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Sap flow of black ash in wetland forests of northern Minnesota, USA: Hydrologic implications of tree mortality due to emerald ash borer

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ABSTRACT

Black ash (*Fraxinus nigra*) mortality caused by the invasive emerald ash borer (EAB) is of concern to land managers in the upper Great Lakes region, given the large areas of ash-dominated forest and potential alteration of wetland hydrology following loss of this foundation tree species. The importance of changes in evapotranspiration (ET) following black ash mortality is currently unknown and is the focus of this study. Sap flux density rates were evaluated at three black ash stands with differing moisture regimes within the Chippewa National Forest, Minnesota, USA using the Granier thermal dissipation method. Sapwood area and sap flux density were combined to determine sap flow. Tree level sap flux density estimates were comparable to other reported values and averaged 4.59, 2.31, and 1.62 $m^3\,m^{-2}\,day^{-1}$, respectively, for the very wet, wet, and moderately wet field sites. However, black ash exhibited small sapwood area in general, resulting in lower overall sap flow values. Scaled stand-level transpiration followed a similar trend as the tree-level estimates; mean daily transpiration over 10 weeks was 1.62 (80% of PET), 1.15 (53% of PET), and 0.90 (42% of PET) mm for the very wet, wet, and moderately wet site, respectively. Sap flux density was positively related to vapor pressure deficit when soil moisture was at or near saturation and negatively related when soil moisture content was lower. There was also a significant positive relationship between sap flux density and relative soil moisture saturation at the stand scale. Our results indicate that hydrologic regime has substantial influence on sap flow with highest transpiration when soil moisture is at saturation, underscoring the unique ecological role that black ash plays in these wetland forest types. The effects of EAB-induced black ash mortality on overall ET and related hydrologic processes will likely be greatest in the wettest hydrologic regimes.

1. Introduction

Black ash (*Fraxinus nigra*) is a common ring porous tree species found in forested wetlands in the northern Lake States (Michigan, Minnesota, and Wisconsin). This species is under threat of extirpation following the introduction of the invasive emerald ash borer (EAB; *Agrilus planipennis*), which girdles ash trees and causes stand mortality within 3–5 years of infestation (Gandhi et al., 2008). Since its discovery in 2002, EAB has spread rapidly and caused extensive economic and ecological damage throughout North America (Kovacs et al., 2010; Gandhi and Herms, 2010). In Minnesota, there is particular concern that EAB will have large impacts on black ash wetlands because the species occurs in almost pure stands on poorly drained sites across more than 400,000 ha (MN DNR, 2003). In particular, changes in hydrology following ash mortality are likely, potentially leading to changes in species composition and a shift to a non-forested ecosystem state (Toner and Keddy, 1997). Despite the widespread occurrence of black ash wetlands and the impending EAB threat, the likelihood and magnitude of changes in wetland hydrology following black ash loss is currently unknown.

One likely mechanism where loss of the black ash overstory would alter hydrological processes is through a reduction in overall stand transpiration. Transpiration is an important component of the water budget for plant-dominated environments as it is a

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primary component of evapotranspiration (ET) (Tang et al., 2006; Ford et al., 2010; Oishi et al., 2010). In forested wetlands with minimal groundwater or surface flow inputs, transpiration may be a particularly important controller of site hydrology, but the relative contribution of trees compared to other vegetation likely varies depending on species and site characteristics. Understanding the contribution of overstory trees to overall ET is critical for anticipating the impacts of human-induced and natural disturbances on the hydrology of forested watersheds (Ice and Stednick, 2004). Almost no information is available regarding black ash transpiration and the factors influencing it, constraining our ability to evaluate the potential impacts of EAB as they relate to wetland hydrology.

Sap flux density measurement is a common method used to assess tree water movement and estimate transpiration. We use the term sap flux density to denote the rate at which sap is moving through the xylem and sap flow to denote the volume of sap that moves through the xylem during a given time period. In particular, the thermal heat dissipation system pioneered by Granier (1985, 1987), has been widely used to measure sap flux density of many different forest types and assess radial variability of sap flux density, change in sap flux density with stand age, and estimate transpiration (Ford et al., 2004b, 2010; Delzon and Loustau, 2005; Tang et al., 2006). The method involves measurement of the voltage differential between thermal dissipation probes, which is then converted to an estimate of sap flux density with an empirically-derived equation. The validity of the original equation developed by Granier (1985) to estimate sap flux density in ring porous species has been questioned because the original equation was developed using a diffuse porous tree species that likely contained lower gradients of sap velocity through the sapwood and greater sapwood depth compared to ring porous trees (Gebauer et al., 2008; Bush et al., 2010; Wullschleger et al., 2011). Differences in pore structure between ring and diffuse porous tree species may warrant the use of other empirically-derived equations to estimate sap flux density in ring porous species (Herbst et al., 2007; Taneda and Sperry, 2008; Bush et al., 2010), but the utility of these equations in estimating black ash sap flux density is unclear.

In addition to physiological controls associated with wood structure, sap flux density is influenced by environmental factors, including soil water availability and atmospheric characteristics that influence evaporation from the leaf surface (i.e., wind speed and vapor pressure deficit). Soil water availability has fundamental control on transpiration, but studies which have examined relationships between soil moisture and sap flux density have reported mixed results (Stoy et al., 2006; Tang et al., 2006; Oishi et al., 2008, 2010; Ford et al., 2010). For example, soil moisture has been found to have limited effect on tree water use in a number of studies (Wullschleger et al., 1998; Granier et al., 2000; O'Brien et al., 2004), but others have found decreasing soil moisture to result in linearly decreasing sap flux density for many species, but not for European ash (Holscher et al., 2005). The variability of soil moisture control on transpiration is likely because of differences in site variables and climate that interact to cause soil moisture limitation in some instances, but not others (Oren et al., 1996; Ford et al., 2010). When soil moisture is not limiting, vapor pressure deficit has been found to be a dominant control over transpiration (Oren and Pataki, 2001); however, ring porous tree species have been found to be less responsive to vapor pressure deficit than diffuse porous tree species under similar conditions (Holscher et al., 2005). The relative degree to which black ash transpiration is controlled by soil moisture and vapor pressure deficit is currently unknown.

To address the above knowledge gaps, we measured sap flux density and estimated sap flow in three black ash dominated wetland sites with contrasting hydrologic regimes in north central Minnesota. Our primary objectives were to (1) estimate sap flux density and sap flow rates of black ash and compare them to previously reported rates for other species and estimates of PET, and (2) examine the role of soil water content and vapor pressure deficit on our estimates. The overall underlying objective of this study was to assess how site hydrology might be altered following EAB infestation and the corresponding loss of black ash, and increase our understanding of the ecohydrology of black ash wetland ecosystems.

2. Materials and methods

2.1. Site selection and description

The study was conducted on the Chippewa National Forest in Itasca County, Minnesota, USA and is part of an ongoing project examining the influence of forest harvesting and simulated EAB mortality on hydrology and plant community dynamics (Slesak et al., 2014). For this study, a subset of three field sites were selected to cover a range of soil moisture regimes and were designated as the very wet site (VWS), the wet site (WS), or the moderate site (MS) (Table 1). All of the sites were classified using the state's native plant community classification system (MN DNR, 2003). MS was classified as Northern Wet Ash Swamp (WFn55). WS and VWS were classified as Northern Very Wet Ash Swamp (WFn64). The overstory of all sites was dominated by black ash with minor components of American elm (*Ulmus americana*), American basswood (*Tilia americana*), bur oak (*Quercus macrocarpa*), northern white cedar (*Thuja occidentalis*), red maple (*Acer rubrum*), quaking aspen (*Populus tremuloides*), and yellow birch (*Betula alleghaniensis*) contributing no more than 7% of the total basal area. At each site, eight trees of varying size were selected for monitoring of sap flux density that encompassed the range of tree diameters present. Field measurements 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.

2.2. Probe installation and heat dissipation measurement

The Granier (1987) heat dissipation method was used to determine sap flux density for black ash trees at each study site. Thermal dissipation probes were constructed in accordance with the method set forth by Lu et al. (2004). Two sensor probes, 20 mm in length, were inserted into the conducting sapwood of the tree at approximately 1.3 m above the ground. Probes were consis-

Table 1
Soil and stand characteristics at three black ash wetlands in Minnesota.

Parameter	Very wet site (VWS)	Wet site (WS)	Moderate site (MS)
Tree density (stems ha^{-1})	680	580	830
Mean DBH (cm)[a]	26.7 (3.1)	26.6 (3.4)	27.0 (3.9)
Range DBH (cm)[a]	14.4–40.5	15.6–41.8	13.9–41.9
Basal area (m^2 ha^{-1})	30.8	27.8	30.7
Sapwood area (m^2 ha^{-1})[b]	3.2	5.1	5.5
Leaf area index[c]	2.30 (0.05)	2.12 (0.13)	2.52 (0.04)
Soil texture[d]	Sandy clay loam	Loamy sand	Sandy loam
Bulk density[e]	1.46 (0.06)	1.39 (0.13)	1.38 (0.09)
Mean SWC[f]	0.43	0.31	0.22
SWC at field capacity[g]	0.28	0.13	0.22

[a] Mean DBH and range is for trees where sap flux was measured; standard error in parenthesis, $n = 8$.
[b] Estimated from empirically derived linear relationships between DBH and sapwood area developed for each site.
[c] Determined with hemispherical photography in 2013, stand error in parenthesis, $n = 12$.
[d] Determined with the hydrometer method from sample at 15–30 cm depth.
[e] Determined with the core method; standard error in parenthesis, $n = 8$.
[f] Soil water content at 15 cm depth from July 19 to August 31, 2012.
[g] Estimated from equations presented in Saxton and Rawls (2006).