus planipennis*) will spread to northern Minnesota has become an issue of concern for many land managers and communities across the region. Emerald ash borer (EAB) targets ash species and causes tree mortality in ash stands. EAB typically kills nearly 100% of ash trees in infected stands over a period of 3-10 years (MN DNR, 2010a). Removal of black ash by EAB could cause substantive hydrologic changes in many wetland systems in areas across northern Minnesota because of the dominance of black ash and its potential contribution to evapotranspiration. EAB has already been documented in the Twin Cities and is likely to progress northward (Minnesota Department of Agriculture, 2012a). If black ash populations diminish in northern Minnesota, infrastructure and forest management activities could be impacted as a result of increased water available for overland and subsurface flow. Culverts directing water under forest roads and areas where streams abut roadways could be areas particularly impacted following increased surface and subsurface flow.

Transpiration is one of the primary ways that overstory vegetation contributes to the hydrologic budget of forest stands. Transpiration is the escape of water from plant pores to the atmosphere during the sequestration of carbon dioxide. This water loss can be substantive and can impact the hydrology of many natural systems (Brooks et al., 2003). One method to determine the importance of transpiration in hydrologic budgets is to assess the amount of total evapotranspiration accounted for by transpiration. Total evapotranspiration includes evaporation from the landscape, transpiration of all vegetation on the landscape, and interception and evaporation of rainwater from vegetation (Figure 1). Total change in storage of water of a forest system can be determined by assessing above and belowground elements of the hydrologic cycle in the form of an equation:

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$$\Delta S = P - E - T - G - R$$

where ΔS is change in storage, P is precipitation, E is evaporation, T is transpiration, G is groundwater, and R is runoff. Previous work has been done to assess the amount of potential evapotranspiration (PET) accounted for by transpiration with different results depending on factors including tree species and study location (Calder, 1998; Granier et al., 2000a; Wilson et al., 2001; Wullschleger et al., 2001; Schafer et al., 2002; Bovard et al., 2005; Delzon and Louostau, 2005; Stoy et al., 2006; Tang et al., 2006; Poyatos et al., 2007; Ford et al., 2010; Oishi et al., 2010). By calculating transpiration of black ash stands and comparing the findings to total evapotranspiration values, land managers will be able to consider the impacts of black ash on the water budgets of black ash swamps and anticipate issues that could arise with EAB incursion.
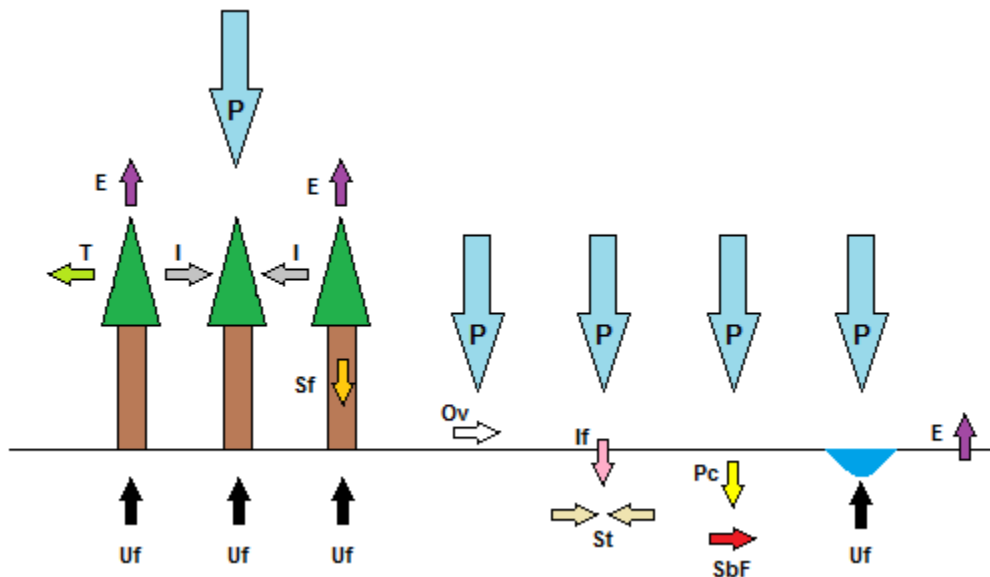
Figure 1. Diagram representing the general hydrologic cycle found in a forest system. Components of the hydrologic cycle include precipitation (P), evaporation from vegetation and the landscape surface (E), transpiration (T), interception (I), stemflow (Sf), overland flow (Ov), infiltration (If), percolation (Pc), soil water storage (St), subsurface flow (SbF), and upward flow of soil water (Uf).

Soil moisture depletion is another means to determine the amount of water leaving a forest system due to evapotranspiration. The impact of soil moisture on transpiration has been shown to be variable and is an important process in evapotranspiration. Previous work has been done to examine if a link exists between soil moisture changes and elements of evapotranspiration with mixed results (Oren et al., 1996; Wullschleger et al., 1998; Granier et al., 2000a; Lu et al., 2000; Wilson et al., 2001; Ewers et al., 2002; O'Brien et al., 2004; Bovard et al., 2005; Delzon and Loustau, 2005; Holscher et al., 2005; Kubota et al., 2005; Stoy et al., 2006; Tang et al., 2006; Oishi et al., 2008; Ford et al., 2010; Oishi et al., 2010). To address the issue of potential black ash mortality as a result of EAB in these wetland forest systems, three items need to be addressed: black ash physiological characteristics, EAB location and impact on ash trees, and methods to quantify transpiration, PET, and soil moisture.

1.1 Black Ash Characteristics

Black ash (*Fraxinus nigra*) is a water tolerant hardwood found in the temperate boreal forests of North America. Black ash has some habitat requirements which restrict the water tolerant species to relatively humid climates, specifically in areas with precipitation ranges of 510 to 1140 mm. Locations which support black ash get much of their precipitation during the growing season. The frost free season in these climates ranges from 80 to 180 days (Burns and Honkala, 1990). Regions of North America that contain environmental conditions necessary to support black ash include the upper Great Lakes and northeastern states and provinces (USDA Plants Profile). Within Minnesota, black ash comprises half of the lowland forest cover type (MN DNR, 2010b). Landscape systems that support black ash stands include bogs, streams, and poorly drained areas that experience seasonal flooding. Local surface flow in the spring is the main source of hydrologic input for black ash stands (Lenhart et al., 2012). Surface fed systems such as the black ash stands evaluated in this study can have less stable water levels compared to deep groundwater fed wetland systems (Lenhart et al., 2012). Despite the flooded growing environments of black ash stands, water movement throughout the soil profile is beneficial because soil aeration promotes oxygen exchange which is important for black

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ash (Burns and Honkala, 1990). Ash species seem to become more abundant in relatively open and recently disturbed forest areas (MacFarlane and Meyer, 2003). Loss of black ash from the landscape could have important impacts on the availability of timber and non-timber forest products currently harvested from these areas, as well as wildlife species. Black ash has many uses in the production of forest products including furniture production, veneer, pulpwood, and non-timber forest products such as baskets (Benedict and Frelich, 2008). Black ash forests are also important sources of wildlife habitat and black ash seeds and buds have been found to be valuable sources of forage (Anderson and Nelson, 2003).

It is important to understand growth form and physiology of black ash when making comparisons between black ash transpiration and transpiration of other tree species. Black ash trees typically grow to between 18 and 21 meters tall with average diameter at breast height (DBH) between 30 and 61 centimeters (Burns and Honkala, 1990). Black ash reach between 9 and 13 meters tall around 50 years of age and between 15 and 18 meters tall around 100 years of age (Anderson and Nesom, 2006). The relatively shallow and fibrous root systems of black ash are well adapted to high moisture conditions (Burns and Honkala, 1990). Black ash trees have a ring porous xylem structure. Ring porous tree species have vascular vessels concentrated directly beneath the bark (Purdue Extension, 2009) and in the early sapwood. Diffuse porous tree species contain vascular vessels of similar size throughout each successive growth ring. The nature of ring porous structure can impact sap flux and sap flow (Taneda and Sperry, 2008), making the consideration of pore structure crucial in the analysis of transpiration values. Ring porous tree species develop larger pores in the earlywood and smaller pores as the growing season progresses. The earlywood pores can conduct larger amounts of water than smaller late season pores, resulting in variability in water movement throughout individual growth rings. Ring porous trees also demonstrate variable radial water movement. The combination of growth ring and radial variability of water movement make the consideration of tree pore structure critical for examining sap flux.

Black ash has been thought to be declining across its range (Croxton, 1966; Trial and Devine, 1994; Livingston et al., 1995; Palik et al., 2011), particularly in the upper

portions of the Midwest, since the early 1990s (United States Forest Service, 2004). EAB invasion will further the decline of black ash, compounding any existing problems for health of black ash stands. The Minnesota Department of Natural Resources (MN DNR) estimated that as of 2009, 21,940 acres of wetland forest experienced ash decline in Minnesota alone (MN DNR, 2010b). Dieback symptoms include thinning crowns, epicormic branching, twig dieback, branch dieback, and small discolored leaves (Trail and Devine, 1996). Dieback is thought to be related to soil moisture conditions because black ash dieback has been found to be greater on sites with wetter soil moisture conditions (Ward et al., 2006; Palik et al., 2011). Palik et al. (2011) found that older populations and cohorts that experienced senescence had higher dieback. Ash sites closer to roads can also experience higher rates of mortality (Ward et al., 2006; Palik et al., 2011). Black ash has been found to replace itself poorly following dieback, especially on wet sites. Other tree species that fill the same niche in ash swamps also appear to replace ash poorly, indicating that black ash areas could transition to systems with more shrubs and grasses following ash dieback (Palik et al., 2012). Increased flooding in black ash wetlands could also cause a transition from trees to grass depending on flooding characteristics (Toner and Keddy, 1997). Changes to community composition could have implications for the water budgets if evapotranspiration were different in shrub and grass dominated systems. Ash dieback is already taking place and EAB invasion could exacerbate this problem.

Understanding the current vegetation in black ash swamps is important when looking at potential shifts in succession that could take place following ash mortality from EAB or other causes. In Minnesota, ash forests are generally classified by the native plant community type Northern Wet Ash Swamp (WFn55) and Northern Very Wet Ash Swamp (WFn64) (MN DNR, 2003). The vegetation communities of black ash areas in northern Minnesota include sedges, mosses, and ferns in the ground layer, beaked hazelnut (*Corulus cornuta*), chokecherry (*Prunus virginiana*), and swamp red currant (*Ribes triste*) in the shrub layer, and black ash and a mix of hardwoods in the subcanopy and canopy layers. Common trees found in black ash areas include American elm (*Ulmus americana*), balsam fir (*Abies balsamea*), basswood (*Tilia americana*), red maple

(*Acer rubrum*), yellow birch (*Betula alleghaniensis*), quaking aspen (*Populus tremuloides*), and white cedar (*Thuja occidentalis*) (MN DNR, 2003).

1.2   Emerald Ash Borer Characteristics and Location

Emerald ash borer (*Agrilus planipennis* (Fairmaire)) (EAB) is an insect native to Asia, which has become invasive throughout many regions of the United States. EAB was first documented in the United States in 2002 in the Detroit, Michigan area, but is estimated to have entered the United States over 20 years ago (Abrahamson et al., 2007). Since its initial discovery, EAB has expanded its range to portions of the United States and Canada including Wisconsin, Minnesota, Missouri, Illinois, Indiana, Kentucky, Ohio, West Virginia, Tennessee, Maryland, Pennsylvania, New York, Ontario, and Quebec (USDA, 2012). Millions of ash trees have been killed by the EAB within the United States (Anulewicz et al., 2008). EAB attacks all species of ash trees within Minnesota. Adult EAB insects lay eggs on the outer bark of ash trees. Larvae hatch and bore into the trees. EAB larvae effectively girdle ash trees; once trees are infected with EAB, death is certain (University of Minnesota Extension, 2012). Minnesota has the highest volume of ash trees in the United States with nearly one billion forestland and urban ash trees and over one million acres of ash-dominated forests (Minnesota Department of Agriculture, 2012a). EAB usually attacks weakened trees in its native range, but in North America EAB appears to kill healthy trees as well. As of 2008, EAB had not been observed attacking non-ash trees in North America (Anulewicz et al., 2008).

On May 14th, 2009 EAB was confirmed in the South Saint Anthony Park neighborhood in Saint Paul, Minnesota. EAB is now estimated to be spreading north, with a confirmed infestation in the northern suburbs of the Twin Cities (Minnesota Department of Agriculture, 2012a). Current plans to combat EAB expansion include prevention, early detection, and rapid response. States have also put restrictions on firewood and nursery stock movements. Currently, a quarantine zone has been placed on Ramsey, Hennepin, Houston, and Winona counties of Minnesota in an attempt to slow the spread of EAB. Regulated materials include ash logs, lumber, tree waste, chips, mulch, and all hardwood firewood (Minnesota Department of Agriculture, 2012b).

Attempts to contain EAB have not been successful in the past. The spread of EAB to northern Minnesota is possible and could impact the hydrologic relationships of black ash dominated wetland systems which is why it is important to understand the hydrological involvement of black ash in wetland forests of northern Minnesota, specifically the impacts of black ash transpiration.

1.3   Transpiration Measurement and Extrapolation

Transpiration by plant species is an important component of the water budget for vegetated environments. Many studies have found that transpiration is a quantitatively important factor of evapotranspiration (Calder, 1998; Granier et al., 2000a; Wilson et al., 2001; Wullschleger et al., 2001; Schafer et al., 2002; Bovard et al., 2005; Delzon and Louostau, 2005; Stoy et al., 2006; Tang et al., 2006; Poyatos et al., 2007; Ford et al., 2010; Oishi et al., 2010). Dominant plant species are especially important to consider when determining the amount of transpiration in a system. Thermal based measurements of sap movement are commonly used by forest ecologists to measure transpiration in tree species (Wullschleger et al., 2011). Different measurement strategies exist to determine sap movement through vegetation, also called sap flux. Three thermal based sap flux measurement methods include heat pulse velocity, heat field deformation, and thermal dissipation (Steppe et al., 2010). Huber (1932) was the first to use heat to detect sap movement in stems. Marshall (1958) took this work further and developed the basis for the heat pulse velocity method. The heat pulse velocity method is designed to measure the velocity of a pulse of heat moving through the xylem. The heat field deformation method measures changes in the heat field based on radial temperature differences around the heater (Nadezhdina et al., 1998). The thermal heat dissipation system (Granier 1985, 1987a) measures voltage differential between thermal dissipation probes and converts the differential to sap flux of overstory tree species. Each of these methods use different techniques to estimate sap flux, but they all incorporate heating elements and thermocouples or thermistors to determine temperature profiles (Wullschleger et al., 2011).

One of the most common methods for measuring whole tree water use is the heat dissipation method developed by Granier (1985, 1987a). This system utilizes heated and unheated thermocouple probes to measure the amount of heat dissipated by sap flow in study trees. The difference in temperature between the heated and unheated probes is used to determine the rate of sap movement within the study tree using an empirically derived relationship. This system of sap flux measurement relies on the assumption that the input of heat from the heater probe is equal to the quantity of heat dissipated at the probe wall at a constant sap flux density and during conditions of thermal equilibrium (Granier, 1985; Cabibel and Do, 1991; Lu et al., 2004). The original Granier (1985) empirical relationship for determining sap flux was developed based on two conifer species and one ring porous species. Tree species used in the original study were Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), Austrian pine (*Pinus nigra* Arnold), and English oak (*Quercus pedunculata* Ehrh.). Advantages of the Granier (1985) sap flux system include its relative ease of installation, relatively low cost of installation and maintenance, and the ability to pair the sap flux equipment with dataloggers for remote operation (Wullschleger et al., 1998). Potential drawbacks of this method include calibration of estimates during a period of zero flow (Regalado and Ritter, 2007), uncertainty with empirically derived relationships, errors associated with variation in sap flux density along the length of the probe, and presence of temperature gradients within the sapwood (Wullschelger et al., 1998; Wullschleger et al., 2011). Further error can be introduced through poor user installation including erroneous placement of probes into the non-conducting heartwood, xylem disruption during probe installation, and placement of probes too close together (Wullschleger et al., 1998; Wullschleger et al., 2011). Black ash is a ring porous tree species which complicates application of the original Granier (1985) equation due to the unique impacts of ring porous structure on sap movement within trees (Herbst et al., 2007, Tenada and Sperry, 2008, Bush et al., 2010, and Steppe et al., 2010).

Once sap flux has been determined for individual trees, scaling can be conducted from the individual tree to the whole stand. Scaling from individual tree transpiration to site level transpiration is often necessary due to logistical issues with measuring

transpiration of all trees within a study site (Hatton et al., 1995). Scaling from individual tree transpiration to stand level transpiration has been questioned as a source of error in stand level sap flux estimation. Ford et al. (2007) and Wilson et al. (2001) both attempted to validate sap flux estimates of transpiration by comparing sap flux values to catchment based evapotranspiration estimates. While both studies found that the sap flux system underestimated evapotranspiration, Ford et al. (2007) concluded that the sap flux system is still an effective method for extrapolating evaporation from individual tree to larger areas especially if plot variation is considered and addressed. Information on the distribution of tree sizes in an area used in concert with individual tree sap flux data can be used to determine site level transpiration (Ewers et al., 2002; Kuimagai, et al., 2005b; Tang et al., 2006; Ford et al., 2007; Hultine et al., 2010). Accurate tree size classification is critical to accurate stand level extrapolation. Accurate measurement of sap flux is also considered to be one of the most important factors for estimating accurate values from transpiration scaling (Hatton et al., 2005). Another important consideration in the scaling process is variation in sap flux between trees in the study and radial variability of sap flux (Kume et al., 2012). Stand transpiration values can be compared to whole site potential evapotranspiration to determine the role of monitored vegetation in evapotranspiration after extrapolation to the stand level.

1.4   Comparison of Transpiration to PET and Soil Moisture

There are many methods available to calculate site level potential ET (PET) including the Thornthwaite (Thornthwaite, 1948), Penman (Penman, 1948), and Penman-Monteith methods (Monteith, 1965). The Thornthwaite method is the simplest; this method only uses air temperature and latitude of the study site to determine ET (Thornthwaite, 1948). The Penman method combines energy balance and mass transfer to calculate evaporation given solar radiation, temperature, humidity, and wind speed (Allen et al., 1998). The Penman-Monteith method incorporates transpiration losses and requires net solar radiation, temperature, relative humidity, and wind speed (Monteith, 1965).

By comparing the amount of water transpired by dominant plant species to the potential maximum amount of water which could leave a system as estimated with PET, the importance of various overstory dominant tree species can be gauged. Previous studies have attempted to determine the amount of evapotranspiration accounted for by transpiration of overstory tree species. Transpiration has been found to be responsible for between 20% and 84% of PET depending on geographic location, tree species, and tree physiology (Table 1). When determining the amount of PET accounted for by transpiration it is important to evaluate the pore structure of the tree species being examined. Bovard et al. (2005) found that the one ring porous species evaluated in their study showed lower water use than the diffuse porous species, regardless of moisture condition. Similarly, Ford et al. (2010) concluded that their lowest transpiring tree species was the ring porous red oak (*Quercus rubra*). Stoy et al. (2006) found the ring porous willow oak (*Quercus phellos*) to exhibit the lowest amount of transpiration of the hardwoods examined in their study. Wullschleger et al. (2001) evaluated multiple ring porous species and found that ring porous tree species contributed less to PET when compared to diffuse porous tree species. Although the amount of PET accounted for by transpiration is variable over geographic space and tree species, ring porous tree species consistently transpire less and account for less PET than diffuse porous tree species.

Table 1. Comparison of the results of previous studies examining the contribution of transpiration to PET by dominant overstory tree species.

Study	Study Location	Forest Type/ Tree Species	Pore Structure	Transpiration (% of PET)
Calder et al., 1978	Plynlimon, Wales	Spruce	Conifer	39
Kelliher et al., 1998	Siberia, Russia	Pine	Conifer	~50
Granier et al., 2000	Eastern France	Mixed hardwood (1)	Mixed	72-76
Zimmermann et al., 2000	Siberia, Russia	Pine	Conifer	~50
Wilson et al., 2001	Eastern Tennessee	Mixed hardwood (2)	Mixed	42-44
Bovard et al., 2005 (3)	Northern Michigan	Mixed hardwood (4)	Mixed (5)	66
Delzon and Loustau, 2005	South-western France	Pine	Conifer	~50
Stoy et al., 2006	Central North Carolina	Planted loblolly pine	Conifer	78-84
Stoy et al., 2006	Central North Carolina	Oak - hickory	Mixed	81-84
Tang et al., 2006	Northern Michigan	Mixed hardwood (6)	Diffuse	65
Poyatos et al., 2007	Northeast Spain	Downy oak	Ring	20-30
Ford et al., 2010(7)	Western North Carolina	Eastern white pine	Conifer	60
Ford et al., 2010(7)	Western North Carolina	Harwood dominated (8)	Mixed	55
Oishi et al., 2010	Central North Carolina	Mixed hardwood (9,11)	Mixed	20
Oishi et al., 2010	Central North Carolina	Mixed hardwood (10,11)	Mixed	64
Shannon et al., 2011	Northern Minnesota	Mixed hardwood and conifer (12)	Diffuse and Conifer	31-42 (13)

1. Beech (*Fagus spp*.), European hornbeam (*Carpinus betulus* L.), silver birch (*Betula pendula* (Roth)), sessile oak (*Quercus petraea* (Matt.), European larch (*Larix decidua* (Mill.)).
2. Red maple (*Acer rubrum*), loblolly pine (*Pinus taeda*), chesnut oak (*Quercus prinus*), white oak (*Quercus alba*), red oak (*Quercus rubra*), and yellow poplar (*Liriodendron tulipifera*).
3. Transpiration was compared to ecosystem water flux.
4. Big-tooth aspen (*Populas grandidentata*), red maple (*Acer rubrum*), paper birch (*Betula papyrifera*), red oak (*Quercus rubra*), eastern white pine (*Pinus strobus*), and American beech (*Fagus grandifolia*).
5. Mixed pore structure refers to both diffuse and ring porous tree species.
6. Sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniesis*), and eastern hemlock (*Tsuga canadensis*).
7. Evapotranspiration determined by summing interception and transpiration.
8. Hickory (*Carya* spp.), tuliptree (*Liriodendron tulipifera*), chesnut oak (*Quercus prinus* L.), red oak (*Quercus rubra* L.).
9. Percent of total evapotranspiration accounts for dormant season.
10. Percent of total evapotranspiration accounts for growing season.
11. Tuliptree (*Liriodendron tulipifera*), sweet gum (*Liquidambar styraciflua*), hickory (*Carya spp*.), oak species (*Quercus alba*, *Quercus michauxii*, *Quercus phellos*).
12. Aspen (*Populas tremuloides*), paper birch (*Betula papyrifera*), red maple (*Acer rubrum*), balsam fir (*Abies balsamea*), red pine (*Pinus resinosa*), and white spruce (*Picea glauca*).
13. Values presented are averages from two different mixed species watersheds.

In addition to PET, it is useful to evaluate changes in soil moisture and its influence on transpiration. Previous studies have found a variety of responses in transpiration to changes in soil moisture. The response of transpiration to soil moisture varies by species, forest stand location, and hydrologic moisture regime making simple conclusions difficult to draw. Studies have found that soil moisture had no effect on tree water use (Wullschleger et al., 1998; Ewers et al., 2000; Granier et al. 2000b; O'Brien et al., 2005). In contrast, decreasing soil moisture has been found to result in linearly decreasing sap flux for many species, but not for European ash (Holscher et al., 2005). Differences have been found in sap flux based on soil moisture condition by field site and between species (Bovard et al., 2005). Stand transpiration of beech trees has been found to be reduced due to soil moisture during the growing season (Granier et al., 2000). Soil moisture deficit can also impact transpiration with an interaction with stand age (Delzon and Loustau, 2005). Changing soil moisture conditions can cause variable sap flux both azimuthally and radially (Lu et al., 2000). Soil moisture impacts to transpiration can be variable and need to be considered when evaluating drivers of transpiration.

Climatic variables can also influence transpirational response to soil moisture changes. Soil moisture can impact transpiration depending on site location and precipitation (Oren et al., 1996). Even precipitation throughout the study period can result in minimal control of transpiration by soil moisture. Soil moisture can also impact transpiration depending on whether the year is wet or dry (Ford et al., 2010). Differences in transpiration response to soil moisture condition can be partially attributed to tree physiological characteristics. Shallow rooted tree species may demonstrate reductions in sap flux in response to low soil moisture content in upper soil layers, while deep-rooted tree species may exhibit a slower reduction in sap flux in response to soil drying in upper soil layers (Granier and Loustau, 1994; Pataki et al., 2000; Oren and Pataki, 2001). Soil moisture can have impacts on transpiration depending on tree species and field site characteristics and warrants review in transpiration studies.

By using the thermal dissipation method with some correction, forest ecologists can determine individual tree transpiration based on tree class, extrapolate transpiration to

the entire stand, and convert the results to a per unit area basis. This study attempts to determine the transpiration rates of black ash stands at multiple sites in the Chippewa National Forest through the Granier (1987a) heat dissipation sap flux measurement system combined with correction methods and vegetation survey data. These determined rates were compared with PET and soil moisture data for each of the field sites to ascertain the importance of transpiration in the hydrology of black ash stands of northern Minnesota. The overall goal of this study was to determine the role of black ash in evapotranspiration processes in wetland forests of northern Minnesota. Specific objectives included: 1) quantifying individual tree transpiration, 2) extrapolating from individual tree to site level transpiration, 3) comparing scaled transpiration to potential evapotranspiration, 4) comparing scaled transpiration to soil moisture depletion through time, and 5) evaluating the role of black ash in these wetland forest systems based on the results of the transpiration comparisons to potential evapotranspiration and soil moisture changes.

2   Methods

2.1   Site Selection

This sap flux study was conducted in the Chippewa National Forest of northern Minnesota. Study sites were located in Itasca County, just north of Lake Winnibigoshish (47°31'57"N, 94°12'39"W). Precipitation in this area averages 70 cm with one third of the precipitation occurring as snowfall (Lenhart et al., 2012). Three field sites were selected based on moisture regime and accessibility. Visual assessment of the sites using ecological indicators was conducted prior to sap flux installation to assure differences in soil moisture regime. Sites were each different in terms of soil moisture (Figure 2) and were named based on moisture regime. Soils at the study sites included muck soils and very fine sandy loams. Both soil types contain a clay layer at 1 meter that acts as a hydrologic restricting layer and limits groundwater seepage (Lenhart et al., 2012). Sites were designated the very wet site (VWS), the wet site (WS), and the moderate site (MS). Sites were classified as Northern Wet Ash Swamp (WFn55) or Northern Very Wet Ash Swamp (WFn64) based on the state's native plant community classification system (MN

DNR, 2003). These sites coincided with those used for a forest management study conducted by the University of Minnesota in conjunction with the Minnesota Forest Resources Council and the United States Forest Service. The overlapping sites were B1 control (VWS), B2 control (MS), and B3 control (WS).
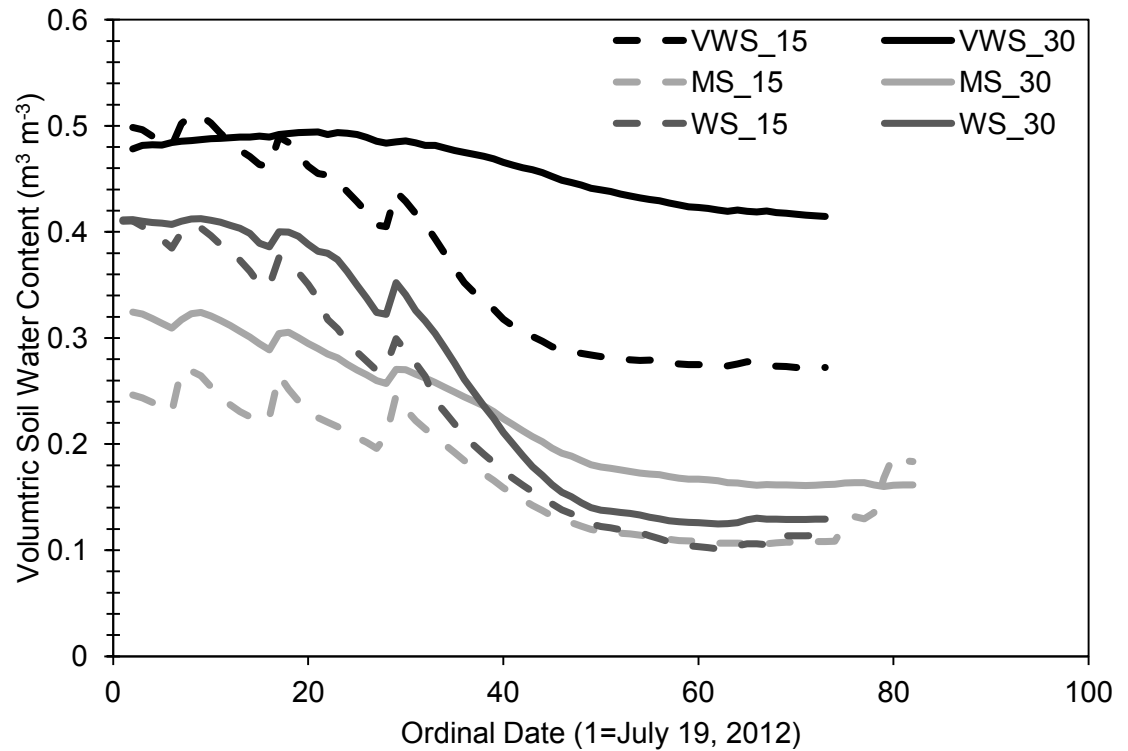
Figure 2. Volumetric soil water content (m^3 m^{-3}) for the very wet site (VWS), the moderate site (MS), and the wet site (WS) throughout the field season. The relationship demonstrates trends in volumetric soil water content for soil depths of 15 and 30 centimeters.

Overstory vegetation surveys were conducted at each of the sites prior to this study. Sites had been divided into six 400 m^2 plots for vegetation measurements as part of a larger research project for a total of 2400 m^2 for each research site. Vegetation inventory data was recorded for all species with DBH greater than 10 cm. Inventory data included tree density, tree mortality status, tree species, and DBH. All sites exhibited black ash as the dominant overstory species (Table 2). Few other tree species were found on the sites; MS was the only site with another tree species that accounted for greater

than five percent of the trees found at the site. MS demonstrated the highest tree density
while WS contained the lowest tree density (Table 2).

Table 2. Tree species composition by site for the very wet site (VWS), the wet site (WS), and the moderate site (MS). Percentage by species was determined for each of the field sites and is represented in the "% by Species" column.

Tree Species by Site	Trees per Hectare	% by Species
VWS Total	683	100
Black Ash	629	92
American Elm	38	5
Basswood	8	1
Bur Oak	0	0
White Cedar	0	0
Red Maple	0	0
Quaking Aspen	8	1
Yellow Birch	0	0
WS Total	579	100
Black Ash	554	96
American Elm	4	1
Basswood	0	0
Bur Oak	0	0
White Cedar	4	1
Red Maple	0	0
Quaking Aspen	0	0
Yellow Birch	17	3
MS Total	829	100
Black Ash	696	84
American Elm	96	12
Basswood	25	3
Bur Oak	4	1
White Cedar	0	0
Red Maple	8	1
Quaking Aspen	0	0
Yellow Birch	0	0

At each site, sap flux of eight trees of varying size was monitored from early June
to early September. Trees were selected for monitoring based on a circular orientation

around the center of each site. A visual assessment of each site was conducted prior to sap flux installation to ascertain ranges of tree diameters and trees were selected for monitoring based on the range of diameters represented within each site. Average monitored tree diameter was similar to measured whole-site average tree diameter for each of the sites. Monitored diameter range was also similar to the measured whole-site diameter range for each of the sites (Table 3). The goal when selecting a wide range of tree diameters was to capture the variability of tree diameters and presumably sapwood area at each site, making it possible to examine the variation of sap flux and sap flow associated with diameter and so as to better estimate stand level transpiration. Reliable sap flux data collection began for VWS and WS on June 12th, 2012 and for MS on June 27th, 2012. Data for VWS and WS were available through August 31st, 2012 and through September 4th, 2012 for MS.

Table 3. Comparison of whole-site and monitored tree diameter (cm) averages and ranges for the very wet site (VWS), the wet site (WS), and the moderate site (MS). Whole-site trees include all trees inventoried across the study sites (6,400 m^2 plots); monitored trees include the eight trees that were monitored for sap flux at each of the field sites.

Field Site	Whole-site DBH Average (cm)	Whole-site DBH Range (cm)	Monitored DBH Average (cm)	Monitored DBH Range (cm)
VWS	22.88 ± 10.04	10.0 - 46.4	26.72 ± 8.65	14.4 - 40.5
WS	23.76 ± 8.59	10.0 - 41.8	26.59 ± 9.60	15.6 - 41.8
MS	22.22 ± 8.28	10.1 - 47.8	26.96 ± 11.11	13.9 - 41.9

Reported errors are one standard deviation from the mean.

2.2   Transpiration Determination

2.2.1   Method for Sap Flux Determination

The Granier (1987a) heat dissipation method was used to determine sap flux for black ash trees at each study site. The heat dissipation method was chosen due to equipment availability and low cost associated with the method. The Granier (1987a) method utilizes two sensor probes that are inserted into the conducting sapwood of the tree. One of these probes is heated while the other serves as a reference probe. The

thermal dissipation probes for this project were constructed in accordance with the method set forth by Lu et al. (2004). Probes consisted of two type-T thermocouples constructed from 36 gauge constantan and 36 gauge copper wire wrapped together and inserted into a 20 mm, 19 gauge dispensing needle. Heater probes were developed by wrapping 16 inches of 36 gauge constantan wire around one of the dispensing needles. This needle, responsible for supplying the heat source for the probe, was supplied with 0.2 watts of constant power and emitted heat into the tree. The other probe did not emit heat and served as the reference probe. The original Granier (1987a) thermal dissipation system calls for 0.2 watts of constant power to be supplied to each heated element. Marine deep cycle batteries were used to power the heating elements. Step-down heater circuits were used to reduce the power coming from the deep cycle batteries to a constant 0.2 watts. Individual circuits were calibrated to ensure that each probe received a constant 0.2 watts of power. Resistance was measured at each circuit following replacement of the deep cycle batteries. Appropriate voltage for each probe was calculated by measuring the resistance of each circuit:

$$V_i = \sqrt{P_w * R_i}$$

Equation 2

where V_i is the voltage required to achieve desired power output, P_w is the power supply generated in output, 0.2 W for this study, and R_i is the resistance of the heater circuit in ohms.

Aluminum sleeves were placed around the thermocouples to minimize temperature differences found along the probes (Granier, 1985). Each thermal dissipation probe was inserted into the tree at 1.3 meters above the ground. Prior to probe installation, pilot holes were drilled with 3/32 inch drill bits. The probes were oriented parallel to the bole of the trees. Probes were placed on the north and south facing sides of each tree in the study. Probes were placed on different aspects of the tree to account for some of the variability in sapwood depth and conductance based on aspect. Averaging the values of two sets of probes from two different aspects of the tree has been shown to reduce error substantially over only measuring sap flux on one aspect of the tree (Lu,

1997). The probes were vertically spaced 10 cm apart. Silicon was placed at the entry point of the probes into the boles of the tree to secure the probes and prevent water from entering the probe holes. Voltage difference between the two probes was measured every thirty seconds with averages calculated for every fifteen minute period. This sampling frequency resulted in 96 voltage differential values for each probe for every field season day. All probes were connected to a multiplexer that relayed the information to a datalogger. Data from the dataloggers were downloaded biweekly. Multiplexers used included a Campbell AM 416 Relay Multiplexer, a Campbell AM 16/32 multiplexer, and a Campbell AM 16/32B multiplexer. Dataloggers used included a Campbell CR-10x datalogger and two Campbell CR10WP dataloggers.

Tree wounding has been proposed as a possible source of error in sap flux studies (Wullschleger et al., 2011). The disruption of the xylem conduit can negatively impact the accuracy of sap flux results and can be especially problematic in ring porous tree species (Wullschleger et al., 2011). Other issues with sap flux accuracy exist due to improper hole size for probe installation (Tatatrinov et al., 2005) and wounding over long periods (Moore et al., 2010), which can subsequently impact sap flux results (Wullschleger et al., 2011). In an attempt to address these issues, drill bits were selected to drill holes that were as close to the diameter of the probe tips as possible. Probes were installed directly after holes were drilled to reduce tylosis and maintain open xylem conduits.

In an effort to address complications with measuring sap flux of ring porous tree species, two empirical relationships were used and compared to potential evapotranspiration and soil water changes to test the efficacy of the two relationships in the study setting. The Granier (1987a) method of thermal heat dissipation was used in conjunction with the Granier (1987a) relationship as well as the Herbst et al. (2007) empirical equation to determine sap flux. While it has been asserted that developing sap flux relationships for trees monitored in individual studies utilizing the Granier (1987a) method improves the accuracy of results (Smith and Allen, 1996; Bush et al., 2010), that was not within the scope of this study because of the necessity for sections of tree stem, the complexity of the calibration procedure (Lu et al., 2004), and the resources required.

The first relationship used to determine sap flux was a modified version of the formula set forth by Granier (1985; 1987a) combined with corrections from Clearwater et al. (1999). The Granier (1985; 1987a) and Clearwater et al. (1999) equations require voltage differences between the probes, maximum difference in voltage, and the proportion of the probe placed in inactive xylem. Voltage difference between the two sensor probes was recorded and converted to sap flux using two different empirical relationships (Granier, 1987a; Herbst et al., 2007). The modified Granier (1985) equation converts the differential voltage values to a sap flux value (F_d) for each time period (Granier, 1987a; Granier, 1987b; Lu, 1997):

$$F_d = 118.99 \times 10^{-6} \left[\frac{\Delta V_{max} - \Delta V}{\Delta V} \right]^{1.231}$$

Equation 3

where ΔV_{max} is the maximum daily difference in voltage between the probes, ΔV is the voltage difference between probes for each of the 96 daily voltage differential values, and F_d is sap flux (m_{sap}^3 $m^{-2}_{sapwood}$ s^{-1}). F_d can be calculated directly from the voltage measurements. The intermediary step of converting the voltage values to temperatures is unnecessary because the conversion factor would be cancelled out in the process (Lu et al., 2004); voltage is converted to temperature using the Seeback coefficient (Lu, 1997).

The second empirical relationship used was taken from Herbst et al. (2007). Similar to the Granier (1987a) relationship, Herbst et al. (2007) incorporates voltage differential into an empirical relationship to yield sap flux (F_d):

$$Fd = 2.023K^2 + 0.428(K)$$

Equation 4

where Fd is sap flux (mm s^{-1}), and K is the difference between ΔV_{max} and ΔV divided by ΔV (Equation 4). K is a dimensionless value necessary for sap flux empirical relationships:

$$K = \frac{\Delta Vmax - \Delta V}{\Delta V}$$

Equation 5

where ΔV_{max} is the daily maximum difference in voltage between the probes and ΔV is the voltage difference between probes at a given point in time.

Daily sap flux was determined by taking the average of all the sap flux values for each day and multiplying by 86,400. It is necessary to multiply by 86,400 to scale from the average of the 96 values to the whole day as the average of the 96 values only accounts for sap flux over one second of each field day and 86,400 represents the number of seconds in one day:

$$Js = 86{,}400 * \left(\frac{1}{96} \sum_{i=1}^{96} a_i \right)$$

<div align="right">**Equation 6**</div>

where Js is total daily sap flux in $m^3 \ m^{-2} \ d^{-1}$, a_i is average sap flux over each 15 minute interval in $m^3 \ m^{-2} \ s^{-1}$, and the 86,400 multiplier serves to scale one second to the whole day.

2.2.2 Data Selection and Modeling

There were several issues associated with the data collected by the sap flux probes due to equipment failure and acts of nature. As a result, the data were put through multiple filters to screen out unacceptable data and to ensure that only sound data was used in analysis. The first filter removed all spurious voltage differential values greater than 1 and less than 0.1. Voltage differential values above 1 and below .1 were always blatantly attributable to equipment malfunction. A second filter was designed to identify the specific point in time that equipment failure impacted the voltage differential values between 1 and .1. Following the failure of a probe or a deep cycle battery, the voltage differential signal would dip below reasonable levels. Once equipment was replaced, the voltage differential signal would return to acceptable levels. To identify a cutoff point for acceptable data, the data were segmented into periods without equipment failure for each probe. The minimum values for all days without equipment failure for the segments were averaged and the average minimum value for the segment was used as the cutoff value for acceptable data for that segment. The third filter incorporated the standard

deviation multiplied by the z-score for the 95th percentile (J. Shannon, personal communication, October 22, 2012). If data was more than the z-score multiplied by the standard deviation away from the daily mean, the data was assumed to be an outlier and removed from the data set:

$$Xout = if(|\bar{x}_d - \Delta V| > (1.96 * \sigma_d))$$

Equation 7

where X_{out} is the presence of an outlier if the statement holds true, $\bar{x}_d$ is average daily voltage differential, ΔV is voltage differential, σ_d is the standard deviation of daily voltage differential, and 1.96 is the z-score for the 95th percentile.

Small data gaps existed following equipment failure and the data screening outlined above. For individual probes, data gaps less than four hours were filled using linear regression with the last point before the data gap serving as the first dependent variable, the first point following the return of voltage differential values serving as the last dependent variable, and time serving as the independent variable (Shannon, 2011). For data gaps less than four hours at the end of a day, with no data following the last data point, linear regressions were applied over the hour preceding the gap with voltage differential values serving as the dependent variable and time serving as the independent variable. These relationships were then used to estimate values following the last available data point through the end of that field day. For data gaps less than four hours at the beginning of the day, with no data preceding the first data point for that day, linear regressions were applied over the hour following the first data point for the day, with voltage differential values serving as the dependent variable and time serving as the independent variable. The regression relationship was then used to estimate values preceding the first data point for the day to the beginning of that field day (Shannon, 2011).

Following data gap filling, linear relationships for voltage differential values were developed between north and south probes. These relationships were used to fill in some gaps in the data that extended longer than four hours. This system was only applicable when one side of the tree was actively collecting sound data, and the other side of the tree

demonstrated a gap in the data. See Appendix A for linear relationships and coefficient of determination values for north and south side relationships. Days with data gaps remaining after data fill-in and modeling were discarded. Only days with data for each of the 96 potential data points were used in analysis. Days with fewer data points were not usable because fewer than 96 data points would have resulted in an underestimation of daily sap flux and cascading impacts to any further estimation of sap flux, sap flow, and transpiration. The final screen for erroneous data was used to remove any daily sap flux values that were identified as outliers using the interquartile range and a multiplier:

$$Xout = SFXd > (Q3 + 1.5(IQR)) \; or \; SFXd < (Q1 - 1.5(IQR))$$

<div align="right">**Equation 8**</div>

where X_{out} is an outlier in the dataset, $SFXd$ is daily sap flux ($m^3 \; m^{-2} \; d^{-1}$), $Q1$ is the first quartile, IQR is the interquartile range, $Q3$ is the third quartile, and 1.5 is a multiplier used in conjunction with IQR. Following all data gap filling and data screening measures, average daily sap flux data retention was 54.1%, 62.5%, and 58.2% for VWS, WS, and MS, respectively. These averages reflect the proportion of days usable data was available for each of the field sites for the field season. While many trees contained values for much of the field season, due to equipment failure and acts of nature, few days contained data for all of the trees at individual field sites. This was problematic for determining daily sap flux averages across monitored trees given the large variability of daily sap flux among trees at each of the field sites.

To address gaps in daily sap flux values, previous studies have found relationships between vapor pressure deficit (Ewers et al., 2002; Muller and Lambs, 2009), latent heat flux (Granier et al., 1996b), canopy conductance (Catovsky et al., 2002) and sap flux or sap flow. These relationships can be used to model sap flux values over the field season to fill in days with missing data. For VWS, WS, and MS, however, there were no strong correlative relationships between sap flux and any atmospheric variable for all of the sites. The field sites also contained large variability in daily sap flux values among monitored trees. Therefore, to account for missing data, weekly averages were taken for each tree for each week. For this study, the first seven day week of the field season started on June 13th, 2012. Data were available for all sites from week

one through week twelve, except for MS which did not have data taken during week one and week two. Only two weeks of the field season did not contain data for every tree at VWS or WS sites; there was not enough data to generate an average for tree 1 at WS for week 4, and not enough data to generate an average for tree 4 at VWS for week 12. All other weeks contain averages for all trees at each site.

2.2.3 Determination of Maximum Voltage Differential

ΔV_{max} was determined based on the assumption that voltage differential is equal to zero at one point during the night due to the cessation of sap flux. This assumption has been found to be flawed, so Granier's double regression method as described by Lu et al. (2004) was used to correct for ΔV_{max} values taken for nights with sap flow values assumed to be greater than zero. Lu et al. (2004) assert that factors that can lead to constant flow include water movement for new growth, prolonged drought (Lu et al., 1995 and Goldstein et al., 1998), and high vapor pressure deficit and wind speed (Snyder et al., 2003). Water redistribution to roots (Sakuratani et al., 1999; Burgess et al., 2000) has also been attributed to nightly sap flow.

Errors associated with ΔV_{max} underestimation were reduced by using the double regression method. This method includes finding a best fit line for all ΔV_{max} values for a given time period. All values beneath this line are removed and a second best fit line is applied to the reduced dataset. All values below this line are also removed. For each day in the given time period the greater of the original value and the predicted value with the second best fit line is used for the ΔV_{max} value (Figure 3). Time periods were divided into periods of at least seven days with periods lasting no longer than ten days (Lu et al., 2004). Time periods were developed to be as close to ten days as possible. This method could become more problematic during periods where nightly sap flow is common (Regalado and Ritter, 2007) and sap flow amount is significant; overnight transpiration is commonly found in plant species and can account for significant amounts of daily transpiration (Snyder et al., 2003; Ford et al., 2004a; Ludwig et al., 2006). Regalado and Ritter (2007) put forth a method for determining ΔV_{max} that does not use the double regression method described by Lu et al. (2004), but rearranges the Granier et al. (1987a)

empirical relationship and includes PET estimations in the equation. This is an alternative method to determine ΔV_{max} that only requires day time voltage differential values. This would be beneficial in terms of lowering the datalogger storage space required and lowering power necessary to power thermal dissipation probes over the required daily study period. Studies have also determined if ΔV_{max} is accurate based on atmospheric conditions and considering the distribution of top ΔV_{max} values on a given day (Oishi et al., 2008). These methods could yield more accurate ΔV_{max} values for the study period than the Granier double regression method. However, Granier's double regression method was employed due to the agreeable assumptions behind the method and the desire to address nightly sap flow.
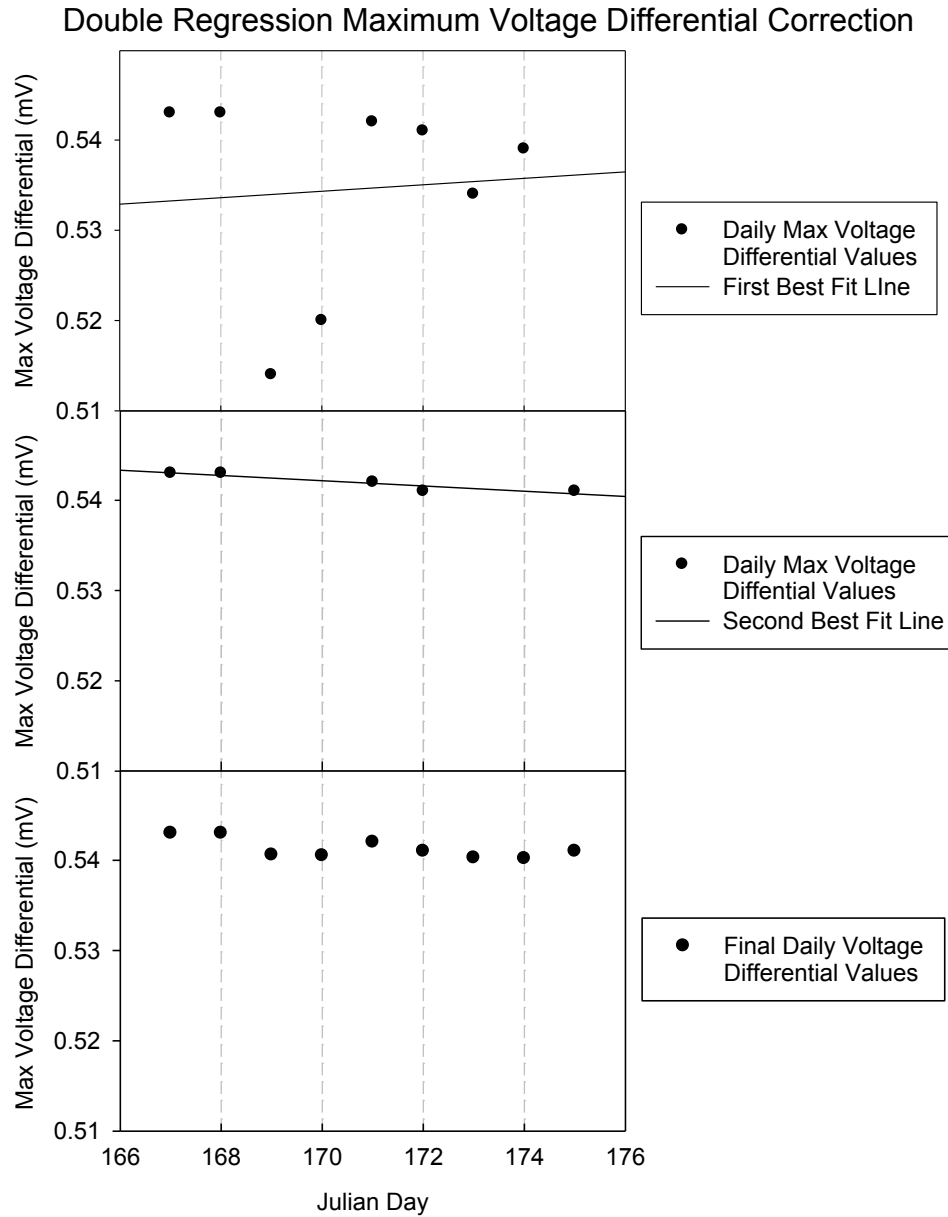
Figure 3. Example of ΔV_{max} (mV) determination using the Granier (1987a) method with the Lu et al. (2004) modified double regression method.

2.2.4   Sapwood Determination and Corrections

Tree cores were removed for both the north and south aspects of each of the monitored trees for calculating heartwood and conducting sapwood. The average of the north and south radii was used to calculate both the heartwood and conducting sapwood area. The boundary between sapwood and heartwood was determined visually (Ewers et

al., 2002; Ford et al., 2004b, Tang et al., 2006, Peters et al., 2010, McCarthy et al., 2011, Pataki et al., 2011b). Field examination of the conducting sapwood boundary was later corroborated in the lab using linseed oil. Linseed oil was applied to the tree cores to make the active sapwood boundary easily visible. Exact sapwood and heartwood depth were then measured to the nearest 0.01 mm using a Velmex micrometer.

Wullschleger et al. (2011) and Bush et al. (2010) point out some potential issues with sap flux systems including problems associated with probe installation, variation in temperature along the heated probe, and variability in sap flow along thermal dissipation probes for ring porous tree species. To avoid some of the problems described by Wullschleger et al. (2011) and Bush et al. (2010) multiple quality assurance measures were adopted. Probes were consistently installed 10 centimeters apart to avoid inaccurate results from the probes being placed too closely together and aluminum sleeves were used to apply consistent voltage to the conducting sapwood along the length of the heated probe. Corrections for sap flux were used from Clearwater et al. (1999) to account for some of the problems associated with probe contact with the heartwood and sap movement variation along the probe. The correction uses the amount of the probe that is extending into the non-conducting sapwood:

$$\Delta V_{sw} = \frac{\Delta V - b \Delta V_m}{a}$$

Equation 9

where ΔV_{sw} is the corrected voltage difference, ΔV is the uncorrected change in voltage, ΔV_m is the average voltage difference in the non-conducting xylem, a is the proportion of the probe that is located in the conducting sapwood, and b is the proportion of the probe located in the non-conductive sapwood, or one minus a.

2.3   Ring Porous Structure, Sap Flux Complications, and Sap Flow Corrections

To account for some of the uncertainty associated with sap movement in ring porous trees (Gebauer et al., 2008, Bush et al., 2010, and Wullschleger et al., 2011) and issues associated with radial variability of sap flux (Lu et al., 2000; Wullschleger and King, 2000; Nadezhdina et al., 2002; Delzon et al., 2004; Ford et al., 2004a; Ford et al.,

2004b; Kumagai et al., 2005a; Fiora and Cescatti, 2006; Poyatos et al., 2007; Saveyn et al., 2008; Muller and Lambs, 2009), the Gebauer et al. (2008) relationship for European ash (*Fraxinus excelsior*) was used to account for lower sap flow closer to the heartwood sapwood boundary and higher sap flow just beneath the cambium (Table 4).

Table 4. Example of relative depth and relative sap flux for European ash (*Fraxinus excelsior*); adapted from Gebauer et al., (2008)

Species	*Fraxinus excelsior*					
Relative Depth	1.0[1]	0.75	0.5	0.25	0.01	0.0[2]
Relative Sap Flux	0.01	0.06	0.28	0.78	0.86	0.0

[1] Sapwood-heartwood boundary.
[2] Cambium.

Sap flow is determined by multiplying daily sap flux (m3 m^{-2} d^{-1}) by the area of conducting sapwood (m^{-2}). When the Gebauer et al. (2008) relationship is applied, relative sap flux and relative sapwood depth are determined. Relative sapwood depth can be converted to sapwood area based on inner bark diameter, heartwood depth, and heartwood area. Relative sap flux (m^3 m^{-2} d^{-1}) was determined based on the Gebauer et al. (2008) relationship. Adjusted sap flux (m^3 m^{-2} d^{-1}) and sapwood area (m^3) were then multiplied to yield the final adjusted sap flow value (dm^3 d^{-1}). Inner bark diameter was determined using the following equation from Dixon et al., 2008:

$$DIB = 0.900 * DBH$$

Equation 10

where *DBH* is diameter at breast height and *DIB* is diameter of the tree beneath the bark.

Gebauer et al. (2008) found that sap flux was not uniform across the xylem of European ash, but instead peaked just beneath the cambium. Following peak sap flux, European ash demonstrated exponential decay of sap flux to the sapwood heartwood boundary (Figure 4). The Gebauer et al. (2008) relationship is applied by determining relative daily sap flux at relative depths using the values set forth in Table 4. Radially corrected daily sap flux is then determined by summing relative daily sap flux at the various relative sapwood depths. This method of radial sap flux correction was applied

to all trees in the study. Further correction of sap flux and sap flow for depths greater than two centimeters were not necessary due to black ash's shallow hydroactive sapwood.
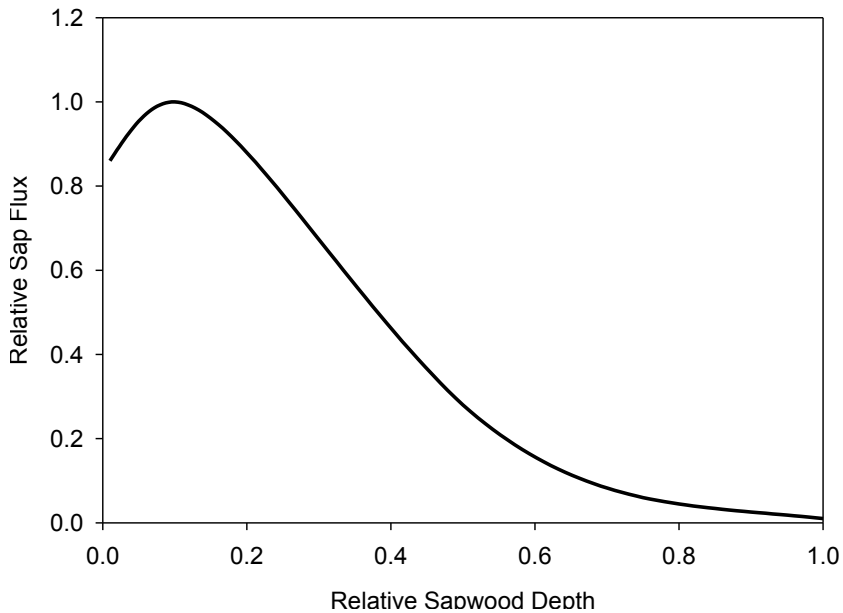
Figure 4. Relationship between relative sapwood depth and relative sap flux determined using radial variability of sap flux in European ash (*Fraxinus excelsior*); adapted from Gebauer et al. (2008). Figure shows declining sap flux with increasing sapwood depth, consistent with radial variability of sap flux in ring porous trees.

2.4   Transpiration Scaling

To scale from daily sap flux of monitored trees to stand level transpiration, a relationship between a morphological tree characteristic and sap flux had to be established. A strong relationship between sap flux and tree diameter would have been the simplest relationship to use to scale from monitored tree sap flux to stand tree sap flux. However, no strong relationships existed between sap flux or sap flow and diameter at any of the study sites (Figure 5a). Previous work has established relationships between sapwood characteristics and tree and population-level characteristics necessary to determine stand level transpiration. Studies have examined the efficacy of using diameter as a predictor of sapwood area (Kuimagai et al., 2005b). Holscher et al. (2005) examined sap flux in multiple species, one of which was a European ash, and scaled to

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whole stand transpiration using a relationship between diameter and sapwood area. It should be noted that European ash exhibited the poorest relationship between diameter and sapwood area of the tree species examined (Holscher et al., 2005). Another approach used for scaling to stand level transpiration is to determine mean sap flux of all monitored trees and multiply by stand sapwood area (Schafer et al., 2002; Tang et al., 2006; Mitchell et al., 2012). This method can be refined by segmenting sapwood and sap flux into different classes (Granier et al., 1996a; Granier et al., 2000a; Herbst et al., 2007). Similar to this study, Morris et al. (1998) found no direct relationship between sap flux and sapwood area. Sap flow values can also be scaled to plot level transpiration using relationships between sapwood area and leaf area (Oishi et al., 2008; Oishi et al., 2010).
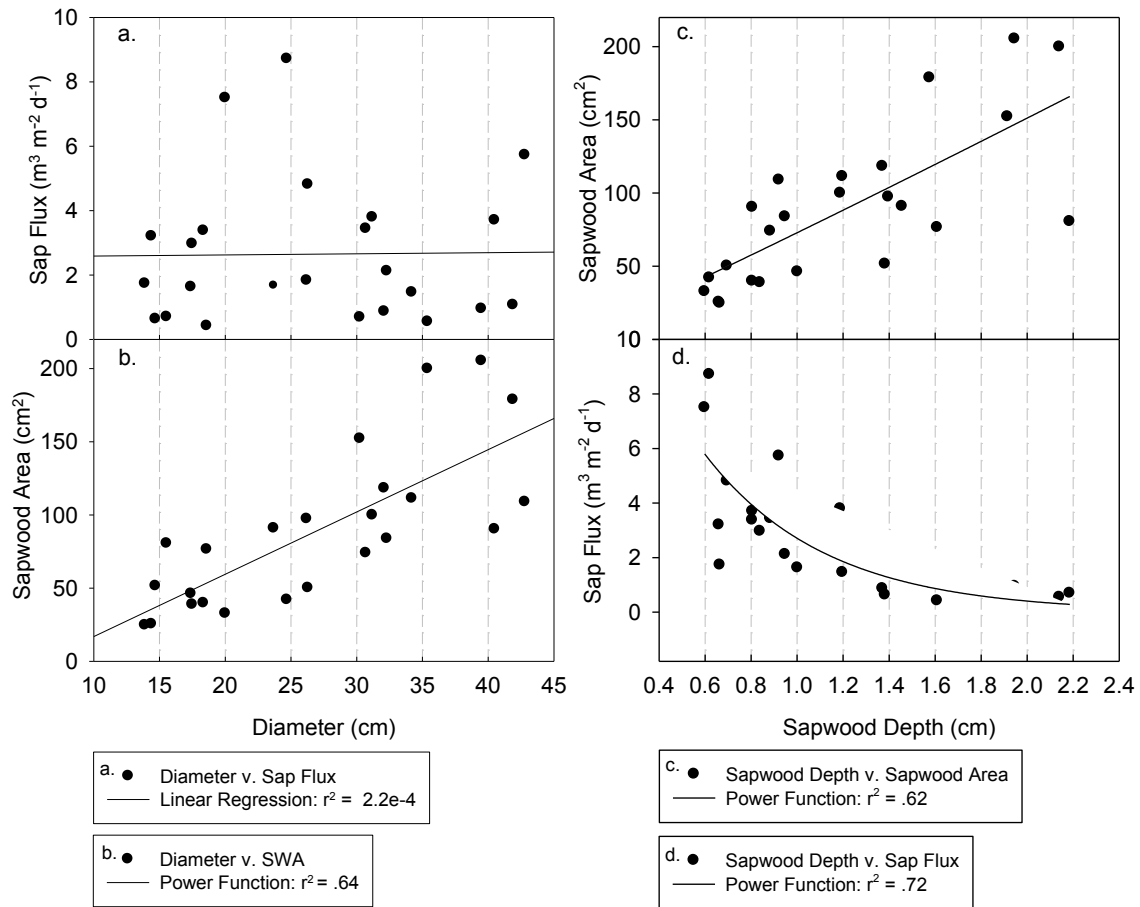
Figure 5. Examples of scaling chain relationships for field sites in aggregate: (a) comparison of diameter (cm) and sap flux (m^3 m^{-2} d^{-1}) of monitored trees, (b) relationship between diameter (cm) and sapwood area (cm^2) of monitored trees, (c) comparison of sapwood depth (cm) and sapwood area (cm^2) of monitored trees, (d) and comparison of sapwood depth (cm) and sap flux (m3 m-2 d-1) for monitored trees during week three of the field season. Week three was selected for display as it was the first week of the field season with all field sites operational.

The variation in sap flux based on diameter and the lack of a direct relationship between sap flux and sapwood area made the previously discussed scaling approaches inappropriate for this study. While no relationship existed between diameter and sap flux and sap flow (Figure 5a), strong relationships were present between other morphological tree characteristics and sap flux. A scaling chain was developed to extrapolate from the sample tree to the stand level. Strong non-linear relationships were found between diameter and sapwood area of sample trees (Figure 5b). Sapwood area was then related to sapwood depth (Figure 5c). Sapwood depth was then related to sap flux (Figure 5d).

Relationships between tree characteristics observed here differ from results observed in other studies. Ewers et al. (2002) discovered a strong relationship between diameter and sapwood depth in some tree species in their study; however, the two wetland species showed no relationship between diameter and sapwood depth.   Wullschleger et al. (2001) found strong relationships between sapwood area and diameter in multiple ring porous species, a more direct relationship than was found in this study. Kumagai et al. (2005a) found no relationship between sapwood depth and sap flux, directly opposite of the findings in this study.

Stand level diameter values were used together with the scaling relationships to scale from sample tree sap flow to stand level transpiration. The Gebauer et al. (2008) relationships were applied and relative sapwood depth and relative sap flux were used to determine sap flow for all trees modeled for each site. Weekly non-linear relationships were developed and applied for sapwood depth to sap flux and for sap flux to sap flow to account for variation in sap flux throughout the field season.

Site level sap flow was extrapolated to a per hectare basis by multiplying the sap flow values for each site determined in conjunction with the Gebauer et al. (2008) relationship, by $4.1\bar{6}$:

$$SFWh = SFWs * (\frac{10,000 \ m^2}{2400 \ m^2})$$

<div align="right">**Equation 11**</div>

where *SFWh* is sap flow per hectare (m^3 ha^{-1} d^{-1}), *SFWs* is sap flow by site (m^3 m^{-2} d^{-1}), 10,000 m^2 is the number of square meters in a hectare, and 2400 m^2 is the number of square meters sampled in each field site.

2.5   Potential Evapotranspiration Determination

Potential evapotranspiration was determined for individual sites through the Penman equation (Penman, 1948) as modified by Shuttleworth (1993):

$$PET = \frac{\Delta Rn + \ \gamma \ [6.43(1 + 0.536 \ U) \ D]}{\lambda(\Delta + \ \gamma)}$$

<div align="right">**Equation 12**</div>

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where *PET* is potential evapotranspiration (mm day^{-1}), Δ is the slope of the saturation vapor pressure curve (kPa $^{\circ}$C^{-1}), R_n is net irradiance (MJ m^{-2} day^{-1}), γ is the psychrometric constant (kPa $^{\circ}$C^{-1}), *U* is wind speed (m s^{-1}), *D* is vapor pressure deficit (kPa), and λ is latent heat of vaporization (MJ kj^{-1}). Atmospheric components used in the Penman equation were determined using climate data from the Stony Brook weather station. This weather station is located near Stony Brook in Itasca County, Minnesota and is a HOBO U30-NRC weather station (Onset Computer Corp., Bourne, MA), at an elevation of 403.56 meters above sea level. The weather station took atmospheric data recordings every ten minutes. Data collected included temperature, relative humidity, wind speed, wind gust speed, and wind direction. These data were used in conjunction with solar insolation data to determine PET for the three sites. Solar insolation data were not available onsite and were provided by the Agricultural Research Service for the Bog Lake Fen Study Area, South Unit within the Marcell Experimental Forest. This data was provided in Watts/m^2 and was converted to MJ m^{-2} day^{-1} as is required for the Penman equation.

To compare PET values to transpiration values, PET was scaled from mm day^{-1} to m^3 m^{-2} d^{-1}. This conversion was made given that one hectare has a surface area of 10,000 m^2 and one millimeter is equal to .001 meters. When converted to a volume, 1 mm d^{-1} of water loss predicted by the Penman (1948) equation is equal to 10 m^3 of water loss per hectare per day. The Penman model was used in this study due to the availability of climate data necessary and the robustness and ease of using the model.

2.6   Soil Moisture Determination

EC-5 soil moisture sensors and Em5b analog dataloggers made by Decagon Devices (Pullman, WA) were used at each of the field sites to measure soil moisture content. Factory calibration equations were used to determine volumetric soil water content. Sensors were installed near six trees at VWS, seven trees at WS, and six trees at MS. The number of sensors deployed was contingent on supplies and not related to any site characteristic. Sensors were installed within one meter of the bole of each of the monitored trees. Sensors were installed at 15 centimeters and 30 centimeters below the

ground surface. Soil moisture sensors relayed soil water content data to dataloggers at fifteen minute intervals. Soil moisture content data was recorded from July 20th through September 4th for all field sites. Daily depletion values were determined for each day of the monitoring period by determining daily soil water change:

$$D = STmax - STmin$$

<div align="right">**Equation 13**</div>

where D is daily soil water depletion (m^3 m^{-3}), $STmax$ is maximum daily water storage (m^3 m^{-3}), and $STmin$ is minimum daily water storage (m^3 m^{-3}). Daily depletion values were determined for each depth. Daily water removal per tree was determined by multiplying daily depletion values per tree by root volume of individual trees. Root volume was determined by multiplying the root area by the depth of soil. Because two soil depths were examined, root volumes were calculated for both the 15 cm and 30 cm depths. The assumption was made that the soil moisture sensor at 15 cm approximated soil moisture from the surface to 15 cm and that the soil moisture sensor at 30 cm approximated soil moisture from 15 cm to 30 cm.   Root area was calculated using the root crown radius assuming the root crowns were a perfect circle. Gilman (1988) sets forth a method to determine root crown radius through a linear relationship between root spread radius and trunk diameter:

$$y = .10 + (.30 * x)$$

<div align="right">**Equation 14**</div>

where y is the root radius (m) and x is the trunk diameter (cm). The linear relationship used was developed for green ash (*Fraxinus pensylvanica*) (Gilman, 1988). Water removal values (m^3 d^{-1}) were scaled to the hectare level for each tree and averaged over all trees by site for each field season day of data collection. Water removal values were converted to mm d^{-1} for comparison with PET and transpiration values. The assumption was made that the monitored black ash trees were responsible for the soil water depletion measured by the soil moisture sensors.

3   Results

3.1   Comparison of Results for the Two Empirical Sap Flux Relationships

The two different empirical sap flux relationships used in this study yielded very different results for sap flux and sap flow. The Herbst et al. (2007) relationship yielded sap flux and sap flow values more than one order of magnitude higher than values determined using the Granier (1987a) relationship (Table 5). This large discrepancy between the Granier (1987a) and Herbst et al. (2007) methods was present for all three sites (Table 5). In an attempt to determine which relationship was more appropriate for sap flux determination in black ash swamps of northern Minnesota, transpiration values determined through both relationships were compared to PET and soil moisture depletion values for all the study sites over the field season. Weeks 7 through 12 were used for this comparison as this was the period when soil moisture sensors were active at the field sites.

Table 5. Comparison of average scaled sap flux values (m^3 m^{-2} d^{-1}) using the Granier (1987a) and the Herbst et al., (2007) methods. Values presented in both columns are average scaled sap flux (m^3 m^{-2} d^{-1}) over the entire field season for the very wet site (VWS), the wet site (WS), and the moderate site (MS) differentiated based on sap flux method.

Field Site	Average Sap Flux: Granier (m^3 m^{-2} d^{-1})	Average Sap Flux: Herbst (m^3 m^{-2} d^{-1})
VWS	3.34 ± 0.63	54.93 ± 16.22
WS	1.75 ± 0.14	23.17 ± 2.07
MS	1.60 ± 0.17	20.47 ± 2.67

Reported errors are one standard deviation from the mean.

The Herbst et al. (2007) relationship yielded sap flow values consistently exceeding PET values throughout the field season. Using the Herbst. et al. (2007) relationship, sap flow values were often more than twice that of PET for VWS and on average more than twice PET for WS and MS (Table 6). For week 7 through week 12 the estimated sap flow values using the Herbst et al. (2007) relationship exceeded soil water depletion at all sites with the exception of week 10 for the WS and MS (Table 6). Given the discrepancies between the sap flow values calculated using the Herbst et al.

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(2007) method and both PET and soil moisture depletion values, only values determined through the Granier (1987a) relationship were chosen to be the final representation of sap flux, sap flow, and transpiration values for the three black ash stands evaluated.

Table 6. Comparison of average weekly soil moisture depletion (mm d^{-1}), PET (mm d^{-1}), and empirically derived sap flow (mm d^{-1}) using the Granier (1987a) and Herbst et al. (2007) relationships for the very wet site (VWS), the wet site (WS), and the moderate site (MS). Week 7 through week 10 were used because those are the field season weeks when the soil moisture sensors were operational. Week 10 is an anomaly in terms of soil moisture depletion and stands out among the field season weeks.

Field Week	Soil Moisture Depletion (mm d^{-1})	Granier Sap Flow (mm d^{-1})	Herbst Sap Flow (mm d^{-1})	PET (mm d^{-1})
VWS Average	**1.23 ± 0.36**	**0.41 ± 0.04**	**6.01 ± 0.71**	**1.94 ± 0.23**
Week 7	1.55	0.41	6.09	2.25
Week 8	1.43	0.42	6.06	2.20
Week 9	0.98	0.37	5.53	1.78
Week 10	1.65	0.42	6.49	1.79
Week 11	1.00	0.47	6.95	1.87
Week 12	0.77	0.36	4.91	1.74
WS Average	**3.17 ± 1.46**	**0.34 ± 0.02**	**4.23 ± 0.21**	**1.94 ± 0.23**
Week 7	2.03	0.35	4.25	2.25
Week 8	3.28	0.35	4.34	2.20
Week 9	3.66	0.32	3.89	1.78
Week 10	5.74	0.33	4.10	1.79
Week 11	2.64	0.35	4.34	1.87
Week 12	1.65	0.36	4.48	1.74
MS Average	**2.75 ± 1.34**	**0.35 ± 0.02**	**4.22 ± 0.36**	**1.94 ± 0.23**
Week 7	3.91	0.35	4.14	2.25
Week 8	3.34	0.38	4.65	2.20
Week 9	1.66	0.37	4.49	1.78
Week 10	4.50	0.36	4.41	1.79
Week 11	1.75	0.33	3.87	1.87
Week 12	1.32	0.32	3.76	1.74

Reported errors are one standard deviation from the mean.

3.2 Sap Flux and Sap Flow

The VWS often demonstrated the highest sap flux, sap flow, and site transpiration while the MS exhibited the lowest sap flux, sap flow, and site transpiration. The WS was often in the middle of the other two sites for sap flux, sap flow, and site transpiration (Table 7). This pattern held true for sap flux and sap flow, however, WS demonstrated a higher maximum sap flow value than VWS. While trends in sap flux and sap flow by site are recognizable, the standard deviations of the sites are substantial and often overlap for the variables examined.

Table 7. Summary of mean and maximum sap flux (m^3 m^{-2} d^{-1}) and sap flow (dm^3 d^{-1}) values by site for the eight monitored trees for the very wet site (VWS), the wet site (WS), and the moderate site (MS) over the entire field season. Mean daily sap flux (m^3 m^{-2} d^{-1}) and sap flow (dm^3 d^{-1}) are presented in the first two columns while maximum daily sap flux (m^3 m^{-2} d^{-1}) and sap flow (dm^3 d^{-1}) are presented in the latter two columns.

Field Site	Mean Daily Sap Flux (m^3 m^{-2} d^{-1})	Mean Daily Sap Flow (dm^3 d^{-1})	Maximum Daily Sap Flux (m^3 m^{-2} d^{-1})	Maximum Daily Sap Flow (dm^3 d^{-1})
VWS	3.20 ± 1.39	9.15 ± 3.71	12.82 ± 1.75	21.26 ± 4.74
WS	2.16 ± 2.13	8.56 ± 7.41	9.19 ± 2.11	31.13 ± 7.28
MS	1.57 ± 0.95	6.93 ± 4.18	4.16 ± 0.97	14.84 ± 4.15

Reported errors are one standard deviation from the mean.

Differences in sapwood depth and sapwood area were prevalent between the three field sites. The pattern for sapwood depth and sapwood area among sites was different than the pattern for sap flux and sap flow among sites. Sapwood depth was greatest at WS and smallest at VWS. Mean sapwood area and total sapwood area followed a reverse pattern of sap flux and sap flow; MS demonstrated the greatest sapwood depth and sapwood area while VWS demonstrated the lowest sapwood depth and sapwood area (Table 8). While VWS did exhibit the lowest mean and total sapwood area, it also exhibited the greatest mean daily sap flow due to high daily sap flux at VWS. MS demonstrated the highest mean and total sapwood area of all of the sites, but exhibited the lowest mean daily sap flux (Table 8). Total sapwood area at MS was likely higher due to high mean sapwood depth and the larger number of trees present at MS.

Table 8. Summary of sapwood depths (cm) and sapwood area (cm^2) for the monitored trees at the very wet site (VWS), the wet site (WS), and the moderate site (MS). Sapwood depth refers to the depth from inside the cambium to the end of the hydroactive xylem. Mean sapwood area is the average area of the hydroactive xylem across the monitored trees at each field site. Total sapwood area is the summation of the sapwood area of the monitored trees at each site.

Field Site	Mean Sapwood Depth (cm)	Mean Sapwood Area (cm^2)	Total Sapwood Area (cm^2)
VWS	0.82 ± 0.19	61.99 ± 28.49	495.89 ± 28.49
WS	1.41 ± 0.56	96.16 ± 49.94	769.32 ± 49.94
MS	1.37 ± 0.46	106.67 ± 67.23	853.34 ± 67.23

Reported errors are one standard deviation from the mean.

Changes in sap flux and sap flow were observed over the course of the field season. Sap flux showed a similar pattern to sap flow for all sites (Figure 6). All sites showed a rise in sap flux and sap flow at the beginning of the field season followed by a decline in the middle of the field season. Patterns of sap flux and sap flow at the end of the field season varied by site. VWS showed the greatest sap flux over the entire field season, while MS exhibited the lowest sap flux. VWS also exhibited the greatest sap flow over the field season; however, WS values were much closer to VWS for sap flow than sap flux, with some weeks exceeding VWS sap flow values late in the field season. The difference between sap flux and sap flow pattern by site is likely due to VWS demonstrating higher sap flux values than WS, but WS had higher sapwood area, causing the sap flow values to be closer between the two sites than sap flux.
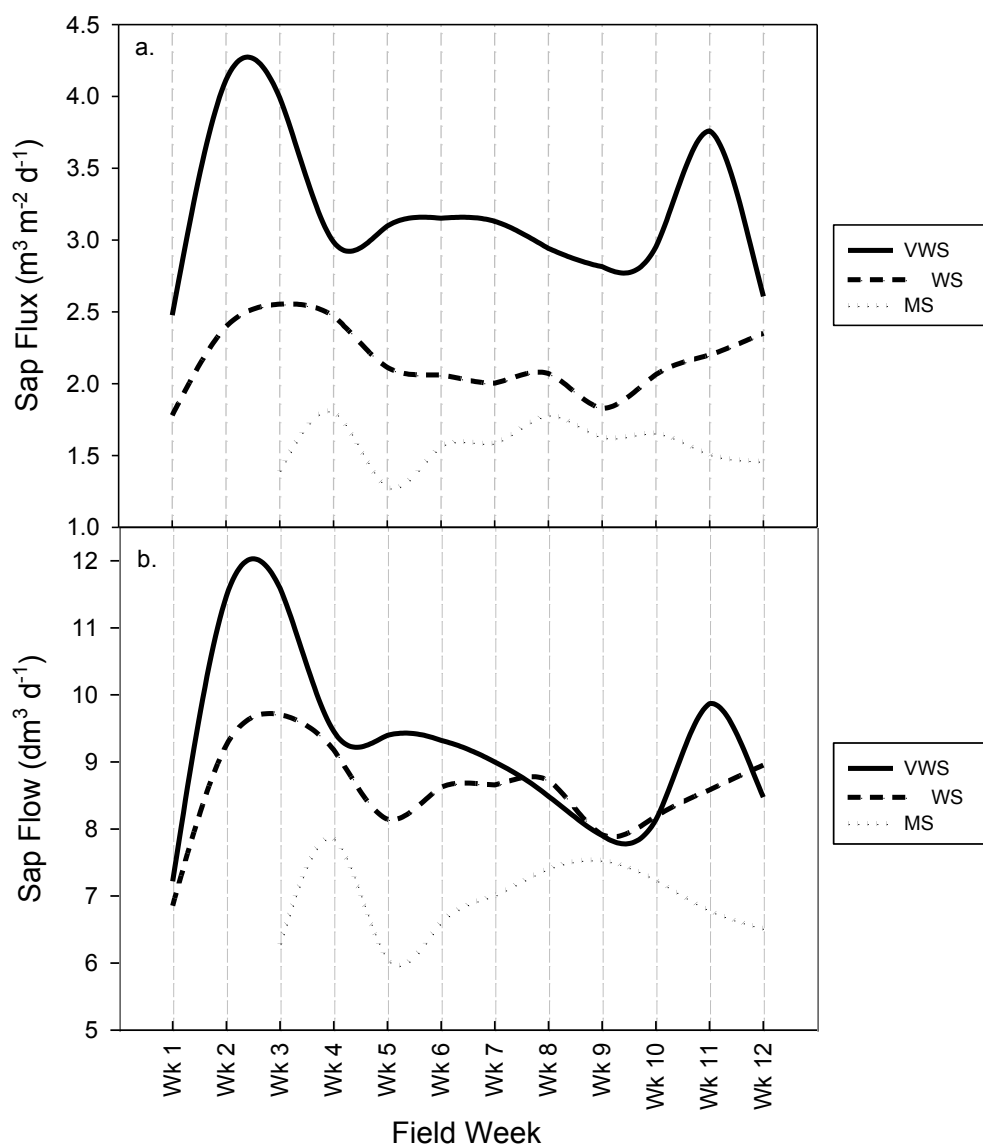
Figure 6. Average sap flux (m^3 m^{-2} d^{-1}) and sap flow (dm^3 d^{-1}) of monitored trees through the field season differentiated by site for the very wet site (VWS), the wet site (WS), and the moderate site (MS): (a.) average sap flux (m^3 m^{-2} d^{-1}) of monitored trees through the field season by site, (b.) average sap flow (dm^3 d^{-1}) of monitored trees through the field season. The field season began in mid June and extended through early September.

3.3 Transpiration Scaling

Transpiration scaling was conducted for all sites using monitored tree sap flux data and tree overstory surveys. Monitored trees are the eight trees per site that were monitored for sap flux throughout the field season. The term scaled trees refers to the

extrapolation from the monitored trees to the whole stand and beyond by using the results for the monitored trees in conjunction with the stand inventory data. Whole site sap flow will be referred to as transpiration from this point forward, because of the shift in scale from examining monitored trees, to assumptions of the entire field site. The term sap flux will continue to be used to describe rate of sap movement for scaled trees. Scaling to whole-stand transpiration yielded results similar to the monitored tree data with the exception of greater differences between sites. Differences in scaled results and actual monitored results are possibly due to error associated with the scaling process, faulty assumptions when scaling, inadequate tree selection, or variability in monitored trees. In the scaled data, WS is often closer to MS; in the actual monitored data, WS is not as consistently close to MS. This difference can be explained by the particular trees selected for study at WS. Tree one and tree five at WS both demonstrated much higher sap flux and sap flow values than other trees at the site. No data outliers were retained for analysis, but these two trees had higher values than other trees at the site and could be partially responsible for some of the trends observed in the monitored data.

With the exception of the degree of separation among sites, trends among sites for mean daily sap flux and mean daily transpiration of scaled trees were similar to results for the monitored trees. Similar to the monitored trees, scaled trees at VWS demonstrated the highest sap flux values while MS demonstrated the lowest. VWS also exhibited the highest daily transpiration, while MS exhibited the lowest daily transpiration. This result for scaled transpiration is similar to the results for sap flow of monitored trees. For scaled estimates, VWS exhibited the highest maximum sap flux while MS exhibited the lowest maximum sap flux. Maximum transpiration results followed a slightly different pattern with VWS exhibiting the highest maximum daily transpiration values and WS demonstrating the lowest maximum daily transpiration values (Table 9).

Table 9. Summary of scaled mean and maximum sap flux ($m^3 m^{-2} d^{-1}$) and transpiration ($dm^3 d^{-1}$) values for the very wet site (VWS), the wet site (WS), and the moderate site (MS). Scaled sap flux and transpiration refers to sap flux and transpiration of the entire field site scaled from the eight monitored trees at each site to all trees at the field site.

Field Site	Mean Daily Sap Flux ($m^3 m^{-2} d^{-1}$)	Mean Daily Transpiration ($dm^3 d^{-1}$)	Maximum Daily Sap Flux ($m^3 m^{-2} d^{-1}$)	Maximum Daily Transpiration ($dm^3 d^{-1}$)
VWS	3.34 ± 0.63	7.17 ± 1.26	8.68 ± 1.17	19.82 ± 2.46
WS	1.75 ± 0.13	6.10 ± 0.40	4.22 ± 0.68	9.43 ± 1.29
MS	1.60 ± 0.17	4.98 ± 0.46	3.55 ± 0.60	11.17 ± 1.61

Reported errors are one standard deviation from the mean.

Sapwood depth and sapwood area values differed among sites but scaled trees demonstrated a similar pattern to monitored trees when considering sapwood depth. VWS demonstrated the smallest sapwood depth while WS demonstrated the largest sapwood depth. Unlike the monitored trees, WS scaled trees exhibited the highest mean sapwood area and fell between the other two sites in terms of total sapwood area values. VWS demonstrated the lowest mean scaled sapwood area and total sapwood area (Table 10).

Table 10. Summary of scaled sapwood depths (cm) and sapwood area (cm^2) for the very wet site (VWS), the wet site (WS), and the moderate site (MS). Scaled sapwood depth and sapwood area refers to the sapwood depth and sapwood area of the entire field site.

Field Site	Mean Scaled Sapwood Depth (cm)	Mean Scaled Sapwood Area (cm^2)	Total Scaled Sapwood Area (cm^2)
VWS	0.75 ± 0.17	50.63 ± 30.14	7,644.92 ± 30.14
WS	1.25 ± 0.22	81.31 ± 25.92	10,814.86 ± 25.92
MS	1.18 ± 0.33	76.11 ± 45.98	12,709.84 ± 45.98

Reported errors are one standard deviation from the mean.

Sap flux and transpiration varied over the course of the field season and among the field sites. VWS scaled trees exhibited the highest weekly sap flux values across the study period. MS and WS demonstrated similar sap flux values and patterns to one another over the study period (Figure 7). The increased similarity of these two sites when compared to the monitored data can be traced back to tree one and tree five of the

monitored trees at WS. Scaled sap flux data over the field season shows a similar pattern when compared to monitored sap flux data over the same period. Transpiration of scaled trees also showed a similar pattern to transpiration of monitored trees for site comparisons and trends through time. VWS exhibited greater transpiration values throughout the study period while MS demonstrated the lowest transpiration values (Figure 7). There was less difference between WS and VWS for transpiration then for sap flux. The upward shift in transpiration for WS is likely due to this site exhibiting the highest mean sapwood depth and sapwood area (Figure 7).
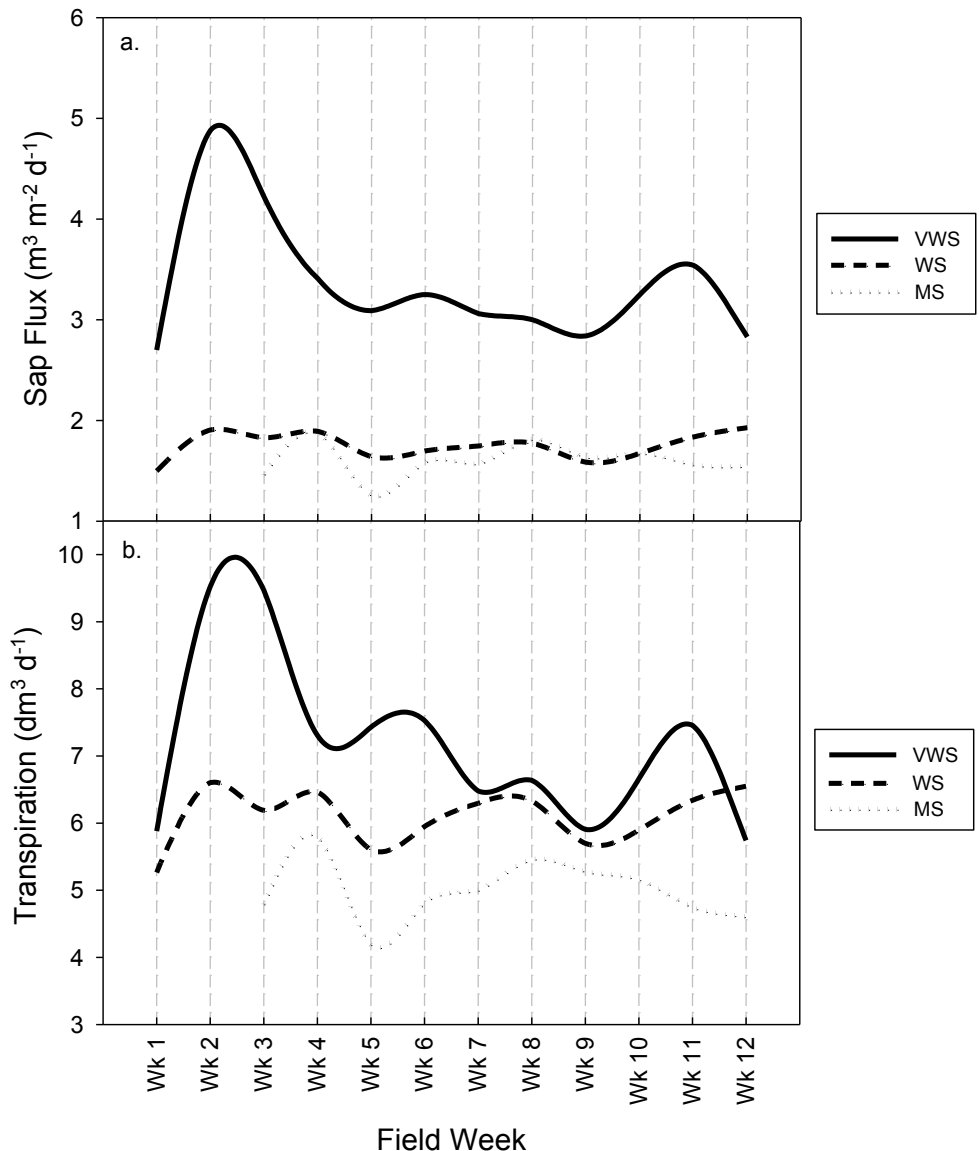
Figure 7. Average sap flux (m^3 m^{-2} d^{-1}) and transpiration (dm^3 d^{-1}) of scaled trees through the field season for the very wet site (VWS), the wet site (WS), and the moderate site (MS): (a.) average sap flux (m^3 m^{-2} d^{-1}) of scaled trees through the field season by site, (b.) average transpiration (dm^3 d^{-1}) of scaled trees through the field season by site. The field season began in mid June and extended through early September.

Once scaled to total site level transpiration and total transpiration on a unit area basis, sites follow a slightly different pattern when compared to scaled mean daily transpiration. Transpiration was converted from site level transpiration (dm^3 d^{-1}) to transpiration on a hectare basis (m^3 ha^{-1} d^{-1}). Transpiration was also converted to mm d^{-1}

for comparison with PET values. VWS exhibited the highest total daily site level transpiration, total transpiration per hectare, and total transpiration (mm d^{-1}). This follows the pattern seen for the monitored sap flow results by site, however, compared to WS, MS demonstrated higher values for total plot level transpiration, total transpiration per hectare, and total transpiration (mm d^{-1}) (Table 11). This is due to the density of trees at each of the plots. WS contains fewer trees than MS. While WS exhibits higher individual tree sap flux and transpiration values, WS has fewer trees to transpire and subsequently lower total plot level and total per unit area transpiration values.

Table 11. Summary of transpiration values at the scaled site level in (dm^3 d^{-1}), per unit area (m^3 ha^{-1} d^{-1}), and scaled site level for comparison with PET (mm d^{-1}) for the very wet site (VWS), the wet site (WS), and the moderate site (MS).

Field Site	Total Site Level Transpiration (dm^3 d^{-1})	Total Transpiration per Hectare (m^3 ha^{-1} d^{-1})	Total Transpiration (mm d^{-1})
VWS	1082.43 ± 190.13	4.51 ± 0.79	0.45 ± 0.08
WS	810.99 ± 55.56	3.38 ± 0.23	0.34 ± 0.02
MS	832.40 ± 76.74	3.47 ± 0.32	0.35 ± 0.03

Reported errors are one standard deviation from the mean.

3.4   Potential Evapotranspiration and Drivers of Transpiration

VWS exhibited the highest mean transpiration values and subsequently accounted for the greatest percentage of PET when compared to the other two field sites. MS and WS transpiration values were very similar to one another and accounted for a lower percentage of total PET. There was no relationship between PET and sap flow for the sites in aggregate (Figure 8a); however, there was a relationship between VWS transpiration and PET over the field season (Figure 8b).
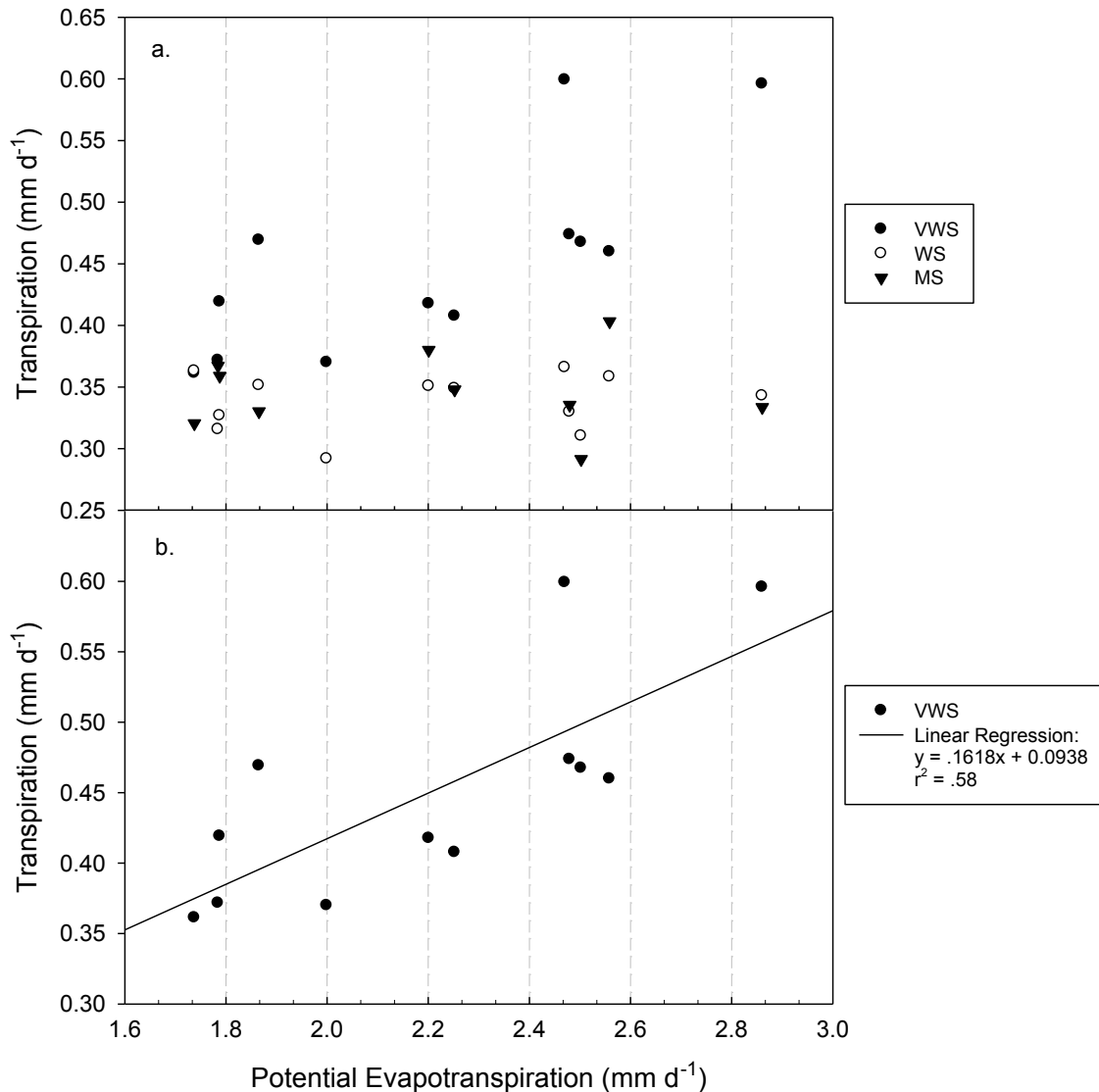
Figure 8. Evaluation of the relationship between PET (mm d^{-1}) and transpiration (mm d^{-1}) over the field season: (a.) comparison of PET (mm d^{-1}) and transpiration (mm d^{-1}) over the field season for the very wet site (VWS), the wet site (WS) and the moderate site (MS), (b.) comparison of PET (mm d^{-1}) and transpiration (mm d^{-1}) over the field season for VWS.

To better estimate the relationship between atmospheric characteristics and transpiration by site, weeks 3-11 were analyzed separately from the whole field season. By removing the early weeks in the growing season, results impacted by early sap flow resulting from higher sap movement in ring porous species during leaf-out were removed. The last week of the field season was removed to negate any impact of increased sap flow

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as a result of translocation. Removing the early and late weeks of the field season resulted in an improved relationship between atmospheric characteristics and transpiration at VWS. Vapor pressure deficit values were compared to transpiration values for all of the sites for the whole field season and for weeks 3-11 (Figure 9). There was no relationship between vapor pressure deficit and transpiration for the WS and MS. At VWS, there was a relationship between vapor pressure deficit and sap flow for the whole study period and the study period with modifications to the beginning and the end of the field season; the relationship was stronger for week 3 through week 11 than for the whole field season. The relationship between vapor pressure deficit and transpiration did not improve at WS and MS when timescale was altered to reduce error associated with tree physiological impacts to sap flow indicating a lack of atmospheric drivers impacting transpiration at WS and MS (Figure 9).
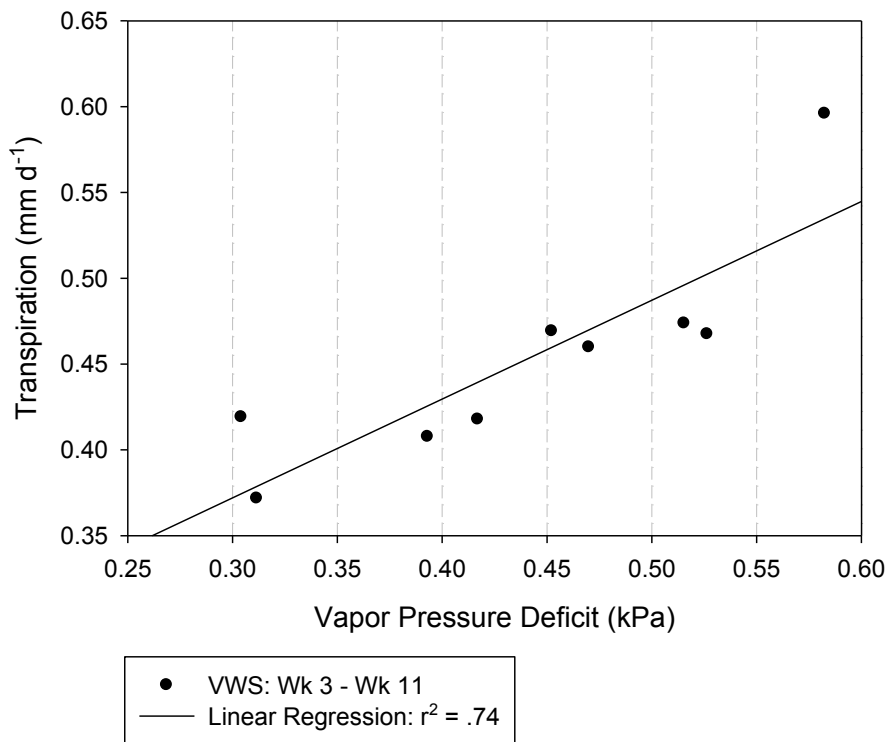
Figure 9. Relationship between vapor pressure deficit (kPa) and transpiration (mm d^{-1}) for the very wet site (VWS). This relationship begins in the third week of the field season and continues through the eleventh week of the field season. The beginning and end of the field season is removed to negate seasonal physiological influences of black ash to sap flow within the field sites.
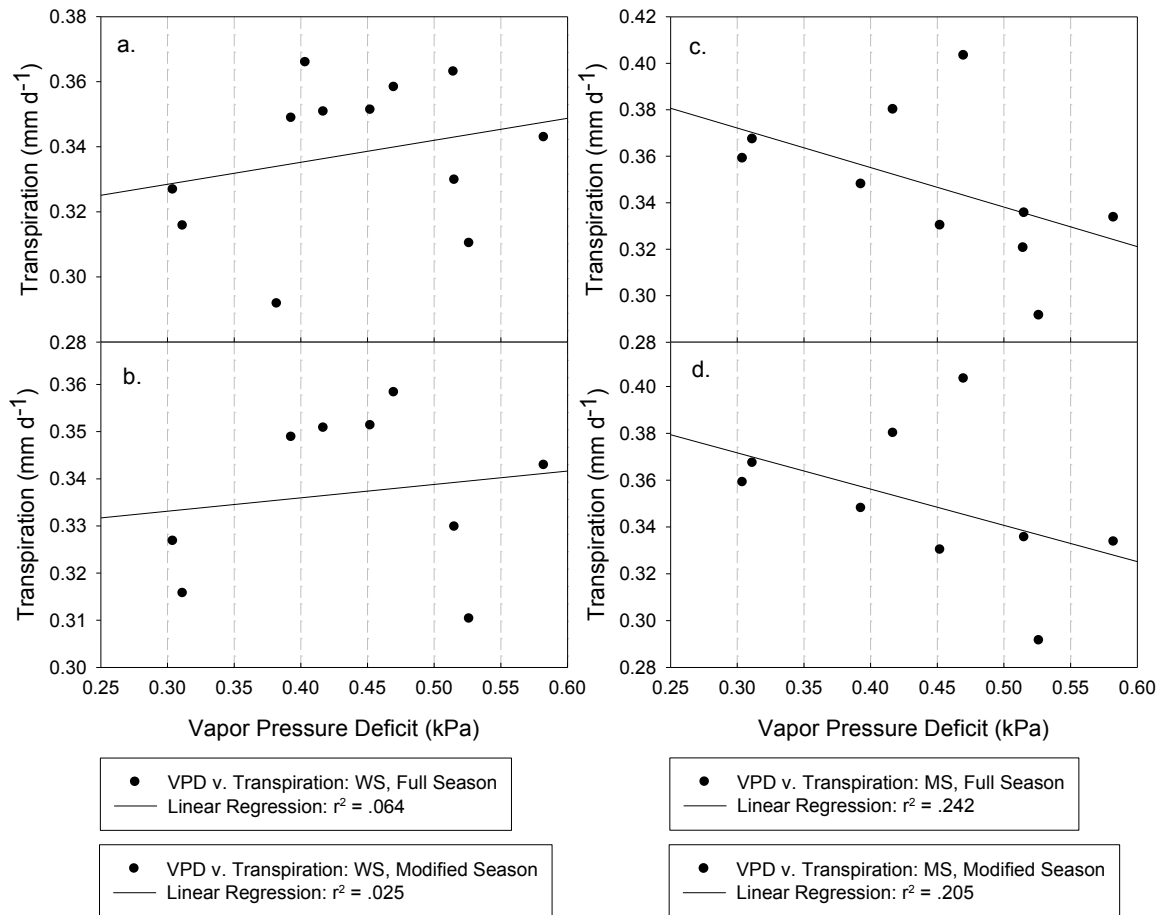
Figure 10. Relationships between average weekly vapor pressure deficit (kPa) and average weekly transpiration (mm d^{-1}) for the wet site (WS) and the moderate site (MS): (a) comparison of vapor pressure deficit (kPa) and transpiration (mm d^{-1}) for WS over the entire 12 week field season, (b) comparison of vapor pressure deficit (kPa) and transpiration (mm d^{-1}) for WS with weeks 1-2, and 12 of the field season removed, (c) comparison of vapor pressure deficit (kPa) and transpiration (mm d^{-1}) for MS over the entire 12 week field season, (d)) comparison of vapor pressure deficit (kPa) and transpiration (mm d^{-1}) for MS with weeks 1-2, and 12 of the field season removed.

WS and MS did not share a relationship with PET or other atmospheric drivers of transpiration. Soil water availability was assumed to be partially responsible for influencing transpiration at the field sites. To test for relationships with soil water availability, sap flux was compared to soil moisture depletion at both shallow (0-15 cm) and deeper (15-30 cm) soil profile depths. A relationship between sap flux and soil moisture depletion existed for some of the trees at MS for the shallow depth. Figure 11 demonstrates one of the better relationships between sap flux and soil moisture depletion

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at MS. No relationships existed at the deeper soil depth. See Appendix B for all late season sap flux and soil moisture depletion relationships at MS. The strong relationships between sap flux and soil moisture depletion at MS demonstrate a possible link between soil moisture, sap flux, and transpiration. This relationship only existed for MS late in the field season when moisture was most limited (Figure 11). This indicates that soil moisture is an increasingly important factor in controlling transpiration rates as water restrictions increase. Soil moisture content was also compared to PET through the field season for each of the field sites. None of the sites demonstrated a relationship between PET and soil moisture depletion for the mid and late field season (Appendix C).
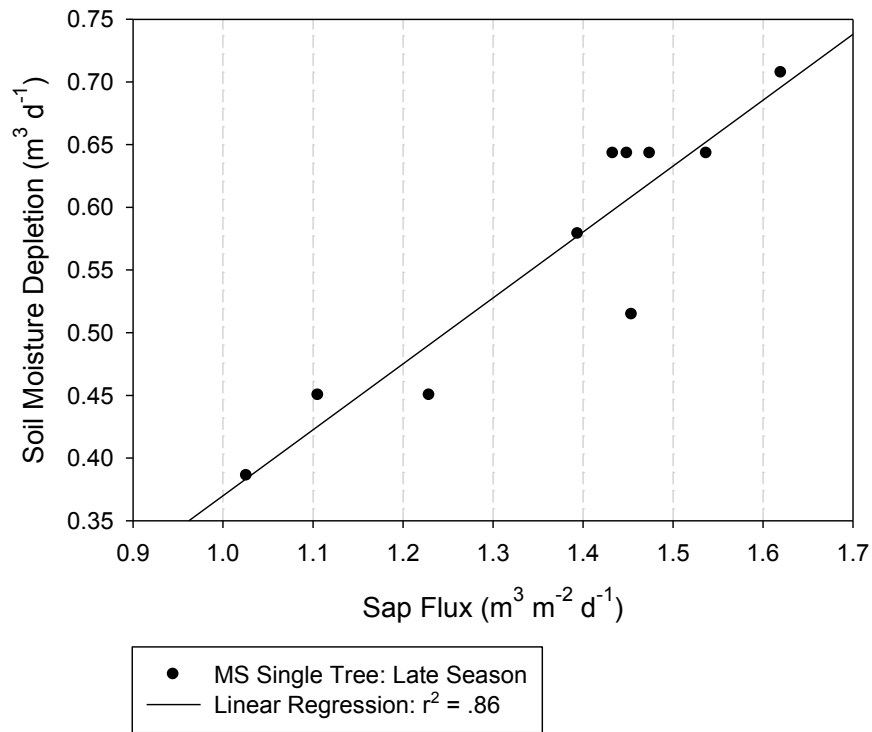
Figure 11. Comparison of daily sap flux (m^3 m^{-2} d^{-1}) and daily soil moisture depletion (m^3 d^{-1}) from 1-15 cm depth for a single tree at the moderate site (MS) during the late field season.

Transpiration varied over the course of the field season and was different between the field sites. VWS exhibited the highest average weekly transpiration values over the field season; neither of the other two sites exhibited higher weekly average transpiration values for any individual week. VWS demonstrated the highest average transpiration

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values over the entire field season. WS and MS exhibited very similar transpiration

values to one another (Table 12). Transpiration by week and over the entire field season

varied among sites with VWS demonstrating the highest transpiration values, however,

transpiration at all sites was low when compared to PET values throughout the field

season.

Table 12. Comparison of average transpiration values by site (mm d^{-1}) to PET (mm d^{-1}) over the field season for the very wet site (VWS), the wet site (WS), and the moderate site (MS). MS transpiration (mm d^{-1}) values begin in the third week of the field season because that is the first week that the sap flux equipment at the site was operational.

Field Week	VWS Transpiration (mm d^{-1})	WS Transpiration (mm d^{-1})	MS Transpiration (mm d^{-1})	PET (mm d^{-1})
Week 1	0.37	0.29		2.00
Week 2	0.60	0.37		2.47
Week 3	0.60	0.34	0.33	2.86
Week 4	0.46	0.36	0.40	2.56
Week 5	0.47	0.31	0.29	2.50
Week 6	0.47	0.33	0.34	2.48
Week 7	0.41	0.35	0.35	2.25
Week 8	0.42	0.35	0.38	2.20
Week 9	0.37	0.32	0.37	1.78
Week 10	0.42	0.33	0.36	1.79
Week 11	0.47	0.35	0.33	1.87
Week 12	0.36	0.36	0.32	1.74
Average	0.45 ± 0.08	0.34 ± 0.02	0.35 ± 0.03	2.21 ± 0.37

Reported errors are one standard deviation from the mean.

VWS, the site which exhibited the greatest transpiration by week and over the

entire field season, was only responsible for 1/5th of PET on average. The other two sites

were responsible for slightly less. Neither WS nor MS contributed more to PET than

VWS for a given week (Table 13).

Table 13. Comparison of the estimated contribution of transpiration to PET as a percentage for the very wet site (VWS), the wet site (WS) and the moderate site (MS). MS does not contain values for week 1 and week 2 because the site was not operational until week 3.

Field Week	VWS Transpiration % of PET	WS Transpiration % of PET	MS Transpiration % of PET
Week 1	18.50%	14.59%	
Week 2	24.26%	14.81%	
Week 3	20.83%	11.99%	11.66%
Week 4	17.97%	14.00%	15.76%
Week 5	18.68%	12.40%	11.64%
Week 6	19.10%	13.30%	13.53%
Week 7	18.10%	15.49%	15.45%
Week 8	18.98%	15.94%	17.27%
Week 9	20.83%	17.69%	20.58%
Week 10	23.44%	18.28%	20.08%
Week 11	25.15%	18.83%	17.70%
Week 12	20.79%	20.89%	18.44%
Average	20.55% ± 2.49%	15.68% ± 2.74%	16.21% ± 3.19%

Reported errors are one standard deviation from the mean.

PET and transpiration values were compared throughout the field season to discern if any trends were present. PET exhibited a downward trend throughout the field season with a spike at the beginning of the field season, and a small increase towards the end of the field season. Over the field season, transpiration followed a similar pattern to PET at VWS, where both transpiration and PET values experienced a sharp rise at the beginning of the field season followed by a steady decrease through time (Figure 12). There was not a strong similarity between PET patterns and transpiration at WS and MS throughout the field season. All sites exhibited transpiration values far below PET with VWS being the closest to PET, followed by WS and MS (Figure 12).
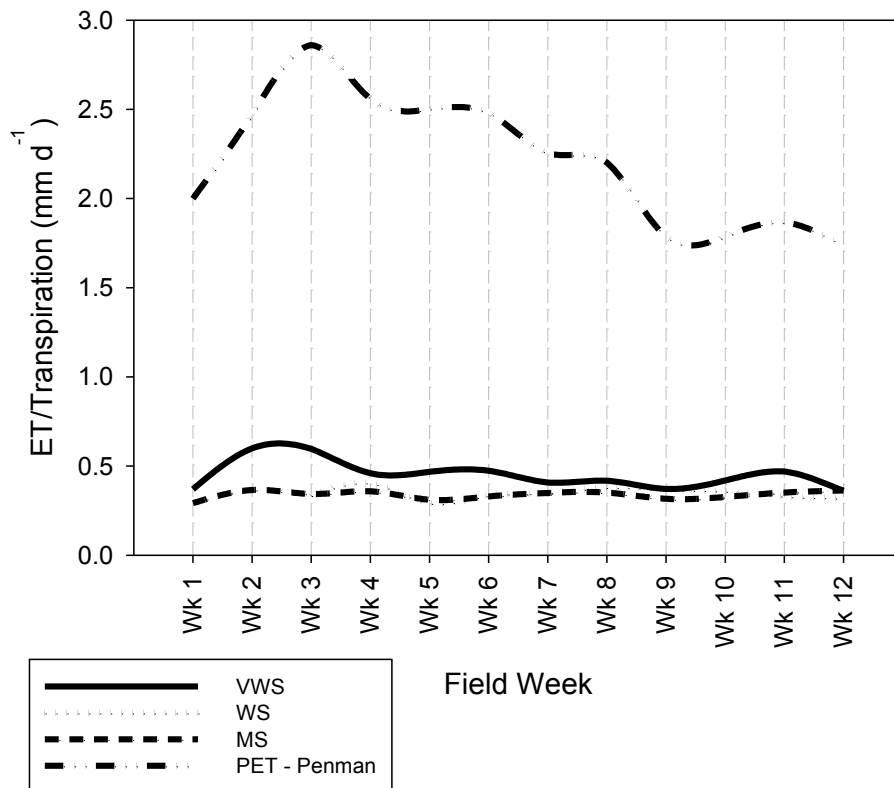
Figure 12. Comparison of PET (mm d^{-1}) for all sites and transpiration (mm d^{-1}) of the very wet site (VWS), the wet site (WS), and the moderate site (MS) over the field season.

4   Discussion

4.1   Addressing Inaccuracy Associated with Transpiration Determination

Recent studies have found that the original Granier (1985, 1987a) empirical relationship is problematic for sap flux determination in ring porous species, asserting that the original relationship could be underestimating sap flux for these species by many orders of magnitude. (Herbst et al., 2007; Taneda and Sperry, 2008; Bush et al., 2010). Black ash is a ring porous species, therefore, each of the relationships put forth in Herbst et al. (2007), Taneda and Sperry (2008), and Bush et al. (2010) were applied to a small subset of data to test each of the empirical relationships and see if the relationships yielded reasonable results. The Herbst et al. (2007) relationship was chosen because it was the most conservative estimator of sap flux when compared with results using other relationships for ring porous trees (Taneda and Sperry, 2008; Bush et al., 2010), and

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Herbst et al. (2007) used a European ash when developing their empirical relationship. It is critical to use the best estimator of sap flux when choosing a relationship to determine sap flux and stand transpiration; as Hatton et al. (2005) point out, accurate measurement of sap flux is one of the most important elements to reduce error in whole stand transpiration estimation. Given the voltage differential values collected for this study and the PET and soil moisture content results, a more conservative estimator that yielded results closer to results from the original Granier (1987a) relationship was appropriate for the circumstances of this study. Transpiration values determined using the Herbst et al. (2007) relationship were often twice that of PET and also larger than soil moisture depletion. While it is likely that the Granier (1987a) relationship underestimated sap flux to an unknown degree affecting the accuracy of the results of this study, the Granier (1987a) relationship was determined to be a better estimator given the relationships of estimates using this method with PET and soil moisture depletion data.

The amount of missing sap flux data is a source of error that needs to be considered. The methods to collect sap flux data rely on technology and environmental conditions conducive to data collection. The equipment used to collect sap flux data in this study malfunctioned during the course of the field season which contributed to incomplete datasets. Acts of nature also contributed to incomplete sap flux datasets for the entire field season. Each field site contained different levels of missing data. The VWS, WS, and MS contained data for, on average, 54.1%, 61.7%, and 58.2% of the field days, respectively. If added to the final dataset, the missing data could have altered the final sap flux or sap flow values in this study. However, the addition of the missing data would not likely change the overall trends seen in the study. The amount of PET accounted for by black ash would likely be similar and differences between the three field sites would likely remain. Missing data is a source of error in all sap flux studies; the addition of the missing data to the final datasets of this study would possibly increase the accuracy of the results, but not likely change the trends of the data or the conclusions of the study.

Variability in sapwood depth can be problematic in determining tree-level sapwood depth and subsequently sapwood area. This uncertainty can cause problems

with confidence in scaled transpiration estimates. Previous studies have found little uniformity in sapwood depth and azimuthal variation in sapwood depth; however, sapwood depth is known to vary with aspect (Ewers and Oren, 2000; Lu et al., 2000; Ewers et al., 2002; Hultine et al., 2007; Cohen et al., 2008; Kim et al., 2008). This is consistent with the results of this study; no pattern could be found between sapwood depth or sap flux and tree aspect.

Radial variability of sap flux within monitored trees can also reduce the accuracy of results; many studies have investigated radial variability in tree species (Lu et al., 2000; Nadezhdina et al., 2002; Delzon et al., 2004; Ford et al., 2004a; Ford et al., 2004b; Fiora and Cescatti, 2006; Poyatos et al., 2007; Gebauer et al., 2008; Saveyn et al., 2008). To address the variability in radial sap flux, the Gebauer et al. (2008) relationship was applied to sap flux data in this study. The Gebauer et al. (2008) relationship was chosen because the relationship was developed for an ash species and did not address radial variability of sap flux in tree species with sapwood depths specifically greater than two centimeters. Other studies have employed the Pataki et al. (2011) relationships to account for radial decreases in sap flux. The Pataki et al. (2011) method is especially useful for correction in studies with angiosperms and gymnosperms, and studies that evaluate trees with sapwood depths greater than those in this study. Although the diameters of trees examined in the Pataki et al. (2011) study were fairly similar to those examined in this study, sapwood depth was often many times greater than depths observed in this study.   Sapwood depths in this study only exceeded two centimeters for one tree at one of the sites.

A common source of error in sap flux studies is scaling from individual tree sap flux to stand level transpiration. The most common method involves determining mean sap flux of all monitored trees and multiplying by stand sapwood area (Schafer et al., 2002; Tang et al., 2006; Mitchell et al., 2012). Some studies have taken this method a step further by segmenting sapwood and sap flux into different classes and then multiplying mean sap flux by stand sapwood area (Granier et al., 1996a; Granier et al., 2000a; Herbst et al., 2007). While these methods have the advantage of being simple and only involving a few tree and stand level characteristics, no direct relationship was found

between sap flux and sapwood area for this study. There was also variability in sap flux values among and within sites due to the wide array of diameters examined and the variety of soil moisture regimes present within field sites. In an attempt to reduce error in the scaling process, a scaling chain was developed to scale from individual tree sap flux to stand level transpiration. Most of the relationships developed for the scaling chain demonstrated moderate to strong (.4-.9) coefficients of determination (Appendix D). While this scaling method was employed to reduce error associated with scaling, multiple steps in any scaling process result in error at each of the scaling steps. A more direct scaling relationship would have resulted in less error accumulation in estimation of the final values. While error is present in the scaling process, the scaling chain used in this study was developed based on relationships with strong coefficient of determinations and logical relationships between tree physiological characteristics and sap movement.

Aside from the method employed for scaling sap flow values to transpiration, previous work has shown that important aspects of scaling include accurate determination of sapwood area (Kumagai et al., 2005b), species composition by site (Moore et al., 2004), number of stems of each study site (Ewers et al., 2002), and variation in stand density and stand sapwood area (Ford et al., 2007). To account for these concerns sapwood area was determined for each tree in the study. Information on tree characteristics such as diameter, number of live stems, and tree species was obtained prior to transpiration determination and used in concert with the scaling chain to determine scaled transpiration.

PET was used to determine the contribution of black ash to the hydrologic budget of ash swamps; however, estimation of PET contains multiple steps and unit transfers which can increase estimation error (Valiantzas, 2006). Weather stations often do not contain equipment necessary to measure net radiation and vapor pressure deficit directly (Shuttleworth, 2003), as was the case in this study. Net radiation values were supplied from the Marcell Experimental Forest located over fifty miles from study sites. This distance likely introduced error in PET calculation. The number of parameters and many unit transfers associated with the equation increase the likelihood of error in the estimation process. Due to the complexity of the Penman equation and the increased

likelihood for error, the Thornthwaite, Hamon (1963), and other similar methods can also be used to determine PET. However, simplified methods use fewer parameters and can result in inaccurate PET estimations (Chen et al., 2005). The amount of error accrued through the Penmen method is unknown, but error accrued through the complexity of the equation was determined to be more desirable than error accrued through use of a simpler equation.

4.2   Comparing Transpiration with PET

Sap flux rates and sapwood area are components necessary to determine stand transpiration. These components both influence transpiration determination and the estimated proportion of ET accounted for by transpiration. Daily sap flux rates determined in this study were similar to those determined in other sap flux studies (Ewers et al., 2002; Holscher et al., 2005; Tang et al., 2006; Oishi et al., 2010, Peters et al., 2010) (Table 14). However, stand transpiration values and proportion of PET (Table 1) were both lower than expected given the results of other sap flux studies (Calder, 1978; Kelliher et al., 1998; Granier et al., 2000a; Zimmermann et al., 2000; Wilson et al., 2001; Wullschleger et al., 2001; Delzon and Loustau, 2005; Bovard et al., 2005; Ford et al., 2010; Oishi et al., 2010; Tang et al. 2010). Results were similar, however, to Poyatos et al. (2007) who also determined transpiration to be a small component of PET in downy oak (*Quercus pubescens*) in Northeast Spain under a sub-Mediterranean climate. Differences between the proportion of PET accounted for by transpiration in this study compared with other studies could be due to a number of factors, including physiological differences in the species evaluated, stand density and basal area, and applicability of current empirical sap flux relationships to black ash. Black ash trees evaluated in this study had very shallow hydroactive sapwood depth and relatively small sapwood area. Other studies examining sap flux of ring porous oak tree species found average sapwood area to be between 207 cm^2 and 395 cm^2 (Wullschleger et al., 2001; Ford et al., 2010). Holscher et al. (2005) included an ash species in their study and found average sapwood area to be 134 cm^2 for European ash (*Fraxinus excelsior*). Gebauer et al. (2008) found sapwood area of European ash (*Fraxinus excelsior*) to be between 15 cm^2 and 521 cm^2

with a median value of 88 cm^2. Studies have reported higher sapwood area values for diffuse porous species. Wullschleger et al. (2001) reported sapwood area of diffuse porous species such as yellow poplar (*Liriodendron tulipifera*), red maple (*Acer rubrum*), and black gum (*Nyssa sylvatica*) to be 493 cm^2, 742 cm^2, and 417 cm^2, respectively. Ford et al. (2010) found sapwood area values of 491 cm^2, 726 cm^2, and 498 cm^2 for ring porous hickory (Carya spp.), diffuse porous yellow poplar (*Liriodendron tulipifera*), and eastern white pine (*Pinus strobus*), respectively. Sapwood area of black ash at VWS, WS, and MS in this study varied between 25 cm^2 and 205 cm^2 with an average of 88 cm^2; sapwood values for trees in this study were often lower than those in other studies, even studies examining ring porous tree species. This could account for some of the difference in the proportion of PET accounted for in this study compared with others. The low sapwood area values seen in this study could be the result of many different factors including the method used to estimate sapwood depth, the flooded status of black ash forests, or the amount of leaf area of black ash stands. Hydroactive xylem depth was used to estimate sapwood depth in this study. It is possible that studies with higher sapwood area values did not distinguish between hydroactive and non-hydroactive xylem. Black ash physiology and the common flooded status of black ash forests could also be partially responsible for the lower sapwood area values seen in this study. Studies that examine diffuse porous tree species or tree species growing in drier environments may have determined higher sapwood area values due to tree physiology or growing environment. While not examined in this study, leaf area could play a role in the amount of water transpired by tree species. If leaf area of black ash stands were low, the amount of area available for transpiration could also be low leading to small hydroactive xylem area.

Table 14. Comparison of sap flux studies which demonstrated sap flux values similar to those seen in this study.

Study	Study Location	Forest Type	Pore Structure	Sap Flux (m^3 m^{-2} d^{-1})
Ewers et al., 2002	Northern Wisconsin	Mixed hardwood (1) and softwood (2)	Diffuse	0.78 - 2.59 (8)
Holsher et al., 2005	Central Germany	Mixed hardwood (3)	Mixed	0.67 - 1.52 (9)
Tang et al., 2006	Northern Michigan	Mixed hardwood (4)	Diffuse	1.80 - 3.14 (10)
Oishi et al., 2010	Central North Carolina	Mixed hardwood (5)	Mixed	0.60 - 4.32 (11)
Peters et al., 2010	Central Minnesota	Mixed (6) hardwood and softwood (7)	Mixed	1.53 - 2.11 (12)

1. Sugar maple (*Acer sacharum*), basswood (*Tilia americana*), speckled alder (*Alnus regosa*), and trembling aspen (*Populas tremuloides*).
2. Red pine (*Pinus resinosa*), balsam fir (*Abies balsamea*), and white cedar (*Thuja occidentalis*).
3. Sycamore maple (*Acer pseudoplatanus*), European hornbeam (*Carpinus betulus*), European ash (*Fraxinus excelsior*), small-leaved lime (*Tilia cordata*), and European beech (*Fagus sylvatica*).
4. Sugar maple (*Acer saccharum*), yellow birch (*Betula alleghaniesis*), and eastern hemlock (*Tsuga canadensis*).
5. Tuliptree (*Liriodendron tulipifera*), sweet gum (*Liquidambar styraciflua*), hickory (*Carya spp.*), and oak species (*Quercus alba, Quercus michauxii, Quercus phellos*).
6. Green ash (*Fraxinus pennsylvanica*), red oak (*Quercus rubra*), basswood (*Tilia americana*), eastern black walnut (*Juglans nigra*), Siberian elm (*Ulmus pumila*), rock elm (*Ulmus thomasii*).
7. Blue spruce (*Picea pungens*), White spruce (*Picea glauca*), Norway spruce (*Picea abies*), eastern white pine (*Pinus strobus*), European black pine (*Pinus nigra*), (*Pinus glauca*), and Scots pine (*Pinus sylvestris*).
8. Lowest to highest peak sap flux.
9. Range of twenty-one day sap flux averages. Low end was European hornbeam, high end was European beech.
10. Lowest to highest peak sap flux over two field seasons.
11. Range of peak sap flux from the early to late growing season.
12. Range of average sap flux over the growing season. Low end was the P*inus* genus, high end was the *Tilia* genus.

Higher stand densities and higher basal area values can contribute to differences in stand transpiration determinations. Basal area values for each of the stands (Table 15) were similar to other studies which evaluated sap flux in hardwood tree species; other studies have found basal area values between 22.1 m^2 ha^{-1} and 39.1 m^2 ha^{-1} (Phillips et al., 1996; Ford et al. 2010). Given the comparability between the basal area values determined in this study and those determined by others, differences in stand density and basal area are assumed to not be the main factor differentiating proportion of PET made up by transpiration in this study and the results of other studies.

Table 15. Comparison of basal area (m² ha⁻¹) among the very wet site (VWS), the wet site (WS) and the moderate site (MS).

Study Site	Basal Area (m² ha⁻¹)
VWS	30.82
MS	27.76
MS	30.71
Average	29.76 ± 1.74

Reported errors are one standard deviation from the mean.

Differences in the proportion of PET made up by transpiration could also be partially explained by the use of the Granier (1987a) relationship in a ring porous tree species. While many studies have examined ring porous species and used the original Granier relationship (Wilson et al., 2001; Wullschleger et al., 2001; Stoy et al., 2006; Ford et al. 2010; Oishi et al., 2010; Peters et al., 2010), relationships that differ from the original Granier (1987a) equation have been developed for ring porous species (Herbst et al., 2007; Taneda and Sperry, 2008; Bush et al., 2010). The choice to use the Granier (1987a) relationship is unlikely to be the only cause of the difference between proportion of PET made up by transpiration between this and other studies because of the overestimation of transpiration when using the newer ring porous sap flux relationships when compared to PET and soil moisture depletion.

Given that the small proportion of PET accounted for by transpiration is unlikely to be wholly caused by stand density and basal area or the use of the Granier (1987a) relationship, it is likely that the small proportion is partially caused by the small sapwood depth and sapwood area associated with black ash at the study sites. The black ash at the study sites demonstrated reasonable sap flux values, but low transpiration values. Sapwood area in ring porous trees species can be far less than sapwood area in diffuse porous tree species, leading to lower sap flux determinations (Bush et al., 2010) and stand level transpiration. Ring porous species have been shown to transpire less than non-ring porous tree species (Wullschleger et al., 2001; Bovard et al., 2005; Ford et al., 2010; Stoy et al., 2010). Black ash is a ring porous hardwood and, given the findings of others, transpiration values would be expected to be low. Wullschleger et al. (2001) assert that

when determining sap flux of a forest with ring and diffuse porous species, the main factor that will determine the most important species in terms of transpiration is sapwood area. This is concurrent with the findings of this study; black ash is a ring porous hardwood with very shallow sapwood depth and small sapwood area, which could be responsible for low levels of stand transpiration observed at the field sites. Low levels of stand transpiration could result in black ash accounting for a small proportion of PET; however, some element on the landscape such as understory vegetation must be responsible for the additional water that is leaving the field sites for this to be feasible.

4.3   Drivers of Transpiration

Sap flux and transpiration varied by field site. In both the monitored and scaled trees VWS demonstrated the highest sap flux and sap flow values, followed by WS. MS exhibited the smallest sap flux and sap flow values. The impact of soil moisture on sap movement in black ash trees was apparent, but the influence of atmospheric drivers was not initially obvious. The source of variability in transpiration among sites was tested by comparing sap flux and sap flow rates to atmospheric weather characteristics and belowground soil moisture depletion. PET was found to be a predictor of transpiration for VWS, but neither WS nor MS displayed this relationship. The relationship improved once the beginning two weeks and last week of the growing season were removed due to variability in transpiration based on initial sap flux from leaf out of the ash trees at the beginning of the growing season and translocation at the end of the growing season. Vapor pressure deficit was also a predictor of transpiration at VWS. Studies have postulated that the relationship between stomatal closure and high vapor pressure deficit (Peters et al., 2010) is due to the propensity of ring porous species for cavitation (Hacke et al., 2006; Taneda and Sperry, 2008). Interestingly, in this study, transpiration did not level off at high levels of vapor pressure deficit. Holscher et al. (2005) also found little relationship between sap flux and vapor pressure deficit or soil moisture content for European ash (*Fraxinus excelsior*); however, relationships between sap flux and vapor pressure deficit and soil moisture did exist for broad-leaved diffuse porous species in their work. These relationships between atmospheric characteristics and transpiration

throughout the field season indicate that VWS did not experience soil moisture limitation through the field season and was free to transpire based on atmospheric characteristics and physiological limitations. There was no relationship between atmospheric characteristics and transpiration at the other two sites. This indicates some limitation preventing atmospheric characteristics from being the primary drivers of transpiration.

Based on the soil moisture variability among the sites, soil moisture content could be one limitation to black ash transpiration at WS and MS. Previous work has established variability in transpiration response to soil moisture depending on precipitation and the moisture regime of the forest stand (Oren et al., 1996; Bovard et al., 2005; Ford et al., 2010). Small and McConnell (2008) also found variability in response of transpiration in coniferous diffuse porous species to atmospheric drivers and soil moisture depending on tree species and site location. Belowground characteristics were tested in this study to see if soil moisture was either impacting transpiration, or being impacted by transpiration at any of the sites throughout the field season because atmospheric drivers did not impact transpiration at WS or MS. None of the sites demonstrated a relationship between soil moisture depletion and transpiration in the early or middle part of the field season. However, MS demonstrated a relationship between transpiration and soil moisture depletion at the shallow depth from mid-August to late-August when soil moisture was most limiting. This positive relationship indicated a connection between black ash transpiration and soil moisture depletion late in the field season under low soil moisture conditions. In contrast, Lagergren and Lindroth (2002) found variability in relationships between transpiration and soil moisture depletion for early season coniferous stands as a result of water content changes, indicating the potential for the variability in the early season relationship between transpiration and soil moisture depletion to be a result of changing soil water content regardless of sap flux. Stoy et al. (2006) determined that available water was the primary external control over growing season evapotranspiration. Results of this study were similar to Stoy et al. (2006) at MS with soil moisture properties exhibiting stronger control on evapotranspirative than atmospheric influences. Results of this study indicate that the relationship between atmospheric and soil moisture drivers and transpiration may be

partially contingent upon soil moisture at specific sites. Soil texture may also play an important role in determining transpiration at the field sites. Clay layers in the soil profile may be limiting soil moisture utilization by black ash when the water table drops into these layers. If soil moisture is not limiting, transpiration may proceed, restricted by atmospheric characteristics and plant physiological limitations. If soil moisture is depleted to a certain threshold, changes in soil moisture may be attributable to changes in transpiration rates.

Although moisture limitation to transpiration was apparent at MS late in the season, the general independence of transpiration of black ash and soil moisture depletion through much of the field season for all three sites suggests other ecosystem components, such as understory vegetation, are influencing soil water depletion. Another consideration necessary to assess hydrologic interactions between soil moisture depletion and transpiration is the seasonal variability of moisture at the field sites. Growing season for black ash was assumed to be May through September. The year this study was conducted (2012) was the fifth driest growing season for the north-central region of Minnesota compared to the preceding ten growing seasons and the 30th driest compared to the century preceding the growing season (NOAA, 2013). Precipitation distribution for the 2012 growing season was comparable to the previous fifty years for the first half of the growing season, with lower precipitation for the latter half of the growing season (R. Slesak, personal communication, May 23, 2013). Temperature followed a similar pattern with 2012 being the third warmest growing season compared to the previous decade, and the 12th warmest compared to the past century (NOAA, 2013; see Appendix E for graphs of precipitation and temperature for north-central Minnesota). This indicates that the growing season was relatively normal for both overall temperature and precipitation given the previous ten growing seasons, but precipitation distribution was skewed towards the early part of the growing season. While overall temperature and precipitation conditions experienced for the 2012 growing season will likely be repeated in the future, precipitation distribution for these black ash swamps was unusual and could be responsible for some of the plant water interactions observed late in the growing season.

To test for impacts of understory vegetation on soil moisture depletion, PET was compared to soil moisture depletion through the field season to ascertain if other vegetation on the sites was transpiring based on the influence of atmospheric characteristics. There was no relationship between PET and soil moisture depletion at any of the field sites through the field season. Possible reasons for this lack of relationship include evaporative and transpirative processes at the field sites are being regulated by more than atmospheric drivers, soil moisture depletion is a poor measure of water flux, or the method employed to estimate soil moisture depletion was not accurate. Interactions between atmospheric conditions and transpiration seem to be variable based on the moisture regime of individual sites. Given the lack of relationship between soil moisture depletion and PET, and that transpiration was related to PET at VWS, overstory vegetation appears to be freely transpiring under atmospheric limitations at VWS while the understory transpiration and soil evaporative processes may be limited by factors other than atmospheric interactions. At MS, sap flux did have an impact on soil moisture towards the end of the field season when moisture was most limiting. Interactions between atmospheric and below ground processes and black ash stands seem to vary based on the moisture regime of specific locations.

VWS appeared to transpire based on atmospheric influences and physiological restraints, yet there is a large gap between the amount of water transpired and PET. Shallow soil moisture depletion at MS is related to PET, but transpiration of black ash is not related to PET. This indicates that if PET and actual evapotranspiration are similar some vegetation or evaporative properties are losing water based on atmospheric characteristics. There is also a gap between transpiration of black ash and soil water depletion, indicating that some other element on the landscape is responsible for water removal at the field sites. Based on the gap between transpiration and PET and lack of interaction between soil moisture and PET, the understory vegetation is likely responsible for some of the gap between transpiration and PET at the field sites. All three stands evaluated are mature black ash stands, which could impact the amount of transpiration by the understory. Delzon and Loustau (2005) found increasing importance of understory vegetation in older forest stands with understory vegetation and soils accounting for

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approximately half of total stand transpiration. Work has been done to evaluate the contribution of understory vegetation to total stand transpiration. Studies have found that understory vegetation can account for between 9% and 54% of stand transpiration depending on study site location and forest type (Loustau and Cochard, 1991; Wullschleger et al., 2001; Wedker et al., 1996; Blanken et al., 1997; Kelliher et al., 1998; Herbst et al., 2008). Kelliher et al. (1998) asserted that understory micrometeorology is one of the potential causes of variation in understory contribution to PET   Although it does not appear that any other sap flux study pertaining to understory vegetation has been conducted with the species mix involved in this study, it can be assumed that the understory component is likely responsible for some of the gap between overstory transpiration and PET. There could also be some minor contribution of other overstory species to stand transpiration due to the lack of overstory homogeneity of the black ash stands evaluated; however, the abundance of non-ash species was quite low at all sites (<10% of the overstory basal area).

Conclusions and Management Implications

Transpiration was determined for three black ash stands of varying moisture regime within the Chippewa National Forest in 2012. The objectives of this study were to 1) quantify individual tree transpiration, 2) extrapolate from individual tree to site level transpiration, 3) compare scaled transpiration to potential evapotranspiration (PET), 4) compare scaled transpiration to soil moisture depletion through time, and 5) evaluate the role of black ash in these wetland forest systems based on the results of the transpiration comparisons to potential evapotranspiration and soil moisture changes. Hydrologic changes to these systems could be substantive following black ash overstory mortality resulting from EAB incursion. However, due to the late leaf out of black ash and the seasonality of moisture pulses in northern Minnesota, the hydrologic impact of black ash removal may not be as large as previously expected. Black ash are not actively transpiring until late May or early June which is after the largest moisture pulse in these systems. This indicates that the transpiration of black ash may do little to impede early flooding in these systems now and the removal of black ash may not impact flooding

from early moisture pulses in these wetland systems in the future. Nevertheless, the changes in hydrologic regime due to the loss of black ash transpiration (up to 21% of PET in this study), could further reduce the hospitality of these wet environments for other tree species and forested conditions.

Overall temperature and moisture conditions experienced in north-central Minnesota in 2012 were normal given the preceding decade and century. However, the precipitation distribution for the 2012 growing season was abnormal with much of the precipitation falling in the early portion of the growing season. Drier conditions than usual in the late growing season could be partially responsible for the relationship between soil moisture and transpiration demonstrated at MS. Sites exhibited a wide variability of sap flux and sap flow both within and among sites. Large variability in sap flux and sap flow is reasonable given the wide diversity of tree sizes selected to better approximate stand level sap flux and sap flow. The variability associated with sap flux and sap flow of the sites does indicate the need for caution when drawing any conclusions about sap flux and sap flow among field sites. Tree level transpiration was quantified and determined to be less than what many others have found. Sap flux rates were reasonable, but when sap flux was converted to sap flow and extrapolated to stand transpiration, values were smaller than expected. One explanation is that the small transpiration values were caused by small sapwood area associated with black ash trees.

Comparisons of stand transpiration to stand PET were surprising; black ash were determined to account for at most 21% of PET depending on moisture regime of the site. The large gap between overstory transpiration and PET is assumed to be the result of low transpiration values associated with small sapwood area in black ash trees. There are other possible explanations for the gap between overstory transpiration and PET, including missing data, the empirical relationship used in sap flux determination, error accrued in the scaling process, and stand characteristics. To determine drivers of transpiration at the field sites, transpiration values were compared to PET, vapor pressure deficit (VPD), and soil moisture depletion. Transpiration at VWS was controlled by atmospheric drivers. The WS and MS were not controlled by atmospheric drivers. Transpiration at MS was related to soil moisture depletion late in the growing season

indicating control of transpiration by belowground processes only when moisture is most limited. Soil moisture depletion was also compared to PET to ascertain if other vegetation at the field sites was reacting to atmospheric drivers. There was not a relationship between PET and soil moisture depletion at any of the field sites for any portion of the field season, indicating that atmospheric drivers were not solely responsible for water removal at the field sites and that soil moisture depletion could be a poor estimator of water removal in black ash systems.

Given the variability in transpiration results between the three field sites, black ash water use was at least partially dependent upon moisture conditions. This indicates that if black ash were to be removed from the overstory, impacts to the landscape would be variable depending on the moisture regime of different areas. The large gap between black ash canopy transpiration and PET indicates that the understory could contribute more to overall total evapotranspiration than was expected. While black ash contribute a significant portion of total transpiration at black ash stands, results of this study suggest that the understory vegetation could also be significant in terms of transpiration. Understory growth which develops in the absence of an overstory canopy could also transpire more than the current shaded understory, depending on species composition (Siegert and Levia, 2011). This could make up for some of the loss in transpiration if the black ash overstory were destroyed by EAB. However, current understory vegetation may not be able to persist under moisture conditions following black ash removal. The species composition and transpirational response of the understory of black ash stands remains uncertain and warrants further research before any firm conclusions can be drawn regarding impact of understory vegetation to black ash stand hydrology. Recruitment of overstory species other than black ash in these wetland systems is questionable and black ash self-replacement is limited following overstory canopy removal (Palik et al., 2012). The loss in overstory transpiration could result in regeneration failures of black ash (Erdmann et al., 1987). Loss of overstory black ash trees and species composition changes could result in alterations to ash stand hydrology potentially resulting in a non-forested state. This shift in vegetation type could result in changes to ecosystem function and necessitate alterations to current forest management

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strategies. Results of this study indicate that black ash transpire less than anticipated and impacts to the hydrology of black ash stands from understory vegetation remains worth investigating. Land managers should be aware of the potential for increased water availability onsite, changes in overstory species composition, and changes in understory species composition if EAB incursion removes the black ash overstory from wetland forests of northern Minnesota.

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Appendices

Appendix A: Relationships of North and South Aspects of Monitored Trees

| Tree Number by Site	Period (Julian Days)*	Slope**	Y-intercept**	r^2
VWS				
1	223-244	3.7387	-2.00E-06	0.7344
2	212-228	0.3667	2.00E-06	0.6347
3	212-244	1.7212	-8.00E-06	0.8545
4	184-218	1.5723	2.00E-07	0.7281
5	218-244	0.5684	-4.00E-08	0.9667
6	170,171,174,181-190	2.9182	-4.00E-06	0.5246
7	222-244 (except 225)	1.9747	1.00E-05	0.7113
8	227-244	0.3574	-2.00E-06	0.7616
WS				
1	192-207	0.5663	2.00E-05	0.7333
2	191-221	3.0300	4.00E-07	0.7283
3	226-229, 234-240	3.8432	-2.00E-06	0.8813
4	168-244	0.8355	-2.00E-07	0.7211
5	172-244	0.2938	1.00E-05	0.6920
6	165-176, 222-229	0.8656	3.00E-06	0.7236
7	165-172, 178-200, 211-244	0.6425	5.00E-07	0.7096
8	165-225, 230-244	0.2410	1.00E-06	0.5799
MS				
1	217-236	0.3535	4.00E-06	0.8309
2	180-247	1.6822	2.00E-06	0.9078
3	198-217	0.6017	7.00E-06	0.6743
4	214-247	1.1613	1.00E-07	0.8304
5	180-229	0.4620	4.00E-06	0.8598
6	180-247	0.4737	9.00E-07	0.8763
7	180-247	0.6297	4.00E-07	0.8684
8	234-247	0.5657	4.00E-06	0.6935

* Periods used to develop north and south side linear relationships were designed to be as long as possible to capture the variability of the field season while still maintaining a strong coefficient of determination.

** All slope and y-intercept values are based on the north side of the tree as the explanatory variable and the south side of the tree as the response variable.

Appendix B: Relationships between Sap Flux and Soil Moisture for MS
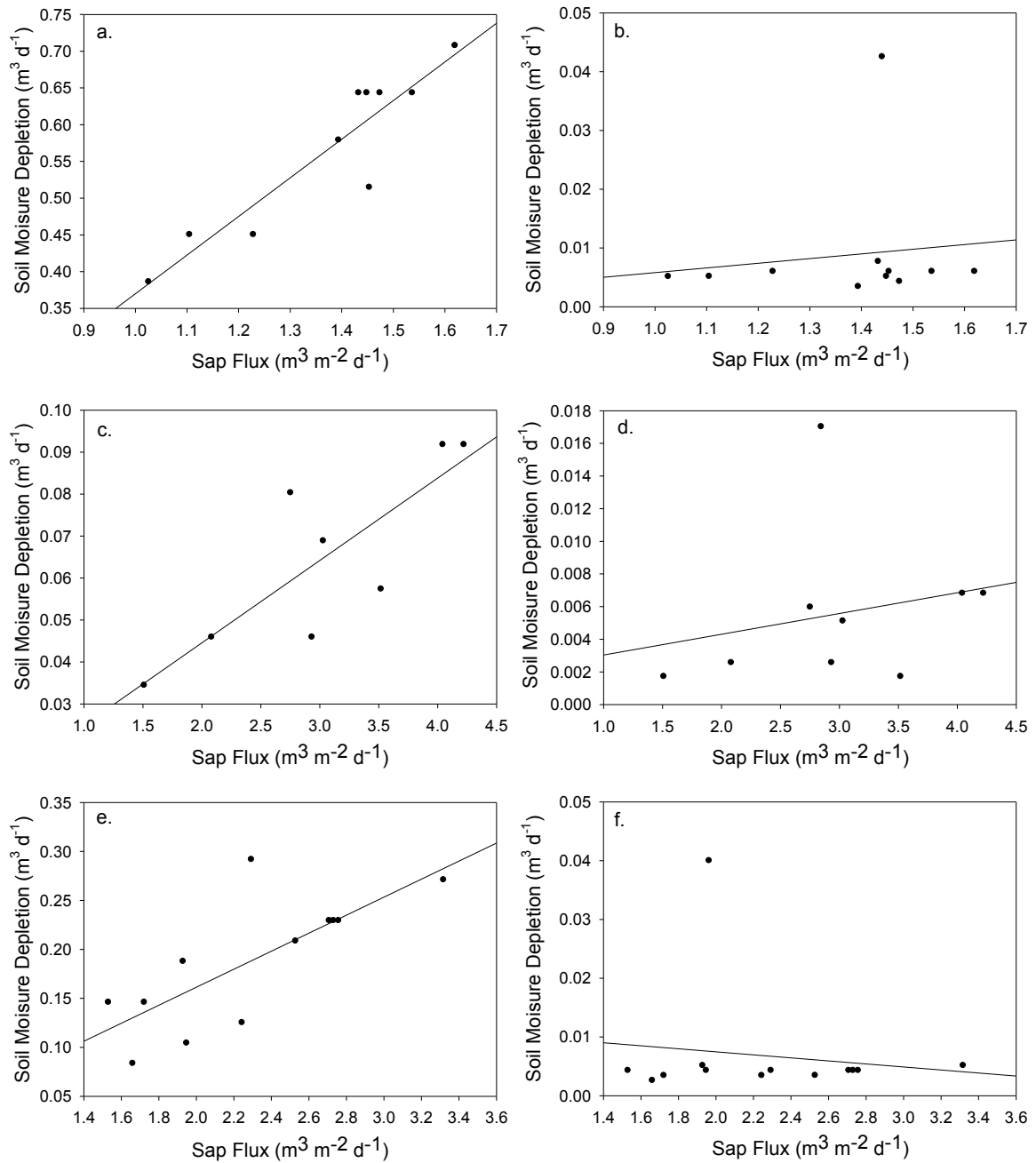
(a.) tree two at MS, shallow depth (0-15 cm), (b.) tree two at MS, deep depth (15-30 cm), (c.) tree three at MS, shallow depth (0-15 cm), (d.) tree three at MS, deep depth (15-30 cm), (e.) tree five at MS, shallow depth (0-15 cm), (f.) tree five at MS, deep depth (15-30 cm).
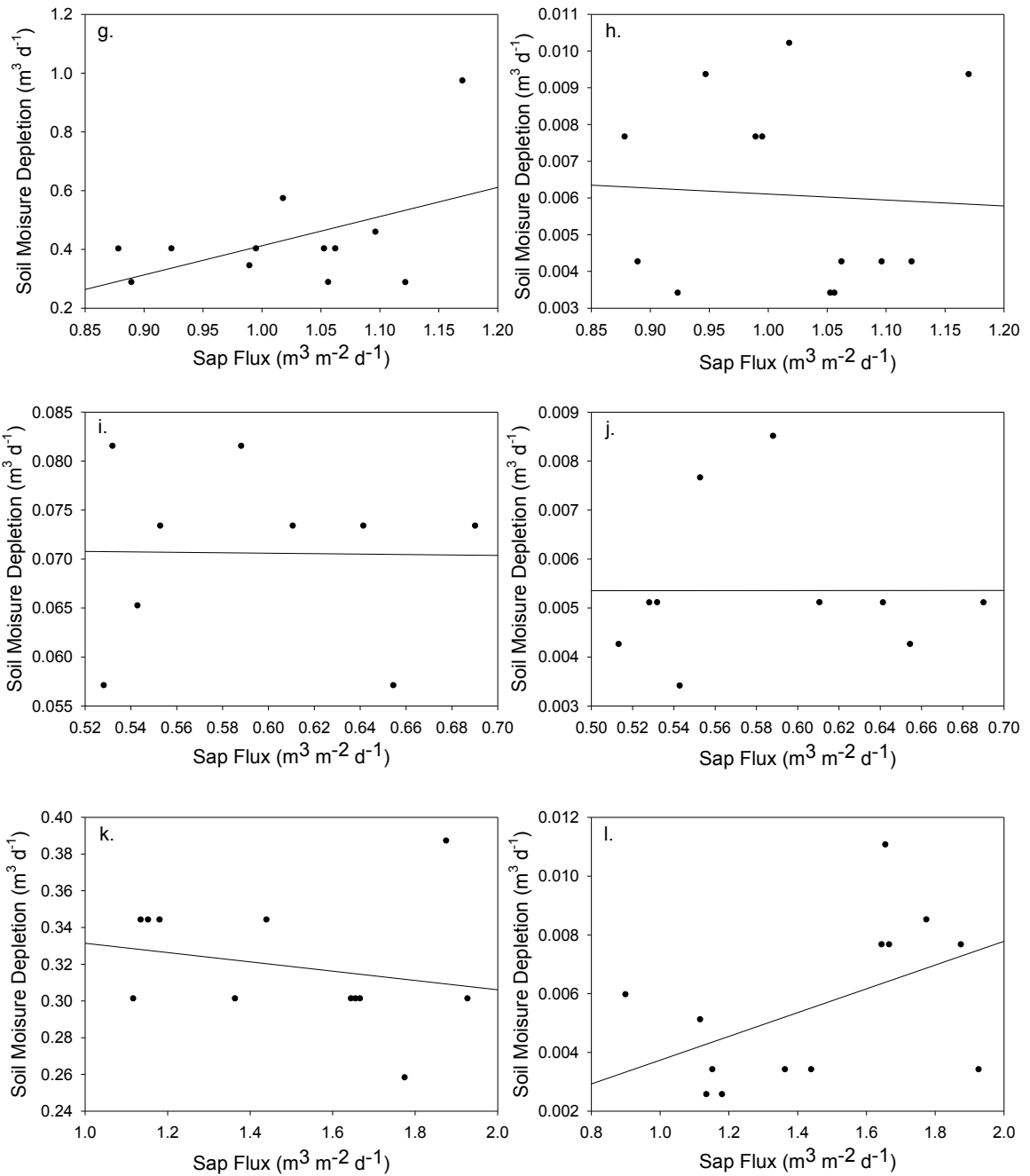
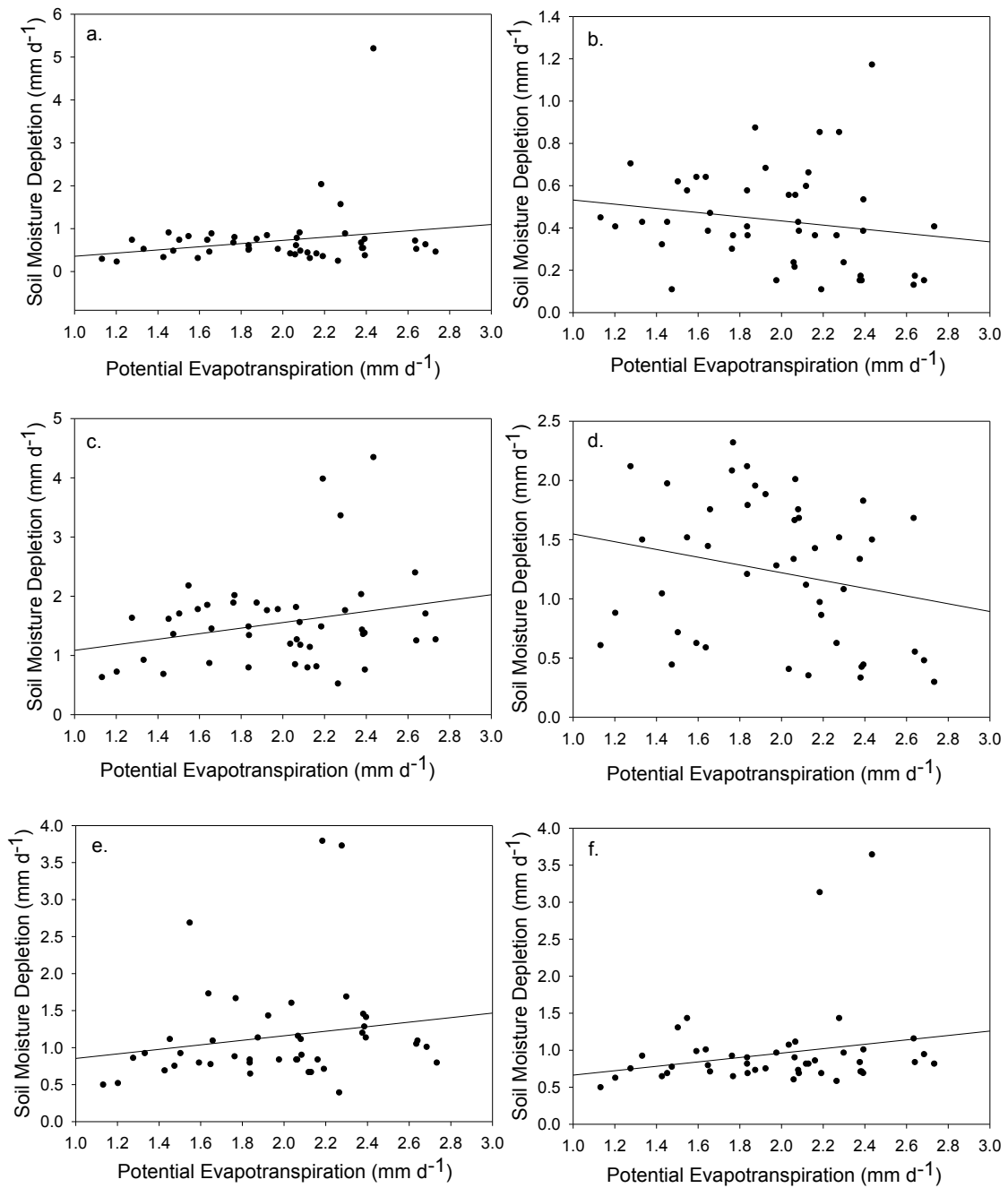(g.) tree six at MS, shallow depth (0-15 cm), (h.) tree six at MS, deep depth (15-30 cm), (i.) tree seven at MS, shallow depth (0-15 cm), (j.) tree seven at MS, deep depth (15-30 cm), (k.) tree eight at MS, shallow depth (0-15 cm), (l.) tree eight at MS, deep depth (15-30 cm).

Appendix C: Comparison of PET and Soil Moisture Depletion by Site

(a.) VWS at shallow depth (0-15 cm), (b.) VWS at deep depth (15-30 cm), (c.) WS at shallow depth (0-15 cm), (d.) WS at deep depth (15-30 cm), (e.) MS at shallow depth (0-15 cm), (f.) MS at deep depth (15-30 cm).

Appendix D: Power Functions for Scaling Relationships

Sapwood Depth to Sap Flux Scaling Power Function Components
by Week Using the Granier (1987a) Relationship

Combined Sites				VWS*			
Field Week	a	b	r^2	Field Week	a	b	r^2
Week 1	1.7772	-1.5889	0.8011	Week 1	1.8390	-1.1071	0.4240
Week 2	2.5237	-1.9328	0.8659	Week 2	2.4845	-1.8513	0.6569
Week 3	2.2694	-1.7788	0.7205	Week 3	3.0819	-0.9175	0.3096
Week 4	2.2242	-1.6321	0.7129	Week 4	2.2206	-1.2256	0.4569
Week 5	1.8986	-1.5865	0.6402	Week 5	2.6646	-0.4461	0.0687
Week 6	2.0386	-1.6166	0.6892	Week 6	2.5627	-0.7048	0.2013
Week 7	1.9609	-1.3734	0.4848	Week 7	1.9314	-1.3078	0.1165
Week 8	2.0462	-1.4488	0.6312	Week 8	2.1186	-1.0069	0.1757
Week 9	1.8633	-1.3221	0.5309	Week 9	1.7169	-1.4161	0.2008
Week 10	1.9798	-1.5428	0.6779	Week 10	1.8881	-1.5199	0.4728
Week 11	2.0764	-1.6900	0.6447	Week 11	2.2055	-1.3413	0.2072
Week 12	1.9037	-1.6542	0.5831	Week 12	1.6033	-1.5818	0.1709
WS				MS			
Field Week	a	b	r^2	Field Week	a	b	r^2
Week 1	2.0785	-1.9175	0.8649	Week 1			
Week 2	2.6919	-2.0512	0.8669	Week 2			
Week 3	2.6567	-2.2729	0.7990	Week 3	1.5934	-0.9793	0.5161
Week 4	2.7175	-2.1809	0.8778	Week 4	2.0580	-1.2826	0.4762
Week 5	2.3547	-2.1830	0.8880	Week 5	1.3508	-0.8509	0.2629
Week 6	2.3618	-1.9391	0.8342	Week 6	1.7485	-1.3860	0.4537
Week 7	2.3401	-1.6727	0.8083	Week 7	1.7161	-1.1228	0.3632
Week 8	2.4041	-1.7591	0.8628	Week 8	1.9959	-1.4249	0.4796
Week 9	2.1287	-1.6931	0.8175	Week 9	1.7800	-1.0441	0.3388
Week 10	2.3118	-1.8887	0.8521	Week 10	1.8397	-1.3031	0.4144
Week 11	2.6049	-2.0846	0.9072	Week 11	1.7110	-1.3577	0.4153
Week 12	2.7911	-2.2390	0.9595	Week 12	1.6998	-1.4757	0.4682

* Coefficient of determination values were lower for VWS largely due to the influence of tree seven at VWS. Removal of tree seven from the data set raised the coefficient of determination for the weekly power function relationships, but did not significantly modify the constant or the power of the independent variable; tree seven was not removed from the data set.

Sapwood Depth to Sap Flux Scaling Power Function Components
**by Week Using the Herbst et al. (2007) Relationship**

Combined Sites				VWS*			
Field Week	a	b	r^2	Field Week	a	b	r^2
Week 1	23.4210	-2.0429	0.8157	Week 1	22.9547	-1.5922	0.5746
Week 2	36.7528	-2.6002	0.8684	Week 2	32.4684	-2.8754	0.7251
Week 3	31.0472	-2.2787	0.7397	Week 3	47.4117	-1.1336	0.3101
Week 4	30.1853	-2.1199	0.6961	Week 4	28.4109	-1.8260	0.5048
Week 5	24.8444	-2.0543	0.6490	Week 5	36.7138	-0.6553	0.0844
Week 6	26.9107	-2.0824	0.6937	Week 6	32.0846	-1.2472	0.2681
Week 7	26.1344	-1.8048	0.5027	Week 7	25.4814	-1.8157	0.1404
Week 8	27.3887	-1.9150	0.6359	Week 8	27.6222	-1.4724	0.1924
Week 9	25.0668	-1.7704	0.5360	Week 9	21.5228	-2.0941	0.2311
Week 10	27.1827	-2.0735	0.6815	Week 10	24.1042	-2.2612	0.4939
Week 11	27.5508	-2.2006	0.6698	Week 11	28.2512	-1.9290	0.2393
Week 12	24.4182	-2.1271	0.6086	Week 12	19.1174	-2.0920	0.1842
WS				MS			
Field Week	a	b	r^2	Field Week	a	b	r^2
Week 1	29.7380	-2.5030	0.8703	Week 1			
Week 2	40.4460	-2.7189	0.8683	Week 2			
Week 3	35.1640	-2.7654	0.7996	Week 3	20.6822	-1.3719	0.5533
Week 4	40.9242	-2.8951	0.8695	Week 4	26.1853	-1.5645	0.4402
Week 5	34.1027	-2.8605	0.8808	Week 5	16.2355	-1.1518	0.3061
Week 6	33.5995	-2.5270	0.8330	Week 6	22.6756	-1.8071	0.4808
Week 7	31.8455	-2.1314	0.7869	Week 7	21.9413	-1.4707	0.3732
Week 8	34.0305	-2.3246	0.8578	Week 8	26.4386	-1.8634	0.5045
Week 9	29.8344	-2.2328	0.8074	Week 9	23.3465	-1.3780	0.3547
Week 10	33.7216	-2.5411	0.8396	Week 10	24.4371	-1.7102	0.4349
Week 11	37.1860	-2.7211	0.9155	Week 11	21.5638	-1.7516	0.4746
Week 12	39.9257	-2.9043	0.9574	Week 12	21.4847	-1.8923	0.5390

* Coefficient of determination values were lower for VWS largely due to the influence of tree seven at VWS. Removal of tree seven from the data set raised the coefficient of determination for the weekly power function relationships, but did not significantly modify the constant or the power of the independent variable; tree seven was not removed from the data set.

Power Function Relationships Preceding Sap Flux Estimation				
Site	Relationship*	a	b	r^2
Sites Combined	Diam. to SWA	0.9851	1.3405	0.6406
	SWA to SWD	0.1160	0.5238	0.6214
VWS	Diam. to SWA	0.6019	1.3994	0.8916
	SWA to SWD	0.1956	0.3522	0.6823
WS	Diam. to SWA	5.0919	0.8768	0.3921
	SWA to SWD	0.1100	0.5548	0.4238
MS	Diam. to SWA	0.4294	1.6469	0.8954
	SWA to SWD	0.1773	0.4472	0.8157

* Diam.: outer bark diameter of monitored trees (cm^2), SWA: sapwood area of monitored trees (cm^2), SWD: sapwood depth of monitored trees (cm).

Appendix E: Climate and Weather Patterns for north-central Minnesota
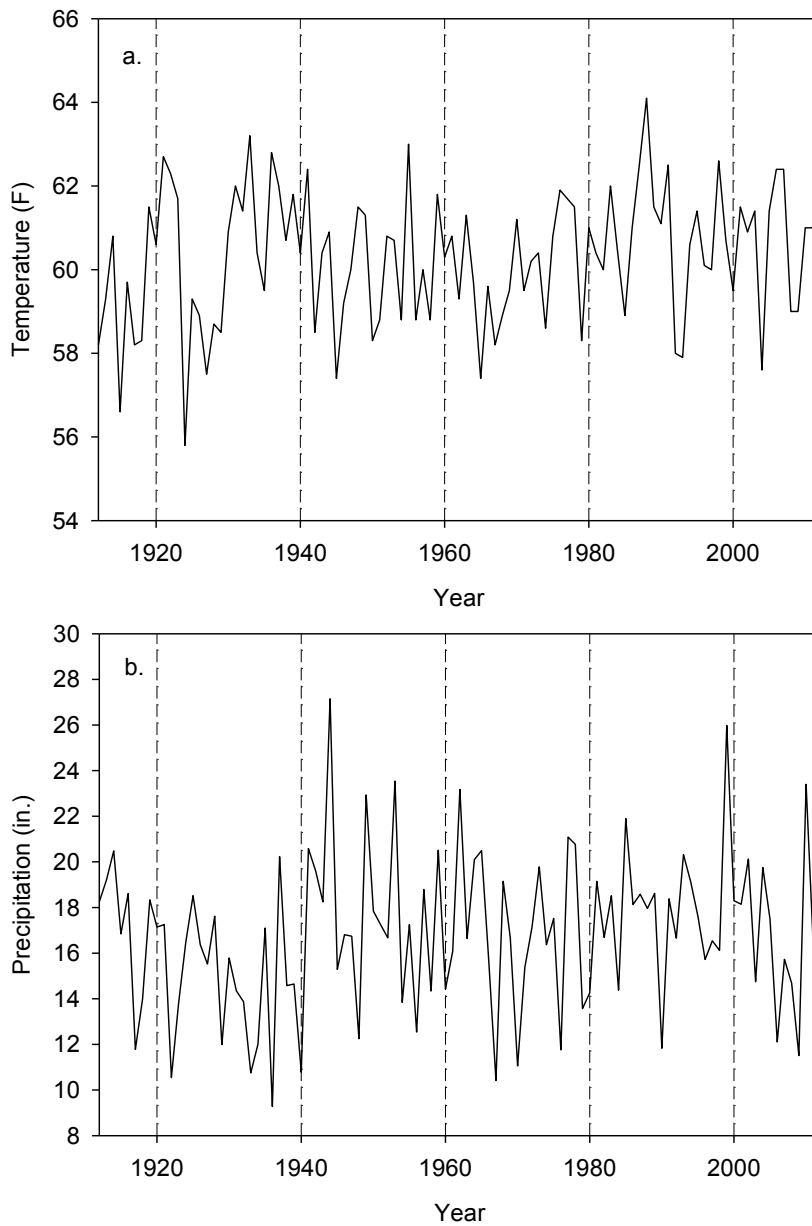
(a.) average growing season temperature (F) for north-central Minnesota from 1912 to 2012, (b.) average growing season precipitation (in.) for north-central Minnesota from 1912 to 2012. Growing season is assumed to be May through September.
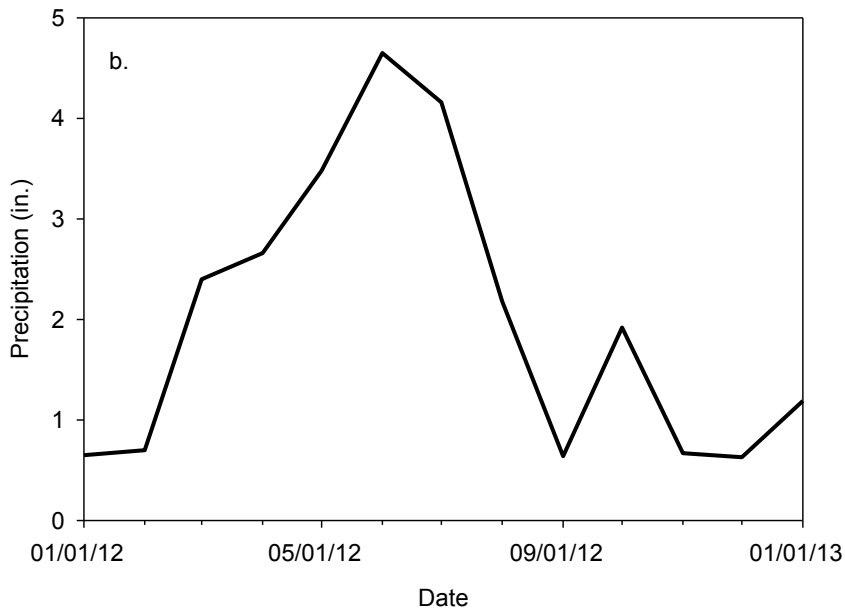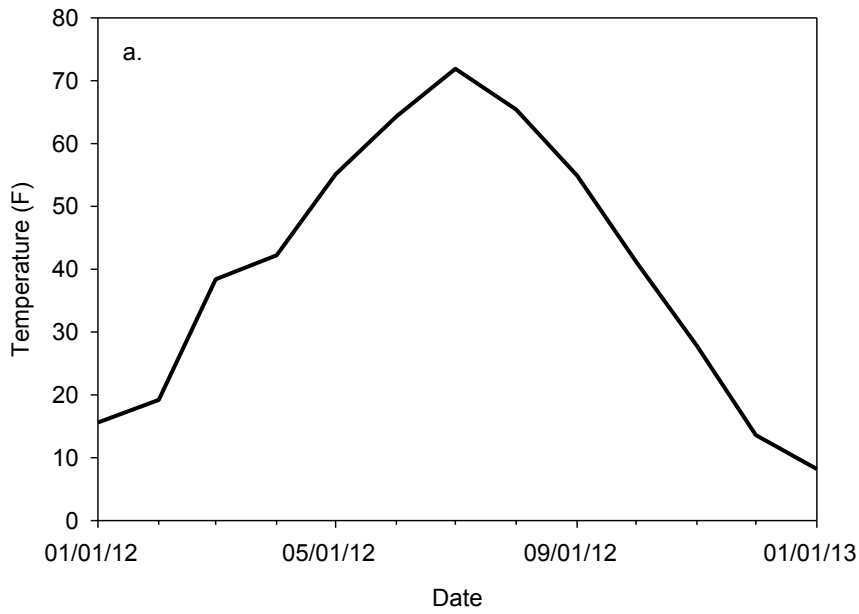
(a.) average monthly temperature (F) for north-central Minnesota from January 2012 to January of 2013, (b.) monthly precipitation (in.) for north-central Minnesota from January 2012 to January 2013.