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Canopy spectral invariants, Part 2: Application to classification of forest types from hyperspectral data

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ABSTRACT

Many studies have been conducted to demonstrate the ability of hyperspectral data to discriminate plant dominant species. Most of them have employed the use of empirically based techniques, which are site specific, requires some initial training based on characteristics of known leaf and/or canopy spectra and therefore may not be extendable to operational use or adapted to changing or unknown land cover. In this paper we propose a physically based approach for separation of dominant forest type using hyperspectral data. The radiative transfer theory of canopy spectral invariants underlies the approach, which facilitates parameterization of the canopy reflectance in terms of the leaf spectral scattering and two spectrally invariant and structurally varying variables—recollision and directional escape probabilities. The methodology is based on the idea of retrieving spectrally invariant parameters from hyperspectral data first, and then relating their values to structural characteristics of three-dimensional canopy structure. Theoretical and empirical analyses of ground and airborne data acquired by Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) over two sites in New England, USA, suggest that the canopy spectral invariants convey information about canopy structure at both the macro- and micro-scales. The total escape probability (one minus recollision probability) varies as a power function with the exponent related to the number of nested hierarchical levels present in the pixel. Its base is a geometrical mean of the local total escape probabilities and accounts for the cumulative effect of canopy structure over a wide range of scales. The ratio of the directional to the total escape probability becomes independent of the number of hierarchical levels and is a function of the canopy structure at the macro-scale such as tree spatial distribution, crown shape and size, within-crown foliage density and ground cover. These properties allow for the natural separation of dominant forest classes based on the location of points on the total escape probability vs the ratio log–log plane.

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1. Introduction

Vegetated land is a special type of surface where various physical, biogeochemical, physiological and meteorological processes and interactions between them

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determine the functioning of terrestrial ecosystems. Their distribution is largely controlled by climate and alternations of the ecosystem composition at local and landscape scales are ecological variables indicative of climate change [1,2]. Ecosystem changes in turn have the potential to influence regional climate via biophysical mechanisms [3,4]. Satellite remote sensing serves as the most effective means for mapping the current distribution of ecosystems globally, monitoring their status and improving our understanding of feedbacks among ecosystems, climate and disturbance. The scope of these activities is among the primary objectives of the Hyperspectral Infrared Imager (HyspIRI) mission [5] recommended for implementation by the US National Research Council [6].

Capabilities of hyperspectral data to detect ecosystem changes over a wide range of scales have been demonstrated in space- and airborne imaging spectrometer observations. The unique spectral signatures of plants have been used to discriminate and map dominant plant species and plant functional types [7–11]. It has been shown that hyperspectral data convey information about leaf physiological state [12], water content and evapotranspiration [13–15], vegetation chemical constituents such as nitrogen, lignin, and cellulose [13,16–19]. These results have employed the use of empirically based techniques, which are site specific, requires some initial training based on characteristics of known leaf and/or canopy spectra and therefore may not be extendable to operational use or adapted to changing or unknown land cover. Development of physically based approaches to interpret hyperspectral data is therefore required not only to take full advantage of the existing and proposed missions but also to advance our understanding of requirements for measurements of terrestrial ecosystem processes.

Spectral response of the vegetated surface to incident solar radiation results from interaction of photons with vegetation over wide range of scales. Challenges in developing physically based approaches to operationally interpret satellite data include an accurate quantification of the notion of scale and understanding of how variation in radiometric and structural properties of the vegetation at different scales impact the spectrum of radiation reflected by the vegetated surface [20–22]. The concept of canopy spectral invariants provides the required framework [26]. The approach expresses the observation that simple algebraic combinations of leaf and canopy spectra become wavelength independent and determine two spectrally invariant and structurally variant variables—the recollision and escape probabilities [21,23–26]. These variables specify an accurate relationship between the spectral response of a vegetation canopy to incident solar radiation at the leaf and the canopy scale [27]. They are sensitive to important structural features of the canopy such as tree geometry [28–30], stand age [31] and small-scale canopy structure [32–35]. The escape and recollision probabilities have the potential to separate forest types based on variability of canopy structure across multiple scales from leaves to canopies and stands. The objective of this paper is to demonstrate the feasibility of deriving distribution of dominant species from hyperspectral data using the concept of spectral invariants [26].

The paper is organized as follows. The concept of canopy spectral invariants and canopy spectral behavior at different scales are described in Sections 2, 3 and Appendix A. Method and data used to derive the spectral invariants and limitations of the proposed approach are discussed in Sections 4 and 5. The ability of the spectral invariants to discriminate dominant plant species is demonstrated in Section 6 and Appendix B. Finally, concluding remarks are given in Section 7.

2. Theory

The bidirectional reflectance factor (BRF) of a vegetated canopy bounded from below by a non-reflecting surface can be approximated as [22,25,26,30]

$$BRF_{\lambda} = \frac{\omega_{\lambda}}{1-p\omega_{\lambda}} R(\Omega,\Omega_0). \tag{1}$$

Here $R(\Omega,\ \Omega_0)=\rho(\Omega)i_0(\Omega_0)$ is an escape factor, p and ρ are the probabilities that a photon scattered from a phytoelement will interact within the canopy again (recollision probability, p), and escape the vegetation in a given direction Ω (escape probability, $\rho(\Omega)$) [25,26,32]. The integration of $\rho(\Omega)$ over all directions gives the portion, $1-p$, of canopy leaving photons, or the total escape probability. Further, $i_0(\Omega_0)$ is the probability of initial collisions, or canopy interceptance defined as the portion of incoming photons that collide with phytoelements for the first time. It does not depend on the wavelength and varies with the direction, Ω_0, of the incident beam. The recollision and escape probabilities do not depend on the wavelength under certain conditions on leaf spectral transmittance and reflectance [24,26]. Finally, the probability of a scattering event is quantified by the wavelength-dependent scattering albedo ω_{λ}.

Eq. (1) can be rearranged to a form, which we will use to retrieve the canopy spectral invariants $R(\Omega,\ \Omega_0)=\rho(\Omega)i_0(\Omega_0)$ and p using hyperspectral reflectance data, namely

$$\frac{BRF_{\lambda}}{\omega_{\lambda}} = pBRF_{\lambda} + R(\Omega,\Omega_0). \tag{2}$$

By plotting $BRF_{\lambda}/\omega_{\lambda}$, versus BRF_{λ}, a linear relationship is obtained, where the slope and intercept give the recollision probability, p, and the escape factor, R [26,30]. We will suppress the directional dependence in further notations.

Eq. (1) requires the use of a scattering albedo, ω_{λ}, which depends on the *scale,* at which the quantity is defined. This is illustrated in Fig. 1. The vegetation canopy is idealized as a medium consisting of several hierarchical levels of structural organization. Each level is represented by objects distributed within a higher level. The object represents a clump of phytoelements (e.g., tree crown, shoot) or an individual element (e.g., leaf, needle). The scale is associated with the object size (e.g., crown scale, shoot scale, leaf or needle scale, etc.). The scattering albedo is the probability that a photon intercepted by an object will escape the object and therefore is a function of the object size, or scale. In Fig. 1 tree crowns distributed within a pixel (“level 0”) constitute “level 1” of canopy

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