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On the potential of Wireless Sensor Networks for the in-situ assessment of crop leaf area index

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ABSTRACT

A precise and continuous in-situ monitoring of bio-physical crop parameters is crucial for the efficiency and sustainability in modern agriculture. The leaf area index (LAI) is an important key parameter allowing to derive vital crop information. As it serves as a valuable indicator for yield-limiting processes, it contributes to situational awareness ranging from agricultural optimization to global economy. This paper presents a feasible, robust, and low-cost modification of commercial off-the-shelf photosynthetically active radiation (PAR) sensors, which significantly enhances the potential of Wireless Sensor Network (WSN) technology for non-destructive in-situ LAI assessment. In order to minimize environmental influences such as direct solar radiation and scattering effects, we upgrade such a sensor with a specific diffuser combined with an appropriate optical band-pass filter. We propose an implementation of a distributed WSN application based on a simplified model of light transmittance through the canopy and validate our approach in various field campaigns exemplarily conducted in maize cultivars. Since a ground truth LAI is very difficult to obtain, we use the LAI-2200, one of the most widely established standard instruments, as a reference. We evaluate the accuracy of LAI estimates derived from the analysis of PAR sensor data and the robustness of our sensor modification. As a result, an extensive comparative analysis emphasizes a strong linear correlation ($r^2 = 0.88$, RMSE = 0.28) between both approaches. Hence, the proposed WSN-based approach enables a promising alternative for a flexible and continuous LAI monitoring.

1. Introduction

Crop types, fertilization, irrigation, and crop protection have to be adapted to steadily changing conditions in modern agriculture. An earlier and more precise situational awareness of the site-specific status of agricultural fields is crucial for an efficient and sustainable agricultural management and could also improve the prediction of yield rates. For the realization of a spatial fine-grained and timely situational awareness, there is a high demand for in-situ exploration of bio-physical and bio-chemical crop parameters like fractional cover, biomass, leaf area index (LAI), and fraction of absorbed photosynthetically active radiation (fPAR) by advanced sensor technology.

In this context, LAI is one of the most important bio-physical plant parameters and an indispensable factor in climatological, meteorological, ecological, and agricultural modeling (Asner et al., 2003). It is a valuable indicator and an integrative measure for the photosynthetic performance of plants and its interaction with the atmosphere. Since LAI provides important information for yield models, it also serves as an indicator for yield-reducing processes caused by diseases or mismanagement (Carter, 1994). For flat-leaved vegetation, LAI is commonly defined as the dimensionless ratio of total on-sided foliage area to ground surface area (Jonckheere et al., 2004).

In the last decades, various methods for LAI assessment have been developed. The *destructive* assessment of LAI usually provides the most precise results because the individual leaf area of manually collected leaves is directly measured by planimeters. However, this direct assessment is time-consuming, and, therefore, expensive and often limited to small areas (Bréda, 2003; Jonckheere et al., 2004). In recent years, LAI assessment has been significantly improved by an increasing use of *non-destructive* methods. These methods mainly derive LAI indirectly by measuring a certain quantity that is related to LAI. For that reason, they are also referred to as indirect methods. There exist diverse indirect methods which differ in many aspects and can be grouped into in-situ and remote sensing approaches. The in-situ methods use optical instruments such as ceptometers (e.g., AccuPAR (Decagon Devices, USA) and

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SunScan (Delta-T Devices, UK)) or the LAI-2200 plant canopy analyzer (LI-COR Bioscience, USA) to estimate LAI in the field in a fast and very convenient manner. In this context, Jonckheere et al. (2004) and Weiss et al. (2004) provided a comprehensive survey on common ground-based methodologies. Moreover, various instruments that have become popular and scientifically accepted were extensively reviewed by Bréda (2003). Intercomparisons of these methods comprising specific handheld instruments and also digital hemispherical photography (DHP) approaches were furthermore given by Wilhelm et al. (2000) and Garrigues et al. (2008). All optical methods mentioned above infer LAI from the inversion of *gap fraction*, defined as the fraction of gaps in the canopy, or the fraction of sky seen from below the canopy, respectively. Different statistical and probabilistic gap fraction models, which express the likelihood of a beam penetrating all the way through a canopy without contacting any element of vegetation until it reaches the ground, have been proposed and successfully applied. These models differ in the level of abstraction and simplification and, under certain assumptions, they can be transformed into radiation-based models, describing the relationship between LAI and canopy transmittance. In most cases, these assumptions include a random leaf distribution and a radiation measurement at wavelengths for which the assumption of black vegetative elements is valid (Weiss et al., 2004). On the other hand, LAI assessment derived from remote sensing high-resolution imagery (airborne or satellite) represents an established non-destructive and indirect alternative, but still needs in-situ assessment for model calibration and validation (cf. e.g., Boegh et al., 2002; Jarmer, 2013). Nevertheless, common drawbacks of all available assessment methods are their relatively low temporal and/or spatial resolution as well as the monetary and labor costs.

Wireless Sensor Networks (WSNs) are composed of a large number of small, low-cost, and low-power sensor devices, wirelessly interconnected in a self-organizing manner (Akyildiz et al., 2002). The primary task of each individual device within such a network is environmental sensing of physically measurable parameters, e.g., temperature, humidity, or ambient light. Beyond this data acquisition, each device is responsible for data transmission and forwarding to a central base station, possibly connected to the Internet. As WSNs are designed for large-scale and long-term deployments, the typically battery-driven sensor devices are highly resource-constrained and, thus, have limited sensing accuracy. However, this limitation is compensated by the large number of collaborating devices, which are able to continuously provide sensor information at high temporal as well as spatial resolution. Hence, WSNs are tailored for ground-based monitoring of crop parameters as has been realized by research in the context of precision farming since one decade. A promising progress has already been made in this area (Yuan et al., 2009; Bauer et al., 2014; Qu et al., 2014b). Eventually, WSNs have the potential to reduce time and labor costs of conventional in-situ acquisition and to beneficially assist the validation of parameter maps derived from remote sensing data.

In this paper, we continue our previous approach (Bauer et al., 2014) of non-destructive in-situ LAI estimation. We present a novel low-cost sensor modification that significantly enhances the investigated potential in terms of accuracy and robustness. Moreover, we exemplarily evaluate the benefit of our approach in various maize field campaigns. At the same time, we turn our attention to its feasibility in practice. The core contributions of this paper are:

- the design of a novel low-cost sensor modification for in-situ LAI retrieval,
- six extensive maize field campaigns, and
- an evaluation showing the impact of our approach.

2. Related work

First preliminary experiences in the area of precision agriculture, gained by an in-situ WSN deployment, are shared by Langendoen et al. (2006). The authors reported many engineering difficulties of large-scale and long-term deployments and create a foundation for future WSN research.

Pioneer research in the special domain of non-destructive LAI assessment based on WSN technology is presented by Yuan et al. (2009). The authors propose an iterative scheme to deploy sensors into farmland and apply statistical filters to the raw sensory data in order to cope with variations of light reflection and refraction. Nonetheless, they do not take advantage of any optical filter or diffuser. A continuous LAI monitoring WSN is proposed by Shimojo et al. (2013) and demonstrated using commercial off-the-shelf (COTS) sensor nodes in a tomato greenhouse. The authors emphasize that diffuse illumination conditions are crucial for LAI assessment based on gap fraction analysis. Hence, a diffusing hemispherical plastic cover is used on top of each sensor. LAINet (Qu et al., 2014b) represents another holistic WSN for agricultural LAI monitoring. Recently, Qu et al. (2014a) focused on the in-situ assessment of the clumping index, which is closely related to LAI. Moreover, the authors presented details of MLAOS, a custom multi-point optical sensor system, which provides the basis of LAINet. MLOAS uses optical diffusers and band-pass filters in order to minimize the influence of scattering.

In our previous work (Bauer et al., 2014), we investigated LAI accuracy achieved using a COTS sensor platform by conducting a direct comparison of WSN results and values obtained by conventional standard instrumentation, namely the LAI-2200 (LI-COR Biosciences Inc., USA). Moreover, we suggest the *view pipe* concept as simple modification of the optical sensor, which was shown to significantly improve the correlation between both devices and, thus, the potential of WSNs. However, this approach requires multiple sensors with different view pipes, which hinders the use of a COTS sensor platform and its practicability. Following our previous approach, our general goal is a feasible sensing system with sufficient accuracy for LAI estimation enabling a prospect of a cost-efficient large-scale deployment. Therefore, we focus on a simplistic low-cost realization that is not aimed at providing single results that are more accurate than ones of expensive commercial instruments. In contrast, due to the large number of replicates enabled by a fine-grained spatiotemporal resolution during the crop cycle, reliable estimates are expected to be rendered possible. For the purpose of a low-cost realization, we reuse the chosen open-source sensor platform as a low-cost proof of concept device in this paper. Again, we evaluate the achieved accuracy by a correlation analysis with the LAI-2200 and the coefficient of determination as a metric as also done by Qu et al. (2014b). With regard to the sensor unit, MLAOS (Qu et al., 2014a) is most related with our approach. However, we consider a different range in the solar spectrum and achieve feasible results with a single COTS sensor.

3. Background

3.1. Theoretical background

In the visible (VIS) region of the electromagnetic spectrum (390–770 nm), spectral reflectance and transmittance of vegetation are dominated by the impact of pigments, e.g., chlorophyll and carotenoids. Due to the fact that green vegetation strongly absorbs the energy of radiation in the range of blue (400–500 nm) and red light (600–700 nm) in order to carry out photosynthesis, reflectance and transmittance in these ranges are on a very low level, whereas being higher in the green domain