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Linking Landsat to terrestrial LiDAR: Vegetation metrics of forest greenness are correlated with canopy structural complexity

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ABSTRACT

Vegetation metrics derived from satellite imagery provide continuous and large spatial-scale measurements that are critical for interpreting and predicting ecosystem function. However, uncertainty still remains as to the precise structural information that could be estimated from these metrics. Landsat-derived metrics provide pixel measurements of vegetation across the landscape, whereas Light Detection and Ranging (LiDAR) provides multidimensional data on the vertical arrangement of forests. Terrestrial LiDAR metrics of structural complexity describe the arrangement of vegetation in the canopy, and could be coupled with Landsat-derived metrics through their influence on energy and light. Linking Landsat to terrestrial LiDAR estimates of canopy structure could expand the interpretation of Landsat-derived metrics and broaden the spatial scale at which structural complexity can be evaluated. Here, we examined associations between Landsat-derived metrics and terrestrial LiDAR measurements of structural complexity. Structural complexity measurements were obtained with terrestrial LiDAR from plots within eight forested NEON sites across eastern North America. Vegetation metrics (NDVI, EVI, tasseled cap metrics) were calculated for corresponding locations from Landsat 8 satellite imagery. Results showed that canopy reflectance, greenness and brightness, were linked with several measures of canopy structure. Higher levels of greenness were associated with stands having a taller canopy, greater leaf area density and variability, and a less open and porous canopy. Among greenness metrics, NDVI was most strongly correlated with structural complexity metrics (adj. R^2 = 0.52 – 0.62 for six metrics). Additionally, we found that a brighter canopy was associated with greater leaf area density and variability, canopy cover, porosity, and lower leaf clumping. Our results demonstrated the potential for large-spatial extent estimates of structural complexity using satellite imagery, and may lead to improved predictions of forest ecosystem functioning such as those predicted in "big leaf" ecosystem models.

1. Introduction

Vegetation metrics have long been inferred from satellite imagery (Crist and Cicone, 1984), but understanding the structural information represented in these spectrally-derived proxies remains challenging (Huete et al., 2002). Vegetation metrics modeled from global Landsat imagery include information on canopy greenness (Gamon et al., 1995; Huete et al., 2002), brightness, and water content (Crist and Cicone, 1984). The metrics of greenness, NDVI and EVI, are widely used as proxies for leaf area and vegetation cover (Zheng and Moskal, 2009). These continuous and large spatial-scale measurements are critical for interpreting and predicting ecosystem function at landscape to global scales (Glenn et al., 2008; Fisher et al., 2018). However, uncertainty remains in understanding which structural information can be represented by Landsat-derived metrics (e.g. Huete et al., 2002).

Satellite imagery and terrestrial Light Detection and Ranging (LiDAR) are typically applied to characterize different features of vegetation, but may provide related information on multidimensional

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structure. LiDAR creates detailed three-dimensional profiles of forest structure (Nychka and Nadkarni, 1990). Specifically, terrestrial LiDAR is useful for measuring different aspects of canopy structural complexity (hereafter structural complexity), which is the *arrangement* (rather than *quantity*) of leaf area within the canopy (Parker et al., 2004; Hardiman et al., 2011, 2013a). The structural complexity of forest canopies provides a linkage to mechanistically predict how forest structure influences ecosystem function (Hardiman et al., 2011, 2013a; Fahey et al., 2015). Previous studies that have used optical satellite imagery to map forest structure in comparison to LiDAR have primarily focused on tree height or biomass (Matasci et al., 2018), but none have focused on the potential to use Landsat-derived metrics as proxies of canopy structural complexity. Linking common Landsat-derived metrics to structural complexity metrics from terrestrial LiDAR could broaden understanding of the structural information represented by vegetation metrics. Furthermore, large spatial-scale prediction of structural complexity could improve the prediction of biogeochemical cycling and ecosystem functioning using "big leaf" ecosystem models (Fisher et al., 2018).

Canopy greenness and brightness derived from Landsat may contain more information than previously expected about structural complexity, with the two coupled through their shared relationship with canopy light distribution and interception (Funk and Lerdau, 2004). Landsat-derived metrics could therefore be correlated with metrics of structural complexity (Table 1). Structural complexity as measured by terrestrial LiDAR can be grouped into categories that describe how vegetation is distributed within the canopy: canopy height, density and area, arrangement, cover, and variability (Atkins et al., 2018b, In Review). Taller (Freitas et al., 2005), more heterogeneous (Hardiman et al., 2011), dense (Ren et al., 2015), and clumped canopies (Thomas et al., 2011) might also be greener and more reflective (Table 1) (Gemmell, 1995; Freitas et al., 2005), because these structural complexity metrics are also correlated with light acquisition (Atkins et al., 2018a) and higher forest productivity (Hardiman et al., 2011; 2013b, Fahey et al., 2016). In contrast, heterogeneous or less dense canopies may be darker (Baldocchi and Harvey, 1995; Law et al., 2001), because rougher canopies scatter a greater fraction of incident light (Ogunjemiyo et al., 2005; Atkins et al., 2018a). A correlation between wetness and all five categories of structural complexity across sites and forest types is likely to be negligible, because structure across forest types may not have a strong mechanistic link to canopy water content.

Terrestrial LiDAR provides detailed measurements of structural complexity at a sub-hectare spatial scale (Parker et al., 2004; Hardiman et al., 2013b), but covering areas larger than this can be logistically challenging. The prohibitive cost and time requirements have limited the quantification of structural complexity in ecological studies at larger spatial extents, but Landsat imagery is globally available (Glenn et al., 2008). The ability to link structural complexity with Landsat-derived metrics could provide the potential to understand multi-dimensional forest structure at a larger spatial extent and could even improve global predictions of ecosystem function. Our overall objective was to evaluate relationships between Landsat-derived metrics of vegetation and terrestrial LiDAR metrics of structural complexity within forest canopies of Eastern North America (Table 1).

2. Methods

2.1. Study sites

We evaluated relationships between Landsat-derived vegetation metrics and LiDAR-derived metrics of structural complexity across eight National Ecological Observatory Network (NEON) sites (Fig. 1A) spanning six ecoclimatic domains of eastern North America (Appendix 1: Table S1). Within each site, we collected terrestrial LiDAR and Landsat imagery from $N = 5$–20 plots (40 x 40 m) (Kao et al., 2012). NEON site information and design can be found at http://www.neonscience.org/science-design/field-sites/list.

2.2. Structural complexity metrics from terrestrial LiDAR

We used a terrestrial portable canopy LiDAR system based on the design by Parker et al. (2004) to collect structural complexity from within NEON plots. Briefly, high frequency laser pulses are emitted from the LiDAR unit and reflect off canopy surfaces as an operator moves the unit along a transect at a constant speed. Both reflected and un-reflected pulses are used to reconstruct a representative vertical cross section through the canopy, illustrating the spatial configuration of surface area within the canopy volume. From this cross-section, structural complexity is characterized via a suite of structural metrics describing 2D and 3D heterogeneity of foliage. Structural metrics describing the arrangement of leaf area are related to, but not identical to, the amount of leaf area in the canopy (Appendix 2). For details on the design, calibration, operation, and validation of the portable canopy LiDAR system see Parker et al. (2004).

Metrics of structural complexity that we measured by terrestrial

Table 1
Predictions for how Landsat-derived metrics might be correlated with LiDAR structural complexity metrics.

Structural complexity	Description	Predicted positive (+) or negative (−) correlation with mean of Landsat-derived metrics		
		Canopy greenness (NDVI, EVI, TC Greenness)	TC Brightness	TC Wetness
Height				
Mean leaf height	Transect mean of column mean leaf height – mean of density-adjusted vegetation heights per each column	+	+	negligible
Mean outer canopy height	Mean of the column maximum canopy height	+	+	negligible
Area and density				
Mean height of VAI_{Max}	Mean height of VAI_{Max} across a transect	+	+	negligible
Mean VAI	Mean of column summed vegetation area index	+	+	negligible
Cover				
Cover fraction	Transect mean of column ratio of canopy hits relative to total leaf returns	+	+	negligible
Heterogeneity				
Mean of vertical SD	Transect mean of column variability of mean leaf height	+	–	negligible
Rugosity	Transect variability of column variability of leaf density	+	–	negligible
Top rugosity	Transect variability of column maximum canopy height	+	–	negligible
Arrangement				
Porosity	Ratio of bins with no leaf area to total bins	–	+	negligible
Clumping metric	Degree of foliar clumping	+	–	negligible