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Airborne hyperspectral data predict Ellenberg indicator values for nutrient and moisture availability in dry grazed grasslands within a local agricultural landscape

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ABSTRACT

Species-based ecological indices, such as Ellenberg indicators, reflect plant habitat preferences and can be used to describe local environment conditions. One disadvantage of using vegetation data as a substitute for environmental data is the fact that extensive floristic sampling can usually only be carried out at a plot scale within limited geographical areas. Remotely sensed data have the potential to provide information on fine-scale vegetation properties over large areas. In the present study, we examine whether airborne hyperspectral remote sensing can be used to predict Ellenberg nutrient (N) and moisture (M) values in plots in dry grazed grasslands within a local agricultural landscape in southern Sweden. We compare the prediction accuracy of three categories of model: (I) models based on predefined vegetation indices (VIs), (II) models based on waveband-selected VIs, and (III) models based on the full set of hyperspectral wavebands. We also identify the optimal combination of wavebands for the prediction of Ellenberg values. The floristic composition of 104 (4 m × 4 m grassland) plots on the Baltic island of Öland was surveyed in the field, and the vascular plant species recorded in the plots were assigned Ellenberg indicator values for N and M. A community-weighted mean value was calculated for N (mN) and M (mM) within each plot. Hyperspectral data were extracted from an 8 m × 8 m pixel window centred on each plot. The relationship between field-observed and predicted mean Ellenberg values was significant for all three categories of prediction models. The performance of the category II and III models was comparable, and they gave lower prediction errors and higher R^2 values than the category I models for both mN and mM. Visible and near-infrared wavebands were important for the prediction of both mN and mM, and shortwave infrared wavebands were also important for the prediction of mM. We conclude that airborne hyperspectral remote sensing can detect spectral differences in vegetation between grassland plots characterised by different mean Ellenberg N and M values, and that remote sensing technology can potentially be used to survey fine-scale variation in environmental conditions within a local agricultural landscape.

1. Introduction

Bio-indicator values are often used in ecological research and conservation management to analyse changes in vegetation and in the environmental variables that influence plant community composition (Diekmann, 2003). Plant indicator values are based on the fact that plant species have specific habitat requirements. Because local environmental conditions may vary markedly in both time and space, data (for example, chemical data on soil nutrients) from a single time-point may not be representative of the environmental conditions that have influenced the present species composition of the vegetation within a site (Diekmann, 2003). In contrast, plant indicator values provide an indirect, but integrated, reflection of the response of the plant community to the environmental conditions at a particular site (Diekmann, 2003). Ellenberg et al. (1991) developed a set of indicator indices (based on ordinal scales), for environmental variables such as moisture, nutrients and pH, for central European plant species. These indices are based on a substantial amount of field data on the habitat preferences of individual species, and can be used to provide reliable indirect information about environmental conditions in, for example, grassland habitats (Schaffers and Sykora, 2000; Chytrý et al., 2009). Although concerns

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have been raised about the use of Ellenberg values in areas outside central Europe (Hill et al., 2000), many studies confirm that they can be reliably applied within much of northern Europe (e.g. Persson, 1981; Thompson et al., 1993; Schaffers and Sykora, 2000; Rowe et al., 2011). For example, Reitalu et al. (2014) used Ellenberg indicator values to characterise the environmental preferences of vascular plant species within dry grasslands, in the Baltic Sea region in northern Europe.

One limitation of using floristic observations as a proxy for environmental conditions is the fact that field-sampling is usually carried out at the scale of plots within geographically limited areas (Schmidtlein, 2005). Plot-scale information within limited areas cannot deliver the detailed information about changes in environmental factors over large geographic areas that is often required in ecological research and conservation planning. Remote sensing technology, on the other hand, can provide continuously updated fine-scale information over large areas. It has been suggested that remote sensing may have the potential to support and supplement field-based inventories of vegetation data (Turner et al., 2003; Gillespie et al., 2008; Rocchini et al., 2010), allowing the assessment of fine-scale environmental conditions over wide areas.

There have been substantial structural changes in the European landscape during the last century, involving both the intensification and abandonment of agriculture. These changes have led to the fragmentation of grassland habitats, creating mosaics of disjunct grassland fragments with different histories of grazing continuity (Johansson et al., 2008; Dengler et al., 2014). The continuity of grazing management can have a significant influence on the availability of nutrients in grassland soils (Austrheim and Olsson, 1999; Breuer et al., 2006). Old grasslands, with a long continuity of grazing management, are often characterised by a lower availability of nutrients and a higher plant species diversity than younger grasslands (Pykälä et al., 2005; Purschke et al., 2013).

Nutrient-poor dry grasslands with a long history of grazing management are one of the most species-rich habitats in the European agricultural landscape (Dengler et al., 2014), contain many rare and threatened plant and animal species, and may contribute to the provision of ecosystem services, such as pollination and carbon sequestration, in agricultural landscapes (e.g. Daily, 1997; Tscharntke et al., 2005). The protection of nutrient-poor dry grassland habitats helps to moderate the accelerating loss of farmland biodiversity, and is identified as a conservation priority throughout Europe (Öster et al., 2007). In addition to the preservation of old, grazed grassland habitats, the transformation of abandoned arable land into grazed grassland opens up new possibilities for mitigating farmland biodiversity loss (Bakker and Berendse, 1999). Optimising the spatial distribution of grassland sites can promote the dispersal of species between sites that vary in nutrient status, facilitating the development of species-rich and diverse vegetation in grasslands with low species diversity (Eriksson et al., 2002). Ellenberg indicator values can be used as a proxy for soil nutrient (Ellenberg N) and moisture (Ellenberg M) availability (Diekmann, 2003; Rowe et al., 2011; Wagner et al., 2007), and environmental assessments based on Ellenberg values can be used as tools in conservation management (de Bello et al., 2010; Lewis et al., 2014).

Variation in the overall soil nutrient and moisture status between grassland habitats leads to between-habitat variation in plant community characteristics such as above-ground biomass (Maestre and Reynolds, 2006), field-layer height (Ceulemans et al., 2011), and the chlorophyll content of the vegetation (Filella and Peñuelas, 1994). The biochemical and biophysical properties of plant communities affect the spectral reflectance from vegetation (Asner, 1998; Ollinger, 2011), and variation in remote sensing data can therefore be expected to be related to variation in Ellenberg indicators, which act as proxies for environmental conditions such as soil nutrient and moisture status in grassland habitats.

Earlier studies based on remote sensing have shown that imaging spectroscopy (hyperspectral remote sensing) can be successfully used to assess Ellenberg N and M at different scales and in different vegetation types (Schmidtlein and Sassin, 2004; Schmidtlein, 2005; Hardy et al., 2012; Klaus et al., 2012). For example, Schmidtlein and Sassin (2004) assessed Ellenberg N and M at a plot scale in managed meadows in Germany, while Schmidtlein (2005) estimated the same two indicators at a landscape scale in mountain grasslands in Austria. Klaus et al. (2012) showed that Ellenberg N and M can be predicted using reflectance-based estimates of above-ground biomass in agricultural grasslands in Germany. However, to our knowledge, no studies have examined the relationships between remote sensing data and Ellenberg indicator values in northern European dry grasslands.

A range of different remote sensing-based approaches have been developed to characterise and quantify vegetation properties, such as above-ground biomass, in grasslands (Cho et al., 2007; Shen et al., 2008). A commonly used approach is to combine surface reflectance from two or more wavelengths into a vegetation index (VI). Many published VIs highlight specific properties of the vegetation, while suppressing the disrupting effects of, for example, variation in soil reflectance, and sun and viewing angle geometry (Dorigo et al., 2007; Roberts et al., 2011). Whereas many predefined VIs, such as the normalised difference vegetation index (NDVI) (Rouse et al., 1974), are significantly associated with different properties of the vegetation (Cayrol et al., 2000; Gould, 2000; Cheng et al., 2006; Heiskanen, 2006), a number of studies suggest that VIs based on all possible waveband combinations in hyperspectral data sets may lead to improved predictions of vegetation properties (Hansen and Schjoerring, 2003; Mutanga and Skidmore, 2004; le Maire et al., 2008; Yi et al., 2014).

Recently developed approaches to the monitoring of vegetation properties include novel types of VIs based on radiative transfer theory (Jin and Eklundh, 2014), and an increasing number of studies use partial least squares regression (PLSR) analysis of remotely sensed data to characterise and distinguish between different types of vegetation (e.g. Schmidtlein and Sassin, 2004; Feilhauer et al., 2011; Klaus et al., 2012; Dalmayne et al., 2013; Cole et al., 2014; Möckel et al., 2014). For example, Cole et al. (2014) showed that hyperspectral measurements, in combination with PLSR-based models, can be used in conservation management to monitor the success of peatland restoration projects.

In the present study, we examine whether airborne hyperspectral data can be used to predict Ellenberg N and M at fine spatial scales in a mosaic of different-aged dry grazed grasslands in an agricultural landscape on the Baltic island of Öland (Sweden). We used data from HySpex hyperspectral spectrometers (415–2501 nm) to predict Ellenberg N and M at a spatial resolution of 4 m × 4 m. We compared prediction quality using three different categories of predictive model: Category I models (based on predefined VIs) and Category II models (based on waveband-selected VIs) were developed using a univariate regression modelling approach, while Category III models (based on the full set of hyperspectral wavebands) were developed using PLSR. We asked the following questions: (1) can hyperspectral HySpex data be used to predict Ellenberg N and M in dry grazed grasslands using the Category I, Category II and Category III models, and (2) which wavelengths (415–2501 nm) are the most important for predicting Ellenberg N and M?

2. Material and methods

2.1. Study area and field sampling

The study was carried out on grassland plant communities within a 22.5 km^2 study area (centred on 56°40′49″ N, 16°33′58″ E)