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Comparative analysis of different retrieval methods for mapping grassland leaf area index using airborne imaging spectroscopy

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ABSTRACT

Fine scale maps of vegetation biophysical variables are useful status indicators for monitoring and managing national parks and endangered habitats. Here, we assess in a comparative way four different retrieval methods for estimating leaf area index (LAI) in grassland: two radiative transfer model (RTM) inversion methods (one based on look-up-tables (LUT) and one based on predictive equations) and two statistical modelling methods (one partly, the other entirely based on *in situ* data). For prediction, spectral data were used that had been acquired over Majella National Park in Italy by the airborne hyperspectral HyMap instrument. To assess the performance of the four investigated models, the normalized root mean squared error (nRMSE) and coefficient of determination (R^2) between estimates and *in situ* LAI measurements are reported ($n = 41$). Using a jackknife approach, we also quantified the accuracy and robustness of empirical models as a function of the size of the available calibration data set. The results of the study demonstrate that the LUT-based RTM inversion yields higher accuracies for LAI estimation ($R^2 = 0.91$, nRMSE = 0.18) as compared to RTM inversions based on predictive equations ($R^2 = 0.79$, nRMSE = 0.38). The two statistical methods yield accuracies similar to the LUT method. However, as expected, the accuracy and robustness of the statistical models decrease when the size of the calibration database is reduced to fewer samples. The results of this study are of interest for the remote sensing community developing improved inversion schemes for spaceborne hyperspectral sensors applicable to different vegetation types. The examples provided in this paper may also serve as illustrations for the drawbacks and advantages of physical and empirical models.

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Introduction

Maps of leaf traits and vegetation biophysical characteristics such as leaf area index (LAI) are useful in ecological research and for modelling of surface energy balance, vegetation productivity, water and CO_2 exchange, as well as biodiversity assessment (Pereira et al., 2013; Pu et al., 2003; Turner et al., 1999). Compared to classical multi-spectral instruments, the quality of such maps has been significantly enhanced through hyperspectral remote sensing (Lee et al., 2004; Schaepman et al., 2009).

Although studies quantifying vegetation biophysical parameters using imaging spectroscopy are numerous, relatively few studies deal with grassland canopies. High quality vegetation maps will help managers of National parks to protect these sensitive ecosystems. More research on the usefulness of imaging spectroscopy for vegetation characterisation is also warranted for preparing the remote sensing community for the upcoming (spaceborne) imaging spectrometers such as EnMap (Segl et al., 2010).

Two main approaches are commonly used for estimating vegetation biophysical characteristics from remotely sensed data (Baret and Buis, 2008; Rivera et al., 2014a):

- Statistical approaches.
- Approaches using physically-based radiative transfer models.

In the statistical approach, regression models are developed from *in situ* data to relate the parameter(s) of interest to the spectral

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data. To minimize topographic, soil background and atmospheric effects most studies involve the use of spectral vegetation indices (*e.g.*, Haboudane et al., 2004; Khanna et al., 2007; Mutanga and Skidmore, 2004; Thenkabail et al., 2000; Yu et al., 2013). Other studies focus on the analysis of the red edge inflection point (Cho and Skidmore, 2009; Darvishzadeh et al., 2009; Haboudane et al., 2008; Horler et al., 1983) or the use of spectral transformations such as band depth analysis (Im and Jensen, 2008; Schlerf et al., 2010). In addition, several studies investigate the usefulness of full spectrum methods such as partial least square regression (PLSR), principal component regression (PCR), Bayesian model averaging or spectral un-mixing approaches (Asner and Martin, 2008; Atzberger, 2010; Hu et al., 2004; Mirzaie et al., 2014; Zhao et al., 2013). Beside these parametric models, non-parametric approaches such as k-NN are also used (Chirici et al., 2008; Corona et al., 2014; McRoberts et al., 2007; Rivera et al., 2014b).

Statistical models have some advantages fostering their widespread use. For example, some of the mentioned statistical models are easy to apply. Also, suitable software is often readily available (Rivera et al., 2014a). It is well known, however, that developed models sometimes lack transferability to other sites with different vegetation, or transferability to other type of image or acquisition conditions (Baret and Guyot, 1991; Vuolo et al., 2013). Another drawback of statistical models is that they require a set of *in situ* data and that their robustness depends on the properties of this data set (*i.e.*, number, quality and representativeness of available reference samples). A systematic investigation of sample size effects would be informative as the collection of ground truth is usually associated with high costs.

To minimize the reliance on *in situ* data, the physical approach involves the use of radiative transfer models (RTM). These models describe the spectral variation of canopy reflectance as a function of viewing and illumination geometry, canopy, leaf and soil background characteristics and are founded on physical principles. RTM, thus, offer an explicit (and physically based) connection between the vegetation biophysical and biochemical properties and the canopy reflectance as measured by a sensor (Houborg et al., 2007). This enables the simultaneous use of all spectral bands acquired by multi- to hyper-spectral sensors and in particular the most sensitive ones. However, for reasonable retrieval performance, RTM usually require the specification of some input parameters (*e.g.*, average leaf angle, soil background reflectance). For structurally heterogeneous vegetation with multiple canopy layers and leaf clumping at different organization levels, canopy reflectance models require additional parameterization often not readily available (Demarez and Gastellu-Etchegorry, 2000). For structurally less complex grass and crop canopies, suitable results were reported using the relatively simple PROSAIL canopy reflectance model – a combination of the models PROSPECT (Jacquemoud and Baret, 1990) and SAIL (Verhoef, 1984) – as reviewed by Jacquemoud et al. (2009).

RTM do not directly yield estimates of the sought vegetation biophysical parameters. Instead, such models need to be inverted using an appropriate inversion strategy (Kimes et al., 2000; Weiss and Baret, 1999). Available methods include iterative optimization methods (Jacquemoud et al., 1995; Le Maire et al., 2011; Richter et al., 2009), look-up-table (LUT) based inversions (Darvishzadeh et al., 2008a; Rivera et al., 2013; Weiss et al., 2000), and neural networks (Bacour et al., 2006; Schlerf and Atzberger, 2006; Verger et al., 2011). Many studies rely on look-up-tables which are relatively easy to implement, and which provide a search across the entire parameter space in a step width solely limited by the available processing power.

To increase the predictive power and robustness of RTM inversions, feature selection approaches are recommended (Baret and Buis, 2008). Published feature selection methods vary in complexity and range from the use of previously identified absorption wavelengths (Darvishzadeh et al., 2008a; Meroni et al., 2004) to more advanced methods based on statistical selection and elimination criteria (Atzberger, 2010; Atzberger et al., 2013; Verger et al., 2011).

To combine the advantages of physical and statistical approaches, Le Maire et al. (2012, 2008),) and Haboudane et al. (2004) amongst others proposed the development of hyperspectral vegetation indices calibrated on RTM-generated synthetic data (*e.g.*, so called predictive equations) for model inversion. No studies evaluating such predictive equations over grasslands are known. Nor are studies evaluating systematically different statistical and physically based approaches over grassland canopies for better understanding their respective advantages and limits.

To address these research gaps, the study presents the results of a comparative assessment of four retrieval methods against *in situ* LAI measurements in Mediterranean grassland:

- Inversion of the PROSAIL radiative transfer model based on LUT.
- Use of predictive equations solely calibrated on PROSAIL generated data.
- Use of predictive equations partly trimmed using available *in situ* (LAI) data.
- Use of narrow-band vegetation indices based solely on available *in situ* (LAI) data.

Mediterranean grasslands are characterized by heterogeneous canopies with a combination of different plant species in varying proportions (Darvishzadeh et al., 2011). This poses challenges for remote sensing applications (Fisher, 1997; Röder et al., 2007). As little is known about heterogeneous (multiple species) grassland canopies (Darvishzadeh et al., 2008b; Vohland and Jarmer, 2008), more research is warranted to better understand the capabilities and limits of different retrieval algorithms. For illustration purpose, the study also addresses the effect of sampling size on the accuracy and robustness of statistical models.

Material

The study focuses on the mapping of LAI in Majella National Park, Italy. To collect the *in situ* LAI data, a field campaign was conducted during the summer of 2005 roughly corresponding to peak vegetation density. Parallel to the measurement campaign, the HyMap sensor was flown providing the corresponding airborne imaging spectrometer data (Darvishzadeh et al., 2011, 2008a). The time of airborne data collection and the field campaign are indicated in Fig. 1 together with average annual growth profiles (NDVI) of major land cover classes in the study region.

Study area

The study site is located in Majella National Park, Italy (latitude 41°50′–42°14′N, longitude 13°50′–14°14′E, Fig. 2). The park covers an area of 74,095 ha. The landscape is composed of bare rock outcrops, shrubby bushes, and patches of grass/herb vegetation. The present study is focused on grassland. The dominant grass and herb species include *Brachypodium genuense, Briza media, Bromus erectus, Festuca* sp., *Helichrysum italicum, Galium verum, Trifolium pratense, Plantago lanceolata, Sanguisorba officinalis* and *Ononis spinosa* (Cho, 2007).

In situ measurements

The field campaign for collecting the *in situ* data was carried out in July 2005 during peak vegetation density (Fig. 1). Vegetation characteristics such as LAI, leaf chlorophyll content and species

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