Remote Sensing of Environment 167 (2015) 168–180

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Detection of gradients of forest composition in an urban area using imaging spectroscopy

Huan Gu *, Aditya Singh, Philip A. Townsend

Department of Forest and Wildlife Ecology, University of Wisconsin-Madison, 1630 Linden Drive, Madison, WI 53706, USA

ARTICLE INFO

Article history:
Received 6 April 2015
Received in revised form 27 May 2015
Accepted 6 June 2015
Available online 13 June 2015

Keywords:
Composition gradients
Foliar functional traits
Imaging spectroscopy
Non-metric multidimensional scaling (NMDS) ordination
Urban forests

ABSTRACT

Forests play an important role in urban environments by providing a range of ecosystem services. However, forest composition and function in urban ecosystems are ecologically complex because of high heterogeneity of the landscape and long legacies of intensive human management. Accurate quantification and mapping of composition of tree taxa in urban forests using remote sensing require high spatial and spectral resolution imagery. As such, mapping of individual species over large areas is impractical, so instead we map gradients of composition based on canopy traits derived from AVIRIS (Airborne Visible/Infrared Imaging Spectrometer) and lidar. This trait-based approach depicts emergent functional overlaps due to pixel-scale mixing of disparate species or genera found in the region. This provides a basis for understanding forest functioning in urban ecosystems where multiple taxa are functionally and spectrally similar. We used non-metric multidimensional scaling (NMDS) to ordinate multi-dimensional forest composition data, where NMDS scores (NMDS1 and NMDS2) represent compositional gradients. Predictive models of NMDS1 and NMDS2 were built using AVIRIS-derived foliar traits such as nitrogen concentration and lidar structural variables. Gradients of composition were strongly related to AVIRIS-derived traits ($R^2 = 0.67$ for NMDS1 and $R^2 = 0.47$ for NMDS2). Lidar-derived structural variables provided no improvement to prediction of the first NMDS axis estimates, and a minimal improvement (3% more variance explained) on NMDS2. We applied predictive models of NMDS1 and NMDS2 to maps of predictor traits to map NMDS1 and NMDS2. From the NMDS1 and NMDS2 maps, we mapped potential composition patterns and associated uncertainties by genus from the ordination of the field data. Our maps of composition gradients show the potential for data from imaging spectrometers such as HyspIRI to comprehensively characterize the diversity of ecosystems in heterogeneous landscapes. Moderate resolution satellite imagery may not facilitate detection of individual species, but imaging spectroscopy provides a basis to estimate the potential distribution of particular taxa based on assemblages associated with foliar traits that can be derived from imaging spectroscopy. Comprehensive satellite-based mapping will provide basic understanding and spatially explicit information on forest functioning suitable for monitoring and management of urban ecosystems.

1. Introduction

Forests play an important role in urban environments by providing a range of ecosystem services, including sequestering carbon through photosynthesis (Nowak & Crane, 2002), mitigating stormwater runoff (Bolund & Hunhammar, 1999), reducing nutrient export (Day, Wiseman, Dickinson, & Harris, 2010) and providing habitat for wildlife (Savard, Clergeau, & Mennechez, 2000). Vegetation species composition is one of the most complex ecological properties controlling ecosystem services and functions in urban settings (Alberti et al., 2003). Species composition in urban settings varies considerably more than adjacent natural areas (Alvey, 2006), and differs among cities due to geographical location, climate, urban history, urban population, forest areas, and history of development and associated management practices (Jim & Liu, 2001). There is a considerable need to understand urban forest species composition and function, especially in light of management needs due to pests and disease (Poland & McCullough, 2006). While cities often rely on tree inventories, these are rarely comprehensive (Nowak, Greenfield, Hoehn, & Lapoint, 2013), and therefore the ability to use remote sensing to characterize the urban forests is of considerable management interest (Myeong, Nowak, & Duggin, 2006).

Remote sensing data have been widely used in mapping species composition in natural forests at a variety of scales by classifying pixels into discrete species or physiognomic types (Cho et al., 2012; Ke, Quackenbush, & Im, 2010; Martin, Newman, Aber, & Congalton, 1998; Ohmann & Gregory, 2002; Plourde, Ollinger, Smith, & Martin, 2007; Wolter & Townsend, 2011). However, the diversity of species in urban forests makes species-level image classification particularly challenging. This is because urban forests may have many times the diversity of canopy species compared to natural forests (Alvey, 2006, notable

* Corresponding author at: Graduate School of Geography, Clark University, 950 Main Street, Worcester, MA 01610, USA.
E-mail addresses: hgu6@wisc.edu, guhuan114031@gmail.com (H. Gu).

http://dx.doi.org/10.1016/j.rse.2015.06.010

exceptions being tropical rainforests), and many of those species may be exotics or hybrids (Jim & Liu, 2001). While recent advances in airborne hyperspectral sensors, e.g., NASA AVIRIS (Airborne Visible/Infrared Imaging Spectrometer, Green et al., 1998), have improved the ability to measure and map spatial variations in vegetation canopy chemistry, they require methods appropriate to the physical context. For example, very high spatial resolution (<0.5–4 m) hyperspectral data are able to identify individual canopies to the species level based on spectral signatures alone since the spatial resolution is sufficient to identify multiple pixels per tree canopy (Alonzo, Bookhagen, & Roberts, 2014; Franke, Roberts, Halligan, & Menz, 2009; Xiao, Ustin, & McPherson, 2004). However, species with similar structure and/or foliar traits are often misclassified (Walker, Kinzig, & Langridge, 1999). In addition, classification accuracy may be affected by insufficient sample sizes for rare and exotic species. As well, very high spatial resolution imagery loses the comprehensive mapping ability (coverage area may be limited), or adds cost and complexity to the mapping process because of the need for multiple overlapping flight lines. Data from proposed imaging spectrometers such as HyspIRI offer great potential to map patterns of vegetation composition across broad regions due to the increased spectral resolution relative to multi-spectral instruments. However, with large pixel sizes (e.g., 30 or 60 m), comprehensive mapping of individual species or assemblages in heterogeneous urban areas requires mapping approaches that incorporate the possibility of pixel-level mixing of multiple species with different functional traits.

An alternative approach to mapping species composition is the identification of gradients of vegetation composition using ordination techniques (Feilhauer, Faude, & Schmidtlein, 2011; Feilhauer & Schmidtlein, 2009; Schmidtlein & Sassin, 2004; Schmidtlein, Zimmermann, Schuepferling, & Weiss, 2007). When only coarser spatial resolution data (e.g., >20 m) are available, ordination techniques may facilitate comprehensive mapping by focusing on assemblages of taxa (species or genera) exhibiting identifiable profiles of ecological traits that can be estimated from imaging spectroscopy. In brief, ordination approaches reduce original vegetation composition in n-dimensional space (where n refers to the number of taxa, i.e., species or genera), to a greatly reduced space in which a smaller number of dimensions describe the overall patterns of distribution and co-occurrence of those taxa (Schmidtlein et al., 2007). Ordination scores obtained in this manner can then be used to represent field-measured gradients of compositional assemblages that portray the multivariate dimensions of "niches" of relative dominance by different co-occurring groups of taxa. Ordination methods are advantageous because they preserve the general patterns in original composition dataset, and avoid problems related to large number of zero observations of individual taxa that are often encountered in plot-level species composition data. Metrics obtained from ordination techniques also allow intuitive visualization of results, which may help elucidate mechanistic basis for interpretation that are not readily apparent from high-dimensional species composition data (Giraudel & Lek, 2001).

The idea of mapping composition gradients using remote sensing is based on the assumption that gradients of vegetation are related to variations in canopy traits such as reflectance spectra, foliar chemical or morphological traits, canopy form and structure or growth environment and substrate (Feilhauer et al., 2011). While classic multispectral imagery (e.g., Landsat) lacks the spectral resolution to effectively resolve these traits, imaging spectroscopy data provide the potential to characterize the variations in compositional assemblages (Asner & Martin, 2009). For example, imaging spectroscopy has recently been utilized to characterize vegetation gradients in continuous grasslands (Oldeland, Dorigo, Lieckfeld, Lucieer, & Juergens, 2010; Schmidtlein & Sassin, 2004) and mixed composition landscapes (Feilhauer et al., 2011), using either raw spectra (Feilhauer et al., 2011; Schmidtlein & Sassin, 2004; Schmidtlein et al., 2007) or spectral indices (Oldeland et al., 2010). At present, however, such techniques have not been utilized to disentangle the compositional complexity of vegetation in urban systems.

As an alternative to directly using vegetation spectra or spectral indices only to map composition gradients, we utilize canopy foliar chemical and morphological traits obtained from imaging spectroscopy data and metrics of canopy structure derived from lidar. We propose that canopy foliar traits, e.g., foliar nitrogen (%N), leaf morphology (LMA), leaf habit (broadleaf deciduous/coniferous evergreen), canopy structure (height, crown dimensions, biomass), in combination with spectral indices, e.g., photochemical reflectance index (PRI, Gamon, Serrano, & Surfus, 1997), provide essential information on the function and status of forests related to forest composition. We posit that these "trait profiles" are functional analogues of taxonomic assemblages, and provide a much more useful and function-based alternative to discrete species-level maps in situations where either 1) the number of species is high (Asner & Martin, 2009), 2) the overlap in trait profiles among taxa is high, and, in particular, 3) when the spatial resolution is not sufficient to identify individual trees.

Imaging spectroscopy data have become increasingly available to quantify vegetation biochemical properties related to photosynthesis and vegetation productivity (Ustin, Roberts, Gamon, Asner, & Green, 2004). Key canopy foliar attributes include nitrogen concentration, lignin, cellulose, fiber, carbon, leaf mass per area and pigments such as chlorophyll and carotenoids (Asner & Martin, 2008; Asner et al., 2011; Kokaly, Asner, Ollinger, Martin, & Wessman, 2009; Le Maire et al., 2008; Martin, Plourde, Ollinger, Smith, & McNeil, 2008; Ollinger, 2011; Singh, Serbin, McNeil, Kingdon, & Townsend, in press; Townsend, Foster, Chastain, & Currie, 2003; Treitz & Howarth, 1999). Relationships between these foliar attributes have been intensively studied among and within species and across a range of natural forests. For example, Martin et al. (1998) identified species based on the combination of foliar nitrogen and lignin from AVIRIS imagery in Harvard Forest, USA. Fuentes, Gamon, Qiu, Sims, and Roberts (2001) used AVIRIS-derived pigment and water absorption to map vegetation types in Canadian boreal forests and Kokaly, Despain, Clark, and Livo (2003) mapped forest cover types from the analysis of chlorophyll and leaf water absorption derived from AVIRIS imagery in Yellowstone National Park. In addition, forest structure variables estimated from lidar data such as aboveground/foliar biomass, stand basal area, diameter, height, crown length and crown width (Hawbaker et al., 2010; Lefsky, Cohen, Parker, & Harding, 2002; Lim, Treitz, Baldwin, Morrison, & Green, 2003; Muss, Mladenoff, & Townsend, 2011; Næsset, 2004) have been related to canopy species (Korpela, Orka, Maltamo, Tokola, & Hyyppä, 2010) and understory plant abundance (Singh, Davis, & Meentemeyer, 2015). In this study, we present an approach to map gradients of composition in lieu of composition or specific assemblages as a basis for understanding the functional composition of forests in urban ecosystems. Forest functional traits (Singh et al., in press) and spectral indices derived from imaging spectroscopy, and structural variables estimated from lidar (Gu, 2015) were employed to relate to composition gradients by NMDS ordination of field-measured species composition data. Our specific objectives in this study are to: (1) derive ordination scores from multi-dimensional urban forest composition data to depict compositional gradients; (2) predict ordination scores as a function of traits and structure data derived from imaging spectroscopy and lidar; and (3) create genus-specific gradient maps and pixel-wise ranges of these estimates. The resulting gradient maps likely provide a better understanding of ecosystem function and the ability of urban ecosystems to respond to environmental perturbations. As well, the mapped uncertainties convey limitations of the mapped estimates for urban forest management and planning. Our research represents an approach to leverage data from moderate-to-high spatial and high spectral resolution imaging spectrometer data for detecting ecosystem function as a basis for using data from the proposed HyspIRI mission to map important ecological gradients in heterogeneous landscapes.