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Review

Review of optical-based remote sensing for plant trait mapping

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ABSTRACT

Plant trait data have been used in various studies related to ecosystem functioning, community ecology, and assessment of ecosystem services. Evidences are that plant scientists agree on a set of key plant traits, which are relatively easy to measure and have a stable and strong predictive response to ecosystem functions. However, the field measurements of plant trait data are still limited to small area, to a certain moment in time and to certain number of species only. Therefore, remote sensing (RS) offers potential to complement or even replace field measurements of some plant traits. It offers instantaneous spatially contiguous information, covers larger areas and in case of satellite observations profits from their revisit capacity.

In this review, we first introduce RS concepts of light–vegetation interactions, RS instruments for vegetation studies, RS methods, and scaling between field and RS observations. Further we discuss in detail current achievements and challenges of optical RS for mapping of key plant traits. We concentrate our discussion on three categorical plant traits (plant growth and life forms, flammability properties and photosynthetic pathways and activity) and on five continuous plant traits (plant height, leaf phenology, leaf mass per area, nitrogen and phosphorous concentration or content). We review existing literature to determine the retrieval accuracy of the continuous plant traits. The relative estimation error using RS ranged between 10% and 45% of measured mean value, i.e. around 10% for plant height of tall canopies, 20% for plant height of short canopies, 15% for plant nitrogen, 25% for plant phosphorus content/concentration, and 45% for leaf mass per area estimates.

The potential of RS to map plant traits is particularly high when traits are related to leaf biochemistry, photosynthetic processes and canopy structure. There are also other plant traits, i.e. leaf chlorophyll content, water content and leaf area index, which can be retrieved from optical RS well and can be of importance for plant scientists.

We underline the need that future assessments of ecosystem functioning using RS should require comprehensive and integrated measurements of various plant traits together with leaf and canopy spectral properties. By doing so, the interplay between plant structural, physiological, biochemical, phenological and spectral properties can be better understood.

Contents

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1. Introduction

Plant traits are structural, physiological, biochemical or phenological features, e.g. plant height, photosynthesis rate, nitrogen content or leaf phenology, respectively, which are being increasingly used in ecology research (Cornelissen et al., 2003; Kattge et al., 2011). Due to the fact that groups of plants sharing a similar function within an ecosystem also tend to exhibit similar plant traits, plant traits are used to study the response of plants to various environmental pressures (e.g. changes in climate and land use) and the effect of plants on important ecosystem processes (e.g. biogeochemical cycles) (Díaz and Cabido, 1997; Lavorel and Garnier, 2002). Moreover, they have been successfully used in various studies related to ecosystem functioning (Díaz et al., 2004; Orwin et al., 2010; Wright et al., 2004), community ecology (Kraft et al., 2008), plant response to environmental pressures (de Bello et al., 2006; Garnier et al., 2007), plant invasion (Kurokawa et al., 2010; van Kleunen et al., 2010) and assessment of ecosystem services (Lavorel et al., 2011).

Nowadays there are hundreds of plant traits identified and measured by ecologists (Kattge et al., 2011). Plant trait data are measured at the level of individual plants and further upscaled to canopy properties (Violle et al., 2007) and data are often being compiled in various local (Kleyer et al., 2008; Paula et al., 2009) and global (Kattge et al., 2011) databases. Evidences are that plant scientists agree on a set of key plant traits, which are relatively easy to measure and have a stable and strong predictive response to ecosystem functions at various scales (Cornelissen et al., 2003; Díaz et al., 2004; Wright et al., 2004). Although data on key plant traits can be relatively well obtained from field measurements, the field measurements are still limited to small area, to a certain moment in time and to certain number of species only. Therefore, remote sensing (RS) offers potential to complement or even replace field measurements of some plant traits (Kokaly et al., 2009) at larger areas.

Capabilities to retrieve plant traits and canopy properties from optical RS have evolved hand in hand with the technological development of RS spectroradiometers (Milton et al., 2009). Early RS spectroradiometers providing data of coarser spatial and spectral resolutions have supported mainly vegetation classification into broader functional groups (Ustin and Gamon, 2010) and the development of simple vegetation indices (VIs) that were sensitive to broad variations in canopy properties (Cohen and Goward, 2004; Turner et al., 1999). Next generation of medium spectral and spatial resolution spectroradiometers together with development of radiative transfer models (Liang, 2004) have facilitated quantitative estimation of some plant traits (e.g. chlorophyll content, Dash and Curran, 2004 and water content, Cheng et al., 2006) and canopy properties (e.g. leaf area index, Myneni et al., 2002). Development of high spectral resolution imaging spectroradiometers encouraged even more the quantitative estimation of plant traits related to physiology and biochemistry. Plant pigments are the most studied traits (Blackburn, 2007; Ustin et al., 2009) and among them chlorophylls a and b (C_{ab}) have received most attention (Haboudane et al., 2002; le Maire et al., 2004; Malenovský et al., 2013; Schlerf et al., 2010; Zarco-Tejada et al., 2004), whereas carotenoids (Gitelson, 2002; Hernández-Clemente et al., 2012) and anthocyanins (Gitelson et al., 2006) have been studied less. Other biochemical traits retrieved from optical RS data are plant macronutrients (N, P, K, Mg, Ca) (Mutanga et al., 2004; Pimstein et al., 2011) and there is clear dominance of N and P related studies (both traits discussed in details later). Furthermore, leaf water content (Clevers et al., 2010; Colombo et al., 2008), leaf mass per area (discussed in details later), lignin and cellulose (Kokaly et al., 2009) or polyphenols (Skidmore et al., 2010) can be potentially retrieved from optical spectral data too.

Advantages of using RS are its capability to provide spatially contiguous and – for certain observations – high revisit frequency at the typical length scale of the trait processes observed. Moreover, it offers different sampling scheme to trait mapping, determined by combination of pixel size, spatial extent and revisit time of RS observations, than in situ measurements. The major challenge in quantitative RS of plant traits plays the canopy structure. It affects interpretation of canopy reflectance and has negative impact on the retrieval accuracy of biochemical traits (Knyazikhin et al., 2012; le Maire et al., 2008). Therefore approaches accounting for integral effects of canopy structure (Knyazikhin et al., 2012) or measurements of canopy structure itself (van Leeuwen and Nieuwenhuis, 2010) have recently gained more attention.

The potential of RS data for ecological applications is large, however, we see that successful integration of RS observations and ecological applications still requires bridging gaps in the perception of traits importance, scientific terminology (Schaepman-Strub et al., 2006; Violle et al., 2007) and scaling among leaf, plant and canopy levels (Malenovský et al., 2007; Messier et al., 2010). In this review, we want to demonstrate the potential of RS for estimating individual plant traits as defined by ecologists and therefore strengthen links between plant ecology and remote sensing research communities. First, we introduce RS concepts of light–vegetation interactions, RS instruments for vegetation studies, RS methods, and scaling between field and RS observations. Further, we discuss in detail current achievements and challenges when using optical RS to estimate key plant traits. We used Cornelissen et al. (2003) as baseline reference for key traits. These included plant growth and life forms, flammability properties, photosynthetic pathways and activity, plant height, leaf lifespan and phenology, specific leaf area, leaf nitrogen and phosphorous. Regenerative (e.g. seed mass) and belowground (e.g. rooting depth) traits are deliberately excluded, since they cannot be estimated using direct measurements from optical RS. We put emphasis on optical, passive RS, but mention active RS (laser scanning and microwave radar) to trait mapping whenever appropriate.