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Fine-scale assessment of hay meadow productivity and plant diversity in the European Alps using field spectrometric data

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ABSTRACT

The potential of field hyperspectral remote sensing data for non-destructive assessment of hay meadow biomass and vascular plant diversity has been investigated. Spectrometric and agronomic data were acquired at peak biomass over 34 sites distributed at diverse elevation and slopes over an area of 220 km^2 in the Central Alps (Valtellina, Northern Italy). Different modelling approaches were tested to evaluate the predictive performance of spectral measurements: (i) the use of two band ratios of reflectance as input in ordinary least square regression models and (ii) the use of all reflectance bands as input in multivariate partial least square regression models. Each model was subjected to leave-one-out cross-validation and evaluated using the cross-validated coefficient of determination and the root mean square error. Fresh biomass and fuel moisture content were predicted with an average error of <20%, while Shannon Diversity Index and plant species richness were predicted with an average error of <15%, with no relevant differences between the two modelling approaches. Best models for plant diversity indicator prediction were based on chlorophyll/nitrogen sensible bands in the blue and red spectral regions. This observation together with the apparent negative correlation between hay meadow plant diversity and canopy chlorophyll/nitrogen content in the study area suggests a potential connection between reflectance and plant diversity indicators based on meadow biochemical properties.

1. Introduction

Permanent hay meadows are the source of a wide range of public goods and services, including high quality forage, protection from natural hazards, recreational and tourism opportunities (Peter et al., 2008), and greenhouse gases sequestration (Gilmanov et al., 2007). Nowadays, European grasslands are disappearing at an alarming rate (12.8% from 1990 to 2003, according to FAO, 2006) and are among Europe's most threatened ecosystems. As a consequence, permanent hay meadows are protected in the European Natura 2000 network, which comprises Sites of Community Importance (SCI), designated under the Habitats Directive (92/43/EEC of 21 May 1992). Developing new methods for spatial characterization and monitoring of hay meadow biophysical and ecological properties is thus fundamental for the sustainable management, valorisation and conservation of their productive and ecological functions.

Several studies have shown that narrow-band vegetation indices derived from hyperspectral remote sensing data provide essential information for assessing biophysical (Thenkabail et al., 2000; Mutanga and Skidmore, 2004) and biochemical characteristics of vegetation (Fava et al., 2009). Nevertheless, vegetation indices are generally calculated using few spectral bands, underutilizing the information provided by hyperspectral sensors, which acquire spectral data in tens to hundreds of bands. Indeed, recent studies have focused on multivariate statistical models, like partial least square regression (PLSR), to exploit all the information available from hyperspectral data and to use several bands in model development (Schmidtlein and Sassin, 2004). Yet a limited number of studies have investigated the use of PLSR models for grassland biophysical and biochemical properties assessment (Cho et al., 2007; Darvishzadeh et al., 2008), and research is needed to understand if these statistic models can improve the predictive potential of hyperspectral remote sensing data compared to traditionally used vegetation indices.

Parallel to the research of methods for estimating grassland biophysical and biochemical properties, in the last few years

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growing interest has been addressed toward the use of remote sensing for biodiversity assessment (Gillespie et al., 2008). Most studies have evaluated biodiversity through indirect approaches based on habitat classification mapping (Nagendra, 2001), which have limited applications for fine-scale diversity assessment established through quantitative indicators, such as plant species richness (PSR) or Shannon Diversity Index (SDI). Hyperspectral sensors, characterized by high spectral and spatial resolution, may offer new potential for overcoming these limitations and for developing biophysically-based approaches for fine-scale biodiversity assessment (Carlson et al., 2007; Nagendra and Rocchini, 2008), based on a direct connection between remotely-sensed data and diversity indicators. Recent studies found significant relationships between hyperspectral indices, PSR and SDI in forest ecosystems (Carlson et al., 2007; Kalacska et al., 2007), in American tall-herb grasslands (Carter et al., 2005), and wet meadows (Lucas and Carter, 2008), using airborne hyperspectral sensors.

Based on these considerations we planned a field experiment with the objective to evaluate the potential of field hyperspectral spectrometric data for assessing at the same time hay meadow biomass (fresh biomass weight and fuel moisture content) and plant diversity indicators (PSR, SDI). To address these issues we compared the performance of two modelling approaches: (i) linear regression models, with narrow-band indices (i.e. two band reflectance ratios) as independent predictors and (ii) multivariate PLSR models, using all reflectance bands (400–1000 nm range, 1 nm interval) as independent predictors.

2. Materials and methods

The study area comprises the central portion of Valtellina valley and its main northern lateral valley, Val Malenco (Northern Italy). The two valleys have an east–west and south–north orientation and cover some 220 km^2. Their climate is continental, with mean annual temperature of 11–12 °C and rainfall of 970 mm (Sondrio, 307 m a.s.l.), the growing season spanning from April to September. Hay meadows represent the main land agricultural type of the region. According to Gusmeroli et al. (2008), four main hay meadow communities can be identified in the study area: lowland mesophilous meadows (*Pastinaco-Arrhenatheretum* Passarge 1964), submontane slightly thermophilous meadows (*Ranuncolo bulbosi-Arrhenatheretum Ellmauer in Ellmauer et Mucina* 1993), mountain meadows (*Trisetetum flavescentis* Rübel 1911), and transition meadows in the montane belt, ascribed to *Agrostio-Festucion* Puscaru et al. 1956. The presence of high representative and widespread mountain and lowland hay meadows belonging to *Arrhenatherion elatioris* and *Polygono-Trisetion* alliances (EU habitats 6510 and 6520, according to Habitats Directive) was also documented. Lowland hay meadows are generally mown 3–4 times per year, submontane and montane meadows 3 and 2–1 times per year, respectively. In the bottom valley meadows are generally subjected to more intensive agricultural use (i.e. fertilization treatments, mechanical farming operations), while in the slopes they are gradually abandoned, leaving space to woody species encroachment.

2.1. Field measurements

Plant species composition and diversity indicators were derived from an extensive phytosociological study conducted by Gusmeroli et al. (2008) in 2005 on 210 hay meadows in the study area, using the Braun-Blanquet methodology (Braun-Blanquet, 1965). All vascular plants were detected in 10 m × 10 m plots and the percentage cover was visually estimated. Plot location was selected randomly in each meadow, with a minimum distance of 10 m from the meadow border, in order to reduce edge effects. From these data, plant species richness (PSR) was measured as the sum of all taxa identified in each plot, while Shannon Diversity Index (SDI) was measured as [Eq. (1)]:

$$\mathrm{SDI} = \sum_i p_i \ln(p_i) \quad (1)$$

where p_i is the proportional abundance of the ith species. Each plot was geo-located with a Differential GPS (Trimble GeoXT). In 2006, among the 210 relevés, 34 sampling sites representative of the variability of hay meadow species composition in the region were selected for the experimental work. The exact location of the previous year phytosociological survey plots was individuated by Differential GPS, and it was verified by an expeditive analysis that no change in hay meadow botanical composition occurred.

Plant biomass was sampled at meadow first biomass peak, just before the first hay cut. This was made in order to characterize meadow production at the same growth stage, independently from the site elevation and exposure. To meet this task, four field surveys were performed in 2006, in May 15th, June 5th, June 15th, and July 5th. Fresh biomass (FB, t ha^{-1}) was clipped along a linear transect 7 m long and 1 m wide and weighted immediately after cutting. A sub-sample of the total biomass was used for biomass dry weight (DB, t ha^{-1}) determination after drying in ventilated oven at 70 °C until constant weight. Finally, the biomass water content, expressed as fuel moisture content (FMC, %), was calculated as the difference between FB and DB divided by FB.

Spectrometric data were collected just before biomass sampling using an ASD Fieldspec HandHeld spectroradiometer. This instrument measures the target radiance in the visible and near-infrared region (325–1075 nm) with a Full Width Half Maximum (FWHM) of 3.5 nm and a spectral resolution of 1 nm. A cosine diffusor foreoptic was mounted on the instrument probe and reflectance was calculated as the ratio between vegetation irradiance (sensor pointing nadir) and sky irradiance (sensor pointing zenith). The instrument was placed on a tripod with a rotating horizontal arm in order to minimize operator influence on the incident radiance. The foreoptic was positioned 70 cm above canopy height. Since the radiance upwelling from the target is "weighted" by cosine law in the measured upwelling irradiance, 90% of the signal came from a circular area having a radius of 1.92 m. Spectra were collected in clear sky conditions around solar noon every 1.4 m along each transect (five measurement spots per transect). Each spectrum was calculated as the average of minimum 10 readings. Transect mean reflectance and coefficient of variation (CV) were finally calculated.

2.2. Data analysis

A correlation analysis between transect mean reflectance in the 400–1000 nm range and all the investigated variables was first performed. For diversity indicators the correlation analysis was extended also to the transect CV of reflectance. Statistical significance of the correlation was evaluated with the Student's *t*-test.

An ordinary linear least square regression (OLSR) analysis was performed between narrow-band reflectance ratios and the investigated variables. Narrow-band ratios (Ri/Rj, where R is reflectance and i and j are sensor bands) were calculated using all the possible two band combinations from 400 to 1000 nm. In order to evaluate vegetation index saturation an exponential fit was also tested.

Finally, a partial least square regression (PLSR) (Wold, 1966) analysis between spectral reflectance and the investigated variables was carried out. In order to avoid model over-fitting, the optimal components of the PLSR were selected minimizing the cross-validated root mean square error ($\mathrm{RMSE_{CV}}$) and adding an