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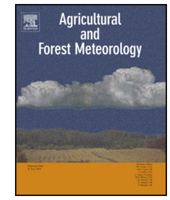


# Temporal dynamics of soil moisture in a northern temperate mixed successional forest after a prescribed intermediate disturbance

Lingli He[a,*], Valeriy Y. Ivanov[a], Gil Bohrer[b], Julia E. Thomsen[c], Christoph S. Vogel[d], Mahta Moghaddam[e,1]

[a] *Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, USA*
[b] *Department of Civil Environmental & Geodetic Engineering, The Ohio State University, Columbus, OH, USA*
[c] *Department of Earth and Environmental Sciences, Wesleyan University, Middletown, CT, USA*
[d] *University of Michigan Biological Station, University of Michigan, Ann Arbor, MI, USA*
[e] *Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI, USA*

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ABSTRACT

Forested ecosystems may experience intermediate disturbances that involve changes of crown-scale canopy characteristics. When such changes occur, soil moisture under disturbed canopy may become either drier or wetter, depending on the interplay between small-scale hydrological processes, tree-scale vegetation function, and meteorological forcing. Understanding the contributing factors that impact small-scale soil water dynamics is vital for predicting long-term and larger-scale changes of forest hydrology following disturbances, succession, and management processes. In this study, we initiated half-hourly, three-meter deep measurements of soil moisture at four plots in a northern temperate mixed forest near the University of Michigan Biological Station. Two of the plots (one aspen- and the other oak-dominated) are located near the AmeriFlux tower; this forest area represents an undisturbed control site. Two other plots are located near the Forest Accelerated Succession Experiment (FASET) flux tower. An intermediate disturbance was prescribed in this area through stem girdling of all canopy-dominant, early successional aspen and birch trees to simulate the anticipated large-scale succession process in the Upper Great Lakes area. The data collected at the four plots provide observational evidence of changes in hydrological dynamics that were induced by species-specific crown-scale disturbances of the canopy structure.

Data analysis reveals that the soil water storage under the girdled aspen was persistently higher, as compared to the undisturbed plots over the observational period of 2009–2011. The study argues that the larger water storage resulted from increased net precipitation and reduced transpiration during growing seasons following the girdling operation. These processes "outcompeted" the presumably enhanced interception and transpiration by understory plants as well as increased soil evaporation. Additionally, surface soil layer at the disturbed plot exhibited highest temporal variability among all monitored plots. The moisture profiles at the four plots were different, with the disturbed plot exhibiting relatively wetter shallow soil layers. Furthermore, water loss at the disturbed plot was concentrated in shallower soil layers, signifying a shift of uptake and/or change of dominant processes.



## 1. Introduction

In forested environments, canopy structure can profoundly influence soil water in a variety of ways, mainly through rainfall interception, moisture uptake for transpiration, and shading of the forest floor that affects sub-canopy microclimate and evaporative drying of soil (Elliott et al., 1998; James et al., 2003; Leuning et al., 1994; Schrumpf et al., 2011; Vertessy et al., 2001). Changes to canopy structure due to large-scale clearings or intermediate disturbance events may lead to changes in statistical moments of soil moisture, such as the mean and the variance (Breshears et al., 1997, 2009; Chen et al., 1993; Guo et al., 2002; Lebron et al., 2007; Olchev et al., 2009; Western et al., 2004). Previous studies have shown that relatively large-scale clearings (at a scale larger than the size of a single tree crown) lead to a higher level of soil water content due to reduced interception and transpiration rates (Bruijnzeel, 2004; Schrumpf et al., 2011). Conversely, increased radiation levels due to sparser canopy may enhance soil

* Corresponding author at: Department of Civil and Environmental Engineering, University of Michigan, 126 EWRE, 1351 Beal Ave., Ann Arbor, MI 48109, USA. Tel.: +1 734 355 4397; fax: +1 734 763 2275.
*E-mail addresses:* linglihe@umich.edu, helingli.hust@gmail.com (L. He).
[1] Current address: Ming Hsieh Department of Electrical Engineering, University of Southern California, Los Angeles, CA, USA.

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evaporation and promote a fast growth of secondary or understory vegetation, both of which can accelerate the depletion of soil moisture (Bhatti et al., 2000; Denslow et al., 1998; Giambelluca, 2002). Similar effects can be expected from changes in crown-scale canopy structures (Bohrer et al., 2005), which are characteristic to trees of different species may also be driven by intermediate disturbances. Common intermediate disturbance events include anthropogenic processes, such as selective logging and forest thinning, or natural processes, such as species shifts due to regional climate change and invasive species, succession and growth, and species-specific pest infestations. In selectively logged forest patches, rainfall interception decreased as a function of the minimal-logged diameter (Dietz et al., 2006). Increased correlation between localized leaf area at a single-tree scale and turbulence can drive changes in surface fluxes that may also contribute to changes of soil water content (Bohrer et al., 2009). A priori, the outcome of these small-scale, canopy-structure-change driven processes is unclear: soil may become either wetter or drier under the removed or modified tree crowns. As such intermediate disturbances usually extend over a very large spatial domain; their implications can be far reaching: the changed soil water status can further influence vegetation dynamics, groundwater recharge, river flow, and regional climate (Hodnett and Bell, 1986; Rodriguez-Iturbe, 2000; Seneviratne et al., 2010). Understanding soil water dynamics under canopies undergoing a disturbance process is therefore essential for predicting the long term consequences of intermediate disturbances.

Various models of water dynamics in forested environments require continuous, deep-profile soil moisture data for initialization and validation purposes (Bhatti et al., 2000; Koster and Suarez, 2003; Vereecken et al., 2008; Wilson et al., 2003). Soil moisture dynamics in the root zone are of particular interest in modeling studies of land–atmosphere interactions, as dry moisture levels may strongly constrain vegetation transpiration through root water uptake. The soil water content in the root zone or deeper layers is usually inferred through model-based or empirical extrapolations from information on surface soil moisture (within top 5 cm depth or less) provided by remote sensing techniques (Albergel et al., 2008; Bisselink et al., 2011; Calvet and Noilhan, 2000; Fernandez-Galvez et al., 2006; Ragab, 1995; Venkatesh et al., 2011). Monitoring soil water content at depths within and beyond the root zone is therefore necessary for accurate modeling efforts. Despite the need for temporally continuous and deep-profile soil moisture datasets, measurements in temperate forests have been mostly carried out either within shallow soil horizons (Hirano et al., 2003; Martin and Bolstad, 2005; Matamala and Schlesinger, 2000; Schmitt and Glaser, 2011; Schäfer et al., 2002), or at a coarse temporal resolution (Greco and Baldocchi, 1996; Wilson and Baldocchi, 2000). Only a few soil moisture datasets exist for temperate forests at a half-hourly temporal resolution, representing relatively deep soil profiles (e.g., 1 m deep, Drewitt et al., 2002; 0.61 m deep, Savage et al., 2009).

The main objectives of this study are: (1) to understand and evaluate the change of magnitude and temporal dynamics of soil water status under forest canopy undergoing a prescribed intermediate disturbance that simulates an accelerated succession process, as compared to an undisturbed canopy; (2) to explain the differences (if any) in soil water content and dynamics as influenced by the canopy change through a quantitative examination of physical processes, such as interception and evapotranspiration; and (3) to examine the soil water dynamics at depths, and to describe a deep-profile soil moisture dataset available for modeling studies in a temperate forest.

This study was conducted in a northern, temperate, mixed deciduous forest near the University of Michigan Biological Station (UMBS). In one experimental site at this location, the Forest Accelerated Succession Experiment (FASET), stems of aspens near a flux tower were girdled in 2008 to accelerate the occurring successional mortality of early successional species and a consequent change of species composition and canopy structure (Nave et al., 2011). As a result of girdling, the treated canopy became patchy and exhibited a reduction of Leaf Area Index (LAI) by about 30%. A soil-moisture measurement network screening a depth range of 5–300 cm and precipitation sensors were deployed at four plots in the treated and undisturbed control sites. Data were collected over a two-year period. The results of this study contribute to the understanding of future projections of soil water conditions for successional forests in the Upper Great Lakes region, and to the general understanding of the effects of intermediate disturbance.

## 2. Methods

### 2.1. Studied forest

The studied temperate forest is located near the UMBS (Fig. 1a, b) in Northern Michigan, U.S.A. (45.56° N, 84.71° W). This location is characterized by a northern hardwood forest, which represents a transitional zone between mid-latitude hardwood and boreal forests. The area is a gently sloping outwash plain at an elevation of ~300 m that varies over a range of ~20 m (Pressley et al., 2005). Soil texture is dominated by well-drained spodosols and contains 92% sand, 7% silt, and 1% clay. The soils tend to exhibit an ortstein layer at 50 cm, which is a cemented layer by amorphous metal and organic materials (Hall, 1986). Well drilling records for a location in the immediate vicinity of the AmeriFlux tower (~50 m distance) show that the water table depth is around 20 m (Tony Sutterley, personal communication, 2012/10). The mean annual rainfall is 817 mm, the average annual temperature is 5.5 °C, and the annual temperature cycle exhibits well-pronounced seasonality (Curtis et al., 2005).

Currently, the forest is dominated by aspen (*Populus grandidentata*) and birch (*Betula paprifera*), with understory of pine (*Pinus strobes*, *Pinus resinous*), red oak (*Quercus rubra*), and maple (*Acer rubrum*, *Acer sacchrum*) (Bovard et al., 2005). Around the study location, aspen and oak contribute 69% of the above-ground biomass, and canopy reaches peak LAI of ~4.0 during summer periods (Curtis et al., 2005). The understory fern (*Pteridium aquilinum*) contributes an additional LAI of ~0.5 and shows similar phenological timing relative to the canopy-dominant tree species (Curtis et al., 2005). The thickness of surface leaf litter layer varies with moisture conditions. Generally, it is between a few millimeters to one centimeter, and could reach around two centimeters during extremely dry periods. The species composition at the UMBS forest is typical of nearly half of the forested area in the Upper Great Lakes region (Cleland et al., 2001; Frelich and Reich, 1995; Schier and Smith, 1979). As the UMBS forest was heavily logged in the late 19th century and further disturbed by fire until the early and mid 20th century, the individual overstory stands are 30–90 years old with an average age of 85 years (Gough et al., 2007). This average age is older than that of other aspen-dominated, early successional forest stands in the upper Great Lakes region, where aspens are ~50 years old and in early-successional stages (USDA Forest Service, 2001). The UMBS area, therefore, provides an ideal setting for studying emerging ecosystem properties before the occurrence of widespread aspen mortality anticipated in the coming decades for the Great Lakes region as part of the natural succession process from early to mid-successional stages (Sakai et al., 1985; Wright, 1964).

### 2.2. AmeriFlux and FASET eddy-covariance sites

There are two flux towers near the UMBS (Fig. 1b). The UMBS AmeriFlux tower (AmeriFlux code: US-UMB) has been monitoring the meteorological conditions and net ecosystem $CO_2$ exchange