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Review

The functional characterization of grass- and shrubland ecosystems using hyperspectral remote sensing: trends, accuracy and moderating variables

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ABSTRACT

Hyperspectral remote sensing is increasingly being recognized as a powerful tool to map ecosystem properties and functions through time and space. However, general information on the accuracy of this technology to assess the vegetation's biophysical and -chemical trait composition, and on the variables which are mediating this accuracy, is often lacking so far. Here, we addressed this knowledge gap for grass- and shrubland ecosystems and applied novel three-level meta-analytical regression equations to 77 studies that validated hyperspectral remote sensing data with field observations. Our results showed that the accuracy of hyperspectral sensors is generally high, but strongly depends on the trait being studied (leaf area index: $R^2 = 0.79$ and nRMSE = 0.19, chlorophyll: $R^2 = 0.77$ and nRMSE = 0.21, carotenoids: $R^2 = 0.80$ and nRMSE = 0.29, phosphorus: $R^2 = 0.75$ and nRMSE = 0.14, nitrogen: $R^2 = 0.74$ and nRMSE = 0.09, water: $R^2 = 0.69$ and nRMSE = 0.13, and lignin content: $R^2 = 0.64$ and nRMSE = 0.26). Moreover, they indicated that the use of multivariate signal processing techniques could improve these estimation accuracies (adjusted $p < 0.06$ for LAI, chlorophyll and nitrogen). Finally, estimations from air- and spaceborne imaging spectrometers, allowing for functional mapping at broader spatial scales, were found to be as accurate as estimations from ground-based spectral measurements. Despite these promising findings, we revealed that leaf morphological properties (*e.g.* specific leaf area and leaf dry matter content) and biochemical traits which are not growth-related (*e.g.* lignin and cellulose) remain underexplored in grass- and shrublands. Moreover there was a strong publication bias towards R^2 for assessing model performance. Our findings foster and direct further methodological and technological developments for a more accurate and complete functional characterization of these ecosystems worldwide.

1. Introduction

The evaluation of management and climate impacts on the Earth's life support system requires an understanding of ecosystem dynamics. The concept of plant functional traits can highly contribute to such understanding (Díaz et al., 2004; Orwin et al., 2010; Shipley et al., 2006). It enables the assessment of plant communities response to environmental change and anthropogenic pressures on the one side (de Bello et al., 2006; Garnier et al., 2007), and the prediction of alterations in the functioning of ecosystems due to changing plant communities on the other side (Kurokawa et al., 2010; Lavorel and Garnier, 2002). Today, a wide range of morphological, physiological and phenological plant characteristics have already been successfully linked to ecosystem properties and processes such as biomass production, soil fertility and biogeochemical cycles (de Bello et al., 2010; Díaz et al., 2007; Lavorel and Garnier, 2002). Easily available and large scale information on the functional composition and diversity of plant communities is hence crucial for tracking the status of Earth's ecosystems (Chapin et al., 2000; Lamarque et al., 2014).

Although the traits of plant species can be manually measured (Cornelissen et al., 2003; Pérez-Harguindeguy et al., 2013) and are widely available in various local (Kleyer et al., 2008; Paula et al., 2009) and global (Kattge et al., 2011) databases, these actually cover only about 2% of currently known vascular plant species (Jetz et al., 2016). Part of the explanation for this lack of data is that measuring functional traits in the field or laboratory is laborious and may even be unfeasible, especially in very diverse ecosystems or at very large geographical scales (Homolová et al., 2013). Even though techniques exist to fill taxonomical and functional data gaps (*e.g.* Schrodt et al., 2015; Shan et al., 2012; Taugourdeau et al., 2014) and to upscale available trait

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data to larger geographical scales (*e.g.* Swenson et al., 2012; van Bodegom et al., 2014), these approaches remain hampered by sample inhomogeneities and do not account for temporal variations. Remote sensing, allowing spatially continuous and frequent observations across ecosystems, is an established technique to map structural and biochemical plant properties (Curran, 1989; Homolová et al., 2013; Ollinger, 2011; Ustin et al., 2009). More recently this potential has been acknowledged in biodiversity science, for example in the mapping of plant species diversity (Asner and Martin, 2016; Lausch et al., 2016; Zhao et al., 2016), plant strategies (Fassnacht et al., 2017; Feilhauer et al., 2016; Schweiger et al., 2017) and invasive plants (Niphadkar and Nagendra, 2016).

Although studies quantifying plant traits using hyperspectral sensors or imaging spectroscopy are numerous, they are to some extent biased towards forest and agro-ecosystems (Asner et al., 2015; Dorigo et al., 2007; Knyazikhin et al., 2013). Despite the extent and ecological value of grass- and shrubland ecosystems, their functional characterization using hyperspectral remote sensing is still somewhat underexplored. Covering up to 40% of the global land area (Latham et al., 2014; Suttie et al., 2005; White et al., 2000) they include among the most species-rich plant communities (Faber-Langendoen and Josse, 2010; Pinches et al., 2013; WallisDeVries et al., 2002), providing essential habitats for other species (Silva et al., 2008; Van Swaay, 2002). These ecosystems play an important role in the functioning of Earth's life system by regulating water quality (Rowe et al., 2006; Stevens et al., 2008), protecting soil from water and wind erosion (De Baets et al., 2006; Li et al., 2007) and sequestering carbon (Derner and Schuman, 2007; Minami et al., 1993).

Despite the exhaustively described potential of remote sensing for mapping and monitoring the status of vegetation in grasslands (Ali et al., 2016), rangelands (Svoray et al., 2013) and wetlands (Adam et al., 2010), we lack a general quantitative assessment of the reliability of remote sensing to quantify a range of ecosystem properties and functions, and of the variables affecting this reliability. This information is crucial for the further adoption of remote sensing techniques in biodiversity science, given the increasing availability and affordability of data generated by hyperspectral sensors. Here we filled this knowledge gap through a comprehensive meta-analysis of trait estimation accuracies obtained with different hyperspectral sensors in grass- and shrublands worldwide. Data-driven meta-analyses combine results across studies, generally assigning more weight to more precise studies, and by doing so improve statistical power compared to individual studies (Borenstein et al., 2009; Curtis and Queenborough, 2012; Lipsey and Wilson, 2001).

Next to quantifying overall trait estimation accuracies, the meta-analytical approach is highly useful to reveal technical and methodological trends in the collection of relevant articles. First, as a result of the progress in sensor technology, a wide variety of handheld and airborne hyperspectral sensors are nowadays operational (Qi et al., 2011). Meanwhile, the increasing interest in large-scale ecosystem functioning and biodiversity (Pereira et al., 2013; Proença et al., 2016; Skidmore et al., 2015) is driving the development of hyperspectral space missions such as EnMAP (Segl et al., 2010; Stuffler et al., 2007), HyspIRI (Pellissier et al., 2015; Turpie et al., 2015) and PRISMA (Labate et al., 2009). The utility of these sensors for global diversity and global change studies will depend on whether satisfying accuracies can be obtained when capturing information at coarser resolution. Second, a large variety of signal processing techniques is available, with different technical strengths and weaknesses (Atzberger et al., 2015; Verrelst et al., 2015). Recently, emphasis has shifted from the use of vegetation indices towards multivariate modelling, where a larger part of the spectrum is used for trait quantification (Verrelst et al., 2015). Because statistical approaches often lack generalization potential and transferability to different images or conditions (Dorigo et al., 2007; Foody et al., 2003), radiative transfer models have been developed which, based on physical principles, disentangle the contribution of structural and biochemical characteristics, but also illumination geometry and soil background characteristics to the spectral signature. In herbaceous ecosystems, mainly the PROSAIL canopy reflectance model (Jacquemoud et al., 2009), combining the PROSPECT leaf optical properties model (Jacquemoud and Baret, 1990) and the SAIL canopy bidirectional reflectance model (Verhoef, 1984), has been exhaustively applied and validated (*e.g.* Darvishzadeh et al., 2008b). The extent to which the computational complexity of enhanced methods is worth the effort in terms of trait estimation accuracy will influence researchers in making methodological choices.

In this study we sought to quantitatively synthesise previous research on the functional characterization of grass- and shrubland ecosystems using hyperspectral remote sensing. Our specific aims were to:

(i) Determine geographical distribution patterns of published studies and to identify research trends in the use of different sensor scales and signal processing techniques over time;
(ii) Determine the overall estimation accuracy and precision of several key grass- and shrubland traits;
(iii) Evaluate the potential of airborne and satellite missions for detecting functional traits in comparison with ground-based hyperspectral measurements; and to
(iv) Explore the capacities of different signal processing techniques for estimating functional traits.

2. Materials and methods

2.1. Literature search and criteria for inclusion

In order to assemble a representative sample of studies quantifying functional traits with hyperspectral data in grass- and shrubland ecosystems, two procedures were followed. First, we conducted an extensive database search of Thomas Reuters Web of Science using combinations of keywords looking for 1) hyperspectral studies in 2) grass- and shrubland ecosystems, investigating 3) plant functional traits (Table S1). We focused on a wide variety of quantitative biochemical and structural traits which are easy to measure in the field/laboratory (Garnier et al., 2016), have a clear expression in the vegetation's spectral signature (Ollinger, 2011), and support multiple interdependent functional processes. These included light capture and growth biochemicals such as pigments, nitrogen and phosphorus, essential supporting compounds such as water and lignin, and morphological leaf and plant properties such as LAI, SLA and canopy height (Table S1). Although from a forage quality perspective for livestock industry several other characteristics such as crude protein and ash content, metabolizable energy, acid and neutral detergent fibre are interesting (Beeri et al., 2007; Pullanagari et al., 2012), we did not include these traits in our meta-analysis. The keywords were combined with Boolean AND's (between the three search strings) and Boolean OR's (within each search string). No restrictions were set on document type and time span. Our most recent search (April 10th, 2017) identified 483 publications. In addition to the systematic database search, we examined the reference sections of relevant literature reviews for additional publications.

From the retrieved list of studies, only these were retained that (i) focused on non-agricultural grass- and shrublands, (ii) reported R^2 and/or nRMSE (*i.e.* RMSE expressed as a percentage of the mean trait value) as measure of trait estimation precision and accuracy, and (iii) reported the number of samples used for model development and/or testing. The coefficient of determination and normalized root mean square error were selected over other goodness-of-fit statistics because they were most frequently reported in the identified studies, or derivable from the text and figures. Moreover, the non-dimensionality of both indicators allows for comparability and therefore enabled us to combine studies expressing traits in different units and scales. Lastly, because they indicate different aspects of a model's performance, the sole consideration