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Are vegetation indices derived from consumer-grade cameras mounted on UAVs sufficiently reliable for assessing experimental plots?

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ABSTRACT

Recent technological advances in UAV (unmanned aerial vehicle) technology offer new opportunities for assessing agricultural plot experiments using UAV imagery. Vegetation indices (VIs) based on aerial images derived from consumer-grade cameras are a simple and cheap alternative compared to VIs derived from proximal (on-ground) sensors. The objective of this study was to assess whether VIs derived from consumer-grade cameras mounted on UAVs are reliable and whether there are any shortcomings in image acquisition and analysis that need to be addressed before their general application. This objective was investigated using a rotary-wing and a fixed-wing UAV, true colour (RGB) and colour-infrared (CIR) cameras, four different VIs (ExG, NGRDI, NDVI and ENDVI), altitudes in the range of 30–100 m, different ambient lighting conditions and two different software packages for stitching images together. Results were compared with ground-based recordings by consumer-grade cameras and multispectral sensors. Field experiments in cereals were used to evaluate the assessments. The study showed that VIs based on UAV imagery have the same ability to quantify crop responses to experimental treatments as ground-based recordings with cameras and advanced sensors. However, there are shortcomings that need to be taken into consideration: (1) angular variation in reflectance (bidirectional reflectance), (2) stitching and (3) ambient light fluctuations. Bidirectional reflectance was so extensive that it could lead to misleading conclusions in sunny conditions and this effect could be amplified further by stitching. A procedure for avoiding impacts from bidirectional reflectance is demonstrated when plots were cropped from individual images and a procedure is suggested for stitching images. Camera, VIs and image acquisition altitude were of minor importance, but fluctuating ambient lighting conditions is an issue that should be addressed in future studies.

1. Introduction

Unmanned aerial vehicles (UAV) have become popular for taking aerial snapshots, and recent technological advances in UAV technology have increased interest in their application in precision agriculture (Zhang and Kovacs, 2012; Huang et al., 2013; Christensen et al., 2014). Valuable information on crop heterogeneity can be extracted from aerial photos by visual interpretation, but digital image analysis is required to take the application a step further.

A common and simple way of extracting information about crops from digital images is through the estimation of vegetation indices (VIs). These are arithmetic calculations on light reflected at different wavelengths. Different VIs highlight various vegetation properties (Agapiou et al., 2012; Hunt et al., 2013; Li et al., 2014) and they vary due to different spectral wavebands used in calculations, different spectral resolutions (waveband widths) and different arithmetic calculation formulas. One of the most commonly used VIs is the normalised difference vegetation index (NDVI), which is the ratio of near infrared (NIR) minus red over NIR plus red (Tucker, 1979). This index is often referred to as a measure of biomass, chlorophyll content, nitrogen content or something else entirely, but it is primarily an indicator that correlates with biomass and other vegetation parameters. Exact biomass

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measurement requires destructive sampling methods. The spectral signature of the reflected light from crops is affected by plant-related factors such as plant morphology and physiology (Gates et al., 1965) and by soil in open canopies. The reflectance of the visible light mainly relies on the leaf chlorophyll content (Daughtry et al., 2000), and near-infrared (NIR) reflectance mainly relies on the leaf structure (Knipling, 1970). This means that with a green leaf and a yellow leaf, visible light will reflect differently even though NIR reflectance may be unaffected.

Recent agricultural studies based on VIs calculated from UAV images have demonstrated a variety of applications, such as mapping of leaf cover in cereals (Kipp et al., 2014; Torres-Sánchez et al., 2014), chlorophyll content in cereals (Berni et al., 2009), weed infestations (Torres-Sánchez et al., 2013), plant diseases (Garcia-Ruiz et al., 2013) and crop impacts from weed control (Rasmussen et al., 2013; Streibig et al., 2014). Thermal imagery has also shown promising results for detecting water stress in cereals (Berni et al., 2009) and vineyards (Bellvert et al., 2014), and 3D models generated on the basis of images originating from digital consumer cameras have provided accurate olive tree height measurements that are comparable with expensive LIDAR systems (Zarco-Tejada et al., 2014).

VIs are useful for mapping spatial variability within plots and fields (Govaerts et al., 2007; Mulla, 2013) and constitute the basis of precision agriculture, which requires cost-effective crop monitoring for site-specific application of fertilisers and pesticides (Dammer and Wartenberg, 2007; Shanahan et al., 2008; Merotto et al., 2012; Portz et al., 2012).

Measurements are taken with a variety of sensors (Erdle et al., 2011; Peteinatos et al., 2014), ranging from non-imaging opto-electronic sensors to image-generating sensors, from low-cost consumer-grade cameras to high-cost spectroradiometers, from passive sensors to active sensors providing their own light source, and from narrow spectral band sensors to broadband sensors.

For scientists without considerable expertise of UAVs and remote sensing, it may appear overwhelming to embark on UAV imagery in agricultural research. However, Huang et al. (2013) recommend starting with low-cost UAVs because they are useful and it is not as disastrous if they crash. Low-cost UAVs are easily equipped with consumer-grade cameras such as compact true colour cameras (RGB), which are powerful tools for assessing green vegetation (Saberioon et al., 2014; Torres-Sánchez et al., 2014; Kazmi et al., 2015) or modified consumer cameras with a near-infrared channel (colour-infrared cameras), which are theoretically superior to visible light in vegetation analysis (Jackson and Huete, 1991).

Based on experience, it was evaluated that aerial image acquisition with small rotary-wing UAVs should be possible in most agricultural research environments. The main challenge is not the image acquisition itself, but the image analysis and interpretation. Analysis and interpretation of UAV images lies far behind the interpretation of satellite and ground-remote sensing and have to be fairly straightforward in order to be adopted in agricultural research environments.

The overall objective of this study was to evaluate whether the assessment of field plot experiments using digital cameras mounted on UAVs was straightforward, based on the assumption that the UAV is stable and unproblematic to manoeuver. It was examined whether there were shortcomings related to image acquisition with consumer-grade cameras mounted on UAVs and whether VIs derived from UAV images were just as reliable as ground-based recordings with the same cameras. True colour (RGB) cameras were compared with colour-infrared cameras (CIR), and investigations were carried out to see whether stitching influenced the VI estimates. Stitching is not necessary, but it may ease plot cropping due to a better overview of the experiment. Finally, investigations were undertaken to ascertain whether more advanced ground sensors produced more reliable VIs than VIs based on the ground and aerial images originating from consumer cameras.

2. Materials and methods

Two field experiments on winter barley and spring wheat respectively were used to evaluate VIs based on UAV imagery in spring 2014. Experimental plots were assessed at different growth stages to include a wide range of vegetation cover, and UAV-derived VIs were calculated and compared with ground recordings and subjected to statistical analyses. In winter barley, images were captured in the beginning of stem elongation (BBCH 30) on 30 April 2014 on a sunny day. To investigate the importance of clouds, additional UAV images were captured one week later (7 May 2015) in approximately the same growth stage on a cloud-covered day. In spring wheat, recordings were taken in two early growth stages: growth stage 12 (BBCH) on 28 April and growth stage 22 on 19 May. Both recordings were taken on sunny days.

Two types of UAV-mounted cameras were used-true colour (RGB) and colour-infrared (CIR) cameras–two VIs were calculated for each type of camera and two different software packages were used for stitching. Ground data was acquired with digital cameras (RGB and CIR), a spectrometer and a mobile multispectral imaging platform (Svensgaard et al., 2014).

2.1. Field experiments

Both experiments took place on the experimental farm owned by the Faculty of Science, University of Copenhagen about 20 km west of Copenhagen (55°40′N, 12°18′E). The plots were 1.5 m × 12 m. In winter barley, a factorial split-plot design with 4 replicate blocks was applied, with three sowing dates in autumn 2013 (16 September, 26 September and 6 October) and 4 seeding rates to establish 130, 160, 190 and 220 plants m^{-2} giving 48 plots. The sowing dates applied to the main plots and the seeding rates were subplot treatments. The experiment was investigating the impacts of late sowing and low crop densities because mid-September and 275–300 plants m^2 are considered optimal under Danish conditions.

In spring wheat, a two-factorial randomised complete block design with four block replicates was applied with four Danish spring wheat varieties, Quintus (A), KWS Scirocco (B), Økilde (C) and Hovsa (D) (called A, B, C and D in this study), with differences in terms of earliness and plant height and two nitrogen fertilisation levels (100 kg N ha^{-1} and 200 kg N ha^{-1}), giving 32 plots. Quintus is characterised as a variety with a short maximum canopy height, KWS Scirocco is medium, Økilde is tall, and Hovsa is shot. Quintus matures relatively late, KWS Scirocco relatively early, and Økilde and Hovsa mature late.

2.2. UAV image acquisition

Two types of UAVs were used for image acquisition: a rotary-wing hexacopter (6 rotors) (Hexa XL from MikroKopter, HiSystems GmbH, Moormerland, Germany) and a fixed-wing eBee from Sensefly (Cheseaux-Lausanne, Switzerland). Both UAVs followed pre-programmed route plans to ensure that all the plots were covered by overlapping images. For the hexacopter, vertical take-off and landing were manually controlled using a remote control unit, whereas flights with the eBee were fully automatic.

Two cameras were mounted on the hexacopter to capture nadir JPEG images concurrently every three seconds. The true colour camera was a Canon PowerShot G15 (Canon Inc, Tokyo, Japan) with a 12 megapixel (MP) CMOS sensor (4000 × 3000 pixels), and the colour-infrared camera was a 3-Band NDVI Vegetation Stress Camera (XNiteCanonELPH110NDVI), which is a converted