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On variable relations between vegetation patterns and canopy reflectance

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ABSTRACT

Statistical relations between the species composition of plant assemblages and canopy reflectance are frequently employed in remote sensing for mapping vegetation at local scales. Reflectance is influenced by species composition but also affected by dynamics such as seasonal vegetation development or plant stress. Due to this variability in time and space, doubts are frequently raised with respect to the transferability of statistical relations in remote sensing of plant assemblages. Hence, this study addresses the stability of statistical relations between species composition and reflectance despite of spatiotemporally changing vegetation conditions. We established permanent plots at three temperate sites (nutrient-poor grassland, wet heath, and floodplain meadow). We measured canopy reflectance at multiple dates over the vegetation period using a field spectrometer with hyperspectral resolution. Simultaneously, plant species composition and other vegetation and surface parameters that may exert influence on reflectance were recorded. Species composition was statistically related to the corresponding reflectance data using ordination (Isometric Feature Mapping) and cross-validated regression models (Partial Least Squares Regression). Time series of model fits as well as regression coefficients were used to estimate the temporal stability of the models. Model fits were further compared to changes in vegetation conditions. Model residuals were tested for co-variable influences. Finally, we tested the transferability of the statistical relations in time. Results showed that species composition could be modeled with rather high accuracies (R^2 in validation up to 0.78 and for only three measurements lower than 0.5), with the highest fits near the vegetation optimum (i.e., the date with maximum cover of photosynthetically active vegetation). The transferability in time varied with the vegetation type. Uncertainties in the models were strongly related to variable canopy height and to the occurrence of litter. Since such spatial heterogeneities may be a result of non-stationary processes, we conclude that statistical methods taking into account such effects may further improve the accuracy of vegetation mapping.

1. Introduction

Canopy reflectance of plant assemblages is a result of biochemical and structural properties such as leaf area index (LAI), leaf orientation, leaf structure, pigmentation, and leaf water content (Kumar et al., 2001). These properties are partially dependent on species composition (Asner et al., 2009) but are also influenced by other factors such as the condition of vegetation (e.g., with regard to phenology or stress, Carter and Knapp, 2001; Sanger, 1971). Further influences may be exerted, for example, by litter or soil (Asner, 1998; van Leeuwen and Huete, 1996). Canopy reflectance is thus always an expression of intermingling patterns of species composition, effects of short-term dynamics, and additional site properties not related to plant species composition.

Various remote-sensing applications in the fields of ecology, conservation, forestry, vegetation science, and rangeland management target the species composition of a certain area (see, e.g., Gillespie et al., 2008; Kerr and Ostrovsky, 2003; Turner et al., 2003 for reviews on this topic). Such applications have to cope with a fundamental issue: small inter-species differences in biochemistry and structure intermingle with effects of variable vegetation or plant conditions. Thus, approaches based on physical relations between plant species composition and reflectance have not been realized to date. Instead, statistical relations are frequently employed as a straightforward approach.

Statistical relations between species composition and reflectance require permanent recalibration, are considered poorly transferable in time and space (Kumar et al., 2001), and may temporarily vary in their reliability, even under controlled conditions (Feilhauer et al., 2010b). These uncertainties can likely be ascribed to variability in vegetation conditions as well as to heterogeneously distributed amounts of litter and bare soil. Still, certain conditions may also accentuate spectral differences between stands of varying species composition and thereby strengthen the statistical relations (Laba et al., 2005; Verrelst et al., 2009). Also, stand properties such as structure, LAI, and accumulated litter may be typical for a distinct plant assemblage and

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hence helpful in spectral discrimination (Verrelst et al., 2009). Because such 'contrast enhancing' properties change over the vegetation period, the quality of statistical relations between species composition and reflectance is variable in time.

To profit from the enhancing effects of stand properties and vegetation conditions, plant assemblages with similar species composition have to be in a comparable state across the mapped area. The validity of this precondition is threatened if non-stationary processes alter vegetation conditions (and hence reflectance) heterogeneously. However, the precondition that spatially separated plant assemblages are in a similar condition throughout the mapped area will rarely be the case. The opposite has often been observed, even within monocultures in agricultural applications. In precision agriculture, for instance, sensor applications rely on the observation that small-scale patterns of plant pathogens or nutrient supply within a homogeneous stand alter plant conditions and thus reflectance (Steiner et al., 2008; West et al., 2003).

It is also well known that the seasonal development of plants may show spatially heterogeneous trends. Spurr, 1948 stated that "in an area covered by a single photograph it is entirely possible to find the same species with normally green foliage at one elevation, with colored foliage at another, and defoliated in a nearby frost pocket." Such effects may also occur within small areas without topographical differences (e.g., Almeida-Neto and Lewinsohn, 2004). Even if differences in phenology are not detectable, within-species spectral variability has nevertheless been observed: Castro-Esau et al. (2006) tested the potential of leaf-level reflectance to discriminate various Mesoamerican trees. They successfully distinguished species within one site but found that between-site variation in species reflectance exceeded between-species variation. Triggers for such divergence from uniform plant behavior are related to genetic similarity, small differences in nutrient or water availability, and climate (Jackson, 1966). Other studies from arid ecosystems report interference in mapping attempts due to local, stochastic precipitation events (e.g., Karnieli et al., 2002; Wagenseil and Samimi, 2006). These precipitation events caused local greening of otherwise dry vegetation and resulted in reflectance patterns not bound to patterns of species composition. The appearance of such heterogeneities in the vegetation conditions hence interferes with the statistical relation between vegetation patterns and reflectance.

Although such effects frequently appear, their influences on mapping accuracy are (at least in temperate regions) often neglected. Most remote-sensing approaches presume (and require) spatial stationarity and are hence impaired by heterogeneity in vegetation conditions. No study to date has explicitly addressed the role of enhancing or interfering vegetation conditions on the consistency of hyperspectral remote sensing of plant assemblages over time and space. Hence, the objective of this study was to examine the stability of statistical relations between species composition and reflectance despite spatiotemporally changing vegetation conditions. For analysis, we considered: (1) How stable are these relations despite temporally changing vegetation conditions?, and (2) are the relations affected by spatial differences in the respective vegetation conditions?

2. Materials and methods

2.1. Study area

Three temperate biotopes (a nutrient-poor grassland, a wet heath, and a floodplain meadow) near Cologne, Germany were used as test sites (Fig. 1a). All sites were part of conservation areas according to federal and European (Natura 2000 Networking Programme) regulations. The nutrient-poor grassland (hereafter referred to as poor grassland) was a mosaic formed by two assemblages: first, the low growing *Agrostis capillaris–Holcus mollis* grassland community on undisturbed areas and second, the *Calamagrostis epigejos* community, partly as facies of the *Epilobio angustifolii–Digitalietum purpureae* as successional stage favored by disturbance. This site covered 26 ha. The wet heath (12 ha of *Ericetum tetralicis* dominated by *Molinia caerulea*) consisted of low growing heather (*Calluna vulgaris* and *Erica tetralix*), interspersed with tussocks of *Molinia caerulea* and *Sphagnum* mosses in wet hollows. The nutrient-rich floodplain meadow (12 ha of *Arrhenatheretum elatioris* with transitions to *Filipendulion*) was covered with dense grassland vegetation and tall forbs. We established permanent plots at all sites ($n = 57$ at the poor grassland, $n = 36$ at the wet heath, and $n = 37$ at the floodplain meadow) following a constrained random sampling design with enforced minimum inter-plot distances of 5 m. Areas in the shade of trees or shrubs were avoided. The resulting plot arrangement is shown in Fig. 1b–d. The plots were of circular shape and covered 1 m² each. Plot positions were permanently marked with stakes.

2.2. Data collection and processing

For reflectance measurements we used a field spectrometer (ASD Fieldspec 3 JR^{TM}, ASD Inc. Boulder, CO) covering a spectral range from 350 nm to 2500 nm in 2151 bands. The measurements were taken within a two-hour period around solar noon with a handheld probe leveled in nadir view 110 cm above the canopy. The use of a tripod to fix the orientation of the spectrometer probe as sometimes recommended (e.g., Pfitzer et al., 2006) was not implemented in this study for two reasons. First, it was not practicable in the wet heath and floodplain meadow due to unstable ground and dense vegetation. Second, the adjustment of a tripod at each plot would have been too time-consuming and may have also acted as mechanical disturbance to the vegetation structure. Instead, each measure was taken in five repetitions per date to enable an estimation of the resulting uncertainties. With the instrument's field of view of 25°, each measure covered approximately 1/5 of a plot's surface; the whole plot was hence covered with five spot measures. The measures quantified canopy reflectance relative to a reference Spectralon™ panel (Labsphere Inc., North Sutton, NH). The reference was taken at intervals of less than 5 min. Per site, multiple dates were chosen with respect to adequate atmospheric conditions (no clouds or haze covering the sun) for the acquisition of reflectance data. These dates were distributed as evenly as possible across the vegetation period. Seven sampling dates were realized for the poor grassland, five for the wet heath (due to the shorter vegetation period), and six measuring dates for the floodplain meadow.

Water absorption bands were removed during preprocessing. The spectra of the five spot measures within each plot were subsequently averaged to plot-based spectra (each repetition separately). The resulting data set with five repetitions per date and site was smoothed with a Savitzky–Golay filter (Savitzky and Golay, 1964). The spectral resolution was finally averaged to that of the HyMap sensor (125 spectral bands covering a range from 450 nm to 2480 nm) to reduce the asymmetry between the number of spectral bands and the number of plots. Because canopy-reflectance measures at close range are affected by shade resulting from the vegetation structure, we finally performed a brightness normalization of the spectra to eliminate brightness differences (Feilhauer et al., 2010a).

Simultaneous to the reflectance measures, the plant species composition of the plots and additional co-variables were assessed quantitatively. The records comprised visually estimated cover fractions of all photosynthetically active plant species (vascular plants and mosses) to quantitatively assess the species composition. As co-variables, cover fractions of standing litter, bare soil, open water (if present), and plot–based average canopy height (measured with a tape) were estimated. The visual estimations were always carried out by the same experienced person using a frame. Although cover estimates may be prone to errors (e.g., Bergstedt et al., 2009; Klimeš, 2003), this technique is frequently considered as good trade-off between sampling