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Remote sensing models of structure-related biochemicals and pigments for classification of trees

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ABSTRACT

Global vegetation distribution is the result of environmental conditions and the genetic make-up of plants. In view of the intensive discussions on climate change and its effect on living organisms on earth, it has become necessary to develop new methods and strategies to monitor and follow the changes in global plant distribution.

In this research, we focused on a vegetation analysis using spectral reflectance profiles linked to biochemical concentrations. We performed the spectroscopic measurements of *Pistacia* species at canopy and leaf levels. Concomitant chemical analyses of leaf and bark materials enabled the development of remote sensing (RS) indices of structure-related biochemicals and pigments. We developed RS indices for cellulose, lignin, chlorophyll, carotenoid, anthocyanin and wax. Since the wax was the least studied in this context and due to the fact that it is the first layer of the plant surface that interacts with the incident light, it deserved special attention and was assumed to affect the spectral reflectance and, in combination with the other biochemicals, to contribute to better species identification.

In the modeling process, we showed that apart from the major energy absorption spectral bands related to a given biochemical, there were supplementary bands that had a significant effect on the accuracy of the biochemical content estimation. Another factor affecting the accuracy of the biochemical estimation was the season. Thus, we divided the biochemical content estimation models into seasonal groups of spring, summer and fall. The RS indices developed in this work, together with literature-reported RS indices, were used for *Pistacia* classification. The accuracy (69%) of species classification was significantly higher in spring at an early vegetation stage than in summer (50%), and fall (37%). As a proof of concept, the same sets of RS indices were also used for classifying the genera and families of various plants in the Mediterranean forest using EO1 Hyperion images. The accuracy of the classification maps was 79%, when the full set of RS indices developed in this work was used.

1. Introduction

The global distribution of plants is a function of their genetic make-up and adaptation to environmental conditions. In view of rapid climate change driven by anthropogenic processes, it has become necessary to monitor plant species distribution pattern changes in order to improve conservation and forestation/reforestation management practices. Remote sensing is the only non-destructive large-scale monitoring strategy that enables recurrent local and global measurements of plant distribution. The challenge still remains to develop models of high enough resolution and accuracy to distinguish families, genera and species by remote sensing. There have been reports on tree species composition deduced from canopy reflectance (Carlson et al., 2007; Castro-Esau et al., 2006; Clark et al., 2005).

We have hypothesized that linking the reflectance spectra in the range between 400 nm and 2400 nm with tree biochemical constituents that change seasonally, i.e., pigments (chlorophyll, carotenoid and anthocyanin) and surface structure-related cellulose, lignin and wax, would enable the remote sensing classification of trees. For this purpose, *Pistacia* has been selected as the tree model genus. It is globally distributed in various environmental conditions, between latitudes 10° and 45° north. The *Pistacia* genus contains 11 species, *P. vera*, *P. khinjuk*, *P. atlantica*, *P. lentiscus*, *P. terebinthus*, *P. palaestina*, *P. chinensis*, *P. weinmannifolia*, *P. mexicana*, *P. texana* and *P. aethiopica*, of trees or shrubs. It is xerophytic and dioecious, and most species are deciduous (Zohary, 1952). The genetic phylogeny of the genus has been well studied by molecular techniques (RAPD, AFLP, RFLP and others) (Golan-Goldhirsh et al., 2004; Parfitt and Badenes, 1997; Yi et al., 2008). It was shown that the molecular-based taxonomy is closely related to the morphological traits and to the geographical distribution of the genus (Browicz, 1997; Kozhoridze et al., 2015; Sheibani, 1995; Zohary, 1952). Genetic and biogeographic phylogenetic analyses have revealed

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that the genus can be reclassified into two sections, evergreen and deciduous.

The distribution of flora is an outcome of interactions between genetics, environmental conditions and the biochemical compositions of plants with diverse phenologies (Asner and Martin, 2011; Prinzing et al., 2001). On one hand, studies have shown strong phylogenetic links between seasonal developmental cycles and diversity in biochemical composition (CaraDonna and Inouye, 2015; Menzel and Dose, 2005; Parmesan and Yohe, 2003). On the other hand, distribution patterns of flora sometimes represent environmental niche adaptation more strongly than genetic links (Adler et al., 2007; Gravel et al., 2006). Thus, phenological plasticity represents genetic and environmental effects, expressed by differences in plant color, structure and niche selection that are potentially detectable by remote sensing (Madritch et al., 2014). This would require multiple seasonal analyses of spectra concomitant with biochemical analyses, overlaid on a genetic basis, which may lead to higher accuracy of classification and distribution and to better phylogenetic predictions. Here we propose a more involved strategy of multiple seasonal analyses of both spectra and biochemicals that innately affect the reflected spectrum.

Pigments absorb energy in the visible region of the electromagnetic spectrum (400–700 nm). Spectral bands in the regions of 540 nm–560 nm, 630 nm–690 nm and 700 nm–730 nm are closely related to chlorophyll concentration. Carotenoid and anthocyanin absorb energy at 510 nm–520 nm and 540 nm–560 nm, respectively (Feret et al., 2008; Gitelson et al., 2006; Lichtenthaler, 1996; Ustin et al., 2009). Significant energy absorption by the structure-related biochemicals, cellulose and lignin, is found in the shortwave infra-red bands (SWIR), at 1680 nm and 1750 nm and from 2100 nm to 2300 nm (Curran et al., 1997; Kokaly et al., 2009; Serrano et al., 2002). These metabolites are the main elements of the plant cell wall (Sjostrom, 1993). Cellulose is the major structural macromolecule of the primary cell wall, and lignin is synthesized in the secondary wall, imparting structural strength to plants. Variations in the proportion of these biochemicals could be affected by environmental conditions, season, nutrition and exposure to light (Novaes et al., 2010); such changes would be expected to appear in the reflectance spectrum (Daughtry et al., 2004; Serrano et al., 2002). Pigments such as chlorophyll, carotenoid, anthocyanin have been intensively studied and used for modeling remote sensing indices for their quantification (Feret et al., 2008; Gitelson et al., 2006; Sims and Gamon, 2002; Ustin et al., 2009). Cellulose and lignin indices, such as the Cellulose Absorption Index (CAI) and the Normalized Difference Lignin Index (NDLI), respectively, were modeled for content estimation by reflectance (Daughtry et al., 2004; Serrano et al., 2002). However, only a few reports are available on the relationship between leaf wax, surface and spectral reflectance (Grant, 1987; Lu, 2013; Slaton et al., 2001; Heim et al., 2015). The wax plays as a protective role by increasing the reflectance in the range of 400 nm and 750 nm (Eller and Willi, 1977; Heim et al., 2015). In this work, a special focus was put on modeling the remote sensing estimation of wax content in plants. Obviously, it is the outermost surface layer of leaves that first encounters incident light and that may significantly affect the reflected energy. It plays an important role in the physical and structural protection of leaves and in the water relations of plants (Schönherr, 1976).

Attempts to distinguish between populations and species of trees based on spectroscopic techniques have increased because of their potential for offering global views of plant distribution, mapping, conservation and management (Carlson et al., 2007; Clark et al., 2005; Sánchez-Azofeifa et al., 2009; Zhang et al., 2006). Relating hyperspectral resolution bands in field measurements with plant biochemical constituents may offer additional means for vegetation analyses, classification and monitoring seasonal changes in plants (Ustin et al., 2009; Ustin & Gamon, 2010). Studies of tropical forest vegetation by Asner and Martin (2008) and Sánchez-Azofeifa et al. (2009) showed that there were spectral differences between various plants based on their leaf biomass. Asner's group has shown that variation in foliar chemical composition can be related to the phylogenetic division of plants in the lowland Amazonian forest (Asner and Martin, 2011). Approximately 97% of the investigated species were classified correctly using the full chemical signatures of 21 chemicals, and 65.6% accuracy was obtained by using only lignin, carbon, nitrogen and phenols.

The potential for elaborating plant species classification and vegetation mapping has become a viable proposition since the development of airborne and spaceborne hyperspectral sensors (Dalponte et al., 2013; Goodenough et al., 2012; Koedsin and Vaiphasa, 2013). The spectral properties of vegetation allow users to obtain detailed information on biochemical content and the biophysical features of plants (Clark et al., 2005; Curran, 1989; Feret et al., 2008; Martin and Aber, 1997; Ustin et al., 2009). Furthermore, recent improvements in the spatial resolution of the images have significantly impacted the quality of object identification, leading to more accurate species classifications (Treitz, 2000; Underwood et al., 2006). Nowadays, various airborne systems have reached a spatial resolution of 0.3 m to 5 m (AVIRIS, HyMap, AisaSpecim, CASI and others); spaceborne sensors, such as EO1 Hyperion, HyspIRI, and EnMAP, indeed have a lower resolution range of 30 m to 60 m, but may still be useful under certain conditions, such as in research areas with fairly simple flora compositions, as well as with relevant data collection on ground truth points and reference spectra collections. Recent papers reported classification and mapping of different plant species using EO1 Hyperion images with a higher than 75% accuracy (Galidaki and Gitas, 2015; Huang and Asner, 2009; Somers et al., 2013; Wong and Fung, 2014), despite a relatively low spatial resolution.

There are several approaches to analyzing spectral data for classification and mapping (Lu and Weng, 2007). The commonly used classifiers for hyperspectral data are the Spectral Angle Mapper (SAM) and the Support Vector Machine (SVM) (Clark et al., 2005; Dalponte et al., 2009). The SAM is based on determining the spectral similarities between end-member (known) and unknown spectra via a comparison of an angle between the corresponding vectors in the featured space (Kruse et al., 1993) and SVM is a machine learning algorithm used in classification and/or regression analyses based on defining an appropriate hyper-plane in order to differentiate classes accurately. These classifiers take into account the shape of the spectral signature not considering the absolute reflectance. Therefore, SAM and SVM are effective for target discrimination, avoiding the misclassification due to the differences in solar illumination and topography (Waske et al., 2014).

The objective of this work was to develop new remote sensing indices for classifying tree species based on the biochemicals in plants that most directly interact with the incident light, chlorophyll, carotenoid, anthocyanin, cellulose, lignin and wax. It was hypothesized that seasonal variations contribute significantly to the spectral properties, and thus to the accuracy properties, of the models.

2. Materials and methods

The live germplasm collection of *Pistacia* at The Jacob Blaustein Institutes for Desert Research, Israel (BIDR) (30° 51′25.77″ N 34°46′57.55″ E) (http://in.bgu.ac.il/en/bidr/FAAB/Pages/ pistacia.aspx) was the major study site for the spectral field measurements, and leaf and bark samples were used for the laboratory measurements. In addition, old *P. atlantica* trees, growing naturally in the Negev Highlands at Nahal Nitzana, Israel, (30°34′53.92″N–30°35′42.69″N, 34°41′04.52″E–34°42′54.46″E), were analyzed by spectral field and laboratory measurements. The *Pistacia* tree collection includes seven species (*P.atlantica*, *P.chinensis*, *P.khinjuk*, *P.lentiscus*, *P.palaestina*, *P.terebinthus*, and *P.vera*) of 18-year-old trees developed from seeds obtained from diverse natural populations.

2.1. Chemical determination of structure-related biochemicals and pigments

Leaf material was used for the chemical determination of chlorophyll, carotenoid, anthocyanin, cellulose and wax concentrations, and