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Monitoring the broadleaf fraction and canopy cover of boreal forests using spectral invariants

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ABSTRACT

A recent method based on the spectral invariants theory to retrieve physically-based information on forest properties from remotely sensed hyperspectral imagery was tested in a southern boreal setting in central Finland. An atmospherically corrected Hyperion image and ground measurements from 66 forest stands were used. First, the novel concept of transformed green leaf single scattering spectral albedos was tested against leaf (needle) albedo measurements on Scots pine, Norway spruce and Silver birch from the study area. We found the transformed Beaked hazel albedo applied in previous studies could be used as reference also for the boreal tree species. Second, we derived a newly suggested spectrally invariant variable, the directional area scattering factor (*DASF*), to estimate the broadleaf fraction of forest stands. Based on our results, *DASF* seems highly promising as a potential new hyperspectral satellite product for change monitoring of broadleaf fraction over different vegetation zones. Finally, we plotted our results in the spectral invariants space, and suggest a new interpretation for the reference-dependent structural parameter p_R. We propose this parameter is an indicator of canopy cover and suffers less from saturation problems than vegetation indices.

1. Introduction

Schull et al. [1] set forth a hypothesis for a novel method based on the spectral invariants theory to retrieve physically-based estimates of forest properties from remotely sensed hyperspectral imagery. In a later study, they demonstrated the feasibility of the method in mapping the distributions of dominant species in the spectral invariants space [2]. Recently, Knyazikhin et al. [3] extended the analysis and showed that the broadleaf fraction of a forest can be estimated by a new spectrally invariant variable, the directional area scattering factor (*DASF*). *DASF* describes the proportion of photons scattered from a canopy in a particular direction, typically near nadir. The data in Schull et al. [2] and Knyazikhin et al. [3] comprised species-rich forests from the temperate zone and only dense forest canopies where the influence of the forest floor on stand reflectance was assumed negligible. The forests fulfilled the black soil assumption, which is a condition in Schull et al.'s method [1], but as a consequence did not realistically represent the natural variation in forest structures.

The spectral invariants theory, in short, predicts that the amount of radiation scattered by a canopy in a given wavelength is a simple function of the green leaf single scattering spectral albedo (leaf albedo, ω_L) and a spectrally invariant parameter (p), which can be interpreted as the probability that a photon scattered from a leaf (needle) in the canopy will interact within the canopy again – the "recollision probability" [4]. Knowing the leaf albedo, the value of p and thus information on canopy structure can be retrieved from remote sensing data using the method by Schull et al. [1]. Usually, however, the leaf albedo is not known and, instead, a transformed leaf albedo can be used

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as reference [2,5]. In such cases, the interpretation of the retrieved p is not trivial, but *DASF*, on the other hand, remains independent of the reference leaf albedo [3]. Therefore, *DASF* is hypothesized to be applicable over a range of different types of canopies.

Here, we tested the applicability of the method by Schull et al. [2] using data from southern boreal forests representing a wide range of natural stand structures, including open canopies with green understory vegetation. In addition, we evaluated the performance of *DASF* in estimating the broadleaf fraction of these forests, and suggest an interpretation for the p-values retrieved using a transformed leaf albedo as reference.

2. Materials and methods

2.1. Study area

Hyytiälä forest area in central Finland (61°50′ N, 24°17′ E) represents the typical southern boreal forests of Finland. The dominant tree species in the area are Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and Silver birch (*Betula pendula*). Other deciduous trees in the area are mainly Downy birch (*Betula pubescens*) and European aspen (*Populus tremula*), but Silver birch is clearly the most common deciduous tree species. The understory of the forest is composed of two layers, with low dwarf shrubs or seedlings, graminoids and herbaceous species on top, and mosses and lichens on the ground.

2.2. Ground reference

The ground reference data for the study consist of 66 forest stands (Table 1). Forest structural properties (basal area, tree height and diameter at breast height) were measured during 2007–2012. For all stands, the species proportions (pine, spruce and broadleaves) were determined from the basal area.

Additionally, a subset of 50 stands was measured for canopy gap fractions from hemispherical images taken between June 17 and July 24, 2008 (same phenological stage as the satellite image; Section 2.4) [6]. Each stand was photographed with a hemispherical lens at the height of 1.3 m from 12 points according to the sampling protocol of the Validation of Land European Remote sensing Instruments (VALERI) network [7]. In this study, one minus the mean gap fraction within a field-of-view of 15° around the zenith was used as an approximation of (vertical) canopy cover (see [6] for the definitions).

2.3. Leaf and needle albedos

Four datasets on leaf and needle albedos ω_L were included in the analyses. Scots pine, Norway spruce and Silver birch data described the ω_L of the dominant tree species in the study area, while Beaked hazel (*Corylus cornuta*) leaf albedo was used to allow for comparison to previous studies [2,3].

The Scots pine, Norway spruce and Silver birch spectral albedo measurements were made with an ASD FieldSpec 3 PRO spectroradiometer (Analytical Spectral Devices, Inc., USA) coupled to an integrating sphere (ASD RTS-3ZC). Samples were collected from ten trees per species from two canopy positions (exposed and shaded), and measured separately for abaxial and adaxial sides. In this study, the albedos were averaged over both sides. At 700 nm, the spectral resolution of the spectroradiometer was 3 nm, but the results were interpolated to 1 nm spectral resolution. Further details on the measurements can be found in Lukeš et al. [8].

The Beaked hazel spectrum is the same as used by Knyazikhin et al. [3] and Schull et al. [2]. The measurements were made as part of the Boreal Ecosystem Atmosphere Study (BOREAS) campaign with a Spectron Engineering SE590 spectroradiometer (Spectron Engineering, Inc., USA) attached to a LICOR LI-1800-12 integrating sphere (Li-Cor, Inc., USA). The hazel albedo represents the average of 9 samples from central Canada, measured in native resolution of 5 nm. More details of the measurements are described in Hall et al. [9]. To achieve 1 nm spectral resolution for this study, linear interpolation was applied.

2.4. Hyperion image

A midsummer Hyperion image from July 3, 2010 (DOY 184) was used. It is taken in a slightly tilted viewing angle of −13.8° (WRS-2 orbit path 187, target path 189) and has a low cloud cover (0–9%).

The Hyperion end user products are provided as calibrated radiance for each band without atmospheric correction. To eliminate the effect of particulate and molecular absorption and scattering in the atmosphere, the image was corrected from at-detector radiance to values of Hemispherical-Directional Reflectance Factor (*HDRF*), using the Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) with initial visibility set to 50 km. Simultaneous to the atmospheric correction, the image was geocorrected, and corrected for striping and the Hyperion "spectral smile". See [10] for details on the corrections

Table 1
Descriptive statistics for the reference stands (n=66, except for canopy cover n=50). Height and diameter at breast height were measured for basal area median trees.

Dominant species	n_{66} (n_{50})	Basal area (m^2 ha^{-1})		Height (m)		Diameter at breast height (cm)		Canopy cover (%)	
		Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)
Scots pine	24 (24)	6.0–44.1	23.0 (10.2)	6.7–30.6	16.9 (6.0)	8.6–39.5	21.1 (7.5)	12.5–78.7	49.4 (17.3)
Norway spruce	18 (17)	17.3–51.3	29.5 (8.7)	10.2–29.5	19.8 (5.6)	12.2–33.8	22.5 (6.6)	41.6–73.5	62.6 (10.4)
Silver birch	24 (9)	0.8–34.3	22.7 (9.2)	2.2–23.1	14.9 (4.6)	1.1–24.3	13.3 (4.5)	0.1–84.4	54.3 (29.3)