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Linking seasonal foliar traits to VSWIR-TIR spectroscopy across California ecosystems

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ABSTRACT

Vegetation traits provide critical information on ecosystem function that can be used to assess the effects of disturbance, land use, and climate change. Recent studies have demonstrated the use of spectroscopy to predict vegetation traits accurately and efficiently. To date, most spectroscopic studies have utilized data from the Visible Short Wave Infrared spectrum (VSWIR) or, occasionally, the Thermal Infrared spectrum (TIR), but not in combination. This study focuses on VSWIR and TIR synergy to evaluate the ability to predict leaf level cellulose, lignin, leaf mass per area (LMA), nitrogen, and water content across seasons. We used fresh leaves from sixteen common California shrub and tree species collected in the 2013 spring, summer, and fall seasons. The 284 samples exhibited a wide range of leaf traits as determined by standard analytical procedures: 4.2–27.3% for cellulose, 2.6–22.5% for lignin, 34.7–388.9 g/m^2 for LMA, 0.45–3.81% for nitrogen, and 20.2–76.9% for water content. For each leaf trait, partial least squares regression (PLSR) models were fit using different portions of the spectrum: VSWIR (0.35–2.5 μm), TIR (2.5–15.4 μm), and Full spectrum (0.35–15.4 μm). We also fit PLSR models using spectra resampled to simulate three airborne sensors: the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS; 0.4–2.5 μm), the Hyperspectral Thermal Emission Spectrometer (HyTES; 7.5–12 μm), and the Hyperspectral InfraRed Imager (HyspIRI; 0.4–12 μm). The majority of best performing models used the Full spectrum, demonstrating the value of combining TIR and VSWIR spectra for leaf trait prediction. Sensor-simulated PLSR models created with the entire data set yielded validation R^2 and root mean square error of prediction (RMSEP) values as follows: $R^2 = 0.70$ and RMSEP = 13.1% for cellulose, $R^2 = 0.50$ and RMSEP = 17.7% for lignin, $R^2 = 0.56$ and RMSEP = 18.3% for LMA, $R^2 = 0.56$ and RMSEP = 18.1% for nitrogen, and $R^2 = 0.89$ and RMSEP = 5.7% for water content. General models successfully captured the variability among all seasons and leaf forms for cellulose and water content, while the other leaf traits were better modeled with season or leaf form-specific models. This study successfully captured the large seasonal and geographical variation in leaf traits across California's diverse ecosystems, supporting the possibility of using HyspIRI's imagery for global mapping efforts of these traits.

1. Introduction

Concerns over climate change, human-caused disturbances, and land-use effects on ecosystems have made it critical to quantify and characterize ecosystem functions, such as nutrient cycling, litter decomposition, and plant productivity (Ustin, 2013). Knowledge and understanding of these functions allow us to assess the health of an ecosystem. Plant traits play an important role in controlling these functions, which makes measurements of plant traits highly valuable (Ollinger et al., 2002; Smith et al., 2003; Atkin et al., 2015). However, traditional methods of collecting and processing extensive measurements of plant traits through time are expensive and time consuming. Using relationships derived between spectra (i.e., spectroscopy) and laboratory measured leaf traits can decrease processing time through faster analytical speed and minimal sample preparation (Lawler et al., 2006; Serbin et al., 2014). These relationships once derived using field plots or ground-based measurements can be used in conjunction with imaging spectroscopy to further increase spatial and temporal sampling (Asner et al., 2015).

To date, most spectroscopic studies have utilized the Visible Shortwave Infrared spectrum (VSWIR) to measure plant chemistry

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and biophysical properties. Laboratory VSWIR spectroscopy began in the field of agriculture to measure forage quality (Shenk et al., 1979), but has since been extended to other vegetation traits from the leaf to canopy scale. At the leaf level, Serbin et al. (2014) determined seven spectroscopic models to predict leaf chemistry, morphology, and isotopic composition of temperate and boreal tree species with validation results ranging from R^2 of 0.60–0.97 and RMSEP of 4–16.2%. At the canopy level, Asner et al. (2011) used imaging spectroscopy at 61 sites located in humid tropical forests to predict 21 leaf trait properties with correlations ranging between an R^2 of 0.24–0.88 and RMSEP of 5.2–21.2%. More recently, Singh et al. (2015) developed seven canopy chemical and morphological prediction models across 51 images using Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) with site-level $R^2 > 0.48$ and RMSEP < 15%. However, complications arise and model accuracy can decrease due to large portions of the VSWIR spectrum being obscured by water and pigment absorption features in fresh leaves, which hinder prediction capabilities for other leaf traits (Ribeiro da Luz and Crowley, 2010).

A smaller number of studies have used the Thermal Infrared (TIR) spectral measurements to describe plant characteristics. In general, the TIR wavelength region has not been widely adopted for vegetation studies due to the limited availability of TIR sensors and subtle features of plant spectra (Ribeiro da Luz and Crowley, 2007). However, there are exceptions, including Salisbury (1986) who was the first to show that spectral signatures varied among plant species in the 8–14 μm range. Elvidge (1988) followed by quantifying TIR reflectance features resulting from biochemical and biophysical traits of dry plant materials. More recently, Ullah et al. (2012) showed that plant species from the Netherlands have enough spectral diversity in the mid-infrared (MIR) from 2.5–6 μm and the TIR from 8 to 14 μm to support species discrimination. Another study, conducted by Fabre et al. (2011), found that leaf spectra in the 3–15 μm region were sensitive to variations in leaf water content. Research conducted by Ribeiro da Luz and Crowley (2007) identified spectral features in the TIR (8–14 μm) associated with cellulose, cutin, xylan, silica, and oleanolic acid. These studies support the use of information in the TIR region for quantifying leaf biochemical properties and improving species discrimination.

Integration of the VSWIR and TIR to cover a much larger range of wavelengths would enable researchers to utilize the strengths of each spectral region while minimizing limiting factors (Ribeiro da Luz and Crowley, 2007). However, little is known about the potential of combined VSWIR and TIR for ecological research due to a lack of studies in which both data types have been evaluated simultaneously. One of the few studies is by Ullah et al. (2014) who used the Full spectrum (0.39–14 μm) to successfully retrieve leaf water content from eleven different plant species. The main limiting factor for vegetation research using combined VSWIR and TIR data is the lack of sensors covering the full range of wavelengths. The proposed National Aeronautics and Space Administration (NASA) space-borne Hyperspectral InfraRed Imager (HyspIRI) mission would measure solar reflected and emitted radiance (Abrams and Hook, 2013; Green et al., 2013; Lee et al., 2015). The unique feature of HyspIRI is the inclusion of two instruments that measure wavelengths in the 0.38–12 μm range: an imaging spectrometer measuring the VSWIR wavelengths and a multi-spectral imager measuring several bands in the TIR (Lee et al., 2015). With these combined sensors, HyspIRI would provide combined VSWIR spectroscopy and broad band TIR data, enabling scientists to expand the wavelengths that can be used to estimate leaf traits and their relationships to ecosystem function. Still, the value of combined VSWIR-TIR data for estimating leaf traits is not fully understood, even at the leaf level.

The focus of this paper is to analyze synergies between the VSWIR and TIR prediction of leaf levels of cellulose, lignin, leaf mass per area (LMA), nitrogen, and water content across seasons. First we evaluate the capability of VSWIR and TIR spectra, individually and together, to predict lignin, cellulose, nitrogen, LMA, and water content. Secondly, we determine if these relationships can be extended to the reduced spectral resolution available in airborne and proposed spaceborne sensors, including the AVIRIS, the Hyperspectral Thermal Emission Spectrometer (HyTES), and the HyspIRI. Lastly, we test the development of a generalized and transportable model which captures the variability among seasons and leaf forms.

2. Methods

2.1. Study sites

We collected and analyzed plant samples from three different sites within California, United States: coastal Santa Barbara County, Sedgwick Reserve, and Sierra Nevada Mountains (Fig. 1). These study sites cover a large range in elevation (0–1400 m) with contrasting ecosystem characteristics (chaparral versus conifer forest) leading to a wide range of leaf traits and spectral values for analyses. The coastal Santa Barbara site is comprised of three sub-sites near the city of Santa Barbara, California and was designed to capture a cross section of the ecosystems present in coastal California (Fig. 1). These sub-sites were located at three elevations: 5 m, 515 m, and 1080 m. All three sub-sites are dominated by chaparral vegetation, a product of the region's Mediterranean climate which averages 38 cm of rain annually (Quinn and Keeley, 2006). Chaparral species form a nearly impenetrable thicket of shrubs with hard leaves and stiff twigs, which makes them well adapted for the hot, dry summers and unpredictable precipitation during the winter (Quinn and Keeley, 2006).

The Sedgwick Reserve site is located in the Santa Ynez Valley in Santa Barbara County, California (Fig. 1) and is the largest reserve within the University of California Natural Reserve System. With an annual precipitation of 38 cm, the three main vegetation communities are coastal sage scrub, oak woodland, and non-native grasses (Mahall et al., 2005). Our sampling locations within Sedgwick Reserve were located at elevations of 382 m and 400 m. The Sierra Nevada Mountains

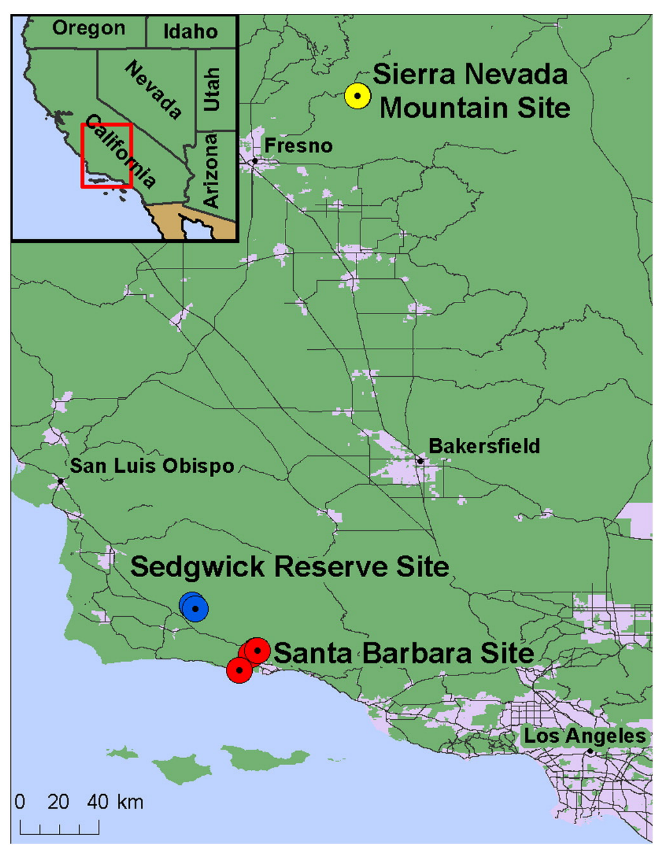

Fig. 1. Map showing locations of study sites.