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Combining UAV-based plant height from crop surface models, visible, and near infrared vegetation indices for biomass monitoring in barley

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ABSTRACT

In this study we combined selected vegetation indices (VIs) and plant height information to estimate biomass in a summer barley experiment. The VIs were calculated from ground-based hyperspectral data and unmanned aerial vehicle (UAV)-based red green blue (RGB) imaging. In addition, the plant height information was obtained from UAV-based multi-temporal crop surface models (CSMs). The test site is a summer barley experiment comprising 18 cultivars and two nitrogen treatments located in Western Germany. We calculated five VIs from hyperspectral data. The normalised ratio index (NRI)-based index GnyLi (Gnyp et al., 2014) showed the highest correlation ($R^2 = 0.83$) with dry biomass. In addition, we calculated three visible band VIs: the green red vegetation index (GRVI), the modified GRVI (MGRVI) and the red green blue VI (RGBVI), where the MGRVI and the RGBVI are newly developed VI. We found that the visible band VIs have potential for biomass prediction prior to heading stage. A robust estimate for biomass was obtained from the plant height models ($R^2 = 0.80$–0.82). In a cross validation test, we compared plant height, selected VIs and their combination with plant height information. Combining VIs and plant height information by using multiple linear regression or multiple non-linear regression models performed better than the VIs alone. The visible band GRVI and the newly developed RGBVI are promising but need further investigation. However, the relationship between plant height and biomass produced the most robust results. In summary, the results indicate that plant height is competitive with VIs for biomass estimation in summer barley. Moreover, visible band VIs might be a useful addition to biomass estimation. The main limitation is that the visible band VIs work for early growing stages only.

1. Introduction

It is a well-known fact that biomass estimation is crucial for yield prediction of crops (Oerke et al., 2010). Crop parameters, like biomass, are frequently used to assess crop health status, nutrient supply and effects of agricultural management practices (Adamchuk et al., 2010). For management optimization, the nitrogen nutrition index (NNI) plays a key role (Chen et al., 2010; Tremblay et al., 2011). Biomass is needed for calculating the NNI (Lemaire and Gastal, 1997). A well-established method for biomass estimation is the calculation of vegetation indices (VIs) in the near infrared region (NIR) (Qi et al., 1994; Rouse et al., 1974), here defined as the range between 700 and 1300 nm (Kumar et al., 2001). Field spectroradiometers are commonly used for the collection of hyperspectral reflectance data that are used for such calculations (Clevers and Jongschaap, 2001; Kumar et al., 2001; Royo and Villegas, 2011).

An alternative possibility is to model biomass using plant height information. Lumme et al. (2008) and Tilly et al. (2014) demonstrated the suitability of the method in wheat, oat, barley and paddy rice. Plant height information is most useful when it is available at high spatial and temporal resolution. The method of multi-temporal crop surface models (CSMs) derived from 3D point clouds delivers the desired centimeter resolution (Bendig et al., 2013; Tilly et al., 2014). The method was studied for different crops by Hoffmeister et al. (2013, 2010),) for sugar beet, Tilly et al. (2014)

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for paddy rice and Bendig et al. (2014, 2013),) for summer barley. For small fields of a few hectares, suitable data collection platforms can be ground-based like terrestrial laser scanners (i.e., Hoffmeister et al., 2013; Tilly et al., 2014) or airborne like unmanned aerial vehicles (UAVs) (Bendig et al., 2014, 2013). Through the availability of high resolution consumer digital cameras, red green blue (RGB) aerial imaging with cm-resolution can easily be obtained using UAVs (D' Oleire-Oltmanns et al., 2012; Lucieer et al., 2014; Neitzel and Klonowski, 2012). At the same time, the emergence of structure from motion (SfM)-based software (Dandois and Ellis, 2010; Verhoeven, 2011) has enabled efficient creation of 3D point clouds and super high detail orthophotos.

Visible band VIs (VI_{RGB}) may be calculated from the orthophotos as demonstrated by Hunt et al. (2014, 2005). Motohka et al. (2010) used RGB-imagery obtained from a tower. These are some of the rare examples for small-scale field trials. Near infrared VIs (VI_{NIR}) are more widely used because of the characteristic difference between red and NIR reflection in green vegetation (Bannari et al., 1995). In addition, smaller, but significant spectral differences in the visible bands exist, which are caused by biochemical plant constituents such as chlorophyll (Hatfield et al., 2008; Roberts et al., 2011).

Collecting RGB-imagery by UAV is simple, cost-effective and VI_{RGB} can easily be calculated from the imagery. Consequently, the goal of this study is to investigate if UAV-based VI_{RGB} can compete with VI_{NIR} for biomass estimation. Crop monitoring by UAV-based RGB imagery enables obtaining the VI_{RGB} and the plant height information from the same dataset suggesting to combine both parameters to improve biomass estimation. According to Koppe et al. (2013), a combination of hyperspectral satellite imagery and radar can improve the model quality of biomass prediction. The objective of this study is to build up on this approach of combining the two parameters plant height and vegetation indices for biomass estimation by developing suitable regression models for UAV-based non-calibrated RGB imagery and ground-based hyperspectral reflectance data. We investigate the combination of VI_{NIR} and VI_{RGB} with CSM-based plant height information.

2. Materials and methods

2.1. Test Site

The study site is based at the Campus Klein-Altendorf agricultural research station (50°37′N, 6°59′E, altitude 186 m), located 40 km south of Cologne, Germany. In 2013, 18 summer barley (*Hordeum vulgare*) cultivars were planted, of which 10 were new cultivars and eight were old cultivars (Fig. 1, Bendig et al., 2014). They were treated with two levels of nitrogen fertilizer (40 and 80 kg N/ha). The experiment was organized in 36 small 3 × 7 m plots with a randomised order of the cultivars. Seedlings were planted with 300 plants/m^2 and a row spacing of 0.104 m. In addition, the plots are divided into a 3 × 5 m measuring area for plant height (PH) and reflectance measurements, and a 3 × 2 m sampling area for destructive biomass sampling. Biomass samples were taken frequently from April to July in 36 of the plots. For the UAV image collection, ground control points (GCPs) were evenly distributed across the field (Fig. 1). The positions were taken using a HiPer® Pro Topcon DGPS (Topcon Corporation, Tokyo, Japan) with 0.01 m horizontal and vertical precision. Later, the GCPs were identified in the images and used for georeferencing.

2.2. Biomass sampling and BBCH measurements

A destructive sample of 0.2 × 0.2 m above ground biomass was taken in the sampling area for each date (Fig. 1). The sampling dates were within one day before or after the UAV campaigns and the field spectroradiometer measurements. For the fresh biomass, the samples were cleaned, the roots were clipped and stem, leaves and ears were weighed. In a next step, the samples were dried at 70 °C for 120 h and dry biomass was weighed again for each plant. The weights were extrapolated to kg/m^2 for analysis. Plant growth stages were determined according to the 10 principal growth stages and 10 secondary growth stages of the “Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie” (BBCH) scale

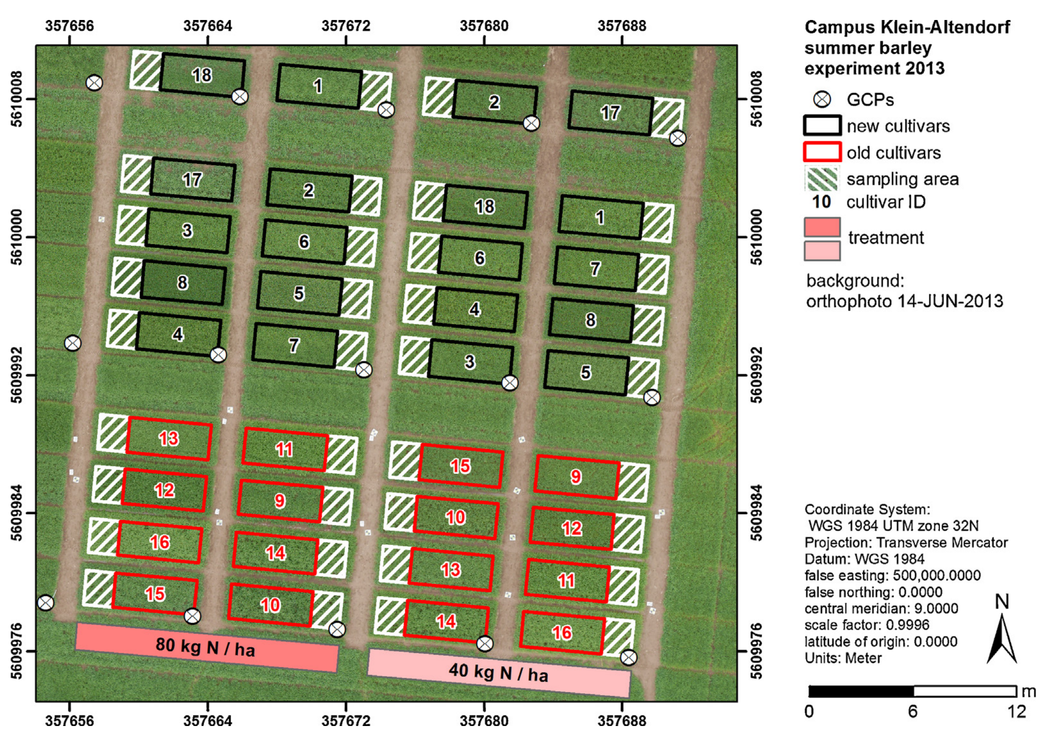

Fig. 1. Test site: summer barley experiment at Campus Klein-Altendorf agricultural research station in 2013 (Bendig et al., 2014); GCPs = ground control points used for crop surface model (CSM) generation.