ISPRS Journal of Photogrammetry and Remote Sensing 74 (2012) 1–10

Contents lists available at SciVerse ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Constructing satellite-derived hyperspectral indices sensitive to canopy structure variables of a Cordilleran Cypress (*Austrocedrus chilensis*) forest

Marco A. Peña [a,*], Alexander Brenning [b], Ariel Sagredo [a]

[a] *Centro de Estudio de Recursos Naturales Oterra, Universidad Mayor, Camino La Pirámide #5750, Huechuraba, Santiago, Chile*
[b] *Department of Geography and Environmental Management, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada N2L 3G1*

ARTICLE INFO

Article history:
Received 13 December 2011
Received in revised form 12 June 2012
Accepted 16 June 2012
Available online 18 September 2012

Keywords:
Hyperspectral imaging
Spectral indices
Austrocedrus chilensis
Forest canopy structure
False discovery rate
Multiple comparison problem

ABSTRACT

Satellite hyperspectral data were used to construct empirical spectral indices related to the canopy structure of a Cordilleran Cypress (*Austrocedrus chilensis*) forest located in the Andes of central Chile. Measurements of tree diameter at breast height (DBH) and tree height (TH) were performed for a set of plots located within a pure and unevenly aged stand of *A. chilensis* with moderate cover. Normalized difference vegetation indices (NDIs) related to DBH and TH were constructed from the corresponding hyperspectral data in Hyperion imagery. NDIs construction utilized the original spectral reflectance curve, its first derivative, and the continuum-removed reflectance in a two-step procedure that ranks NDIs based on their Spearman correlation with the response variable while controlling the false discovery rate. Several reflectance-based NDIs as well as a larger group of derivative-based NDIs were significantly related to DBH or TH ($\rho > 0.70$). The NDIs most strongly related to the field variables were based on derivative bands located within the same spectral regions used by the broadband greenness index known as green normalized difference vegetation index. Most other significant NDIs used NIR bands, which are well-known for their sensitivity to foliage amount changes. The results obtained in this exploratory study mostly agreed with the spectral regions expected to be most sensitive to changes in the canopy structure of vegetation. Further research in other *A. chilensis* forests subject to different site and environmental conditions is needed in order to assess the applicability of the NDIs over a wider range of this endemic species.

1. Introduction

Advances in imaging spectroscopy (i.e., hyperspectral imaging) have provided novel insights into forest canopy structure. Hyperspectral technology samples the radiation reflected by an element in hundreds of narrow (⩽10 nm) and contiguous spectral intervals, or bands. Because of this, it can detect distinctive spectral signals associated with critical properties of vegetation that will likely be blurred at the coarser spectral resolutions of multispectral sensors (Lefsky and Cohen, 2003; Lucas et al., 2004; Govender et al., 2007; Schaepman et al., 2009).

A simple and widely used technique to retrieve information about a biogeochemical variable of any remotely-sensed target is by means of a spectral index, i.e. an algebraic combination of bands sensitive to changes in the variable of interest. Experience has shown that these changes may often be detected using a spectral index simply based on a band ratio. While the band corresponding to the formula's numerator provides a spectral signal directly related to the variation of the variable, the band corresponding to the formula's denominator is insensitive to these, serving as a baseline that minimizes the detrimental effect that external factors may have on the relationship between the formula's denominator and the variable of interest (e.g., variable surface illumination). The bands that conform a spectral index may be inferred from the theoretical spectral behavior of the target, or they may be found by empirical–statistical relationships. Once the spectral index is validated, it can be applied to the complete study population, thus allowing to map the variable of interest, usually at lower costs in comparison to ground-based methods (Treitz and Howarth, 1999; Fournier et al., 2003; Liang, 2004).

In the context of forest-related studies, spectral indices have allowed to retrieve measurements closely related to changes in canopy structure variables, such as leaf area index (LAI), fractional photosynthetically active radiation and vegetation cover fraction (Baret and Guyot, 1991; Wiegand et al., 1991; Gitelson et al., 2002a). Due to the distinctive high reflection that leaf cell walls promote at near-infrared (NIR) wavelengths (from 700 to 1300 nm), at the canopy level spectral signals from this region of the spectrum are good indicators of foliage amount changes. Accordingly, a typical ratio-based spectral index that relates

* Corresponding author.
E-mail addresses: marco.pena@umayor.cl (M.A. Peña), brenning@uwaterloo.ca (A. Brenning), ariel.sagredo@umayor.cl (A. Sagredo).

0924-2716/$ - see front matter © 2012 International Society for Photogrammetry and Remote Sensing, Inc. (ISPRS) Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.isprsjprs.2012.06.010

changes in canopy structure variables considers a NIR band as the formula's denominator. A red band, in contrast, is usually incorporated as the formula's numerator. This is because radiation absorbed by vegetation at red wavelengths (from 600 to 700 nm) is largely due to the foliar chlorophyll content. Therefore, the red band not only serves as the index's baseline but also enhances its response because the larger the foliage amount, the stronger the absorption feature associated with the foliar chlorophyll content (Jackson and Huete, 1991; Jones and Vaughan, 2010).

Many broadband spectral indices sensitive to changes in canopy structure variables based on the aforementioned ratio-based approach have been proposed (Baret and Guyot, 1991; Wiegand et al., 1991; Gitelson and Merzlyak, 1994; McDonald et al., 1998), and in some cases an empirical or semi-empirical term has been added to the ratio in order to correct unwanted effects that a simpler formulation cannot handle, like those related to soil background (Richardson and Wiegand, 1977; Huete, 1988; Baret et al., 1989; Clevers, 1989; Qi et al., 1994; Gilabert et al., 2002) or atmospheric aerosols (Kaufman and Tanré, 1992; Pinty and Verstraete, 1992; Karnieli et al., 2001).

Nonetheless, due to their simplicity and robustness, the normalized difference vegetation index (NDVI = $(R_{NIR} - R_{Red})/(R_{NIR} + R_{Red})$) remains the most widely used. The normalized formulation of the NDVI allows to compensate illumination differences within the scene and eventual radiometric miscalibrations. In addition, it provides a value scale that facilitates the interpretation of the canopy foliage amount and state (Baret and Guyot, 1991; Zhang et al., 2006; Jones and Vaughan, 2010). Due to these properties, the formulation of ratio-based spectral indices in the form of normalized differences has been used to find empirical–statistical relationships between remotely-sensed data and vegetation properties such as foliar nitrogen content, LAI and green biomass (Zhao et al., 2005; Hansen and Schjoerring, 2003; Ferweda et al., 2005; Stroppiana et al., 2006).

Despite the bulk spectral signals that leaf structure may promote in some spectral regions such as NIR, there is evidence that the specific wavelengths that best relate to changes in a canopy structure variable may vary from one study to another, particularly when hyperspectral imaging techniques are used (McDonald et al., 1998; Hamlyn and Vaughan, 2010). This is because several external factors distort the radiation measured from the targets (e.g., atmospheric aerosols, mix of elements contained within the image's pixels, soil background, solar and sensor viewing geometries). In addition, radiation interacts in a unique manner with each canopy as a result of its particular structural properties such as LAI and leaf angle distribution (Baret and Guyot, 1991; McDonald et al., 1998; Asner, 1998; Asner et al., 2003; Liang, 2004).

Assuming that the external factors are controlled, the canopy-related factors imply that the intensity of the spectral signals recorded from the canopy by passive optical remote sensing is strongly conditioned by the horizontal and vertical abundance and distribution of leaves. This may lead to shifts in the spectral position of wavelengths expected to be most sensitive to changes in canopy structure variables. Therefore, spectral indices that are related to these variables are to some extent scene- and site-dependent, which reduces their transferability to a wide range of environmental and ecological conditions (McDonald et al., 1998; Jones and Vaughan, 2010). To overcome this limitation, site-specific spectral indices may be constructed for any particular study based on empirical–statistical relationships between ground-based and remotely-sensed data.

The monitoring and management of Chilean native forests may benefit from empirical spectral indices by using them to retrieve information about the conservation state of particular species. This can be especially significant in light of the size and inaccessibility of areas hosting vulnerable forest species, which increases the costs and limits the availability of ground-based surveys. The Cordilleran Cypress (*Austrocedrus chilensis* (D. Don.) Pic. Serm & M.P. Bizzarri) is a vulnerable *Cupressaceae* species (Hechenleitner et al., 2005) endemic to Chile and Argentina, whose conservation is difficult because most of their stands are located in mountainous terrain. The species is distributed along steep terrains of the central Chilean and Argentinean Andes mountains over a 1200-km north–south extent (Rodríguez, 2004). In Chile it ranges from 32° 39′ S (V Region of Valparaiso) to approximately 44° S (X Region of Los Lagos) (Donoso, 1982; Rodríguez, 2004), while in Argentina it ranges from 36° 30′ S (Province of Neuquén) to 43° 35′ S (Province of Chubut) (Pastorino and Gallo, 2002; Pastorino et al., 2006).

Over the last years, the monitoring and management of *A. chilensis* has become a priority for Chilean government authorities because it has been strongly affected by several pests such as the aphid *Cinara cupressi* ((Buckton) (Hemiptera: Aphididae)), the fungus *Phytophthora austrocedrae* (Gresl. & E.M. Hansen) and the larvae *Nanodacna austrocedrella* (Landry & Adamski), all of which have negatively impacted the health status of the species (Gómez and Klasmer, 1997; Baldini et al., 2008; Greslebin et al., 2005). To be able to map *A. chilensis* canopy structure variables over large areas, a cost- and time-efficient method that requires a limited number of field measurements is required. In this work, we explore the utility of satellite hyperspectral imagery to estimate canopy structure variables of an *A. chilensis* forest in the Andes of central Chile. To accomplish this goal, empirical normalized difference indices (NDIs) based on original and transformed reflectance bands of a Hyperion hyperspectral image were calculated and then correlated to field measurements of tree diameter at breast height (DBH) and tree height (TH).

As a novel approach in this context, a multiple comparison procedure is used to identify statistically significant NDIs. A drawback of the use of large numbers of statistical hypothesis tests is that the number of false positive test results expected under the null hypothesis is unacceptably high for tests performed at the nominal 5% significance level. Thus, if the number of true positive tests is small, they may account for only a small fraction of all positive test results, making it impossible to interpret the results. Multiple comparison procedures, however, are able to control the false discovery rate (FDR) of a family of hypothesis tests, i.e. the portion of false positive tests among all positive tests, at a desired level (Benjamini and Hochberg, 1995). Such adjustments for multiple comparisons have only recently been adopted in a remote sensing context (e.g., Brenning, 2009; Brown et al., 2010).

2. Material and methods

2.1. Study area

The study area (34° 43′ 31″ S, 70° 45′ 32″ W) forms part of the Priority Area for Biodiversity Conservation established by Chile's environmental agency CONAMA (Comisión Nacional del Medio Ambiente) in 2005 with the purpose of preserving the forest types of the central Chilean Andes, particularly those of *A. chilensis*. The study area is located to the south-east of the city of San Fernando, VI Region of O'Higgins, Chile, in the foothills of the Andes (Fig. 1). Climate is temperate Mediterranean with hot, dry summers and cool, wet winters. Vegetation in the mountainous area at lower elevations is primarily sclerophyllous forest and shrubland. At higher elevations it consists of mixed and pure, unevenly aged stands of *A. chilensis*, some stands of southern beech, and above the treeline grasses, *krummholz* and cushion plants. In general, the terrain is steep, and weathered bedrock is often exposed at the ground surface.

2.2. Field measurements

Field work was carried out between February 9 and 15, 2008 (austral summer). Seventeen plots of 40 m × 40 m were placed