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Forest productivity varies with soil moisture more than temperature in a small montane watershed

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ABSTRACT

Mountainous terrain creates variability in microclimate, including nocturnal cold air drainage and resultant temperature inversions. Driven by the elevational temperature gradient, vapor pressure deficit (VPD) also varies with elevation. Soil depth and moisture availability often increase from ridgetop to valley bottom. These variations complicate predictions of forest productivity and other biological responses. We analyzed spatiotemporal air temperature (T) and VPD variations in a forested, 27-km^2 catchment that varied from 1000 to 1650 m in elevation. Temperature inversions occurred on 76% of mornings in the growing season. The inversion had a clear upper boundary at midslope (~1370 m a.s.l.). Vapor pressure was relatively constant across elevations, therefore VPD was mainly controlled by T in the watershed. We assessed the impact of microclimate and soil moisture on tree height, forest productivity, and carbon stable isotopes ($\delta^{13}C$) using a physiological forest growth model (3-PG). Simulated productivity and tree height were tested against observations derived from lidar data. The effects on photosynthetic gas-exchange of dramatic elevational variations in T and VPD largely cancelled as higher temperature (increasing productivity) accompanies higher VPD (reducing productivity). Although it was not measured, the simulations suggested that realistic elevational variations in soil moisture predicted the observed decline in productivity with elevation. Therefore, in this watershed, the model parameterization should have emphasized soil moisture rather than precise descriptions of temperature inversions.

1. Introduction

In the western US, 70% of the terrestrial carbon sink is located above 750 m elevation, 50%–85% of which is hilly or mountainous (Schimel et al., 2002). However, it is more challenging to simulate ecosystem productivity in mountainous than in flat areas because climatic variables can vary dramatically over short distances in complex terrain (Barry, 1992; Holden et al., 2011b; Hubbart et al., 2007a) and the eddy-covariance technique, which is often used for model parameterization, is difficult to use in complex terrain (Novick et al., 2014; Yi, 2008).

Fine-scale microclimate heterogeneity in mountainous areas can be observed in many variables including precipitation, shortwave radiation (0.28–3.5 μm), and air temperature (*T*). For example, precipitation typically increases with elevation (Barry, 1992; Kräuchi et al., 2000). Shortwave radiation varies between aspects and slopes and may be blocked by surrounding topography (Duursma et al., 2003). Similarly, air temperature is related to topographic features, especially aspect and elevation (Ashcroft and Gollan, 2012; Holden et al., 2011a; Holden et al., 2011b; Hubbart et al., 2007a; Suggitt et al., 2011) and topographic position (Daly et al., 2010). Temperature generally decreases with increasing elevation. However, due to nocturnal longwave

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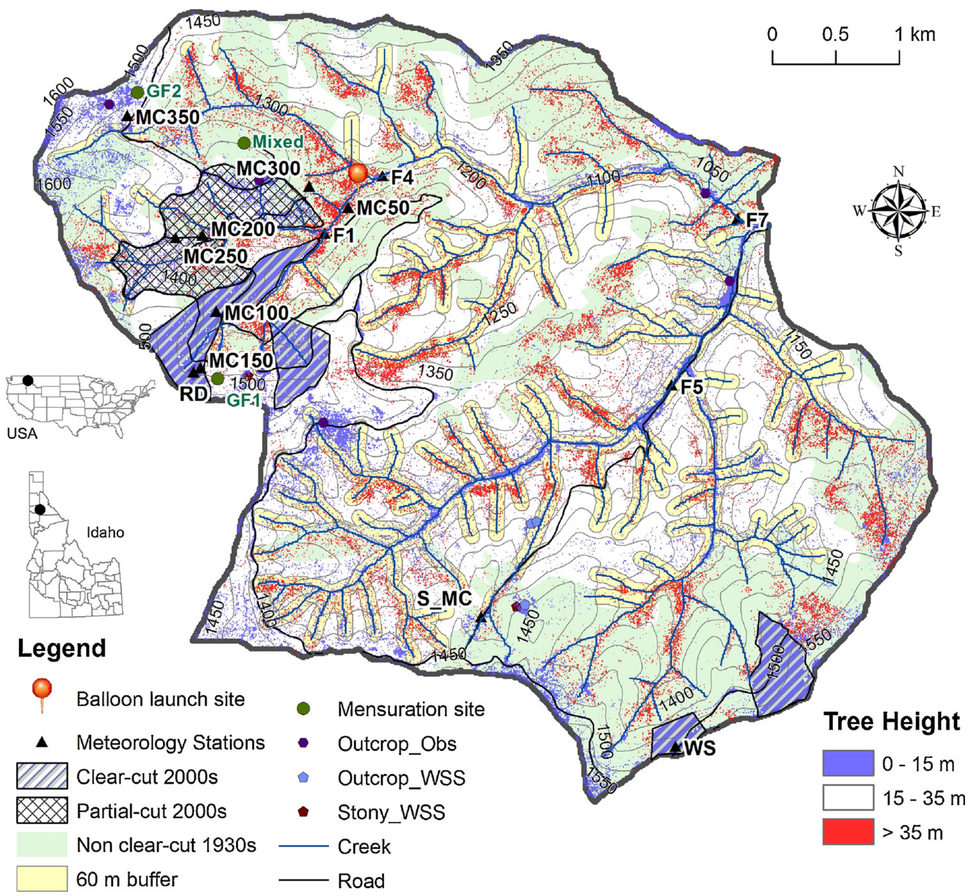

Fig. 1. Map of Mica Creek Experimental Watershed (MCEW). Elevation decreases from the southwest (1600 m) to the northeast (1000 m). Fifteen hydrometeorological stations were installed throughout the watershed (F2 station is located within 20 m of F1; not marked). Most of the area was clearcut around 1930 ("1930s-clearcut area"), but some area was not clear cut ("non-clear-cut area"). Lidar-derived vegetation height (collected in 2003) demonstrated that tall trees often occurred in the non-clear-cut area and near the creek ("60 m buffer" area). Short vegetation was common at the high elevation, which may be related to stony soil. Stony areas and outcrops are marked on the map; these were obtained either from the Web Soil Survey (WSS, Natural Resource Conservation Service, http://websoilsurvey.nrcs.usda.gov) or our field observations (Obs). Thin gray lines are contour lines (meters above sea level). Helium-filled balloons were launched from a ~one-hectare clearing between the MC50 and F4 station.

radiation emission, cold, dense air may produce katabatic flows that drain to valley bottoms, thereby reversing the temperature lapse rate and producing temperature inversions (Fleagle, 1950a; Fleagle, 1950b; Whiteman, 2000). The pool of cold air usually dissipates after short-wave radiation warms the ground, but the dissipation process may take up to five hours after sunrise (Manins and Sawford, 1979).

Inversions complicate the prediction of climate patterns in mountainous areas. Regional-scale weather conditions may not be sufficient to predict air temperature, especially in valleys (Bigg et al., 2014; Daly et al., 2010; Holden et al., 2011a; Lundquist et al., 2008) and the average environmental lapse rate (-0.0065 $^{\circ}C\,m^{-1}$) may not be a reliable predictor of air temperatures (Minder et al., 2010).

Due to the elevational heterogeneity of microclimate variables, plants at different elevational positions may differ in their growth responses, especially when they are under stress (Elliott et al., 2015). Therefore, it would be challenging to predict forest productivity in mountainous areas. The topographic effects on radiation intensity and terrain shading (i.e., the hillshade effect) reduce solar radiation in the valley, which may either reduce forest productivity if the tree growth is radiation limited, or increase productivity if trees are under water stress. Warm temperature generally benefits photosynthesis and productivity (Way and Oren, 2010). However, higher temperature also accompanies higher vapor pressure deficit (VPD); both high temperature and high VPD increase evapotranspiration and hence increase plant water stress. High VPD also leads to stomatal closure, which limits photosynthesis. Therefore, the benefit of higher temperature on photosynthesis may be diminished by higher VPD.

Nocturnal temperature inversions may reverse the usual temperature gradient, which may impact forest productivity in mountainous areas. Low temperatures on inversion days reduce respiration in the valley (Novick et al., 2016), but restrict photosynthesis if inversions persist in the daytime. Inversions may also reduce the growing season length (Adams, 1979), which further reduces forest productivity. As regional warming proceeds, cold air drainage may cause microclimate to further deviate from regional climate (Daly et al., 2010; Keppel et al., 2012), which will further increase the difficulties of predicting temperature effects on forest productivity. It is hence an urgent need to accurately estimate microclimate in mountainous areas with cold-air drainage and to model its impact on forest productivity.

Besides microclimate variables, soil depth and hence available soil moisture can vary considerably over short distances in mountainous areas. Although low elevation typically have lower precipitation than high elevation (Barry, 1992; Kräuchi et al., 2000), soil depth and moisture availability often increase from ridgetop to valley bottom (Bolstad et al., 2001; Helvey et al., 1972; Lin et al., 2006; Markesteijn et al., 2010; Yeakley et al., 1998). This is because topography modifies water flow and particle redistribution, topographic characteristics like slope and flow accumulation determine soil properties (Gessler et al., 2000; Gessler et al., 1995; Moore et al., 1993). Therefore, forest productivity in the valley normally benefits from deep soil and extra soil moisture, while productivity on ridges may suffer more from drought due to shallower soil than in the valley (Bolstad et al., 2001). Note that air temperature also generally increases from ridgetop to valley bottom in the absence of inversions, which makes it difficult to separate the impact of air temperature and soil moisture on forest productivity; inversions may break the confounding of these variables.

The general objective of this study was to assess the respective influences of microclimate and soil moisture on forest ecosystem processes on a small forested watershed in complex terrain. Specific objectives were three-fold. First, we aimed to understand the spatiotemporal dynamics of temperature inversions in a small forested catchment. Second, we used 3-PG, a quasi-mechanistic forest growth model, to analyze the effects of inversions and soil depth on forest productivity. Thirdly, we ran models of different scenarios to determine