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Review Article

Optical remote sensing and the retrieval of terrestrial vegetation bio-geophysical properties – A review

Jochem Verrelst [a,*], Gustau Camps-Valls [a], Jordi Muñoz-Marí [a], Juan Pablo Rivera [a], Frank Veroustraete [b], Jan G.P.W. Clevers [c], José Moreno [a]

[a] Image Processing Laboratory (IPL), Parc Científic, Universitat de València, 46980 Paterna, València, Spain
[b] Department of Bioscience Engineering, University of Antwerp, Groenenborgerlaan 171, BE2020 Antwerp, Belgium
[c] Laboratory of Geo-Information Science and Remote Sensing, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands

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ABSTRACT

Forthcoming superspectral satellite missions dedicated to land monitoring, as well as planned imaging spectrometers, will unleash an unprecedented data stream. The processing requirements for such large data streams involve processing techniques enabling the spatio-temporally explicit quantification of vegetation properties. Typically retrieval must be accurate, robust and fast. Hence, there is a strict requirement to identify next-generation bio-geophysical variable retrieval algorithms which can be molded into an operational processing chain. This paper offers a review of state-of-the-art retrieval methods for quantitative terrestrial bio-geophysical variable extraction using optical remote sensing imagery. We can categorize these methods into (1) *parametric regression*, (2) *non-parametric regression*, (3) *physically-based* and (4) *hybrid methods*. Hybrid methods combine generic capabilities of physically-based methods with flexible and computationally efficient methods, typically non-parametric regression methods. A review of the theoretical basis of all these methods is given first and followed by published applications. This paper focusses on: (1) retrievability of bio-geophysical variables, (2) ability to generate multiple outputs, (3) possibilities for model transparency description, (4) mapping speed, and (5) possibilities for uncertainty retrieval. Finally, the prospects of implementing these methods into future processing chains for operational retrieval of vegetation properties are presented and discussed.

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1. Introduction

Vegetation bio-geophysical variable extraction, quantitatively retrieved and spatio-temporally explicit, is required in a variety of ecological and agricultural applications. Earth observation satellites in the optical domain enable the retrieval and monitoring of plant bio-geophysical variables (Moulin et al., 1998; Dorigo et al., 2007). The forthcoming super-spectral 'Copernicus' Sentinel-2 (Drusch et al., 2012) and Sentinel-3 missions (Donlon et al., 2012), as well as the planned EnMAP (Stuffler et al., 2007), HyspIRI (Roberts et al., 2012), PRISMA (Labate et al., 2009) and ESA's candidate FLEX (Kraft et al., 2012) imaging spectrometer missions will produce large data streams for land monitoring, which will soon become available to a diverse user community (Berger et al., 2012; Malenovsky et al., 2012). This vast data stream requires enhanced processing techniques that are accurate, robust and fast. The last few decades witnessed a variety of retrieval methods for vegetation attribute extraction coming into existence. Only a few made it to the status of genuine operational processing chain. Many others remained in an experimental state.

This paper provides a qualitative review of recently developed methodologies to estimate vegetation properties based on optical remote sensing (RS), covering the visible to shortwave infrared (SWIR) spectral region. By nature, bio-geophysical variables are continuous. Hence, methods which yield per-pixel estimations will be discussed, and which are potentially applicable in highly automated processing chains. Quantification of surface bio-geophysical variables with optical RS always relies on a model, enabling the interpretation of spectral observations and their translation into a surface bio-geophysical variable. Statistically, this boils down to a regression problem (Fernandes and Leblanc, 2005). Bio-geophysical variable retrievals, as described in terrestrial RS literature, are typically grouped in two categories: (1) the statistical (or variable-driven) category; and (2) the physical (or radiometric

* Corresponding author.
E-mail address: jochem.verrelst@uv.es (J. Verrelst).

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data-driven) category (Baret and Buis, 2008). Over the last decade, however, both methodological categories expanded into subcategories and combinations thereof. Exemplary is the increasing number of elements of both categories which have been integrated into hybrid approaches. Hence, a systematic categorization is a strong requirement. Retrieval methods can be binned in the following four methodological categories:

(1) *Parametric regression methods:* Parametric methods assume an explicit relationship between spectral observations and a specific bio-geophysical variable. Thus, explicit parameterized expressions are built, typically by relying on statistical or physical knowledge of the variable and the spectral response. Typically a band arithmetic formulation is defined (e.g., a vegetation index) and then linked to the variable of interest based on a fitting function.
(2) *Non-parametric regression methods:* Non-parametric methods directly define regression functions according to information from RS data. Hence, in contrast to parametric regression methods, a non-explicit choice is to be made on spectral band relationships, transformation(s) or fitting functions. These last ones can further be split into linear or non-linear regression methods.
(3) *Physically-based methods:* Physically-based algorithms are applications of physical laws establishing cause-effect relationships. Model variables are inferred based on specific knowledge, typically obtained with radiative transfer functions.
(4) *Hybrid methods:* A hybrid-method combines elements of non-parametric statistics and physically-based methods. Hybrid models make use of the generic properties of physically-based methods combined with the flexibility and computational efficiency of non-parametric non-linear regression methods.

This review paper aims to (1) provide a systematic overview of state-of-the-art bio-geophysical variable retrieval methods, and (2) evaluate strengths and weaknesses of these methods for operational application. This paper focuses on methods established for vegetation variable retrieval, typically leaf area index (LAI) and leaf chlorophyll content (LCC), which are very frequently applied terrestrial bio-geophysical products based on optical RS (Song, 2013). Yet, in principle the methods presented are applicable to the retrieval of other vegetation properties as well. For an overview of retrievable leaf biochemical and canopy bio-geophysical variables from superspectral or hyperspectral sensors we refer to Ustin and Gamon (2010) and Malenovsky et al. (2012). The four categories mentioned above will be reviewed in the next sections. For each of the categories, their general properties will be outlined and their use in mapping applications reviewed. Finally, the most important features of these categories will be discussed. The increasing occurrence of non-parametric methods in the recent literature makes us focus strongly on them. The review paper emphasizes on methods directly applicable to a remote sensing image. In principle, however, these methods can also be applied for time series analysis or be implemented in larger assimilation schemes. Also, the large majority of reviewed retrieval methods assumes the availability of surface reflectance, which implies an atmospheric correction prior to application of proposed methods (see Bassani et al. (2010) and Ruddick et al. (2014) for a review on atmospheric correction methods). A conclusion section will finalize this paper with recommendations fostering powerful bio-geophysical variable retrieval strategies that are applicable in next-generation operational processing schemes.

2. Parametric regression methods

Parametric regression methods explicitly determine parameterized expressions relating a limited number of spectral bands with a bio-geophysical variable of interest. This family of approaches has long been most popular in optical RS. These methods make use of subtle spectral features to reduce undesired effects, typically those related to variations of other leaf or canopy properties, soil reflectance, sun and view geometry and atmospheric composition. The principle entails mathematically defined combinations of spectral bands regressed with a bio-geophysical variable using a fitting function. The fitted function can be either linear or non-linear, e.g. an exponential, power, or polynomial fitting function. A scheme of a generalized parametric regression procedure is illustrated in Fig. 1.

2.1. Discrete spectral band approaches: vegetation indices

Parametric statistical approaches based on vegetation indices (VIs) are by far the oldest, most studied and largest group of variable estimation approaches. They are also the simplest ones. VIs are defined to enhance spectral features sensitive to a vegetation property while reducing disturbance by combining some spectral bands into a VI (Glenn et al., 2008; Clevers, 2014). The VI methods have been traditionally developed for sensors configured with only a few (broad) spectral bands. It is beyond the scope of this work to list all published VIs (see Le Maire et al., 2004, 2008, for an overview), though they can be categorized according to their mathematical definition. Some popular VI formalizations are:

- Two-band VIs, encompassing the majority of VIs, e.g., the simple ratio (SR) (Jordan, 1969), the normalized difference vegetation index (NDVI) (Rouse et al., 1974), the photochemical reflectance index (PRI) (Gamon et al., 1992), the optimized soil adjusted vegetation index (OSAVI) (Rondeaux et al., 1996), the chlorophyll index (Gitelson et al., 2003).
- Three-band VIs with, e.g., the triangular VI (TVI) (Broge and Leblanc, 2001), the modified chlorophyll absorption in reflectance index (MCARI) (Daughtry et al., 2000), the transformed CARI (TCARI) (Haboudane et al., 2002), the structure insensitive pigment index (SIPI) (Penuelas et al., 1995).
- Four or more band VIs, which are typically a combination of two VIs such as the TCARI/OSAVI (Haboudane et al., 2002).

The main advantage of VIs is their inherent simplicity. VI based methods found their origin in the first applications of broadband sensor satellites. Only a small set of spectral bands were available at that time and computational power was limited. With the advent of narrowband imaging spectrometers, with a few hundred spectrally narrow bands, paths for new extraction approaches of RS based information were developed. Optimized band information extraction algorithms based on established index formulations (e.g. simple ratio, normalized difference) were developed. By correlating all possible band combinations according to two-band indices, leading to 2D correlation matrices, it became feasible to visually identify optimal band combinations (e.g., Thenkabail et al., 2000; Le Maire et al., 2004, 2008; Mariotto et al., 2013; Rivera et al., 2014b). The so-called optimized or generic VIs permitted to select a 'best performing index'. Nevertheless, when applying this technique in studies making use of narrowband (hyperspectral) imaging, best performing identical spectral band combinations have rarely been reported. This suggests that optimized indices are strongly case specific (Gonsamo, 2011; Heiskanen et al., 2013; Mariotto et al., 2013). Hence, narrowband

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