Crop monitoring using a light-weight hyperspectral mapping system for unmanned aerial vehicles: firs results for the 2013 season

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Abstract

To investigate the opportunities of unmanned aerial vehicles (UAV) in operational crop monitoring, we have developed a light-weight hyperspectral mapping system (< 2 kg) suitable to be mounted on small UAVs. Its composed of an octocopter UAV-platform with a pushbroom hyperspectral mapping system consisting of a spectrograph, an industrial camera functioning as frame grabber, storage device, and computer, a separate INS and finally a photogrammetric camera. The system is able to produce georeferenced and georectified hyperspectral data cubes in the 450-950 nm spectral range at 10-100 cm resolution. The system is tested in a agronomic experiment for a potato crop on a 12 ha experimental field in the south of the Netherlands. In the experiment UAV-based hyperspectral images were acquired on a weekly basis together with field data on chlorophyll as indicator for the nitrogen situation of the crop and LAI as indicator for biomass status.

Initially, the quality aspects of the developed light-weight hyperspectral mapping system will presented with regard to its radiometric and geometric quality. Next we would like to present the relations between sensor derived spectral measurements and crop status variables for a time-series of measurements over the growing season. In addition, the spatial variation of crop characteristics within the field can be adopted for variable rate application of fertilizers within the field. The outcome of the experiments should guide the operational use of UAV based systems in precision agriculture systems.

Keywords: Unmanned Aerial Systems (UAS), hyperspectral remote sensing, vegetation indices, chlorophyll, potato

1   Introduction

Changing needs in food production and associated food safety issues are challenging the agricultural sector to develop a new generation of sustainable agricultural systems. Remote sensing has been identified as a key technology to allow near real-time detection and diagnosis of crop status within the field. The availability of consistent time-series of sensor data with a high spatial and temporal resolution to detect anomalies in crop development is a critical user requirement for application of remote sensing in precision agriculture (Gebbers and Adamchuk, 2010; Hatfield and Prueger, 2010). Although satellite based remote sensing techniques have already proven to be relevant for many requirements of crop inventory and monitoring, they might lack flexibility to support anomaly detection at specific moments over the growing season. Therefore, complementary sensing technologies like unmanned aerial sensing (Zhang and Kovacs, 2012) and near-sensing systems referring to tractor mounted sensor systems (Tremblay et al., 2009) have been evaluated and are increasingly used in agricultural applications (Thessler et al., 2011).

Especially, imagery taken from unmanned aerial vehicles (UAV) are shown to be a potential alternative platform for crop monitoring, given their potential high spatial and temporal resolution, and their high flexibility in image acquisition programming. However, to make optimally use of the currently available constellation of sensors (satellite, (unmanned) airborne and near-sensing systems from tractors) for crop monitoring, innovative concepts and methods are required to integrate different sensing approaches (van Evert et al., 2012) and retrieve crop parameters from high-frequency time-series. From a sensor point-of-view, several studies have shown that an increased spectral resolution as available from hyperspectral systems provide the opportunity to estimate vegetation properties like chlorophyll, nitrogen (Clevers and Kooistra, 2012) and leaf water content (Clevers et al., 2011) with improved accuracies. However, research and operational opportunities using UAV remote sensing techniques are limited by the payload of the platform. Therefore small UAV's are typically not suitable for hyperspectral imaging due to the weight of the mapping system.

This paper presents the first results of a crop monitoring experiment in a potato field using a light-weight hyperspectral mapping system (< 2 kg) suitable to be mounted on small UAVs. As part of the experiment, the radiometric and geometric quality of the hyperspectral system was assessed, relations between vegetation indices derived from UAV acquired imagery and crop properties like chlorophyll and leaf-area-index were evaluated and crop property maps were prepared. Opportunities for UAV based sensing in precision agriculture are discussed.

2   Material and methods

Field experiment
A field experiment was conducted for a potato field in the south of the Netherlands during the growing season of 2013. In the field, plots of 30 by 30 m were prepared with four levels of N fertilization including three replicates (Fig. 1). The potato crop status was monitored on a weekly basis in the period June 6 till August 23, 2013 resulting in 11 observations. For the 12 experimental plots (Fig. 1), the chlorophyll status was measured using the Minolta SPAD-502 chlorophyll meter. Within every plot, four rows were measured (row 3 and 10 left and right to driving path) and for every row six plants and for every plant three leafs to characterize the variability within the plot. For this paper, an average SPAD reading of all measurements per plot as proxy for chlorophyll was used as input for the data analysis. The SPAD measurements were transformed to leaf chlorophyll (g/m2) using the regression relations derived by Uddling et al. (2007).

For the same plots, the leaf area index (LAI) was measured with the LAI-2000 instrument for the same rows in the experimental plots. At the beginning and end of the row an incoming radiance measurement above the canopy was taken, and divided over the row six measurements below the canopy. Based on these measurements and with the LAI-2000 accompanying processing software a LAI value per row was calculated. The product of leaf chlorophyll concentration and LAI yielded the canopy chlorophyll content used in this study.

Finally, spectral reflectance of the potato crop was determined weekly with a Cropscan Multispectral Radiometer (MSR16R). This is a 16-band radiometer, which measures simultaneously the reflected and incoming radiation in 16 narrow spectral bands (10 nm). Specifications are given in Clevers and Kooistra (2012). For the same four rows within a plot, six measurements per row were made and average spectra per plot were calculated and related to the measured crop properties.
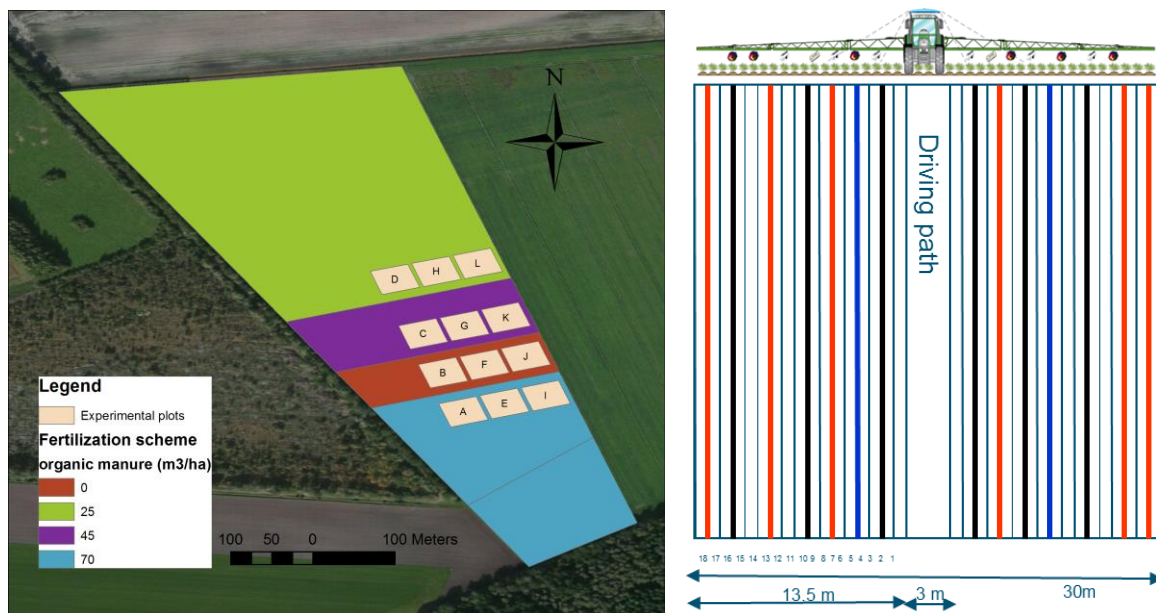

Fig. 1: Overview of fertilizer treatments in the experimental potato field (left) and the location of the measurement rows within the individual plots (right).

Hyperspectral mapping system
To evaluate the opportunities of UAV based hyperspectral remote sensing for potato crop monitoring, we had access to an octocopter based system (Aerialtronics Altura AT8) which can carry payloads up to 2 kg with an associated flight mission time of 5-8 minutes (Fig. 2). Based on these specifications, a hyperspectral mapping system was designed and implemented over the winter season of 2012/2013. The hyperspectral system (Fig. 2) consists of: a spectrograph (Specim ImSpector V10 2/3"); an industrial camera with integrated Digital Signal Processor (DSP) based frame grabber and computer (PhotoFocus SM2-D1312); a GPS inertia navigation system (INS, XSens MTi-G-700); and finally, a photogrammetric camera (Panasonic GX1 +14mm pancake objective) to produce the Digital Surface Model for orthorectification of the hyperspectral data. With the 12-mm spectrometer objective, the necessary wiring, a small LiPo battery, and an aluminium frame, the total take-off weight of the prototype system is 2.0 kg (Fig. 2).

A tailor-made processing chain was developed for hyperspectral mapping system which consists of the following steps (Suomalainen et al., 2013):
•   Photo radiometric processing: the raw airborne photogrammetric images are converted to 16-bit reflectance factor images;

Fig. 2: The light-weight hyperspectral mapping system consisting of an Aerialtronics Altura AT8 octocopter (left) and the mapping system (right) composed of a Panasonic Lumix GX1 camera, XSens MTi-G-700 INS, and a pushbroom spectrometer.

- Photo geometric processing: reflectance factor images paired with INS data are then imported in photogrammetric software – Agisoft PhotoScan Pro. The software is used to further align the images photogrammetrically (optionally with assist of RTK GPS ground control points), to calculate the DSM geometry, and to calculate a RGB reflectance factor;
- Datacube radiometric processing: using an empirical line correction the raw hyperspectral data cube is converted to reflectance factor units;
- Datacube geometric processing: Using the photogrammetrically enhanced image positions, the INS data is corrected for systematic bias errors, improving the alignment accuracy of hyperspectral lines. The reflectance factor data cube, with enhanced INS data, and the photogrammetric DSM is then input to ReSe PARGE georectification program (Schäpfler et al., 1998), producing a georectified reflectance factor data cube.

The hyperspectral mapping system was used to acquire imagery over the experimental field for four days over the growing season: June 6, June 14, July 5 and July 17, 2013. For every day, two flights with the hyperspectral mapping system were made, one covering the six southern plots of the experiment and one covering the upper six plots of the experiment (Fig. 1). After complete processing of the flight lines, the spectral images are joined and maps covering the surface area of all 12 experimental plots can be prepared.

Data analysis
The analysis of this paper focussed on the spatial and temporal variation of the crop properties within the experimental field. The following vegetation indices have been evaluated for the remote estimation of canopy chlorophyll content: REP, MTCI, MCARI/OSAVI, TCARI/OSAVI, CI_{green} and $CI_{red\ edge}$ (Clevers and Kooistra, 2012). The WDVI was evaluated for the estimation of LAI. The indices were calculated both for the cropscan spectra measured in the field and for spectra from the hyperspectral scanning system derived for a region-of-interest (ROI) within the 12 experimental plots. Intercomparison of the various vegetation indices has been performed by comparing the coefficients of determination (R^2 values) of linear estimators.

3   Results and discussion

Temporal development of crop properties
The growth of the potato crop over the growing season of 2013 was influenced by a relatively cold spring resulting in a delay in emergence of around two weeks. Fig. 3 and 4 present the development of the LAI en canopy chlorophyll, respectively, over the growing season for the twelve experimental plots. Initially, differences in biomass between the plots was relatively small (Fig. 3), starting from beginning of July clear differences can be observed between the different fertilization levels. At that point the soil nutrient pool for the low fertilized plots (plots B, F and J) is relatively low and hampering of aboveground crop growth can be detected. Until the end of July, differences in aboveground biomass between the plots are still clearly visible while in August, the decay of leaves results in more comparable LAI values again. In the beginning of July, non-organic fertilizer was added to some of the plots which resulted in a stabilization of the LAI, but due to a long dry period in, not all added nutrients could be effectively used by the plants. The effects of the nutrient addition on crop development requires further analysis.
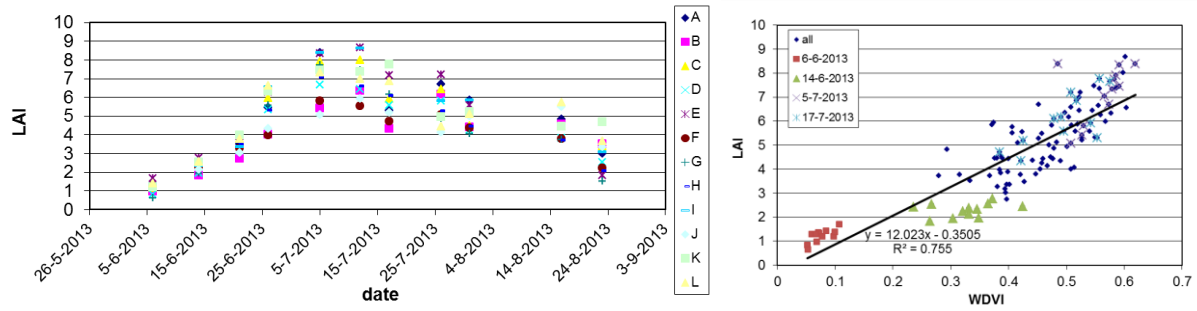
Fig. 3: Temporal development of leaf-area-index (LAI) over 2013 growing season for 12 experimental plots (left); and relation between cropscan measured weighted difference vegetation index (WDVI) and LAI (right).
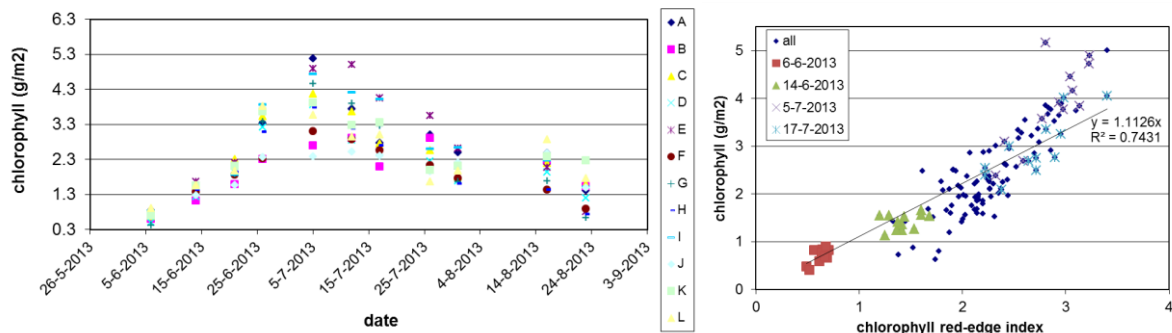

Fig. 4: Temporal development of canopy chlorophyll content over 2013 growing season for 12 experimental plots (left); and relation between cropscan measured chlorophyll red-edge index and chlorophyll content (right).

The Weighted Difference Vegetation Index (WDVI) as derived from the cropscan spectra gave a clear relation with the LAI (Fig. 3). In the beginning of the growing season the range of LAI values and associated WDVI values is relatively small (1 unit), while at the peak of the growing season it ranges from 4.5 till 8.5. Although the data could be fitted with a linear regression model ($R^2 = 0.755$), there seems a saturation tendency for higher LAI values.

The development of the canopy chlorophyll concentration shows a comparable pattern to LAI (Fig. 4). However differences between the plots in the beginning of July are even more pronounced. This can be explained by the combined effect of reduced values for both chlorophyll and LAI with lower fertilization levels. Fig. 4 shows also that clear relations were found between the evaluated chlorophyll red-edge index and the total chlorophyll content ($R^2 = 0.743$). The other indices performed worse in comparison to the $CI_{red-edge}$ according to their R^2 values: e.g., 0.678 for CI_{green}, 0.503 for NDRE, 0.712 for REP and 0.483 for TCARI/OSAVI. Especially the latter two indices were susceptible for the influence of soil reflectance in the beginning of the growing season. Additional research will be done on the use of spectral unmixing techniques for plant production systems (Tits *et al.*, 2013) to reduce the effect of soil background on the retrieval accuracy of crop properties.

Spatial variation of crop properties from UAV hyperspectral scanning system
Based on the point measurements with the cropscan instrument, we get an increased understanding of the radiation processes in cropping systems. However, for operational application of sensing systems in arable cropping systems, image-based sensors will be required, to get a detailed view on the spatial variation of crop properties within the parcel which can be adopted for variable-rate-application. The UAV based hyperspectral scanning system provides different products which can be used to support agricultural management practices. Fig. 4 presents the high resolution ortho-mosaic images (up to 25 mm) which have been acquired with photogrammetric camera for two points within the growing season: June 14, 2013 (left) and July 17, 2013 (right). A clear difference can be observed for the June 14 image, early in the growing season, with high soil background reflectance, compared to the peak season image of July 17. In the latter image the potato canopy is completely closed for a large part of the field. However, in the zero fertilized plots the soil between the rows is still visible (Fig. 4 right: see inset), while also for both dates the tractor paths are clearly standing out. Between the tractor paths differences in soil colour can be observed which are related to the soil moisture status of the soil. For July 17, the tractor path for the left plots was irrigated the day before image acquisition resulting in relatively darker soils, while the path for the plots in the middle would receive irrigation after image acquisition, resulting in relatively dry and bright soils. Further research will focus on the automated detection of soil, vegetation and shadow components within the image up to the level of individual plant detection by using super resolution mapping techniques (Tolpekin and Stein, 2009).
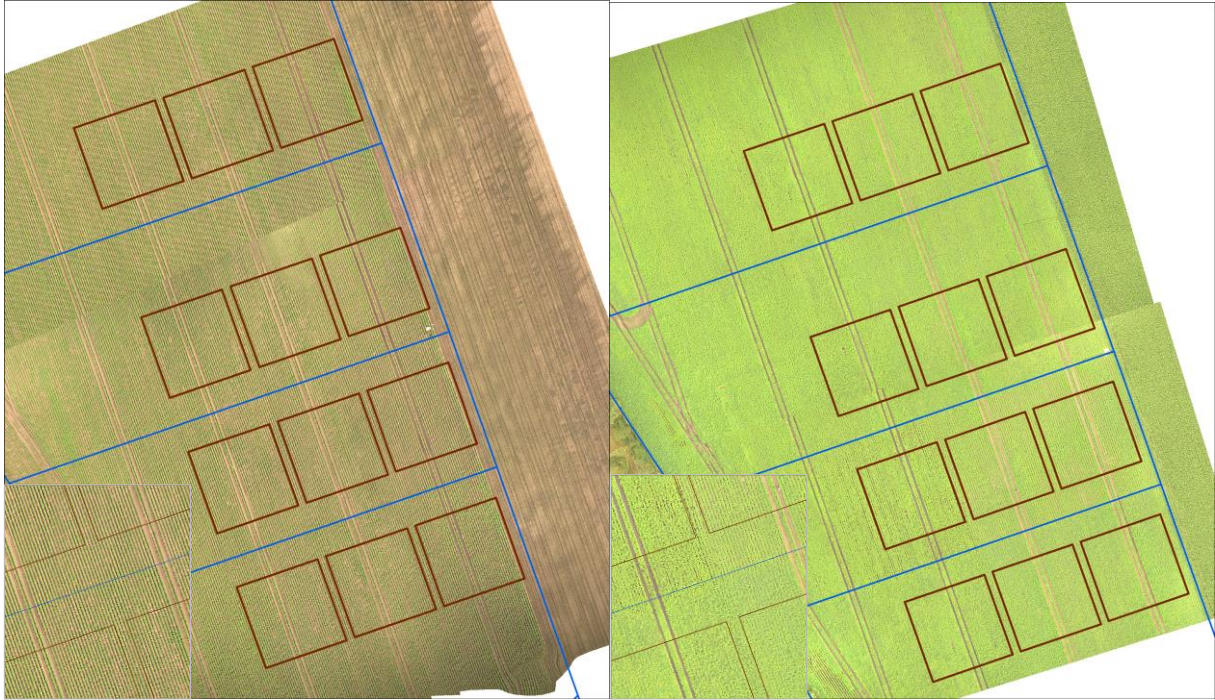
Fig. 4: Orthomosaic RGB image (25 mm) of experimental field on June 14, 2013 (left) and July 17, 2013 (right). The inset images show the boundary between fertilization level 0 and 70 m^3/ha.

To produce the orthomosaic image a large number of individual images have been stitched together using the Agisoft PhotoScan Pro software. Although the geometric quality of the images in general is good, some boundary effects can be observed when the individual images from the two different flight lines are combined. This is especially visible at the transition of the tractor driving paths from one flight line to the other.

Fig. 5 (left) shows the spectra from the hyperspectral data cube of the four acquisition dates for a plot with a zero fertilization level (F) and high fertilization level (E). Clear differences can be observed for the temporal development of the spectra, mainly visible in the NIR related to differences in aboveground biomass and to a lesser extent in the red band related to absorption of chlorophyll. The spectral quality is good, some variation can be observed in the shoulder of the NIR and in the blue band between 450 and 500 nm. In the next phase of the research, the radiometric quality will be evaluated in more depth.

Using the extracted spectra from the hyperspectral data cube for the four acquisition dates, the earlier mentioned vegetation indices were calculated and related to the total canopy content. Again the chlorophyll red-edge index gave a good relation (Fig. 5), but also the other indices performed well in comparison to the CI$_{red-edge}$ based on their R^2 value: 0.887 for CIgreen, 0.753 for NDRE, 0.871 for REP and 0.935 for TCARI/OSAVI. This result shows that the spectra of the hyperspectral mapping system are of sufficient quality to derive a chlorophyll estimation model.
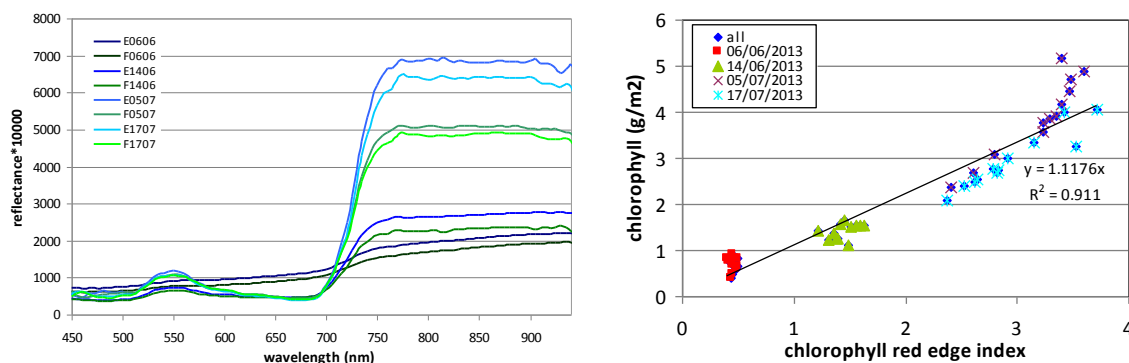

Fig. 5: Spectral curves of potato crop over growing season derived from hyperspectral mapping system for plot with high (E) and low (F) initial fertilization (left); relation between chlorophyll red-edge index derived from plot-averaged spectra of hyperspectral mapping system and canopy chlorophyll content (right).
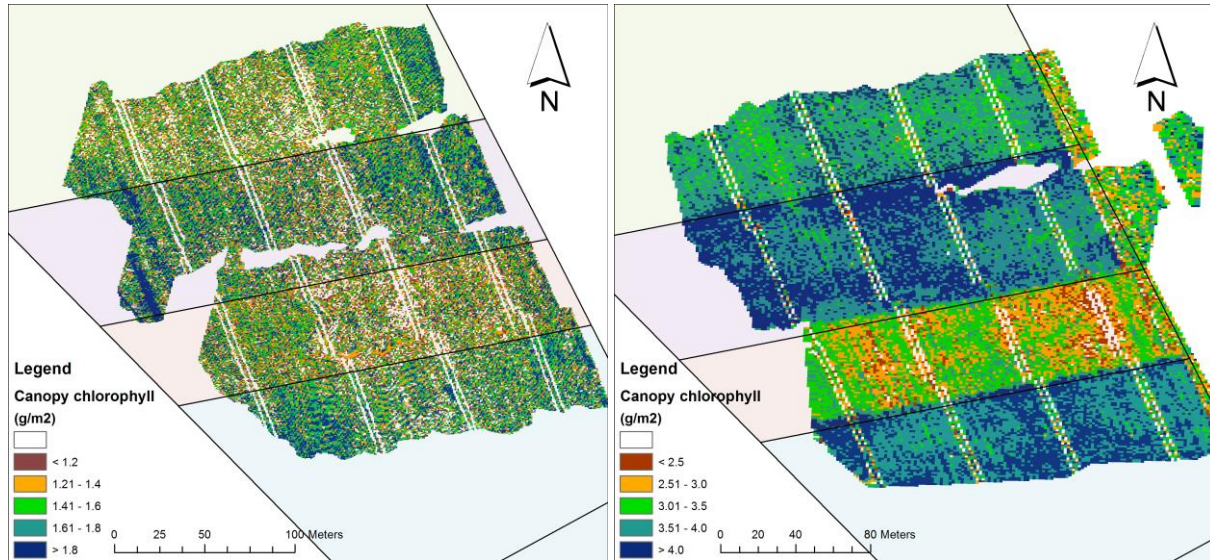
Fig. 6: Canopy chlorophyll maps for potato crop for hyperspectral data cubes acquired on June 14 (left) and July 17(right). Chlorophyll estimation is based on regression model of chlorophyll red-edge index as presented in Fig. 5.

Finally, the regression model for the chlorophyll red-edge index as presented in Fig. 5 was used to calculate continuous chlorophyll maps for the images acquired with the hyperspectral scanning system (Fig. 6). The maps show the overall increase in canopy chlorophyll content from June 14 to July 17 and the more pronounced differences at the peak of the growing season (July 17). The map of July shows more homogeneous patterns compared to the map of June 14 which can be explained by the difference in the spatial resolution of the two images (0.5 m and 1 m, respectively) and the increased influence of soil background for the image of June 14. Evaluation of the geometric quality of the two data cubes shows some clear differences with more deviations for the June 14 image as can be derived from tractor paths within individual flight lines but also transition of the tractor paths from one flight line to the next. The difference in quality can partly be explained by the difference in flight conditions (e.g., wind speed and direction) and the difference in altitude of acquisition. Further research will focus on the improvement of the acquisition protocols and the processing chain.

4   Conclusions

In this paper we present the first results for the lightweight hyperspectral mapping system developed for operation on an UAV platform. The system is composed of off-the-shelf components and has a weight of 1.9 kg which makes it feasible to fly with an Octocopter platform. As part of the mapping system, a processing chain was developed which combines cutting-edge photogrammetry (including GPS/INS data) with traditional hyperspectral georectification. Radiometric correction based on the use of a reference panel and empirical line correction gave a satisfactory spectral quality on the level of reflectance factors.

The hyperspectral mapping system was adopted for a crop monitoring experiment in potato. Vegetation indices based on red-edge bands were evaluated on their relation with measured chlorophyll concentrations in the field. The vegetation indices showed a good linear relation and the empirical model based on the chlorophyll red-edge index was used to derive continuous chlorophyll maps using the acquired hyperspectral data cubes. As chlorophyll is indirectly related to the nitrogen status of the potato crop, the maps could be used as an indication of the fertilization status of the crop and could be transformed to task maps for variable-rate application.

This paper presents the very first results of an experiment carried out in 2013 and more effort will be spend to come to insights to improve the hyperspectral mapping system and to develop (semi)-operational products and services for precision agriculture.

5   Acknowledgements

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