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Research article

Forested *versus* herbaceous wetlands: Can management mitigate ecohydrologic regime shifts from invasive emerald ash borer?

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ABSTRACT

Wetlands self-organize through reciprocal controls between vegetation and hydrology, but external disturbance may disrupt these feedbacks with consequent changes to ecosystem state. Imminent and widespread emerald ash borer (EAB) infestation throughout North American forested wetlands has raised concern over possible ecosystem state shifts (i.e., wetter, more herbaceous systems) and loss of forest function, calling for informed landscape-scale management strategies. In response, we employed a large-scale manipulative study to assess the ecohydrologic response of black ash wetlands to three alternative EAB management strategies: 1) a do-nothing approach (i.e., simulated EAB infestation via tree girdling), 2) a preemptive, complete harvesting approach (i.e., clearcut), and 3) an overstory replacement approach via group selection. We analyzed six years of daily water table and evapotranspiration (ET) dynamics in six blocks comprising black ash wetlands (controls) and management strategy treatments to quantify potential for hydrologic change and subsequent recovery. In both the do-nothing approach and complete harvesting approach, we found persistent changes in hydrologic regime defined by shallower water tables and lower ET rates coupled with increased herbaceous vegetation growth, indicating ecosystem state shifts driven by vegetation-water table interactions. The do-nothing approach showed the least hydrologic recovery after five years, which we attribute to reduction in overstory transpiration as well as greater shade (via standing dead trees) that reduces open water evaporation and herbaceous layer transpiration compared to complete harvesting. We found no evidence of ecohydrologic disturbance in the overstory replacement approach, highlighting its potential as a management strategy to preserve forested wetland habitat if periodically executed over time before EAB infestation. Although the scale of potential disturbance is daunting, our findings provide a baseline assessment for forest managers to develop preemptive mitigation strategies to address the threat of EAB to ecological functions in black ash wetlands.

1. Introduction

Wetlands self-organize through reciprocal controls between vegetation and hydrology. In contrast to uplands, hydrologic controls on wetland vegetation are generally the result of too much rather than too little water (Jackson and Colmer, 2005). This abundance of water results in inadequate oxygen supply (Armstrong and Drew, 2002) and accumulation of ethylene and anaerobic metabolism byproducts (Ponnamperuma, 1984), limiting primary production and preferentially selecting for flora with special adaptations (Kozlowski, 2002; Kreuzwieser and Rennenberg, 2014). At the same time, wetland vegetation controls local hydrology directly through evapotranspiration (ET), which lowers water tables and reduces soil moisture (Marani et al., 2006). These ecohydrologic interactions often enable and promote ecosystem stability (Rodríguez-Iturbe et al., 2007). However, shifts to different ecosystem states can occur with disturbance to hydrologic setting (e.g., flooding, climate; Wang et al., 2016) or vegetation dynamics (e.g., widespread mortality, Heffernan, 2008).

In black ash (*Fraxinus nigra*) wetlands of North America, looming threats of emerald ash borer (EAB; *Agrilus planipennis*) infestation have drawn attention to possible large-scale tree mortality and a resultant whole-scale shift in ecosystem type and function. EAB causes nearly 100% mortality in all ash species within 3–6 years after infestation (Knight et al., 2013), and there is no known host physiological resistance or stand characteristic that inhibits infestation (Smith et al., 2015). Ash regeneration is also susceptible to EAB colonization once it

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reaches 2.5 cm in diameter (Klooster et al., 2014), limiting the potential for reestablishment in the presence of EAB. The extent of EAB infestation is widespread, occurring in 27 U.S. states and two Canadian Provinces as of 2017 (USDA, 2017). Impending infestation throughout the upper Midwestern United States is particularly concerning, as black ash wetlands cover approximately 8000 km^2 and provide myriad functions ranging from shelter and food for wildlife (Anderson and Nelson, 2003) to timber and non-timber forest products (Wright and Rauscher, 1990).

Widespread black ash mortality may equate to loss of a wetland foundational species (*sensu* Ellison et al., 2005), with important consequences for ecohydrologic interactions and successional trajectories (Youngquist et al., 2017). Throughout the upper Midwestern United States, black ash wetlands are highly monospecific, with black ash comprising 75–100% of canopy cover. In these monospecific stands, complete canopy loss following EAB may cause the water table to rise (via reduced transpiration) and favor establishment and growth of other more water tolerant vegetation, particularly marsh species (Erdmann et al., 1987). Recent studies support this general prediction, where canopy disturbance in black ash wetlands resulted in wetter conditions (Slesak et al., 2014) and associated large shifts in species composition towards a herbaceous community (Davis et al., 2016; Looney et al., 2017). Given the extensive coverage and regional importance of black ash wetlands, it is now important to explore possible consequences (and mitigation) of EAB disturbance on ecosystem interactions, state, and function.

Reduced ET is the putative mechanism for expected water table rise and ecosystem state shifts following EAB-induced mortality, but actual changes in ET and how such changes vary over time (seasons to years) and with vegetation structure remain largely unexplored. Although previous studies made a clear link between black ash mortality and altered hydrology (Slesak et al., 2014), the lack of direct ET measurements leaves open questions regarding how black ash regulates water tables compared to other vegetative communities. Post-disturbance community composition, growth, and associated ET rates are likely driven by both hydrologic regime and remnant vegetation structure and recovery, highlighting potential implications of management options that range from a do-nothing approach (i.e., leave standing dead trees) to different degrees of preemptive tree harvest (i.e., partial *versus* clearcutting). Confronting this knowledge gap, we posit a conceptual model of ET drivers that vary with vegetation structure and thus different management strategies (Fig. 1). This model includes availability of energy (e.g., shade from standing dead *versus* open canopy in a complete clear cut) and water (e.g., via differences in rooting depths), with associated feedbacks to water table regime and its control on post-disturbance vegetative communities. Evaluating this model will address more directly the interactions among energy, vegetation, and hydrology in black ash ecosystems, with implications for both recovery times and management options.

Here, we build upon earlier work (Slesak et al., 2014) by integrating multi-year measures of both daily water table and ET dynamics across black ash wetlands that represent different management options and thus vegetation structure: intact black ash stands (controls), simulated EAB-induced mortality (girdled; do-nothing approach), and two management mitigation options (clearcut and group selection harvest) (Fig. 1b–d). Our overarching objective was to assess outcomes of both EAB infestation and management options on post-disturbance hydrologic regime. We hypothesized that: H1) water table regimes and their possible post-disturbance recovery will vary depending on management strategy and thus vegetation structure, and H2) that differences in water table regimes among management options can be explained by coincident differences in ET, where black ash trees exhibit unique ET regimes relative to post-disturbance replacement vegetation. Our research advances fundamental understanding of ecohydrologic interactions in black ash wetlands and has direct implications for management aimed at mitigating consequences of EAB infestation.

2. Methods

2.1. Landscape setting

Our study sites were located within the Chippewa National Forest in northern Minnesota, USA, a 2700 km^2 area with 1600 km^2 of wetlands and over 1300 lakes (Fig. 2). The area encompasses a complex glacial landscape that is flat to gently rolling, with black ash wetlands found in the lowest landscape positions that commonly grade into aspen (*Populus*) or pine (*Pinus*)-dominated upland forests. Most of the black ash wetlands are underlain by lacustrine clay at a depth of 10–150 cm that acts as a confining layer and creates wetland hydrologic conditions (seasonal soil saturation and inundation). Specific soil types vary and include Typic Glossaqualfs with no O horizon, Histic Humaquepts with a 30 cm deep O horizon, and Terric Haplosaprists with a 60 cm deep O horizon and no B horizon (Soil Survey Staff, 2014). However, collected soil samples in our study sites did not significantly differ in overall soil chemistries (total carbon and nitrogen) or bulk densities (Table S1).

Forest structure and composition in black ash stands in the region are characterized by black ash canopy dominance (75–100%) co-occurring with American elm (*Ulmus americana*), balsam fir (*Abies balsamea*), basswood (*Tilia Americana*), red maple (*Acer rubrum*), yellow birch (*Betula alleghaniensis*), quaking aspen (*Populus tremuloides*), or white cedar (*Thuja occidentalis*). Stands are typically strongly uneven-aged and largely influenced by gap-scale disturbance processes with canopy tree ages ranging from 130 to 232 years (Looney et al., 2016).

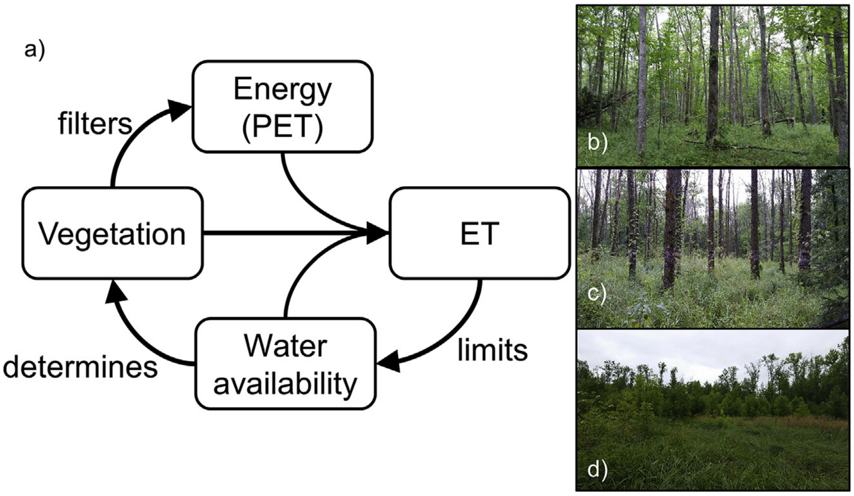

Fig. 1. a) Conceptual model of feedbacks driving ecohydrology of black ash wetlands. Energy from solar radiation and wind (potential evapotranspiration, PET) is filtered through a cascading vegetation structure to drive evapotranspiration (ET) under the combined influence of vegetation and water availability. ET limits water availability through depletion and controls seasonal water table patterns, which in turn determine vegetation species composition and structure. Photos b-d are from treatment plots in August 2015 that are in similar in environmental conditions (e.g., climate, soils, and elevation) but differ in vegetation structure and its influence on energy partitioning: b) example of black ash wetland with energy filtered by the canopy strata; c) example of girdled black ash wetland to simulate EAB mortality with less energy filtered by the canopy strata; d) example of clearcut black ash wetland with increased growth of marsh vegetation due to large reduction in energy filtered from the canopy strata.