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# Canopy-structure effects on surface roughness parameters: Observations in a Great Lakes mixed-deciduous forest

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ABSTRACT

Over forested canopies, the physical structure of vegetation interacts with wind by exerting drag on the flow, thus generating turbulent mixing that is necessary for scalar transport. We use 11 years of above-canopy wind speed measurements from spatially and temporally heterogeneous forest environments to disentangle the effects of different features of changing canopy structure on the surface roughness parameters: displacement height ($d$), roughness length ($z_0$), and the aerodynamic canopy height ($h_a$). We find a significant increasing long-term trend of dormant-season (leaf-off) $h_a$, which closely resembles the rate of biometrically derived vertical stem growth over years. We show that the values of $d$ and $z_0$ trade-off with higher $d$ and shorter $z_0$ when leaf area is high in the growing season. Using airborne lidar measurements and a footprint model for flux-source location detection, we show that these $d$ and $z_0$ trade-offs also correspond with the spatial differences between taller and shorter subplot patches.

We show that incorporating seasonal-scale temporal heterogeneity of $d$ and $z_0$ into surface-flux and ecosystem models will improve their accuracy. However, incorporating simple empirical modifications to surface-structure roughness parameters due to inter-annual variation in canopy height and leaf area did not lead to improved modeling of frictional velocity within this study. Further investigation of structure–roughness relationships is needed to incorporate these aspects. Finally, this study proposes a meteorological-based method for estimating vertical stem growth in undisturbed forest environments by tracking $h_a$ over time.

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## 1. Introduction

Understanding the fluxes of momentum, mass, and energy, such as carbon, water vapor, methane or sensible heat, between the biosphere and atmosphere is critical to our ability to analyze and predict weather and climate at various spatial and temporal scales. Over forested environments, vegetative structures (i.e. trees, tree-stems, leaves) exert drag on the wind and produce turbulent eddies which are largely responsible for the vertical mixing of mass across the biosphere-atmosphere interface (Thomas and Foken, 2007b). Our ability to accurately predict surface-layer mass and energy fluxes at any time scale, therefore, depends on the accuracy of the parameterization of surface drag (Finnigan, 2000; Mahrt, 2010). For example, Pitman (1994) showed a 30% error in the estimation of $z_0$ within land surface models (LSM) could lead to a 15% error in estimates of sensible heat flux over forested environments. Calculations of surface fluxes in models are typically dependent on parameterization of turbulent mixing, which is based on Monin–Obukhov similarity theory (MOST) (Monin and Obukhov, 1954), relating the vertical profile of horizontal wind speed and the physical structure of the ground surface to turbulent mixing (expressed as frictional velocity). The ground-surface structure is described through two drag parameters: displacement height, $d$, and roughness length, $z_0$.

Many studies have shown surface stress over forested canopies to be significantly less than that predicted by MOST (Finnigan et al., 2009; Garratt, 1978; Harman and Finnigan, 2007; Raupach, 1979) and have led to the development of higher order closure models within the surface-roughness layer (RSL) (Baldocchi and Meyers, 1989; Raupach and Thom, 1981). Combining these findings with the need for simplification and the lack of detailed description of the surface have led to approaches that include an additional length scale to correct for dynamics within the RSL, typically based on the height of the RSL ($z^*$), within the MOST framework (Cellier and Brunet, 1992; Garratt, 1980; Molder et al., 1999; Physick and Garratt, 1995; Raupach, 1992). As the

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definition of $z^*$ has been highly debated (Chen and Schwerdtfeger, 1989; Garratt, 1980; Graefe, 2004), further studies have removed *a priori* knowledge of RSL height with wind-profile statistics and the mixing length (Harman and Finnigan, 2007). However, this method relies on detailed wind-profile measurements, which are not available at most sites, requiring iterative calculations for $d$ and $z_0$ (Weligepolage et al., 2012b).

LSM, such as the Community Earth System Model (CESM), Surface Energy Balance Algorithm for Land (SEBAL) (Bastiaanssen et al., 1998), and Mapping Evapotranspiration with Internalized Calibration (METRIC) (Allen et al., 2007), calculate surface fluxes as a function of the aerodynamic resistance for heat transfer, $r_{ah}$, which is a function of $z_0$. In these models $d$ and $z_0$ may be derived from a variety of canopy structure inputs. At the most basic resolution, $d$ and $z_0$ are simple linear functions of site-level canopy height ($h$) – typically, $d \approx 0.66h$ (Cowan, 1968) and $z_0 \approx 0.10h$ (Tanner and Pelton, 1960). To incorporate finer resolutions of canopy structure, SEBAL and METRIC have the ability to use satellite imagery to estimate canopy–roughness relationships over agricultural systems, such as the function based on the Normalized Difference Vegetation Index in SEBAL (Moran, 1990) or the Perrier Function (Perrier, 1982) in METRIC where leaf area index (LAI) is derived from the Soil-adjusted Vegetation Index (Allen et al., 2007).

Over time, estimates of $d$ and $z_0$ have been expanded as functions of structure-driven area-index (AI), specifically leaf area index (LAI) (Choudhury and Monteith, 1988), plant area index (PAI) (Shaw and Pereira, 1982), frontal area index (FAI) (Raupach, 1994) and stem density (Nakai et al., 2008a). These studies find $d$ to be positively correlated with AI. Furthermore, they find a positive correlations between $z_0$ and AI in sparse canopies (when AI terms are low), and a negative $z_0$-AI correlation when the canopy is dense. These estimates are limited, however, by the absence of a representation of the vertical canopy structure, and specifically, the vertical distribution of leaf area density, which has been shown to have a significant effect on roughness parameter values (Massman, 1997; Shaw and Pereira, 1982). Roughness parameters also ignore the small-scale spatial heterogeneity in the structure of the canopy, which is difficult to measure, highly variable in both space and time, and is hard to characterize using simple low-variable-number formulations. Inclusion of these small-scale structure effects requires computationally intensive, high resolution large-eddy simulations (Aumond et al., 2013; Bohrer et al., 2009) or extensive empirical campaigns (Dupont and Patton, 2012a).

More recently, roughness parameters have been derived from above-canopy meteorological measurements (Katul and Albertson, 1998; Nakai et al., 2008a; Raupach et al., 1996) and remote-sensing forest-structure statistics (Schaudt and Dickinson, 2000; Weligepolage et al., 2012a). A closer investigation of meteorological estimates of roughness parameters and canopy structure has created the view that $d$ and $z_0$ are highly variable both spatially and temporally (diurnally, seasonally) (Harman, 2012; Zhou et al., 2012). The heterogeneous nature of these variables has led to the definition of a more robust parameter for the description of the aerodynamic effects of the canopy – the aerodynamic canopy height ($h_a$) – which combines $d$ and $z_0$ into one term and has been shown to scale better with canopy height (Nakai et al., 2008b; Raupach et al., 1996; Thomas and Foken, 2007a). Although typical investigations of $d$, $z_0$, and $h_a$ occur under static canopy conditions, their sensitivity to long-term canopy-structure changes has yet to be investigated. Forest structure can change slowly through stem growth over years, quickly through seasonal senescence in deciduous forests and disturbance such as disease, fire, drought-driven mortality, and pest infestation, or at intermediate rates through species community dynamics, succession, and mortality.

In this study we use over a decade of above-canopy wind speed measurements from 2000 to 2011 (undisturbed control) and 2008 to 2011 (disturbed treatment) to test the effects of different characteristics of the changing canopy structure on surface roughness parameters. We hypothesize that changes to different characteristics of canopy structure will be related to the resulting changes to the canopy's roughness parameters, namely, $d$, $z_0$, and $h_a$. Specifically, we propose that canopy density will have a strong effect on $d$, with sparser canopies (of the same height) having lower $d$. We further propose $h_a$ to be mostly affected by canopy height, regardless of its density. Because $h_a$, which changes slowly over time, is a combination of $d$ and $z_0$, a fast decrease in $d$ due to canopy thinning and LAI reduction without a corresponding change of stem heights will be offset by a corresponding increase in $z_0$, maintaining a fixed $h_a$. We also expect that the vertical profile of leaf density will affect both $d$ and $z_0$. Furthermore, we expect that the effects of spatial differences in canopy structure, measured using light detection and ranging (lidar) scans at different locations near the meteorological towers and at different times over seasons and years, will be detectible from long-term observations when a footprint method is used to detect the narrow location from which observations originate at each 30-min timestep.

## 2. Materials and methods

### 2.1. Site description

This study is located at the University of Michigan Biological Station (UMBS) in northern, lower Michigan, USA (45°33′35″ N, 84°42′48″ W, elev. 236 m). The forest is a mixed, deciduous forest common throughout the upper Great Lakes region. It is dominated by early-successional bigtooth aspen (*Populus grandidentata*) and paper birch (*Betula papyrifera*) with a mean age of 85–90 years (Gough et al., 2008). Understory species include white pine (*Pinus strobus*), red oak (*Quercus rubra*), and red maple (*Acer rubrum*). Mean canopy height is 20–25 m with an average stem density of trees (≥8 cm diameter at breast height) of ≈750 stems/ha. An AmeriFlux (AF, http://public.ornl.gov/ameriflux/) affiliated meteorological tower (US-UMB) has been continuously recording data since the 1999 growing season.

### 2.2. Intermediate disturbance at UMBS

As extensive deforestation and fire shaped the forests in the northern Midwest and Great-Lakes region at the start of the 20th century the mortality of, now mature, early-successional tree species is predicted to occur naturally throughout the region in the next decade or two. Following this successional phase shift, the structure of this forest is expected to change dramatically as late successional species grow into the upper canopy and replace the early successional species. This inspired FASET (Gough et al., 2013; Nave et al., 2011), where all early-successional aspen and birch (>6700 trees) in 39 ha of an experimental forest plot were stem girdled to accelerate the coming succession of the control forest. Stem girdling was conducted prior to the 2008 growing season and resulted in aspen and birch mortality within 2–4 years. An AF affiliated meteorological tower (US-UMd) was installed in this experiment area during the 2007 growing season. The US-UMB meteorological and flux tower serves as the control for FASET.

### 2.3. Meteorological data

Wind velocity and air temperature ($T$) were measured at 10 Hz at 34 m above the ground from 2000 to 2011 at the control site and 32 m above the ground from 2008 to 2011 at the treatment site using 3-dimensional (3-D) ultrasonic anemometers (CSAT3, Campbell Scientific, Logan, UT, USA). 10 Hz wind data was processed using a 3-D coordinate rotation (planar fit method) resulting in

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