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Drivers of spatial variability in greendown within an oak-hickory forest landscape

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ABSTRACT

Declining near-infrared (NIR) surface reflectance between early and late summer, here termed greendown, is a common, yet poorly understood phenomena in remote sensing time series of temperate deciduous forests. As revealed by phenology analysis of Landsat satellite data, there are strong spatial patterns in the rate of greendown across temperate deciduous forest landscapes, and analyzing these patterns could help advance our understanding of surface reflectance drivers. Within an oak-hickory (*Quercus* spp. – *Carya* spp.) forest landscape in western Maryland, USA, we tested how spatial patterns in greendown related to potential drivers at the landscape-, tree crown- and leaf-levels. We found that 50% of the spatial variability in greendown was explained by landscape variables, with greendown particularly higher in locations with higher maximum greenness, more southerly aspects, or locations with greater abundance of white oak (*Quercus alba*). The importance of species composition as a driver of greendown was supported at the tree crown level, where, relative to three other tree species, white oak exhibited the most consistent trend toward more vertical leaf angles later in the season. At the leaf level, NIR reflectance decreased in productive sites where %N increased, and $\delta^{13}C$ decreased, through the season. However, among all sites, there were no consistent seasonal trends in foliar NIR reflectance, and we found no correlation among leaf-level NIR reflectance and satellite-observed greendown. Collectively, these results suggest that the spatial variability of greendown in this oak-hickory forest is most strongly controlled by an interaction of topographic and species compositional drivers operating at the landscape and tree crown levels. We found spatial analysis of greendown to be a useful approach to explore landscape-, tree crown-, and leaf-level controls on surface reflectance, and thereby help translate land surface phenology data into predictions of ecosystem structure and functioning.

1. Introduction

The annual trajectory of spectral reflectance observed in remote sensing data is used to infer many aspects of ecosystem structure and functioning, including land use, forest disturbance, and productivity (Fisher et al., 2006; Elmore et al., 2012; Zhu and Woodcock, 2012; Zhu and Woodcock, 2014; Badgley et al., 2017). As data from medium resolution sensors have become more widely and freely available (Woodcock et al., 2008), these data have been leveraged to describe ever more complex and variable phenomena. This is particularly true when characterizing land surface phenology patterns over space and time (Melaas et al., 2012; Melaas et al., 2016). For instance, one common, but poorly understood, intra-annual phenomenon is declining near-infrared reflectance (NIR) through the growing season in broadleaf deciduous forest canopies, which we call "greendown". Greendown has been observed in data collected by different observation platforms at varying spatial scales, including from tower-based webcams (Elmore et al., 2012; Keenan et al., 2014), from dense stacks of Landsat data organized by day of year (Fisher et al., 2006; Elmore et al., 2012; Melaas et al., 2013), and MODIS phenology products (Zhang et al., 2004; Fisher et al., 2006). Thus, greendown appears to be a common phenological feature of spectral reflectance time series, yet little work has attempted to link spatial patterns of greendown with forest structure or function.

At landscape scales, greendown could be related to abiotic mechanisms related to changing sun-sensor-canopy geometry through the growing season, especially the interaction of a changing sun angle, topography, and canopy structure. Although many common pre-processing algorithms correct satellite reflectance data for these changes in sun-sensor-topography geometry (i.e. Gu and Gillespie, 1998), the physical structure of the canopy itself is not commonly accounted for, and could interact with topography to affect reflectance. Specifically,

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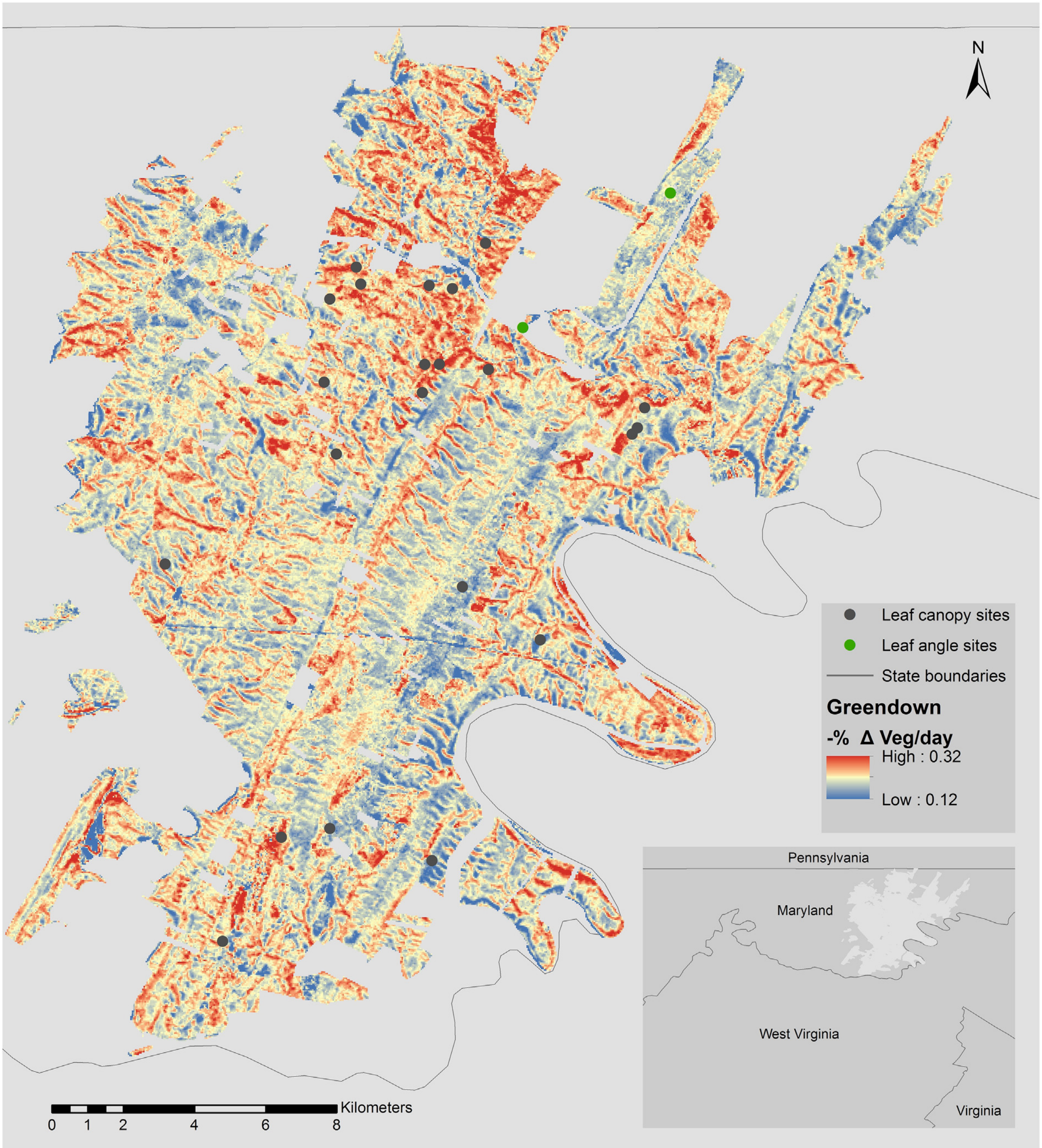

Fig. 1. Map of study area at Green Ridge State Forest. Leaf collection sites (black circles), leaf angle sites (green circles), are overlaid on greendown values (color scale). The greendown scale excludes the highest and lowest 2% of its range which were values not typical of interior forest but rather of open landscapes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

forest stands on different slope aspects experience different light and moisture availability, which can influence canopy structure through changes in tree species composition. Owing to variation in crown architecture between tree species, such as variation in crown shape, density, and leaf angle distribution (Ollinger, 2011), canopies can exhibit variation in shading within and between tree crowns (Asner and Warner, 2003). Thus, the top-of-canopy complexity, or rugosity induced by the mix of species with varying architectures could interact with the seasonal sun angle changes to affect spatial patterns of greendown (Parker and Russ, 2004; Ogunjemiyo et al., 2005).

Leaf angle distribution of forest trees is another important determinant of spectral reflectance (Asner, 1998) and can vary among species, locations, and through the growing season (Pisek et al., 2013; Raabe et al., 2015). Leaf angle influences NIR reflectance by modifying the apparent leaf area as observed from nadir (Asner, 1998). While leaf angle varies characteristically between species, trees may also modify leaf angle in response to changes in environmental conditions, thus representing an adaptive, biotic mechanism by which trees dynamically adjust leaf exposure to sunlight. Especially for anisohydric species that keep their stomata open, even during periods of late-summer drought (Choat et al., 2012; Roman et al., 2015), increasing leaf angle (i.e., more vertical leaf angles) is likely related to reduced evapotranspirative water loss. An empirical link between increasing leaf angle and greendown would therefore suggest that greendown indexes species