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Spectral monitoring of wheat canopy under uncontrolled conditions for decision making purposes

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ABSTRACT

The increase in the supply of devices for acquiring spectral images has enabled its widespread adoption by farmers. These devices combine technical quality and ease of use, but the abandonment of experimental stations has led to the loss of the scientific supervision, which is necessary for the fulfilment of operating conditions. The aim of this study is to quantify the quality of the spectral images taken under uncontrolled conditions. With this objective, workflows in real plots were simulated for three years. Surveys were carried out by a spectral camera mounted on a ground platform without additional systems to control lighting, sun-target-sensor geometry and interferences. Images were processed using the empirical linear method and a set of five references, so that the goodness of fit is the first quality estimator. Over 97% of images reach a coefficient of determination equal to or above 0.75 at all wavelengths. The images were also compared with the spectral signatures obtained by a field radiometer and with images acquired by an airborne hyperspectral sensor. This allows us to quantify the error in determining the crop reflectance and to assess the effect of the uncontrolled conditions. The median error in comparison with data from the field radiometer is 0.01, 0.02 and 0.03 (green, red and near-infrared respectively) and with the airborne hyperspectral sensor the error is 0.01 or lower. The geometry is the key factor but it can be controlled and it is possible to use successfully the current methodologies for the agronomic interpretation. The monitoring quality is comparable, from a practical point of view, with more sophisticated instruments, but there is a need to find a solution to a bad timely operation of the camera for efficient operation of the workflow.

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1. Introduction

Studies supporting the use of spectral measurements in precision agriculture are abundant in the scientific literature (Rodriguez-Moreno and Llera-Cid, 2011; Schepers and Francis, 1998). These improvements are becoming more accessible to the farmers due to increased supply which is reducing cost. Other key factors have been the improvement in ease of use and technical quality (Stafford, 2007).

The ease of use is achieved by automating tasks such as the adjustment of the gain and offset and the radiometric correction. These compact devices can be installed in drones (Schellberg et al., 2008; Zarco-Tejada et al., 2012), which implies the need for geometric and atmospheric correction, both of which can be also automated. The geometric correction is possible thanks to information provided by the navigation system of the drone. The atmospheric correction is made using the information contained in the image itself (Bernstein et al., 2005).

With regard to technical quality, if these devices are operated by scientists and they are used to sample agricultural experimental station, then they reach very high levels of accuracy and precision (Damm et al., 2014; Guanter et al., 2013). There are proven solutions for all necessary transformations such as instant radiometric correction by the image metadata, automatic geo-rectification using integrated systems, and an advanced atmospheric correction, enabling the estimation of the solar-induced chlorophyll fluorescence from aircraft and satellites (Joiner et al., 2013).

One of the remaining tasks is to quantify the error in the spectral images when they are obtained in uncontrolled conditions and

Abbreviations: BRDF, bidirectional reflectance distribution function; ELM, empirical linear method; NDVI, Normalized difference vegetation index; PTFE, polytetrafluorethylene; R^2, determination coefficient.

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are included in the agricultural workflow (Bolaños-González et al., 2007; Broge and Leblanc, 2001; Epiphanio and Huete, 1995). This means that the images are integrated into decision making and, therefore, are taken in a narrow time window and without on-site verification. Protocols for making spectral measurements establish the optimum conditions for light and sun-target-sensor geometry along with the interference sources to be avoided (Kim et al., 2010; Vigneau et al., 2011). When the time window for imaging is narrow and the scenario is not an experimental farm, requirements under such real conditions could only be met partially.

This study evaluates the quality of the images taken for monitoring of winter wheat using a multispectral camera for 3 growing seasons. In addition to covering the whole development of different cultivars under different nutritional regimens, these images are also representative of possible lighting conditions, sun-target-sensor geometry, weather and other interferences (dew, dust, etc.).

This is a complex scenario with highly variable adverse conditions (inter-day and intra-day due to the time required for sampling). Additionally, it includes the fact that a high spatial resolution camera is incompatible with the hypothesis of a Lambertian behavior resulting from integrating different surfaces (Bousquet et al., 2005; Combes et al., 2007; Yi et al., 2008). This study also serves to determine the magnitude of the effects of this deficiency in real conditions because the data necessary to model the bidirectional reflectance distribution function (BRDF) is not available.

The major goal of this study is to quantify the quality of the spectral images of wheat in Central Europe taken under uncontrolled conditions for decision making purposes. The percentage of valid images (those free of errors in radiometric correction and conversion to reflectance) determines the feasibility of its inclusion in the agricultural workflow. Quantification of the error in estimating the crop reflectance is necessary for improving the methodology used in the agronomic interpretation of the data. The data set will also be used to quantify the magnitude of the effect of the unknown bidirectional reflectance distribution function, which is achieved by analyzing the correspondence between the spectral measurements obtained by the different instruments (proximal and remote measurements). It is necessary to know whether it is possible to continue the time series or to replace an entry with another in a decision making process.

2. Materials and methods

2.1. Location and agronomic trial

The data used in this study were obtained in the agricultural experimental station of the Mendel University located in Žabčice (49°01′N, 16°37′E and 179 m above sea level), South Moravia. It is a plain near the river Svratka with uniform soil of the type Gleyic Fluvisol (FAO, 2006). The average annual temperature is 9.2 °C and the average annual precipitation is 483 mm. The average potential evapotranspiration exceeds by 15.5 mm the total precipitation, the average minimum temperature is 4.6 °C and the ground is covered with snow for an average of 45.6 days per year.

The experiment (Fig. 1a) is based upon an agronomic trial with winter wheat and a randomized split–split-plot design with four replications. It tests the effects of the following factors: (1) cultivars (Bohemia, Mulan and Seladon), the (2) nitrogen fertilization (0, 80 and 160 kg per ha) and the (3) seeding density (2, 3.5 and 5 million germinated seeds per ha). The 108 experimental plots, with an area of 10 square meters each, were mapped using an RTK GPS receiver, which allows all samples to be georeferenced with a spatial resolution of centimeters.

2.2. Crop spectral monitoring

Two of the four replicates (54 experimental plots) were sampled at key stages of crop development, BBCH 27/39/57/69 (Hess et al., 1997; Large, 1954), in the 2012–2014 period, making a total of 648 images. Simultaneously, crop samples were taken from each plot within a 0.25 m^2 square for analyses of the foliar nutritional status. An analysis was made in the lab to check the foliar nutrient concentrations.

Multispectral images were acquired by the DuncanTech MS3100 camera (Auburn, CA, USA). Its objective has a focal distance of 14 mm and a luminosity F/2 (Ratio between focal length and diameter of the diaphragm). It integrates three CCD with spectral filters, which record in three broad bands of the electromagnetic spectrum; Green in the range 500–600 nm with the peak at 550 nm, red in the range 600–700 nm and the peak at 650 nm, and near-infrared in 750–900 nm with the peak at 830 nm.

The MS3100 camera has already been used successfully in agricultural research (Abuzar et al., 2009; Backoulou et al., 2011; Kise and Zhang, 2008). In this case, it was installed on a mobile ground platform (Figs. 1b and 2a) to facilitate picture taking. The camera was positioned vertically at an angle of 90° with the ground surface. The height of the platform is 2.5 m, which corresponds with a spatial resolution less than 1 cm per pixel and the image area of 1.15 × 0.86 m (0.98 m^2). The platform was always placed so that the photographed area corresponded with the center of the plot, finding the edge of the plot at 1 m from the edge of the image, thus the edge effect is eliminated. Five spectral references (10%, 25%, 50%, 70% and 99% reflectance) with Lambertian surface were included in all the images. Spectral references were made of polytetrafluorethylene (PTFE) and characterized/monitored periodically in the laboratory by comparison with master reference (Moran et al., 2003).

During the second year, 2013, agricultural plots were also monitored by the FieldSpec Handheld 2 of ASD (Boulder, CO, USA), a photodiode array spectrophotometer (Garrity et al., 2010). This spectrometer has a spectral range of 325–1075 nm, a spectral resolution (FWHM) of 3.5 nm, a sampling interval of 1.6 nm, and a field of view of 25° (Fig. 1c). A total of 216 spectral signatures were obtained according to the manufacturer's protocol, and each signature resulted from the average of 20 readings. The measurements were distributed along the perimeter of the experimental plot, within the experimental plot. The device was elevated to a height of 2 m keeping the edge of the field of vision at 1 m from the edge of the plot in order to eliminate edge effects. The readings were taken at solar noon, simultaneously with the multispectral imaging by the MS3100.

Also during the second year, coinciding with the third sampling of the crop (one day after the third monitoring by the MS3100 camera), the agricultural experimental station was scanned with the AISA Eagle, an airborne hyperspectral sensor of Specim (Oulu, Finland). An image with a spatial resolution of 0.4 m per pixel and a spectral resolution of ~10 nm in the visible-infrared range (400–970 nm) was obtained. The system is shown in Fig. 1d and the image obtained in Fig. 2b. In order that Fig. 2 is more illustrative, the Normalized difference vegetation index (NDVI) is shown instead of the reflectance in one of the wavelengths. NDVI is calculated by dividing the difference in the near-infrared and red bands by the sum of the NIR and red bands (all expressed in terms of reflectance), the result is an indicator that describes the greenness (the relative density and health of vegetation). NDVI values range from +1 to −1. Rock, sand, or snow show low NDVI values, sparse vegetation such as shrubs and grasslands or senescing crops result in medium NDVI values and high NDVI values correspond to dense vegetation such as that found in tropical forests or crops at their peak growth stage (Barrett, 2004).

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