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Research Paper

A mobile sensor for leaf area index estimation from canopy light transmittance in wheat crops

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The leaf area index (LAI) is a key parameter describing the state and progress of crop canopies. Determination of LAI via proximal sensing supports decision-making processes in precision agriculture and improves biophysical modelling. Here we introduce the Canopy-Meter – a mobile sensor designed for determining LAI while driving over the field. The operating principle is based on the transmittance of sunlight passing through the plant canopy. This approach has not been previously applied to a proximal sensor. The sensor setup, its working principle, and the first field measurements are described. The setup of the Canopy-Meter consists of light sensors embedded in the upper and lower end of a tube. While positioned vertically in the plant canopy, the Canopy-Meter measures the above and below canopy irradiation flux. LAI is estimated from the ratio of above and below canopy irradiation through radiation transfer modelling. Spot measurements with the Canopy-Meter were conducted within three wheat fields during growth stages from 45 to 75 (Zadoks). Relationship between the SunScan SS1 LAI and Canopy-Meter LAI was linear for each measurement run (averaged $R^2 = 0.80$) and pooled measurement points ($R^2 = 0.71$). The relationships with biomass were linear and significant. Changing environmental conditions had a minor effect on the Canopy-Meter. The initial online measurements in wheat canopies exhibited a high correlation with the biomass densities observed in aerial photographs and with the reference LAI ($R^2 = 0.86$). The results encourage further investigation on the Canopy-Meter as a new proximal sensor for precision agriculture.

1. Introduction

The leaf area index (LAI), commonly defined as the total one-sided leaf area per unit ground area (Watson, 1947), directly correlates to the density of the foliage in a plant canopy and has become a key biophysical variable in agriculture and many other research fields such as ecology, climatology, and remote sensing. The LAI has been related to crop growth, the fraction of absorbed photo-synthetically active radiation (fAPAR), crop condition, biomass, nitrogen content, and crop yield (Chaudhary, 1987; Ganguli, Vermeire, Mitchel, Wallace, 2000; Stern & Donald, 1961; Yin, Lantinga, Schapendonk, &

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Nomenclature

a	Constant describing the leaf angle distribution
ACS 1–6	Above canopy light sensors of the Canopy-Meter
BCS 1–6	Below canopy light sensors of the Canopy-Meter
I_{ACSx}	Intensity output of the x light sensor above the canopy in arbitrary units (a.u.)
I_{BCSx}	Intensity output of the x light sensor below the canopy in arbitrary units (a.u.)
k_{dir}	Extinction coefficient for direct solar radiation
k_{ind}	Extinction coefficient for indirect solar radiation
LAD	Leaf angle distribution
LAI_{CM}	Leaf area index as measured by the Canopy-Meter
raw LAI_{CM}	sensor-specific unweighted leaf area index by the Canopy-Meter
LAI_{SS}	Leaf area index as measured by the SunScan SS1
MA	Major axis regression (orthogonal regression)
OLS	Ordinary least squares regression
phi	Solar elevation angle in radians
PPFD	Photosynthetic photon flux density (PPFD) in $\mu mol\ m^{-2}\ s^{-1}$

Zhong, 2003) and has been regularly used as an input variable in crop growth and crop yield prediction models (Brisson et al., 2003; Fang, Liang, Hoogenboom, 2011; Steduto, Hsiao, Raes, & Fereres, 2009), ecosystem models (Stockli et al., 2008), and hydrological and climate models (Waring & Landsberg, 2011). Due to its dimensionless property, LAI has been applied from the site-specific scale to the global scale (Wulder & Franklin, 2003). In agriculture, LAI assessment of field crops improves and optimises crop monitoring, modelling, and management (Wallach et al., 2001). For instance, the LAI has served as a measure of canopy density to adapt the fungicide application in cereal fields (Dammer & Ehlert, 2006).

An accurate determination of the LAI is often tedious (through direct or semi-direct methods). It can involve the measurement of leaf area of a subsample of the plant canopy using a leaf area meter and relating it to their dry biomass (specific leaf area, SLA). By collecting the remaining leaves over a specific ground area, the LAI is determined by multiplying the total dry biomass by the SLA (Bréda, 2003; Jonckheere et al., 2004). To make these measurements more efficient and to prevent the destruction of the plant canopy, indirect determination of the LAI has become more popular. Indirect methods at a plot level infer the LAI by measuring the radiation passing through the plant canopy. Essentially, these methods measure only the light that is intercepted by all plant components in the canopy. According to Monteith (1965), light extinction within the canopy is represented by the area of shadow cast on a horizontal surface by the canopy divided by the area of leaves in the canopy; Monteith also suggested that the dry matter production per unit ground area is directly proportional to the light intercepted by the canopy. To infer the LAI, a probabilistic approach is frequently used that includes the fraction of sky seen from below the canopy and the leaf angle distribution (LAD) of the canopy to model the radiative transfer (Bréda, 2003). Based on this principle, many instruments for the determination of the LAI at the plot level have been made commercially available including the SunScan SS1 (Delta-T Devices, Cambridge, UK), AccuPAR LP-80 (Decagon Devices, Pullman, USA), or LAI-2000 Plant Canopy Analyzer (Li-Cor, Lincoln, Nebraska, USA). The SunScan SS1 and AccuPAR LP-80 operate with a pole embedded with photodiodes at a regular spacing, whereas the LAI-2000 uses an ultra-wide-angle lens with a five-ring photodiode optical sensor to measure the below canopy irradiance. Furthermore, an LAI wireless sensor network (LAINet) has been developed consisting of below and above canopy sensor nodes providing a continuous LAI measurement system (Qu et al. 2014).

Although the instruments described above are fast and simple to handle for determining the LAI, they still only allow measurements at specific locations because they have to be hand operated in stop and go mode. However, the plant canopy of agricultural crops is strongly influenced by many factors including soil heterogeneity, dispersal of weeds, plant diseases, field topography, or crop management, so the LAI can exhibit a high spatial heterogeneity across a field and can vary between different fields (Dammer, Wollny, Giebel, 2008; Machado et al., 2002; Stadler et al., 2015). Therefore, some effort has been made to relate the LAI to data derived from passive, optical air- and space-borne remote sensing to allow mapping over larger areas. Several vegetation indices have been found to be suitable for LAI estimation such as the normalised difference vegetation index (NDVI), the red-edge triangular vegetation index (RTVI), or the green NDVI (gNDVI) for various satellite systems (Herrmann et al., 2011; Kross, McNairn, Lapen, Sunohara, Champagne, 2015; Pandya et al., 2006). Vegetation indices from satellite images have become popular to transfer the LAI from field scale to the landscape or even global scale. However, the standard vegetation indices begin to saturate quite early and for LAI values greater than 2–2.5 and canopy closure, the differentiation of the LAI with the NDVI becomes problematic (Heege, Reusch, Thiessen, 2008). Furthermore, the canopy is a three-dimensional structure whereas non-stereoscopic optical approaches from above convey only a two-dimensional image. This also affects other plant parameters, such as the biomass or culm number, so that the relationship between vegetation indices and these agronomic parameters can be described for example as a quadratic polynomial (Dammer et al., 2001). Most standard optical methods for LAI determination suitable for agricultural applications suffer from this problem (Heege et al., 2008).

Different approaches have been tried on the ground using real-time proximal sensors for precision agriculture. A mechanical sensor based on the pendulum principle for measuring crop biomass density, the CropMeter, was developed and tested for site-specific farming (Dammer & Ehlert, 2006; Ehlert, Horn, & Adamek, 2008). Regression analyses between mobile CropMeter measurements and SunScan SS1 LAI readings have yielded significant relationships and the CropMeter was found to be suitable for use in precision plant protection (Dammer et al., 2008). A sensor combination with a radiometer and an ultrasonic sensor was tested for estimating