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Extracting leaf area index using viewing geometry effects—A new perspective on high-resolution unmanned aerial system photography

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ABSTRACT

Extraction of leaf area index (LAI) is an important prerequisite in numerous studies related to plant ecology, physiology and breeding. LAI is indicative for the performance of a plant canopy and of its potential for growth and yield. In this study, a novel method to estimate LAI based on RGB images taken by an unmanned aerial system (UAS) is introduced. Soybean was taken as the model crop of investigation. The method integrates viewing geometry information in an approach related to gap fraction theory. A 3-D simulation of virtual canopies helped developing and verifying the underlying model. In addition, the method includes techniques to extract plot based data from individual oblique images using image projection, as well as image segmentation applying an active learning approach. Data from a soybean field experiment were used to validate the method. The thereby measured LAI prediction accuracy was comparable with the one of a gap fraction-based handheld device (R^2 of 0.92, RMSE of 0.42 m ^{2}m^{-2}) and correlated well with destructive LAI measurements (R^2 of 0.89, RMSE of 0.41 m^2 m^{-2}). These results indicate that, if respecting the range (LAI ≤ 3) the method was tested for, extracting LAI from UAS derived RGB images using viewing geometry information represents a valid alternative to destructive and optical handheld device LAI measurements in soybean. Thereby, we open the door for automated, high-throughput assessment of LAI in plant and crop science.

1. Introduction

Unmanned aerial systems (UASs) are increasingly used for high resolution monitoring purposes (Colomina and Molina, 2014). Particularly in agriculture, it is assumed that large collections of data with high spatial and temporal resolution will facilitate basic research, but also industry-related tasks such as innovative breeding, crop protection, or fertilizer monitoring programs (Walter et al., 2017). Moreover, high-throughput, automated phenotyping approaches for traits such as leaf area index (LAI), canopy cover (CC) or plant height are urgently needed to facilitate the assessment of large breeding populations or precision agriculture approaches (Fiorani and Schurr, 2013; Walter et al., 2015).

Especially plant growth is a trait of enduring interest—the ability to grow is a central driver of yield in crops (White et al., 2016) and an important parameter in assessments in plant ecology (Asner et al., 2003; Moser et al., 2007; Clark et al., 2008). For soybean, growth of canopies is an essential part of the vegetative stage which directly affects yield: Board and Harville (1992) and Malone et al. (2002) could show that higher yield is related to a larger LAI in later growth stages. In addition, Shibles and Weber (1965) showed that larger LAI caused a higher light interception and hence a higher photosynthetic rate. LAI and canopy structure, both essential elements of growth, depend on environment and management practice, but also on genotype (Board and Harville, 1992). It is therefore reasonable to assume that breeding for optimized LAI and canopy structure has the potential to increase and stabilize yield. In plant breeding, it is widespread practice to do visual vigor ratings in early growth stages, which supports this hypothesis. Nevertheless, quantitative methods to monitor canopies and measure their growth are to our knowledge rarely used in phenotyping, even though some of the underlying theory was developed decades ago, for example by Monsi and Saeki (1953).

The description of canopy structure includes characteristics such as LAI, plant height, leaf inclination angles and leaf area density (Monsi and Saeki, 1953; Monsi and Saeki, 2005; Anderson, 1966; Nilson, 1971; Campbell and Norman, 1990). Direct methods to extract LAI are based on the technique of harvesting and measuring the leaf area or leaf dry biomass (Bréda, 2003). In remote sensing, techniques to extract canopy structure information are mainly related to optical reflectance and transmission

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measurements. Calibrated passive transmission measurements combined with gap fraction theory allow to estimate LAI (Monsi and Saeki, 1953, 2005), and are implemented in commercially available products, for example the LAI-2200 from LI-COR Biosciences (Welles and Norman, 1991) or the DEMON instrument from CSIRO (Bréda, 2003), while Campos-Taberner et al. (2016) used affordable smartphone hardware to achieve the same goal. Segmentation approaches aim to classify calibrated or uncalibrated reflectance images in plant and soil, hence gaining a CC value related to LAI (e.g. Guo et al., 2013). Another approach to estimate LAI is based on passive multispectral reflectance measurements, processed with band arithmetic calculations and regression models (e.g. Brown et al., 2000; Colombo et al., 2003; Haboudane et al., 2004; Hunt et al., 2010; Gonsamo and Pellikka, 2012; Reichenau et al., 2016) or inverted radiative transfer models (e.g. Ross, 1981; Myneni et al., 2002; Schlerf and Atzberger, 2006). Hybrid methods combine regression and radiative transfer models (Verrelst et al., 2015). Thermal sensing (Neinavaz et al., 2016) and radar (Jin et al., 2017) represent additional sources for LAI estimations. Nevertheless, while band arithmetic approaches based on all these sources have a restricted power due to the required empirical calibration, radiative transfer models are not widely in use either, most probably due to their complexity and computation power requirements (Jacquemoud et al., 2000; Verrelst et al., 2015). Promising new approaches adapt machine learning techniques to overcome these restrictions (Yuan et al., 2017), and allow to combine different sensing sources like spectral sensing and radar (Jin et al., 2017) or RGB photography, spectral sensing and thermal sensing (Maimaitijiang et al., 2017; Houborg and McCabe, 2018). The vast amount of spectral and other data may even call for dimensionality reduction techniques to estimate biophysical variables (Rivera-Caicedo et al., 2017). Finally, gap fraction theory is also applicable to active reflectance measurements, for example made with an air-borne laser-scanning system (Morsdorf et al., 2006).

To our knowledge, applying gap fraction theory to visual images is yet uncommon: Classification techniques segmenting reflectance measurements in plants and soil are mainly applied to nadir images, with some rare, but promising exceptions (e.g. Liu et al., 2013). In remote sensing, much effort has been put into algorithms compensating for distorted images by ortho-rectification (Luan et al., 2008). Nevertheless, while providing more abundant information for geospatial analyses, the process of ortho-rectification presumably reduces information content for canopy structure analysis, as recently shown by Duan et al. (2017) and Roosjen et al. (2018).

As a consequence, this study focuses on enhancing measurements with viewing geometry information by combining uncalibrated reflectance measurements (by the use of RGB photography), a segmentation approach, and gap fraction theory. The assumption is that including viewing geometry effects (off-nadir views) in RGB photography allows to link canopy structure and remotely sensed visible plant area.

Using the described techniques, the following hypotheses are tested in this study: (1) The projected visible plant area on an RGB image is related to plant traits such as LAI and canopy structure, but also related to other viewing geometry effects such as row interference and leaf overlap. (2) If correcting for the two effects—row interference and leaf overlap—remaining viewing geometry effects are sufficiently related to canopy structure to allow a reliable LAI estimation.

2. Materials and methods

First (Part I), a model was developed describing viewing geometry effects on segmented images using canopy cover (CC) and lateral cover (LC) values, the "CC/LC viewing geometry model" (Section 2.1). This model was then enriched with gap fraction theory, resulting in a combined model performing LAI estimation based on viewing geometry effects, the "gap fraction viewing geometry model" (Section 2.2). In Part II, 3-D simulations were used to verify the models (Section 2.4f.), while in Part III, field experiment data were collected and used to validate them (Section 2.6ff.).

Part I: Canopy structure estimation based on viewing geometry effects

To precisely describe viewing geometry effects on visible plant area, one has to define a suitable coordinate system. The viewpoint of an observer in relation to the observed object can be defined in an celestial coordinate system, the horizon system (Encyclopaedia Britannica, Encyclopædia Britannica, 2017). In this celestial system, the position of an object is specified by the zenith angle θ (the diverging angle to a zenith position) and an azimuth angle δ (the angle clockwise around the horizon from a pre-defined direction) (Fig. 1).

2.1. The CC/LC viewing geometry model

As a simplification, one may assume a single plant leaf to be perfectly planar, to have a certain inclination angle θ_L, to have no preferred azimuth orientation, and a leaf area L (defined as the one-sided leaf area). The leaf area L can then be expressed as leaf area projected to a horizontal plane h, $L_{proj\to h}$, and as leaf area projected to a vertical plane v, $L_{proj\to v}$. The relation between L, $L_{proj\to h}$, $L_{proj\to v}$ and θ_L is Euclidean geometry:

$$L = \sqrt{L^2_{proj\to h} + L^2_{proj\to v}},\quad \tan(\theta_L) = \frac{L_{proj\to v}}{L_{proj\to h}}. \tag{1}$$

If estimating LAI (defined as the proportion of one-sided leaf area per ground surface area, Watson, 1947), one is interested in the leaf area of a whole canopy rather than the leaf area of a single leaf. For soybean, leaf inclination angles are known to change significantly in time, but to be synchronized in space (e.g. Oosterhuis et al., 1985; Rosa et al., 1991; Friedli et al., 2016). If assuming all leaves to have the same inclination angle θ_L at any point in time, the canopy leaf area can be expressed as the sum of single leaf areas,

$$C = \sum_i L_i = \sum_i \sqrt{L^2_{i,proj\to h} + L^2_{i,proj\to v}}, \tag{2}$$

where C denotes the canopy leaf area and L_i the leaf area of the i-th leaf. One can approximate Eq. (2) by replacing the sum of projected leaf areas of single leaves $L_{i,proj\to h}$ and $L_{i,proj\to v}$ by the canopy leaf area

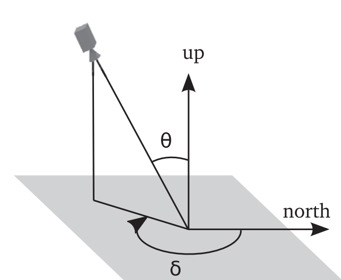

Fig. 1. Viewing geometry parameters in the horizon coordinate system: The zenith angle θ and the azimuth angle δ.